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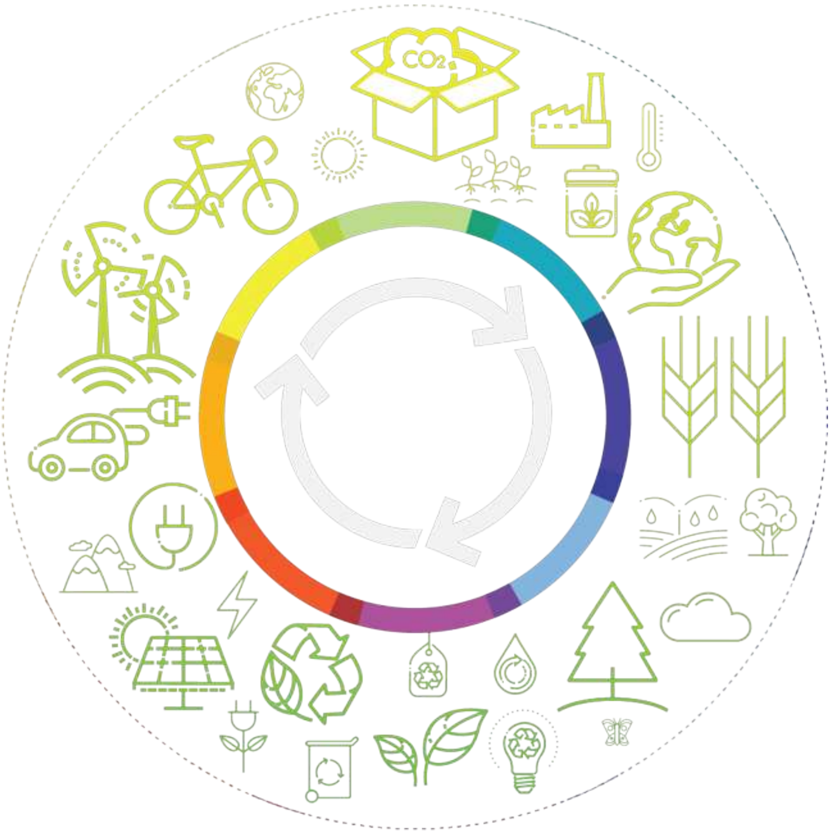
# IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773

## A Clean Planet for all
## A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy



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# 1 INTRODUCTION AND CONTEXT

We are experiencing rising, record temperatures and extreme weather events which impose ever growing costs and threaten the livelihood of all of us. Seventeen of the eighteen warmest years on record have occurred in the 21st century[1]. The message from the recent Intergovernmental Panel on Climate Change (IPCC) report on 1.5°C is clearer than ever before[2]. Human activities have caused around 1°C of global warming to date, we are already experiencing changes in weather and climate extremes, and temperatures continue to rise[3]. If not managed well, these impacts will significantly compromise global human health and safety, development, economic growth, biodiversity and can have an impact on migration flows and spur a downward global spiral of social fragility and conflict. Climate change is a threat multiplier that can undermine – both inside and outside the EU – security and prosperity, including economic, food, water and energy systems[4]. For a discussion on the impacts and concerns for Europe, see section 5.7.

At the same time, combatting climate change in a context of global "mega-trends" – changing demography, technologies, digitalisation - presents an unprecedented opportunity to prepare the European Union for a safe, prosperous and competitive 21st century. The transformation away from a fossil fuel based economy is a vital part of sustainable development, and can be combined with a host of benefits such as improved human health and air quality, greater energy security, more efficient resource use and even more economic and political stability in the third countries. The transformation provides an important opportunity for our long-term competitiveness. As innovation accelerates, and costs of low-carbon technologies continue to fall, it is important to ensure that the EU remains an industrial leader, that citizens are empowered in the process, and, at the same time, to ensure that no-one is left behind. These different dimensions have been brought together in the Energy Union and Digital Single Market[5].

Recognising that climate change represents an urgent threat to societies and the planet, the Paris Agreement sets all countries the goal of keeping global warming well below 2°C, and pursuing efforts to limit the increase to 1.5°C. To achieve this goal, the Agreement also sets out the aim of peaking global greenhouse gas emissions as soon as possible, and achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.

The Paris Agreement also invites all Parties to communicate, by 2020, to the UNFCCC, mid-century, long-term low greenhouse gas emission development strategies. On the basis of the best available scientific knowledge, these strategies should allow our societies to plan and prepare for the long term, and inform policy making in the short term. This assessment supporting the long term strategy explains not only how energy and climate policy measures have developed and continue to evolve; it also highlights the industrial competitiveness consequences and

[1] *European State of the Climate 2017, Copernicus Services of the European Centre for Medium-Range Weather Forecasts (ECMWF) - the Climate Change Service (C3S) and the Atmosphere Monitoring Service (CAMS).* https://climate.copernicus.eu/CopernicusESC

[2] IPCC SR15 (2018), Special Report on Global Warming of 1.5°C

[3] The years 2013-2017 were the warmest five-year period on record and 2018 is set to continue this pattern, see WMO Statement on the State of the Climate in 2017, World Meteorological Organisation (2018); and Global Climate Report - June 2018, National Oceanic and Atmospheric Administration (2018). Climate change is increasing global average temperatures. The recent IPCC report (IPCC (2018) Special Report on Global Warming of 1.5°C) concluded that human-induced global warming reached approximately 1°C above pre-industrial levels in 2017 (see FAQ of the report's Chapter 1), and is currently increasing at around 0.2°C per decade.

[4] See also section 5.6 regarding the impact of climate change and the need to adapt to it.

[5] https://ec.europa.eu/commission/priorities/digital-single-market_en

implications for jobs and economic growth that come with the innovations and technology necessary to deliver on energy and climate goals. Together with the development of the circular economy, the transformation of the energy sector is harnessing a range of technologies and new practices which are changing the way our energy markets and indeed the way our economy work, creating dynamic new sectors and opportunities for jobs and growth and a more prosperous Union.

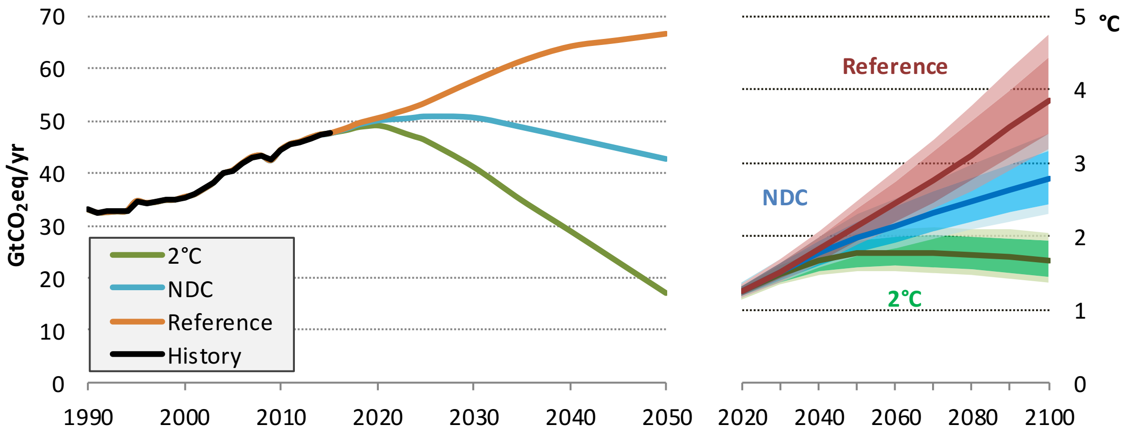
## 1.1 Global and EU action to achieve the Paris Agreement

Keeping average global temperature rise well below 2°C and pursuing efforts to achieve 1.5°C compared to pre-industrial levels will require global action. The Paris Agreement fully recognises this.

In pursuit of Paris Agreement goals, over 190 countries made mitigation pledges to reduce emissions, so called nationally determined contributions (NDCs). The NDCs' collective contribution to the Paris goals has been examined in a number of studies[6] [7]. These clearly show that the NDCs represent a considerable step forward compared to a baseline without global climate action. However, achieving the NDCs would leave global emissions in 2030 above a level consistent with well below 2°C. They are broadly consistent with pathways resulting in 3°C warming by 2100, and, according to the IPCC[8], would not limit warming to 1.5°C even if supplemented by very challenging emissions reduction after 2030. The Joint Research Centre, in its annual Global Energy and Climate Outlook[9], found that achieving the targets of the NDCs[10] would still lead to continued global emission increases in the coming decade, with potential global emissions peaking at 51 $GtCO_2eq$ per year as early as 2025. Assuming a continuation of efforts at this level[11] beyond 2030, would see emissions starting to decrease at a global scale but not at all at the scale required to achieve the well below 2°C objective. Projections instead see these efforts as consistent with a temperature rise of around 3°C by the end of the century (Figure 1).

[6] See for example United Nations Environment Programme (UNEP) (2017), The Emissions Gap Report 2017.
[7] UNFCCC (2016), Aggregate effect of the intended nationally determined contributions: an update.
[8] Unless otherwise stated, references to IPCC in this document refer to the 2018 Special Report on Global Warming of 1.5°C
[9] JRC (2017), Global Energy and Climate Outlook 2017: How climate policies improve air quality, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC107944/kjna28798enn(1).pdf
[10] Both conditional and unconditional NDCs - and including achievement of the US NDC.
[11] Continuing the same level of effort assumes global GHG intensity of GDP continues to decline at the 2020-2030 rate.

**Figure 1: Left: world emissions ($GtCO_2eq$) and percent change in emissions intensity per unit of GDP. Right: global average temperature change.**




*Source: POLES-JRC model (left), used in combination with MAGICC model (right).*

What is clear is that global action presently is changing the global emission pathway but not at sufficient pace. After three years of flat emissions globally, 2017 actually saw global $CO_2$ emissions from energy and industry rising again by +2%[12 13].

The pace of greenhouse gas (GHG) reductions will have to shift strongly at a global scale. The EU has long supported the global objective of reducing global emissions by at least 50% by 2050 compared to 1990 to ensure global temperature stays below 2°C[14]. Recent science[15] confirms that such an objective, with a further decline to near net zero GHG by 2100 or just below, remains consistent with pathways that have a likely chance (above 66% chance[16]) of keeping temperature rise below 2°C this century. This finding is also supported by analysis conducted by the Netherlands Environmental Assessment Agency and JRC for this report (see Figure 2)[17].

Achieving net zero GHG emissions by the end of the century will require significant amounts of negative emissions from the land use sector through for instance afforestation, reforestation and other types of ecosystem restoration or from carbon dioxide removal technologies (CDR) to compensate for the remaining emissions that are hardest to eliminate, for instance non-$CO_2$ emissions related to food production.

Acting to reduce global emissions as quickly as possible will place the world on a safer path and reduce the need for negative emissions technologies later on. A slower pace of emissions reduction by 2050 would require steeper reductions thereafter, including deployment of negative emissions technologies at even greater scale and faster. This may require net negative greenhouse gas emissions towards the end of this century, with a net withdrawal of $CO_2$ from the atmosphere

[12] IEA (2018), Global Energy and $CO_2$ Status Report 2017, p.3 http://www.iea.org/publications/freepublications/publication/GECO2017.pdf

[13] Le Quéré et al. (2017) Global Carbon Budget 2017. Earth System Science Data Discussions. https://doi.org/10.5194/essd-2017-123

[14] European Council Conclusions, 29/30 October 2009

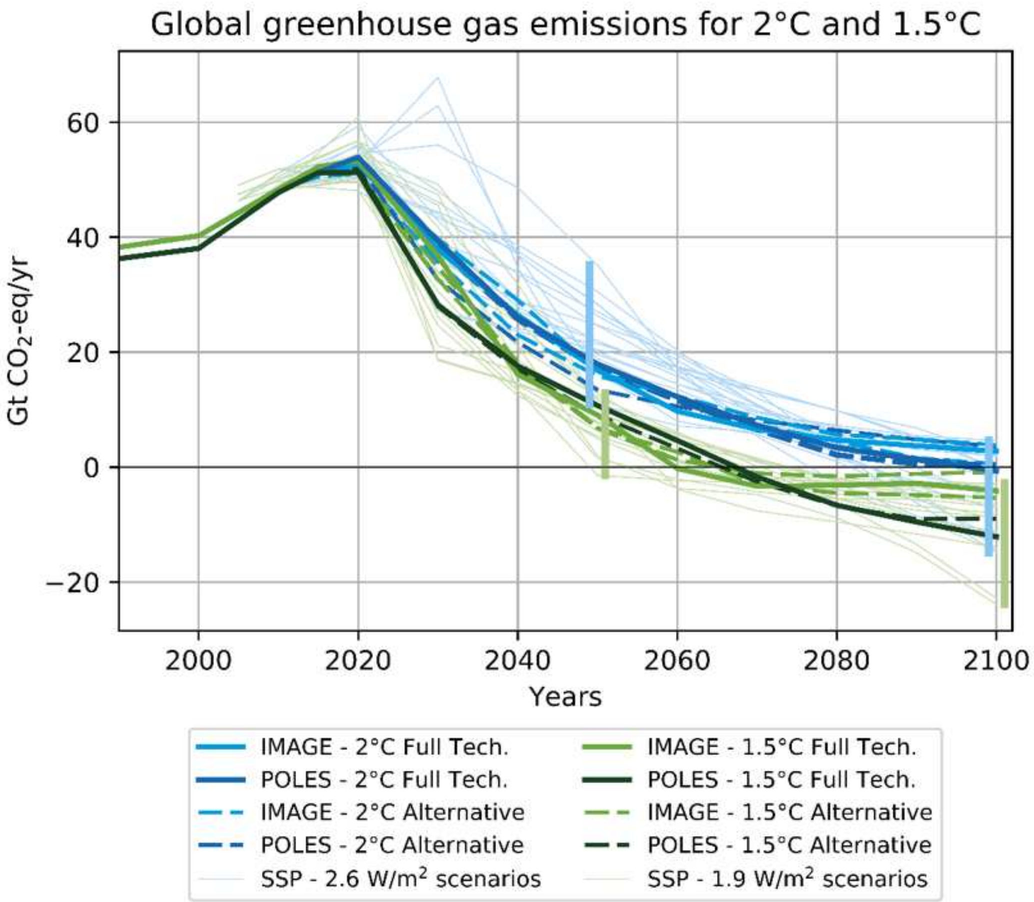
[15] Based on Table 2.4 of the Special Report on 1.5°C, supplemented by EDGAR database and Global Carbon Project to track global emissions from 2010 back to 1990.

[16] While there is no official definition of 'well below' 2°C, studies typically refer to pathways with a >66% chance of keeping global warming below 2°C. The *average* temperature change expected in such pathways is therefore lower – typically 1.7-1.8°C in 2100.

[17] Esmeijer K., den Elzen M.G.J., Gernaat D., van Vuuren D.P., Doelman J., Keramidas K., Tchung-Ming S., Després J., Schmitz A., Forsell N., Havlik P. and Frank, S. (2018), 2 °C and 1.5 °C scenarios and possibilities of limiting the use of BECCS and bio-energy. PBL report 3133, PBL Netherlands Environmental Assessment Agency, The Hague

to compensate for past emissions and, possibly, reduce global temperatures following an overshoot of the 2°C threshold. Moreover, delayed actions to reduce greenhouse gas emissions increases the risk of cost escalation, lock-in in carbon-emitting infrastructure and stranded assets.

**Figure 2: Well below 2°C and 1.5°C projections**




*Source: 2°C and 1.5°C runs from POLES-JRC and IMAGE models, and comparable runs from the scientific literature*[17].

Limiting global warming to 1.5°C requires even greater, and more urgent, action. In a 1.5°C world, typical projections reach net zero GHG emissions by 2070, and become negative afterwards[18] (Figure 2). In such scenarios, global $CO_2$ emissions would have to become net zero already by 2050, as confirmed by the IPCC.

Negative $CO_2$ emissions in energy, industry and land use have to compensate not only for residual GHG emissions but also to correct for possible temperature overshoot by achieving net negative GHG emissions. The IPCC Special Report on 1.5°C is also clear: scenarios with no or low overshoot of the 1.5°C temperature objective, and lower amounts of net negative emissions, tend to be closer to zero GHG emissions globally[2] by 2050.

The EU long-term strategy needs to consider the possible contribution of the EU to such global pathways. The EU already has a strong record of considering the global picture when setting its own climate action targets. Our existing objective for 2050 is to reduce emissions by 80-95% in

[18] See in particular Table 2.4 of IPCC (2018), Special Report on Global Warming of 1.5°C.

the context of necessary reductions, according to the IPCC, by developed countries as a group[19]. It is now time to update the evaluation of the EU's possible contribution to global action, following the entry into force of the Paris Agreement, the adoption of legislation to achieve the 2030 Framework (see Section 2.2) and new scientific evidence, as synthesised in IPCC Special Report on 1.5°C.

The 2050 Low Carbon Economy Roadmap[20] demonstrated that it is feasible and affordable for the EU to reduce domestic emissions by 80% by 2050 compared to 1990, with a milestone of reducing by 40% by 2030. Recent science confirms that the EU's reduction of GHG emissions by at least 80%, including emissions and absorptions of the land use, land use change and forestry sector (LULUCF), remains in line with projections that look at global emissions reduction achieving the well below 2°C objective efficiently (see section 7.3).

To be in line with the 1.5°C objective, significantly higher reductions are needed. Full technology pathways with efficient global action beyond 2020 may see EU GHG reductions, including emissions and absorptions of the land use sector, at around -91% to -96% below 1990 levels in 2050 (see section 7.3).

Such scenarios rely heavily on net negative emissions later on in the century to remove actively $CO_2$ emissions from the atmosphere. If the aim is to reduce the need for large net negative emissions in the second half of the century, higher reductions earlier in the order of magnitude of -100% by 2050 need to be considered, achieving a net zero GHG economy by 2050. This would also be a precaution to avoid carbon lock-in.

By doing so, the EU would confirm its leadership, to inform other countries on the challenges and opportunities ahead and catalyse the global transition in line with the 1.5°C objective (see also section 7.3 for further details).

Therefore the assessment presented in this report in support of the development of the Strategy for long-term EU greenhouse gas emissions reduction in accordance with the Paris Agreement is looking at a range of GHG reduction scenarios, starting at -80% going up to -100% by 2050 compared to 1990.

## 1.2 Europe's need to act to achieve the Paris Agreement

All regions across the globe are facing the disruptive force of major mega-trends. Digitalisation is rapidly changing the industrial environment, simultaneously allowing and requiring continuous innovation. A rapidly emerging global middle class will open new markets placing at the same time constraints on scarce resources. Resource constraints will require our economy to continue efficiency gains to remain competitive, in a context where diverging population trends will constitute a clear challenge for Europe. Last but not least, climate change and its associated challenges are global phenomena that will affect all societies.

Many of these trends are independent from the energy transition: the energy system will have to adapt to these dynamics. At the same time, the energy transition will alleviate the problems caused by resource scarcity and climate change. Moreover, many of these trends will continue regardless of EU policies. Europe should prepare for the changes ahead and the European Union is the framework allowing Member States to adapt collectively.

[19] European Council conclusions, 29-30 October, 2009. The objective is based on the findings of the IPCC Fourth Assessment Report, which represented the best available science at the time of its adoption in 2007.

[20] Communication from the Commission, A Roadmap for moving to a Competitive Low Carbon Economy in 2050. COM(2011) 112 final

The scope of these challenges, the need to develop solutions implementable on a large scale, the importance to weigh in the climate and energy diplomacy and beyond, the international nature of energy fuels and technologies markets and the global repercussions of European consumptions, all contribute to the need of developing a concerted action at EU level.

The value of such action is clear when looking at the role the EU played over the last decade. The EU climate and energy policies contributed significantly to global action and awareness on climate change, clearly leading the world and demonstrating how to address the challenge. Further decarbonisation will increase energy security, while demonstrating feasible economic and technological pathways to a prosperous and sustainable society.

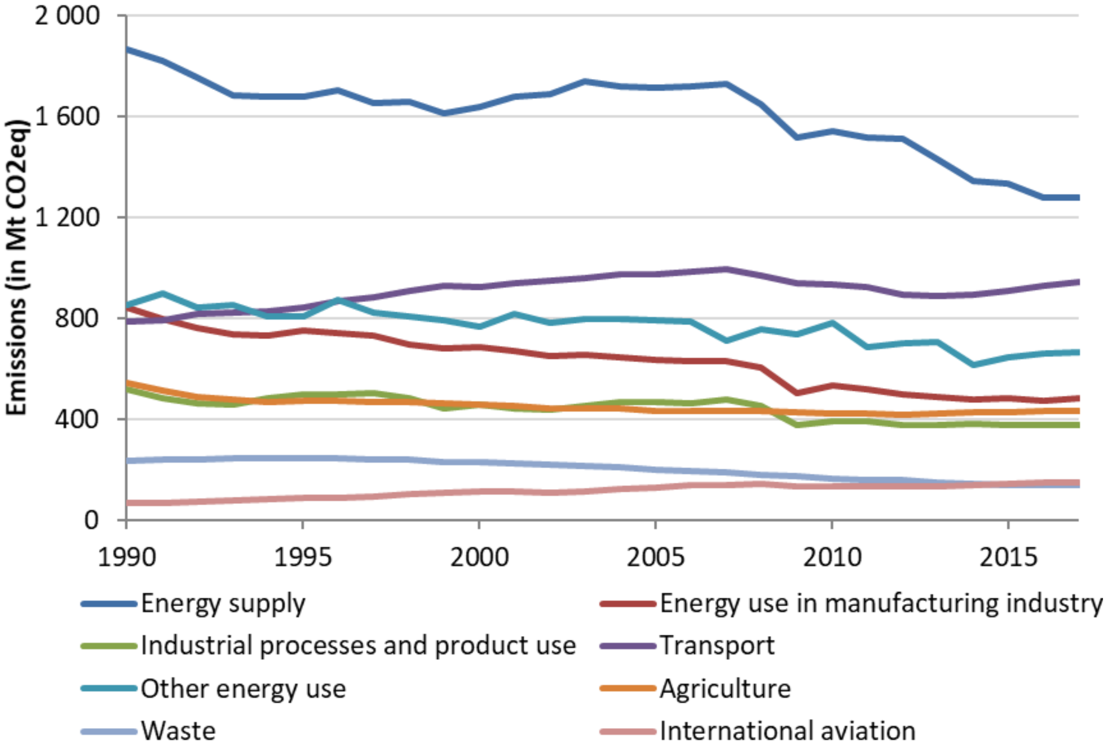
The EU can act as a catalyst of concerted global responses that put multilateralism at their core. This may be through research and innovation programmes, large-scale flagship technology projects, or the development of new industrial strategies and market designs, or simply by its ambition. In a world of large trade blocks competing for technological leadership, the EU needs to act jointly. A core virtue of EU action is bringing together a common vision, resources, financing and regulatory regimes to implement coherent policies action across a domestic market of 500 million people. This is the scale required to deal with the vast global challenges. This was demonstrated with the European drive to promote renewable energy technologies, which scaled up industrial effort, in the EU and around the world, reducing costs to the benefit of the entire world. The public consultation conducted by the European Commission in preparation for this strategy found that there is significant support, both from individuals and from organisations, for the EU to achieve a balance between GHG emissions and removals by 2050 (see section 7.1).

# 2 EU ACTION TO DATE REDUCING GHG EMISSIONS AND TRANSFORMING ITS ENERGY SYSTEM

## 2.1 Decarbonisation and energy transformation to date

Since 1990, Emissions have reduced in all sectors, except for the transport sector (Figure 3). Over the last 3 years changes in emissions were small, with slightly increasing emissions in 2015 and 2017 and slightly decreasing emissions in 2016.

**Figure 3: EU greenhouse gas emissions by sector 1990-2017**




*Source: EEA*[21].

Structural changes in the European economy and policies for supporting renewables and energy efficiency resulted in a decoupling of economic growth from GHG emissions and energy consumption. GHG emissions in the EU peaked several decades ago and continuous decoupling of growth and jobs creation from GHG emissions and energy has been observed since 1990. Between 1990 and 2017, provisional data indicate a total emissions decrease of 22%, while the EU's combined GDP grew by 58%, which implies that the greenhouse gas intensity of the economy was halved in this period[22].

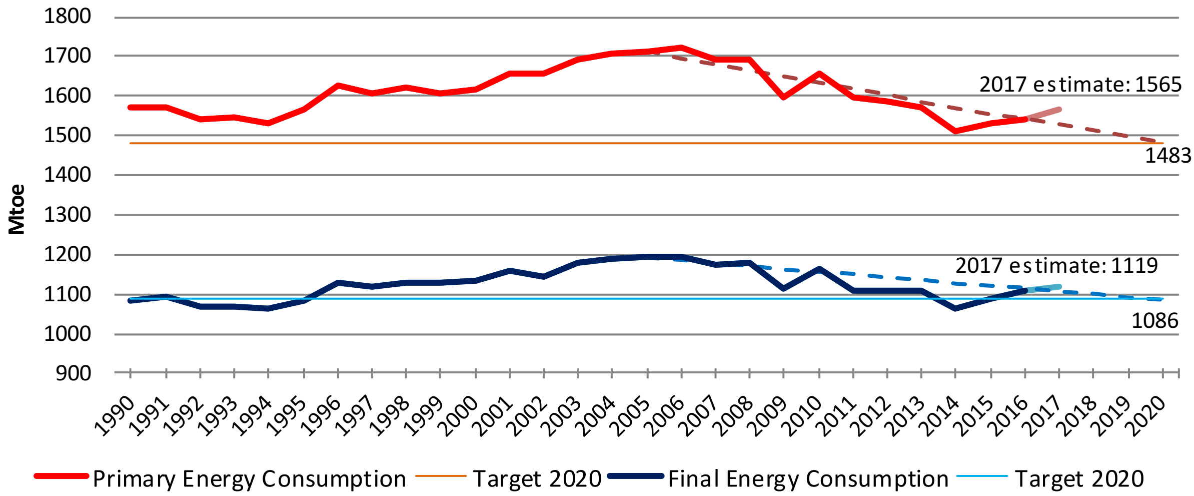
Over the past years, economic growth and energy consumption have also decoupled. The steadily declining demand for energy in the EU is attributed primarily to energy efficiency measures in the Member States.

[21] European Environmental Agency (2017), EU GHG inventory 1990-2016, proxy GHG estimates for 2017.

[22] COM(2018) 716 final

The long-term decoupling trend is clear: in 2016, the EU consumed 2% less primary energy than it did in 1990, while GDP grew by 54% over the same period. EU energy consumption gradually decreased between 2006 (its highest point) and 2014, with the primary consumption reducing by 12% over the period (-1.5% per year) and the final demand reducing by 11% (-1.4% per year). However, since then, energy consumption has started to rise again in part due to colder winters, continued economic growth and lower fuel prices. Statistics show that, in 2016, primary energy consumption was 2% higher than in 2014 and final demand was 4% higher. Preliminary estimates indicate that energy consumption has been further increasing in 2017 (+1.4% for primary consumption and +1% for final consumption compared to 2016). It is clear that with economic growth pushing energy consumption upwards, further efforts are needed in order to reach the 2020 energy efficiency target (primary and final energy have to reduce by respectively 5.2% and 3% over 2018-2020). In this context, a stricter enforcement of the existing legislation is desirable. Figure 4 shows energy consumption trends in the EU.

**Figure 4: Primary and final energy consumption in the EU**




*Source: Eurostat.*

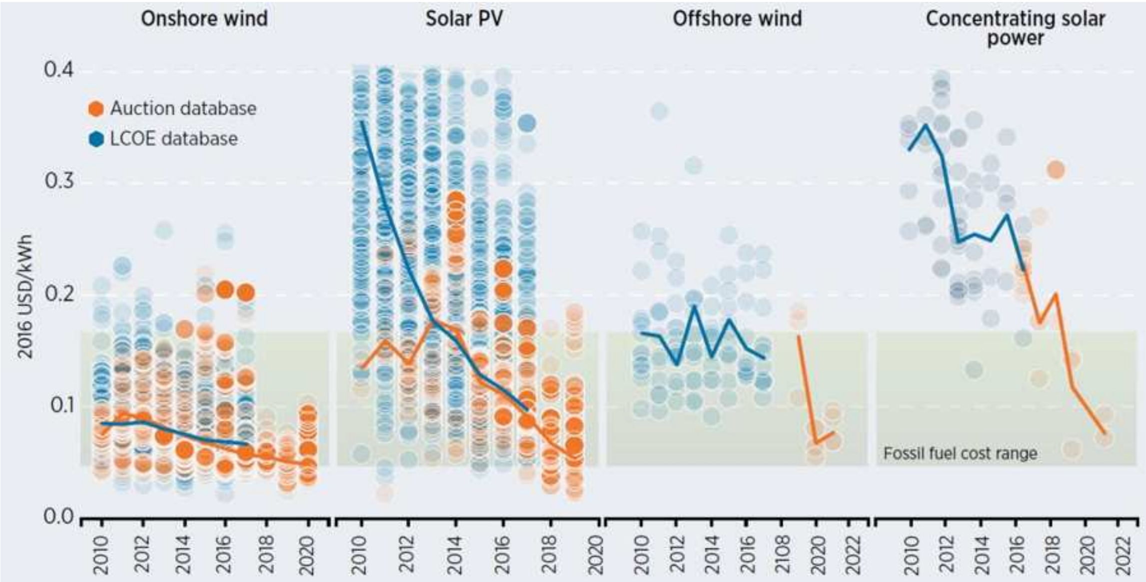
## Renewable energy

In the last decade, policies implemented by the European Union and other frontrunners in the fight against climate change have transformed the energy industry. Support programs worldwide have kick-started a dramatic decrease in the cost of renewable energy technologies (Figure 5**)**. As the IPCC notes in the Special Report on 1.5°C, the energy system transition is underway, and the political, social, economic and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years[23].

Renewable energy technologies such as wind energy, bioenergy and solar photovoltaic are now mainstream market players. Investment in renewable power accounted for two-thirds of global spending in power generation in 2017. The increasing share of renewable energy investments is partly the result of a slump in the commissioning of new fossil fuel capacity (in particular coal-fired power plants in India, China and Europe)[24]

[23] IPCC Special Report on Global Warming of 1.5°C, Chapter 4.
[24] IEA (2018), World Energy Investment 2018, https://www.iea.org/wei2018.

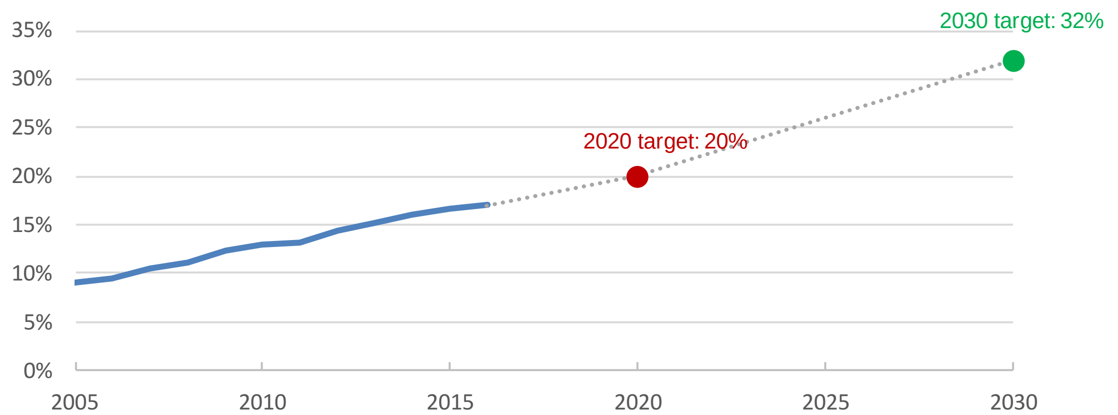
**Figure 5: The levelised cost of electricity for projects and global weighted average values for CSP, solar PV, onshore and offshore wind, 2010-2022**




*Source: IRENA*[25].

Helped by the European support policies, renewable energy has been increasing continuously in the EU, with its share doubling since 2004 when renewables covered only 8.5% of gross final energy consumption **(**Figure 6). In the period 2004-2016, the share of renewable energy grew annually by 6.0% on average. Annual growth slowed slightly to 5.2% in the short-term period 2011-2016. Compared to 2008, direct and indirect employments in renewable energy more than doubled, increasing from 660 000 to 1.43 million jobs.

**Figure 6: Share of renewable energy in gross final energy consumption in the EU**




*Source: Eurostat SHARES tool*[26].

## Electricity

[25] IRENA (2017), Renewable Cost Database and Auctions Database, http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf
[26] https://ec.europa.eu/eurostat/web/energy/data/shares

The power sector has made the most important steps towards decarbonisation with the closure of most inefficient thermal generation, the growth of renewables and the contribution of nuclear (generating together 56% of $CO_2$-free electricity in 2016); better interconnection; more liquid and more flexible markets. Greenhouse gas emissions from the power sector decreased by 26% from 2005 to 2016. Developments in the power market structure allowed integrating an increasing share of variable renewable generation. Connecting markets through appropriate infrastructure and cross border trading rules allowed significant increases liquidity and security of supply significantly. The EU-wide electricity market now allows the aggregation of demand and supply of almost 500 million citizens.

Dedicated infrastructure was built to enable higher penetration of renewable electricity, for instance through interconnection of areas with complementary renewable energy resources or by connecting offshore wind parks to the transmission network. To date, more than 30 Projects of Common Interest (PCIs) have been completed in the power sector and 47 are scheduled to be built around 2020.

**Heating and cooling**

With 50% of EU energy demand that is used for heating in buildings and in industrial processes, renewables have also made an important contribution in this area. Over the period from 2004 until 2016, the renewables share in the heating and cooling sector has almost doubled from 10.3% to 19.1% and provided 99.3 Mtoe. Solid biomass remains the largest contributor with 80% growing from 1.8 Mtoe in 2004 to 78.8 Mtoe of energy in 2016. Other renewable heat solutions has started from very low basis, but has shown rapid growth over the last decade. Heat pumps increased more than fivefold from 1.8 Mtoe in 2004 to 9.9 Mtoe in 2016 and constitutes 9.9% of renewable heat production. Similar spectacular increases were observed in biogas (growing from 0.7 Mtoe to 3.4 Mtoe, (3.5%) and solar thermal (2.1 Mtoe or 2.1%). Renewable waste remains an important heat source (3.4 Mtoe, 3.8%), while direct geothermal heat embarked on a dynamic growth in the last five years (0.8 Mtoe, 0.8% in 2016)[27].

The EU is a market leader in renewable heat technologies. It is second in installed solar thermal capacities and number one in solar district heating. Spain, Greece, Portugal, Cyprus are market leaders in individual solar thermal installations with mandatory solar requirements in new buildings. Large solar installations are used in Denmark, Austria, France, Germany, Sweden, The Netherlands and Poland. In 2017, 9 large-scale solar thermal systems were added in Europe, in Denmark (46% of new capacities), Germany, Sweden and France[28][29].

**Transport**

In 2017, transport emissions excluding international aviation and maritime represented close to 22% of the total emissions. Transport emissions including international aviation and maritime transport emissions were close to 26% of total emissions Transport is therefore a sector with a significant role in the energy and climate policy. Greenhouse gas emissions from transport continue to rise, and in 2017 were 20% higher than in 1990 (excluding international aviation and maritime). Abating transport emissions remains challenging and, in certain regions, the impact of air pollution from fuel combustion on the population is also a concern.

On road, light and heavy duty vehicles are by far the main emitters of greenhouse gas (GHG) emissions from transport. In 2016, it accounted for 95% of all GHG emissions from transport. International aviation is not included in the figures above and account for 3% of total EU

[27] EurObserver, The State of Renewable Energies in Europe, 2017
[28] IEA, Solar Heat Worldwide (2018), Cost-efficient district heating development.
[29] METIS Studies 9 (2018), commissioned by the European Commission.

greenhouse gas emissions. Emissions from international aviation have more than doubled since 1990 (as the improvements in energy and emissions efficiency of aviation have been more than compensated by increase of traffic).

Emissions from road transport experienced a decrease between 2007 and 2013 (-10%) due to increased road vehicle efficiency, high oil prices and slower growth in activity as a result of the crisis. Since then they have started picking up again, driven by the recovery of transport activity in the context of the low oil price environment and economic recovery. Over the last ten years new technologies (electrification) have been penetrating the market, albeit still at relatively slow rates.

The evolution of greenhouse gas emissions in transport follows the evolution of energy use in transport. By 2016, final energy consumption in transport was at similar levels to those observed in 2005. Improvements in energy efficiency of cars, trucks and aircraft counterbalanced the increased transport activity over this period[30]. The impact of modal shift was more limited. Other factors like behavioural change and low capacity utilisation in road freight transport had a negative impact, slightly increasing the energy consumption[30].

The currently dominant transport technologies are tightly linked to liquid fossil fuels. Liquid fuels, with their high energy density, are particularly suited for mobile applications. Oil represented 95% of the energy consumed in the transport sector in 2016: air transport and waterborne transport consume almost entirely petroleum products, road transport depended on petroleum products for 95% of its energy use, but rail transport only 30%.

The EU share of renewable energy in transport reached 7.1% in 2016. Biodiesel remains the most widely used form of renewable energy in transport with 11 Mtoe in 2016, followed by bioethanol with 2.6 Mtoe[31]. However, biofuels consumption slightly declined since 2014, being below the peak levels registered in 2012. Renewable electricity in transport still represents only 1.9 Mtoe in 2016, but its contribution has been significantly increasing recently, with the vast majority of it consumed in rail transport (only around 2% in road transport)[32].

As a result of both EU and Member State level measures, the average specific fuel consumption of the EU passenger cars fleet went down from around 7.4 litres/100km in 2005 to 6.9 litres/100km in 2015[33]. However, after several years of steady decline, the average $CO_2$ emissions of a new car sold in the EU rose by 0.4 $gCO_2$/km in 2017 to 118.5 $gCO_2$/km, according to provisional data published by EEA[34,35]. Since 2010, when monitoring started under current EU legislation, official emissions have decreased by 22 $gCO_2$/km (16%). Nevertheless, further improvements need to be achieved by manufacturers to reach the 2021 target of 95 $gCO_2$/km.

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30 ODYSEE-MURE (2018), http://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/drivers-consumption.html

31 According to Art. 17 (1) of the Renewables Directive, non-certified biofuels cannot be counted towards national and EU renewable energy targets.

32 Eurostat (2018), SHort Assessment of Renewable Energy Sources (SHARES), https://ec.europa.eu/Eurostat/web/energy/data/shares

33 ODYSSEE-MURE (2018), Online energy indicators, http://www.indicators.odyssee-mure.eu/online-indicators.html

34 EEA (2018), No improvements on average $CO_2$ emissions from new cars in 2017, https://www.eea.europa.eu/highlights/no-improvements-on-average-$CO_2$

35 Since 1 September 2017, the 'Worldwide harmonized Light vehicles Test Procedure' (WLTP) has been introduced so that laboratory results better represent actual vehicle emissions on the road. For 2017 EU Member States had for the first time the possibility to report WLTP emission factors, but values were reported for just 7300 vehicles (0.05% of new registrations). According to EEA, the low number of WLTP values means it is not yet possible to provide a representative assessment of the new measurement protocol.

EEA provisional data also show that sales of battery-electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) increased by 42% in 2017. However, the share of these categories in the new fleet remains low, at around 1.5%. Registration of BEVs in 2017 (97 000 vehicles) increased by 51% compared to 2016, while sales of new PHEVs increased by 35%. The largest number of BEV were registered in France (26 100 vehicles), Germany (24 350 vehicles) and the UK (13 600 vehicles). The relative share of BEV and PHEV sales combined in the national car sales in 2017 was highest in Sweden (5.5%), Belgium (2.7%) and Finland (2.6%) [34]. For the first year since monitoring started, petrol cars became the most sold vehicles in the EU ahead of diesel cars, constituting almost 53% of sales.

**Industry**

The industrial sector is an important sector of economic activity, producing a large share of EU GDP and offering employment to a large share of EU population. Moreover, the industry – and especially Energy Intensive Industry (EII) – provides materials and goods that are critical for our way of life: from cement and steel, being the basic materials for constructing the buildings we live in, to plastics and aluminium, used in cars, appliances and packaging. All these materials are produced from industrial processes requiring significant amount of energy and emitting, directly or indirectly, a high amount of GHG emissions.

Industrial activity contributes about 16% of EU's GDP and emits (directly) about 15% of total GHG emissions. In 2015 the energy intensive industry sectors directly emitted approximately 700 million tonnes of $CO_2$, which represents a reduction by more than 30% compared to 1990 levels. This was the second largest source of emissions reduction after the power sector (for production and heat). At the same time, final energy consumption of industry was reduced by about 20%. This was observed especially in the energy intensive industries.

The above changes are due to a combination of factors. On one hand, the EU economy has been restructuring, shifting to an increase of the services sectors and a lower share of the energy intensive industry. On the other hand, industry has been very active in reducing its energy consumption and switching to lower carbon fuels. The energy efficiency investments performed by the industry, together with the increased use of recycled and re-used materials, which require significantly less energy and produce less emissions, were two major drivers for this trend. For example, over the last decades, the recycling rate of paper in Europe has increased substantially from an average of 40% in 1991 to 72.5% in 2016. Moreover certain chemical industries with very high $N_2O$ and fluorinated gases emissions reduced their GHG emissions by 93% between 1990 and 2015.

The situation in the different industry subsectors is not homogeneous. The EU Iron & Steel and the Chemical sectors have reduced their GHG emissions by about 60% between 1990 and 2015. On the other hand, the reductions in GHG emissions for the non-metallic minerals (cement, lime, glass, ceramics) were about half, around 30%. Similarly, the use of low carbon energy carriers, and particularly renewable energy, is mostly limited to the use of biomass resources, e.g. in sectors like the pulp and paper industry.

In addition, the European Commission is working on the European Processor Initiative (EPI)[36] which gathers together 23 partners from 10 European countries, with the aim to bring to the market a low power microprocessor. It gathers experts from the High Performance Computing (HPC)[37] research community, the major supercomputing centres, and the computing and silicon

[36] https://ec.europa.eu/digital-single-market/en/news/european-processor-initiative-consortium-develop-europes-microprocessors-future-supercomputers

[37] https://ec.europa.eu/digital-single-market/en/high-performance-computing

industry as well as the potential scientific and industrial users. This initiative will be buoyed through a Framework Partnership Agreement.

**Land and Agriculture**

The EU's balance of emissions and removals for the land sector ($CO_2$ flux resulting from human management of vegetation and soils, referred to as the natural sink) has remained fairly constant for over two decades, at a little under -300 $MtCO_2eq$/yr, or around 10% of the EU's 2005 EU emissions outside of the Emissions Trading System.

A number of reasons explain this stability since the 1990s. First, the area used for agricultural production has decreased thereby enabling the slow increase in forest area and related sequestration. Second, with the decrease in crop area and an improved technological management of inputs, $CO_2$ released from agricultural soils decreased. Third, European forests are relatively young and annual forest growth (increment) has been strong – although this is projected to decline as the forests age. Fourth, despite increasing forest harvest, on average, only up to 2/3rds of available forest biomass annual increment is exploited, leading to a continued level of carbon sequestration in forests but also in harvested wood products. These positive trends on the LULUCF sink were however partly counterbalanced by steady increase in emissions from settlements.

In contrast to the land sector, agriculture (non-$CO_2$) emissions in the EU28 have declined by over 20% since 1990, or in absolute terms by nearly 150 $MtCO_2eq$ per year. The most important source of the EU's agriculture non-$CO_2$ emissions is nitrous oxide emissions from agricultural soil management. These represent around half of the total agriculture emissions in the EU, mainly due to the application of mineral nitrogen fertiliser. Enteric fermentation emissions of methane gas make up one-third, mainly from cattle and sheep. Emissions of both gases from manure management add a further 16%. Despite historical emissions reduction, maintaining agricultural output can be compatible with a reduction of emission intensities.[38] The decrease so far can be attributed to several factors: on the one hand, productivity increases and a structural decrease in cattle numbers, and on the other hand improvements in farm management practices in general. However, a recent rebound of this trend shows that ensuring future reductions will be technologically difficult and potentially costly.

The impact of increased biomass demand since 2009 on the EU LULUCF sink is so far not very clear, reflecting the interaction of different factors regarding biomass sources. The significant emergence of energy crops on economically marginal agricultural land has yet to materialise, while timber demand has been lower than forecast by Member States in 2011. Forest growth could also have benefited from the double boost of lower harvests and improved fertilisation through atmospheric $CO_2$. Nevertheless, this relatively benign trend could be disturbed and the overall land sink could decrease more significantly through to 2050, partially due to aging of the forests, leading to negative impacts on the EU's overall emissions and removals balance.

In conclusion, the interactions between land uses and the subsequent effect on emission and removals from the land sector is complex. Rules and incentives for food, feed, fibre production and bioenergy may variously support or undermine the historical trend of a stable overall sink in the EU.

**Waste and F-gases**

Greenhouse gas emissions from waste declined from 236 $MtCO_2eq$ in 1990 peaked in 1995 at 344 MtCO2eq and in 2016 were 138 $MtCO_2eq$. Most of the emissions are methane (an important

[38] Fig 3 in LULUCF SWD(2016) 249 final

greenhouse gas, with a 100-year warming potential 28 times larger than $CO_2$[39]), with 124 $MtCO_2eq$ in 2016[40].

The decline is mainly the result of the EU waste legislation. The Landfill Directive[41] diverts biodegradable waste away from landfills and requires recovery and control of landfill gas. The EU Waste Management Framework adds to this by giving priority to recycling and energy recovery over landfilling. In addition, national policies in several member states completely ban landfilling.

Emissions from fluorinated gases (such as HFC and $SF_6$) increased sharply from 72 $MtCO_2eq$ in 1990 to 124 $MtCO_2eq$ in 2014 and have remained stable since (122 $MtCO_2eq$ in 2016). The stabilisation already reflects the F-gas regulation adopted in 2004 as well as the Mobile Air Conditioning (MAC) Directive[42] that limit the use of cooling agents with high greenhouse warming potentials.

## 2.2 EU policies on the way to the Paris objectives

The first explicit energy and climate policy package that addressed emissions reduction at the same time as energy sector reform was the 20-20-20 targets launched in 2007, with the EU Emissions Trading System (EU ETS) improvements, the Renewable Energy Directive[43], the Energy Efficiency Directive[44] as well as the 3rd package of energy market liberalisation[45]. The implementation of the legislation that emerged proved the turning point in creating recognisable change in the energy sector.

### *2.2.1 2011 Roadmaps*

Building on this approach and structure, in 2011 the Commission came forward with three strategic roadmaps based on a consistent analytical framework: the *Roadmap for moving to a competitive low carbon economy in 2050*, the *Energy Roadmap 2050*, and the *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system* (commonly referred to as the *Transport White Paper*)[46]. These Roadmaps presented fundamental aspects of the transition to a low carbon economy in 2050, cost-efficient GHG emissions reduction milestones for 2030, and "no-regret options" – more energy efficiency, higher shares of renewable energy and energy infrastructure development - for the transition towards a competitive, sustainable and secure energy system. These roadmaps cover all sectors of the economy, with a clear emphasis on energy and transport. They jointly serve to demonstrate the consistency, feasibility and credibility of the EU's agreed objective to reduce GHG emissions[47] by 80-95% in 2050 compared to 1990, in the context of necessary reductions by developed countries as a group to limit global warming to below 2°C as stated by the European Council in 2009[19].

[39] IPCC AR5: Myhre et al., 2013.
[40] European Environment Agency data viewer https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer
[41] Council Directive 1999/31/EC
[42] Directive 2006/40/EC
[43] Directive 2009/28/EC
[44] Directive 2012/27/EU
[45] Directives 2009/72/EC, 2009/72/EC, Regulations (EC) 713/2009, 714/2009, 715/2009
[46] COM(2011)112, COM(2011)885, COM(2011)144
[47] Covering all domestic emissions (including agriculture) but not emissions from LULUCF.

The *Roadmap for moving to a competitive low carbon economy in 2050* showed pathways for the EU to cut its domestic greenhouse gas emissions to -80% below 1990 levels by 2050. It defined milestones for a cost-effective pathway towards this objective: a 40% reduction below 1990 levels by 2030 (as later endorsed in the 2030 Climate and Energy Policy Framework[48], see 2.2.2) and 60% below 1990 levels by 2040. All the main sectors responsible for Europe's emissions – power generation, industry, transport, buildings, construction and agriculture – would need to contribute.

The *Energy Roadmap 2050* explored the contribution of the energy sector to such decarbonisation objective (-85% of energy-related $CO_2$ emissions relative to 1990). It set out four main routes to a more sustainable, competitive and secure energy system in 2050: energy efficiency, renewable energy, nuclear energy and carbon capture and storage.

The *White Paper on Transport* defined a mid-century vision for the transport sector that continues to serve the needs of the economy and of the citizens while meeting future constraints: oil scarcity, growing congestion and the need to cut $CO_2$ (-60% by mid-century relative to 1990) and pollutant emissions. To this aim, the White Paper put forward four broad areas of intervention: internal market, innovation, infrastructure, international aspects. For each of these areas, a ten-year programme (by 2020) was defined with 40 specific action points, containing a handful of specific initiatives. The strategy set in the White Paper was to a substantial degree based on low emission fuels, energy efficiency, better multimodality of transport and new technologies that would lead to optimised journeys[49].

These Roadmaps have been instrumental in setting the EU on track with the UNFCCC agenda, setting 2030 targets and exploring the long-term perspective. It was a strong driver for other stakeholders and to develop their roadmaps.

EU legislation governing the reporting of climate related information includes an obligation for Member States to report by 2015 their progress on the development of their low-carbon development strategies. The reported information differs greatly across Member States in terms of type of documents, timeframe, level of details, approach, ambition level, sectors cover and status of legal implementation. A forthcoming report of the EEA summarises the state of reported information, with presently 13 plans reported at Member State level.[50]

### *2.2.2 2030 targets and Energy Union*

Drawing on the analysis presented in the roadmaps and following discussions and guidance from the European Council, the Commission made proposals[51], in 2014, for a policy framework for climate and energy in the period from 2020 to 2030, notably 2030 targets. On this basis, the European Council agreed[52] to the 2030 strategy with targets on reducing greenhouse gas emissions by at least 40%, increasing the share of renewable energy to at least 27%, and achieving an energy efficiency improvement of at least 27%. Legislation provisionally agreed in July 2018 revises two targets upwards to at least 32.5% for energy efficiency and at least 32% for

[48] Conclusions of the European Council of 23 and 24 October 2014.

[49] To date, the Commission has issued proposals in most of the 40 action points of the programme and more than 60% of the initiatives planned could be considered as broadly covered. The White Paper mid-term implementation report of 2016 noted that there was still little progress achieved towards some of the goals, in particular, decreasing the oil dependency ratio and limiting growth of congestion.

[50] Overview of Low-Carbon Development Strategies in European countries Information reported by Member States under the European Union Monitoring Mechanism Regulation, https://acm.eionet.europa.eu/reports/#tp

[51] COM (2014) 15 final. A policy framework for climate and energy policy in the period from 2020 to 2030

[52] EUCO (169/14), European Council Conclusions 24 October 2014

renewables (see 2.2.3) and introduces for the first time, via the Governance Regulation, instruments to ensure coherent long term energy and climate policy planning. The Commission also published its Energy Security Strategy[53] in 2014. The detailed inter-relationships and synergies available in policies and measures addressing decarbonisation *and* energy policy objectives were such that it became clearer that the nexus between energy and climate policies could be drawn even closer together. At the same time, the Commission published its vision of the future of a circular economy[54], bringing together the themes of environmental policy (waste, pollution) with industrial production policy (e.g. recycling and new materials) and with research and innovation policy.

The Energy Union launched in 2015 aimed at exploring and leveraging the synergies between the decarbonisation objectives and other energy policy priorities, by setting broader goals covering five mutually reinforcing dimensions: energy security, internal energy market, energy efficiency, decarbonisation (including renewable energy development), research, development and competitiveness. It is in this context that the most recent initiatives were developed.

An important aspect of the Energy Union is the recognition that citizens must be at the core of the transition. The Commission is thus committed to delivering a new deal for energy consumers helping them to save money and energy through better information; giving consumers a wider choice of action as regards their participation in energy markets; and, maintaining the highest level of consumer protection.

The Commission has by November 2018 tabled the majority of the legislative proposals necessary to establish the Energy Union, and enabling actions are being implemented to accelerate public and private investment and support a socially fair clean energy transition. Further efforts will be required to ensure the completion of the Energy Union by the end of the current Commission's mandate in 2019: not only further progress in adopting the remaining items of the legislative framework but also in implementing the enabling framework and securing the involvement of all parts of society. It should be noted that among those enabling actions, many will have much longer time horizon than 2050: facilitating access to finance or assistance for carbon-intensive regions as the two key ones.

The first legislative deliverable under the Energy Union to implement the 2030 targets was the revised ETS directive[55] which regulates GHG emissions from large point sources (mainly power sector and industry) and aviation. The annual ETS cap reduction was increased with a view of achieving 43% reductions by 2030 compared to 2005, while the Market Stability Reserve was strengthened to address the surplus of EU allowances that has built up historically. This review has already impacted positively the carbon price signal. A second set of legislation, the Effort Sharing Regulation[56] and Regulation on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, regulates emissions and absorptions of the sectors outside the EU ETS. It does so by setting emission trajectories and reduction objectives per Member State, taking into account different capabilities to reduce GHG emissions.

Also within the decarbonisation pillar of the Energy Union and in accordance with Article 40 of the Euratom Treaty, the Commission presented in 2017 the latest nuclear illustrative programme (PINC). The programme provides an overview of developments and investments needed in the nuclear field in the EU for all the steps of the nuclear lifecycle. It underlines that nuclear energy

[53] COM (2014) 330
[54] COM (2015) 614
[55] Directive (EU) 2018/410
[56] Regulation (EU) 2018/842

remains an important component in the energy mix in Europe with a 2050 horizon, as well as identifies some priority areas, such as ways to continuously increase safety, improve cost-efficiency of nuclear power plants and enhance the cooperation among Member States in licensing new and existing nuclear power plants.

The security of supply pillar had also early deliverables: the Regulation on Security of Gas Supply[57] that aims at preventing gas supply crises and ensuring a regionally coordinated and common approach to security of supply measures among the Member States and the Strategy for Liquefied Natural Gas (LNG) and gas storage [58] that outlined future EU action that will contribute to a greater flexibility of gas supply, in particular through LNG and gas storage.

In parallel, the IGA Decision[59], adopted in April 2017 significantly increased the transparency of intergovernmental agreements between Member States and third countries in the field of energy that have become subject to a mandatory ex-ante assessment by the Commission regarding their compatibility with EU law.

For the research, development and competitiveness pillar the Strategic Energy Technologies (SET) Plan has been a key deliverable and crucial component linking EU, Member State and industry action. Following the new strategy as published in 2015[60] public and private parties, at EU and national level, have joined forces to identify targets for R&I in energy technologies in the next 5 to 15 years. These have been turned into 14 implementation Plans that identify concrete action where Member States, industry and the European Commission cooperate to increase the impact of R&I investments.

The majority of legislative proposals building the Energy Union were then delivered as a part of the Clean Energy for All Europeans package (see section 2.2.3) – notably in the field of renewable energy, energy efficiency, internal market operation and remaining aspects of security of supply.

### *2.2.3 Clean Energy for All Europeans*

While an important part of the legislative framework for a 40% GHG emissions reduction target has been established by the revised ETS Directive, the Effort Sharing Regulation and LULUCF Regulation, the two interlinked targets of energy efficiency and renewable energy sources were addressed in the Clean Energy for All Europeans package (CE4AE, also referred to below as "the Clean Energy package"). On 30 November 2016, eight legislative proposals and the European strategy on Cooperative Intelligent Transport Systems in the field of mobility were proposed as part of this package[61]. It was a major milestone in the construction of a robust Energy Union and setting the EU on the ambitious decarbonisation trajectory that was set out with the Paris Agreement.

By November 2018, the European Parliament and the Council have reached an agreement on four of the eight legislative proposals from the Clean Energy package: Energy Performance in Buildings Directive[62], Renewable Energy Directive, Energy Efficiency Directive, and Regulation on the Governance of the Energy Union and Climate Action. Thus, progress and momentum towards completing the Energy Union and combatting climate change are well under way.

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[57] Regulation (EU) 2017/1938
[58] COM(2016) 49 final
[59] Decision (EU) 2017/684 of the European Parliament and of the Council
[60] C(2015) 6317 final
[61] COM(2016)766 final
[62] Amended EPBD entered into force on 9 July 2018.

The novel and robust Governance of the Energy Union and Climate Action Regulation will ensure coherence and better cooperation of Member States' long term energy and climate policy planning and foresee reporting, review and close monitoring of progress. As a result of the Governance Regulation, Member States are expected to establish and to submit their ten year integrated National Energy and Climate Plans (NECPs) by the end of 2019 covering all five dimensions of the Energy Union. These plans will define and explore synergies between Member States' objectives and contributions to the Energy Union goals and, in particular, national targets for the non-ETS sector as set in the Effort Sharing Regulation, national contributions to the EU renewable energy and energy efficiency targets with a view to their achievement by 2030. This will put the EU in a good position to reduce greenhouse gas emissions beyond the 40% target by 2030 and on the decarbonisation trajectory. National energy and climate plans are required to be consistent with both the EU long-term strategy and the national Long Term Strategies to be submitted by January 2020. National Energy and Climate Plans can be updated, for the first time, in 2024 with the requirement that national objectives, targets and contributions can be revised upwards (reductions of net greenhouse gas emissions) or to reflect an equal or increased ambition (energy efficiency, renewable energy sources).

The agreed 2030 EU energy efficiency and renewables targets build on the experience that concrete energy objectives do influence the pace of new technologies development and cost reduction through economies of scale, allowing important benefits be reaped by industries, businesses and citizens. This was experienced over the last decade.

The binding European Union-wide target of at least 32% of renewable energy in gross final energy consumption in 2030 is supported by ambitious measures addressing untapped potential for renewables in heating, cooling and transport. Moreover, measures will be put in place to facilitate the participation of citizens in the energy transition through self-consumption and energy communities and to enhance the sustainability of bioenergy. An ambitious review of electricity market rules underpins the European Union's ambition to further boost penetration of renewables in power.

For energy efficiency, a target of at least 32.5% energy efficiency to be achieved collectively by the EU in 2030 was agreed in the new Energy Efficiency Directive. The Directive also includes an annual energy savings obligation of 0.8% of final energy consumption to be achieved in 2021-2030[63], which will trigger private investments in end-use sectors, especially in buildings, and also in the industry and transport sectors. Other important changes were made to strengthen the rules for metering and billing of thermal energy - especially in multi-apartment buildings with collective heating systems. The revised and improved Energy Performance in Buildings Directive (EPBD) includes measures to strengthen the energy performance of new buildings, to accelerate the rate of building renovation towards greater energy efficiency so as to tap into the huge potential for efficiency gains in the building sector. It also encourages the use of information and communication technology (ICT) and smart technologies to ensure buildings operate efficiently and supports the roll-out of the infrastructure for e-mobility. The Governance Regulation also includes a definition of "energy efficiency first" principle which should now apply across the five

[63] It represents a real annual savings rate to deliver the energy savings obligation from final energy consumption (which also includes energy uses in transport), and the rate of 0.8% is more ambitious than 1.5% (set for the current period 2014-2020) because it is set as a minimum rate to be applied in the calculation of the required energy savings for 2021-2030; the flexibilities may be used only in addition to this minimum. This savings obligation (of 0.8%) would continue to be applicable also after 2030 unless the review by the Commission by 2027 would conclude otherwise. A much lower rate (0.24%) is set for Malta and Cyprus.

dimensions of the Energy Union. This gives recognition to the importance of energy efficiency as a solution in energy planning, policy and investment decisions.

Regarding security of supply, the Commission proposed the Electricity Risk Preparedness Regulation[64]. This addressed the existing shortcomings in the area such as different, often not transparent national rules and procedures and lack of cross-border co-operation. The proposed Risk Preparedness Regulation provided rules on (1) how to assess risks, (2) what a risk preparedness plan should look like, (3) how to deal with crisis situation and (4) how to monitor security of supply.

Regarding the internal market, further (to the existing acquis) regulatory improvements were proposed to the electricity sector to ensure that Europe has the right market design in place to undertake the multiple tasks ahead (notably integration of high amounts of variable renewables in power). The vision behind these proposals is that connecting national markets though appropriate infrastructure and common cross—border trading rules significantly reduces the costs of the energy transition for consumers and enhances security of supply; connected markets require greater coordination and coherence is needed if national markets are to be integrated. If views and requirements for electricity trading, generation adequacy and security of supply converge, markets can function more efficiently and treat market participants more fairly. Such coherence and coordination is also needed to facilitate decarbonisation and energy efficiency objectives.

The Clean Energy package has a very strong consumer focus that is also a leitmotiv of the 2050 decarbonisation strategy. It thus promotes consumers as active and central players in the energy markets of the future. It is designed to facilitate all consumers across the EU having a better choice of supply, access to reliable energy price comparison tools and the possibility to produce and sell their own electricity. The package also proposes further transparency rules and EU-wide regulation principles to facilitate opportunities for citizens to become more involved in the energy system and respond to price signals. Last, but not least, the package also contains a number of measures aimed at protecting the most vulnerable consumers.

### *2.2.4 Industrial policy strategy and strategic value chains*

In September 2017, the Commission adopted the Communication "Investing in a smart, innovative and sustainable Industry – An Industrial Strategy for Europe". This outlined the main priorities and key actions for strengthening Europe's industrial base, including: a deeper and fairer Single Market, upgrading industry for the digital age, building on Europe's leadership in a low-carbon and circular economy, investing in infrastructure and new technologies to drive industrial transformation, supporting industrial innovation on the ground, promoting open and rules-based trade and empowering regions and cities to address challenges. Implementation of the strategy will require a joint commitment from industry as well as all relevant European, national and regional stakeholders.

As follow-up to the Renewed EU Industrial Policy Strategy, the Commission has also established a Strategic Forum on Important Projects of Common European Interest (IPCEI). This expert group will identify by summer 2019 a number of key value chains for Europe, which require well-coordinated action between public authorities and key stakeholders from several Member States, recommend value-chain specific actions and facilitate agreements to take forward new joint investments in those key value chains, including possible new IPCEIs.

[64] Proposal for a Regulation of the European Parliament and of the Council on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC, COM/2016/0862 final - 2016/0377 (COD).

Raw materials have been an important part of the EU's industrial policy since the launch of the Raw Materials Initiative in 2008. In September 2017, the Commission presented its latest assessment of those raw materials that are important or even critical for EU value chains, based on economic importance and supply risk[65]. several technologies that are important for energy system decarbonisation are part of this assessment (e.g. electro-mobility, storage).

### *2.2.5 EU Mobility strategy and mobility packages*

A further major and large sector, critical for energy consumption, emissions and indeed for the functioning of the whole economy, is the transport sector. Here too, the EU has been preparing major advances to improve the functioning of the transport sector and to instil it centrally in Europe's decarbonisation and energy sector strategies. The ***European Strategy for Low-Emission Mobility***[66] was adopted in July 2016. It aims at ensuring that Europe stays competitive and is able to respond to the increasing mobility needs of people and goods, while meeting the challenge of shifting towards low-emission mobility. The Strategy confirms the 2011 White Paper[67] goals: "by mid-century, greenhouse gas emissions from transport need to be at least 60% lower than in 1990 and be firmly on the path towards zero. Emissions of air pollutants from transport that harm our health need to be drastically reduced without delay".

To this end, the *Strategy for Low-Emission Mobility* proposed a comprehensive Action Plan building on three pillars: (1) higher efficiency of the transport system, (2) low-emission alternative energy for transport, and (3) low- and zero emission vehicles, including both legislative and non-legislative action.

The Commission has acted swiftly by adopting proposals on most of the actions listed in the Action Plan of the Strategy, notably through the adoption of the Clean Energy for All Europeans package in November 2016 (which included the European strategy on Cooperative Intelligent Transport Systems), the first Mobility Package in May 2017, the second Mobility Package in November 2017 and the third Mobility package in May 2018.

The ***first Mobility Package*** put forward a first set of eight legislative initiatives with a special focus on road transport[68]. These proposals aimed notably at improving the functioning of the road haulage market, enhancing the employment and social conditions of workers, and promoting smart road-charging in Europe. The Commission also made a proposal, by now adopted, for *a monitoring and reporting system of* $CO_2$ *emissions and fuel consumption for HDV (lorries and buses)* to promote the uptake of the most fuel-efficient vehicles[69]. In addition, a number of non-legislative accompanying documents, presented a wide range of EU policy support measures designed to accelerate the shift to a sustainable, digital and integrated mobility system (investment financing for infrastructure, research and innovation, collaborative platforms, etc.).

The ***second Mobility Package***[70] included legislative initiatives on road transport vehicles, infrastructure and combined transport of goods. The initiatives, including on $CO_2$ standards for cars and vans, public procurement and alternative fuels infrastructure, focus on the reduction of greenhouse gas emissions and air pollutant emissions and aim for a broad take up of low-emission alternative fuels and low-emission vehicles on the market.

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[65] COM(2017) 490 final, 13.09.2017.
[66] COM(2016)501 final
[67] COM(2011)144
[68] https://ec.europa.eu/transport/modes/road/news/2017-05-31-europe-on-the-move_en
[69] Regulation (EU) 2018/956
[70] https://ec.europa.eu/transport/modes/road/news/2017-11-08-driving-clean-mobility_en

With the ***third Mobility Package***[71], the Commission aimed to ensure a smooth transition towards a mobility system which is safe, clean and connected & automated. The package includes legislative initiatives on trucks, a communication on connected and automated mobility[72], and an initiative on battery development. Through these measures, the Commission is also shaping an environment allowing EU companies to manufacture the best, cleanest and most competitive transport-related products.

### *2.2.6 Circular Economy Policy*

In December 2015, the European Commission published its EU Action Plan for the Circular Economy[73], which aims to stimulate Europe's transition towards a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs. The measures foreseen cover the whole cycle: from production and consumption to waste management and the market for secondary raw materials and a revised legislative proposal on waste.

The role of the circular economy to ensure the transition towards a low-carbon economy is already recognised by stakeholders and literature[74].

As part of the measures announced in the Circular Economy Action Plan, the Commission has launched in 2018 the EU Strategy for Plastics in a Circular Economy[75], which targets plastics production and incineration of plastics (that produces every year 400 million of tonnes of $CO_2$).

### *2.2.7 Common Agriculture Policy*

The current Common Agricultural Policy (CAP) provides support to climate mitigation and adaptation, and ensures sustainable management of natural resources and climate action through the following instruments: i) cross-compliance mechanism, representing the compulsory basic layer of environmental requirements and obligations to be met in order to receive full direct payments under the first Pillar ii) “greening" covering a wide geographical range of agricultural area across the EU is expected to improve the overall environmental performance of agricultural production and iii) rural development under the second Pillar which plays an important role in achieving the environmental objectives of the CAP and combating climate change.

### *2.2.8 Cohesion Policy*

Cohesion policy has traditionally been one of the key EU policies for supporting Member States, regions and cities in their development and transition. Over the years, it has, for instance,

[71] https://ec.europa.eu/transport/modes/road/news/2018-05-17-europe-on-the-move-3_en
[72] As announced in this Communication, the Recommendation on the use of pioneer spectrum for 5G large scale testing, cybersecurity and on a data governance framework that enables data sharing, in line with the initiatives of the 2018 Data Package[72], and with data protection[72] and privacy legislation[72] will come in the beginning of 2019.
[73] COM (2015) 614 final
[74] For example according to the International Resources Panel, by 2050, resource efficiency policies could reduce global extractions by 28%. Combined with an ambitious climate action, such policies can reduce greenhouse gases emissions by 63%, and increase economic growth by 1.5%.

Another study from Material Economics and Sitra, focused on sectors with high energy consumption and high level of emissions, like steel, plastics, aluminium or cement. It estimates that the circular economy model could reduce European emissions by 56% (300 Mt) annually until 2050. Globally, emissions savings could reach 3.6 billion of tonnes of CO2eq per year. Even more important: the study shows that the future demand of such materials will lead to emissions exceeding the carbon budget of these sectors, even if implementing energy efficiency and low-carbon measures.

[75] COM(2018028 final

invested in environmental infrastructure, especially in the less developed regions of Europe. For the 2014-2020 period it has been aligned to the smart, sustainable, and inclusive growth priorities of the Europe 2020 Strategy and a number of legal requirements to mainstream climate and sustainable development were introduced (such as earmarking of funds, funding pre-conditions, partnership principle). All this led to considerable re-focusing of the funding and non-funding support (e.g. technical assistance, cooperation, capacity building) available. For example, Cohesion policy will provide EUR 69 billion over 2014-2020 for investments related to all five dimensions of the Energy Union. Close to 50% of these allocations – or about EUR 32 billion – had already been committed to real projects on the ground by the end of 2017. Cohesion policy also supports research and innovation in those areas where regions have competitive advantages, based on a bottom-up identification by industry, researchers and civil society of smart specialisation priorities. For the post-2020 period the support for energy, climate and innovation is proposed to continue with even more focus on cross-sectoral solutions and on innovation to support the transition of all EU regions.

### *2.2.9 Waste policy, F-gas regulations.*

EU waste policy[76] limits landfills while promoting recovery of landfill gas as well as recycling. By 2020 most EU Member States are foreseen to reduce landfilling of biodegradable waste by 65%. An improved waste management following the waste hierarchy is expected to have a significant mitigation potential considering biodegradable and non-biodegradable waste. The revised waste legislation adopted in June 2018 reduces landfilling of municipal waste to 10% of the total amount of this waste category in 2035[77]. This deadline may be postponed by up to 5 years[78].

In 2014, a new F-gas Regulation[79] was adopted to phase-down the total amount of HFCs that can be sold in the EU from 2015 to one fifth of today's sales by 2030. The regulation is expected to result in the reduction of the EU's total F-gas emissions by two thirds compared to today's levels.

The Kigali Amendment, entering into force on 1 January 2019, requires further step down from the EU’s 21% (of the baseline) in 2030 to 15% in 2036.

### *2.2.10 MFF and climate mainstreaming in financing*

The European policy making over a decade has been focused on sustainability and climate change. As the emphasis on decarbonisation increased, more sophisticated measures have been put in place to design and achieve targets. Giving clear policy signals, these targets and policy measures have been crucial to guide investors, allowing world clean energy investments to increase over time (globally USD 360.3 billion in 2015[80]), new technologies to emerge and technology costs to start decreasing in the energy sector. Although the bulk of the necessary capital will have to be mobilised by the private sector, the remaining market failures and barriers provide the rationale for public intervention at a European level and call for European public finance.

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[76] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste

[77] Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste

[78] Directive 2018/850 of 30 May 2018

[79] Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006

[80] Bloomberg New Energy Finance( 2018), Runaway 53GW Solar Boom in China Pushed Global Clean Energy Investment Ahead in 2017, https://about.bnef.com/blog/runaway-53gw-solar-boom-in-china-pushed-global-clean-energy-investment-ahead-in-2017/

The European Fund for Strategic Investments (EFSI) is an example of such interventions. Launched in 2015 in response to the economic downturn, EFSI aimed to unlock additional investment of at least EUR 315 billion over 3 years providing a total guarantee of EUR 16 billion combined with EUR 5 billion contribution from the EIB for business and infrastructure projects. Given its success, EFSI was extended and now aims to mobilise EUR 500 billion of investment in strategic infrastructure and companies, helping to address key market gaps and structural weaknesses to build a more competitive, sustainable and prosperous EU economy. EFSI makes a strong contribution to investments related to the Energy Union. Regular monitoring data indicates that the energy is one of the largest policy area of operations financed under the EFSI, representing 20% of total EFSI support.

The InvestEU Programme is the Union's new investment instrument proposed for the next programming period, built on the success of and lessons learnt from EFSI. The size of the proposed InvestEU guarantee is EUR 38 billion which is expected to mobilise EUR 650 billion investments. It is proposed that 30% of this overall budget will contribute to climate objectives. In particular, 50% of the investments under the "Sustainable Infrastructure" window should contribute to climate and environment objectives.

The long-term budget of the European Union has an important role to play for decarbonisation by supporting investments in and mobilising capital towards climate mitigation and adaptation – including for research and innovation, energy efficiency, renewable energy and network infrastructure. In its 2014-2020 multiannual financial framework (MFF), the EU decided to commit 20% (over EUR 206 billion) of the overall budget to climate change. This climate mainstreaming target has been a useful in integrating climate considerations across the main EU spending programmes. Along with other EU policies, it has supported an increase in average annual investment in the EU energy sector. Concerning the transport sector, the EU research programme Horizon 2020[81] will deploy over EUR 2 billion in the period 2018-2020, focussing on four key energy and climate priorities, including (urban) e-mobility[82].

Reflecting the importance of tackling climate change in line with the Union's commitments to implement the Paris Agreement and the United Nations Sustainable Development Goals (SDG), the Commission has proposed to set a more ambitious goal for climate mainstreaming across all EU programmes, with a target of 25% of EU expenditure, or EUR 320 billion, contributing to climate objectives in the next MFF (2021-2027). The Commission has proposed specific expected contribution for all relevant programmes, including in research, cohesion (see section 2.2.8), common agricultural policy, strategic infrastructure and external action. This commitment reflects our ambition to make the EU a global leader in low carbon technology and to ensure that we achieve our climate and energy targets. Supporting partner countries in achieving the global climate targets represents the external projection of this ambitious internal goal. Catalysing strategic investments, such as those in the energy and mobility sectors is targeted through specific actions, and also identified as a policy goal in horizontal programmes (e.g. Horizon Europe[83], Cohesion Policy, the InvestEU Programme). Budgetary support and technical assistance to areas where large investment gaps exist (energy efficiency in buildings), which are niche areas (cross-border renewable projects), or where the rapid technological and market development has not yet been picked up (capacity building, policy implementation) will provide additional financial

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[81] The EU biggest research and innovation programme, with nearly EUR 80 billion over 2014-2020 https://ec.europa.eu/programmes/horizon2020/en/

[82] COM(2017) 688 final

[83] Horizon Europe is the next EU programme on research innovation that will succeed to Horizon 2020: https://ec.europa.eu/info/designing-next-research-and-innovation-framework-programme/what-shapes-next-framework-programme_en

impetus to decarbonised investments, complementing the programs that have been and will be crucial for constructing a secure, clean and integrated European energy system. Looking beyond its borders, the EU External Investment Plan will aim to leverage private investment to scale up climate finance and closing current finance needs gaps in sectors that are essential for partner countries' transition to low-carbon development paths.

### *2.2.11 Aviation and Maritime sectors*

#### 2.2.11.1 International Aviation

To achieve the temperature goals of the Paris Agreement, all sectors of the economy should contribute to achieving the necessary emission reductions, including international aviation.

In the EU several measures have been taken to address aviation emissions. Air traffic management (ATM), research, development and innovation and sustainable alternative fuels, have the potential to contribute to reducing aviation emissions[84]. The European Union's Single European Sky (SES) policy aims to transform ATM in Europe, tripling capacity, halving ATM costs with 10% less environmental impact. The Clean Sky EU Joint Technology Initiative (JTI) aims to develop and mature breakthrough "clean technologies".

Aviation has been included in the EU ETS since 2012, and has so far contributed to reducing an estimated 100 million tonnes of $CO_2$ emissions between 2012 and 2018 under the EU ETS cap. At its inception in 2012, the inclusion of aviation in the EU ETS also included flights to and from Europe. Presently the EU has limited the scope of the EU ETS to flights within the EEA[85] to support the development of a global measure, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[86], under development in International Civil Aviation Organization (ICAO). CORSIA aims to stabilise $CO_2$ emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020, by purchasing international credits for emissions reduction made elsewhere or by taking actions themselves to limit emissions. Its rulebook for offsetting is still under development.

The next review regarding aviation in the EU ETS has to consider how to amend the EU ETS legislation to take into account the development of CORSIA. In the absence of a new amendment, the EU ETS derogations will end from 2024.

Internationally, the International Civil Aviation Organisation (ICAO) has initiated work for the mitigation of $CO_2$ emissions associated with aviation activities, notably with the two goals: 2% annual fuel efficiency improvement through to 2050; and the stabilisation of $CO_2$ emissions at 2020 levels through a market-based offsetting mechanism. To attain these goals, a *basket of measures* was agreed in ICAO. Next to CORSIA these comprise aircraft-related technology and standards; improved operations and ATM; development and deployment of sustainable aviation fuels[87] [88]. The $CO_2$ standards for new aircraft adopted by ICAO in 2017 will be implemented in EU law in early 2019.

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[84] European Environment Agency (EEA), European Aviation Safety Agency (EASA), EUROCONTROL. (2016). European Aviation Environmental Report

[85] Regulation (EU) 2017/2392 of the European Parliament and of the Council of 13 December 2017 amending Directive 2003/87/EC to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 2021

[86] ICAO. (2016c). Resolution A39-3: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme.

[87] ICAO. (2016a). Resolution A39-1: Consolidated statement of continuing ICAO policies and practices related to environmental protection – General provisions, noise and local air quality.

In addition, it should be pointed out that the international aviation industry, which had originally proposed the "2020 carbon neutral growth" objective, also agreed on an aspirational goal to reduce net emissions from aviation by 50% by 2050 compared to 2005 levels[89].

#### 2.2.11.2 International Maritime Shipping

Following up on the 2011 EU White paper on transport, the Commission adopted in 2013 a strategy on the decarbonisation of shipping, calling for a gradual approach in the EU, starting with an EU monitoring, reporting and verification (MRV) scheme. As a result, the European Parliament and the Council adopted in April 2015 the Regulation (EU) 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport. This EU MRV scheme will start providing information on ships' efficiency to relevant markets as from June 2019.

Meanwhile, the International Maritime Organization (IMO) started working on the reduction of GHG emissions in 1997, but the first measure was only adopted in 2011 with agreement on a mandatory minimum efficiency standard for new ships (Energy Efficiency Design Index, EEDI) and the obligation for ships to carry energy efficiency management plans on board. In 2016, following the entry into force of the Paris Agreement and the adoption of an EU Monitoring, Reporting and Verification Regulation, it adopted an amendment to the MARPOL Convention[90] and specific guidelines for a Data Collection System (IMO DCS) to report fuel consumption of ships to flag States as from 2019. Finally, after two years of negotiation, IMO adopted in April 2018, an initial strategy on the reduction of GHG emissions from ships with the objective to reduce emissions by 50% by 2050 compared to 2008 while pursuing efforts to achieve full decarbonisation as soon as possible in this century.

### *2.2.12 The need for new vision*

Drawing all of the different policy threads together through the Energy Union, the Paris Agreement as well as the economic technological, societal changes and advances that have occurred over the last decade require an updated analysis to elaborate a decarbonisation strategy fully integrated within the Commission’s political priorities, notably: jobs and growth, further integration of the internal market, a fairer and more sustainable economy and making the EU a stronger global actor. The technological developments have been particularly prominent, reshaping energy supply as well as affecting consumer behaviour. The growing consumer awareness and resulting change in consumption patterns will influence how the markets will develop in the future taking also into account the growing role of consumers and new business models spurred through the digitalisation of the economy. The demand side sectors will be shaped by more optimal consumers' and businesses' choices leading to the smarter use of energy, sustained by widespread automation and digitalisation, accurate and useful consumer information, ambitious standards and targeted policies addressing the remaining market and regulatory barriers and behavioural biases.

On the energy supply side, contrasted technological developments over the last decade, with, in particular, lower than expected costs for certain renewable energy sources on the one hand and higher than expected challenges for CCS on the other hand, have changed the perspective when looking at a future decarbonised energy system for the EU. In addition, rapid development of

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[88] ICAO. (2016b). Resolution A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change.
[89] Air Transport Action Group (ATAG)) https://www.atag.org/our-activities/climate-change.html
[90] International Convention for the Prevention of Pollution from Ships

technologies has made some actors willing to look at future alternative low-carbon energy carriers: hydrogen and e-fuels (synthetic fuels produced from decarbonised electricity).

Energy storage emerges as a key enabling technology for addressing the flexibility requirements for integrating variable renewable electricity into the grid and for providing green electricity for electrified transport, industry and buildings sectors (and thus providing further rationale and helping the sectoral integration). Large amounts of variable RES can actually be stored in the form of hydrogen and e-fuels, capable of providing significant flexibility to the electricity system and decarbonising other sectors. The expectations of new technologies in delivering on the Paris Agreement goals is well illustrated by the fact that the Agreement itself was flanked by the launch of Mission Innovation[91], complementing the Clean Energy Ministerial (CEM[92]) created during COP15 in Copenhagen (2009), two global inter-governmental initiatives aiming at accelerating clean energy innovation and making clean energy widely affordable.

It has to be also noted that deployment of some technologies (e.g. for electric vehicles) raise some concerns in terms of future supply of raw materials. These issues make the implementation of circular economy approaches even more desired – not only to reduce direct emissions[93] but also to avoid possible future obstacles of this nature in the deployment of new technologies.

Recent years have also seen significant changes on other fronts than energy technologies that also have or will have impacts on decarbonisation pathways. Notably in the field of mobility connected and automated driving is shifting the paradigm towards 'mobility as a service', 'accessibility' and 'connectivity', which will have potentially big impacts on safety, efficiency and emissions. Considering behavioural change is now possible either, partly because technology progress made certain solutions easily available to consumers (e.g. own energy production from renewables, better control of indoor temperature or more effective travel planning mindful of the carbon footprint). Consumer awareness has also grown that certain choices can lessen the carbon footprint and yield side-benefits, notably on health improvement. Limiting food waste, engaging on active mobility or healthier diets are now mainstream consumer considerations in Europe and other options could follow this suit, including limiting fast growth in long distance travel and shifting to more sustainable transport modes like rail, or limiting the purchase of new consumer goods. These aspects are discussed more in detail in section 5.5. Importantly, the growing consumer awareness and role of consumer choice will have impact on the delivery of the new vision - with increased role of the citizens, organised civil society, local and regional authorities in the governance.

## 2.3 Policy initiatives at national level

### *2.3.1 The implementation of the EU acquis*

The swift and complete national transposition and implementation of the EU acquis by the Member States, complemented with appropriate national actions, is a primary precondition for the delivery of the decarbonised, more competitive and dynamic economy that Europeans seek. The following illustrates the different areas of the EU acquis in the areas of climate and energy, and complements this with examples of national measures.

Security of energy supply also has a significant EU acquis that builds on national measures in the electricity, oil, gas and transport sectors. This includes the oil stocks directive, infrastructure

[91] Mission Innovation (2018), http://mission-innovation.net/
[92] Clean Energy Ministerial (2018), http://www.cleanenergyministerial.org/
[93] Recycling is generally less energy intensive than extraction.

planning or generation adequacy coordination, all areas where regional cooperation and trust would strengthen the situation of the EU and its members. This is currently being fostered through so-called “preventive action plans” and “emergency plans” that are to be notified to the Commission by 1 March 2019 and updated regularly, the conclusion of “solidarity arrangements” containing technical, legal and economic details and the preparation of national risk preparedness plans.

In the area of energy production and transmission infrastructure, Member States formulate and coordinate among each other national infrastructure development plans to manage the adequacy of their energy production, including their maintenance and extensions. Such plans are developed and implemented in conjunction with TEN-E policy, including the identification and co-financing of projects of common interest (PCI). Some 77 PCIs will have been finalised by 2020 and received EUR 2 billion from the EU. The EU has also developed the most advanced legal framework for nuclear energy, ensuring that those Member States who chose nuclear are complying with the highest safety and security standards.

Regarding energy efficiency, the Energy Efficiency Directive (EED) requires that energy efficiency policy measures are taken at national level and reported in the National Energy Efficiency Action Plans (NEEAPs). These should target each sector of the economy (residential, services, industry, transport and energy supply). The types of measures include regulations, standards, funds, financial & fiscal measures (including taxation and incentives and other market-based instruments) and awareness raising, knowledge & advice as well as education, qualification and training.

The residential and service sectors benefit from a wide range of national policy measures to support energy efficiency improvements. In addition to the regulatory measures directly in relation to the Energy Performance of Buildings Directive and specific Eco-design Regulations, measures have been enacted to address split incentives or strengthening energy efficiency requirements for buildings. Typical instruments used for this include grants, low-interest loans and fiscal incentives or more innovative programmes such as energy performance contracts, guarantee facilities, possibly combined with grants and technical assistance, on-bill recovery, Property Assessed Clean Energy (PACE) type financing (proposing low-cost, long-term funding to be repaid as an additional payment on a property’s regular local property tax). Information and awareness-raising measures have also been implemented with the focus on residential and service sectors. In addition, various Member States have mentioned in their NEEAP on-going or planned efforts related to alleviation of energy poverty.

National measures to achieve the energy savings obligation of 1.5% each year by 2020 (from annual energy sales to customers) will be key for the 2020 energy efficiency target. Energy efficiency obligation schemes (putting an obligation on energy distribution operators or energy retail companies) are a key instrument since they trigger private investments in residential or services sectors through for example installation of more efficient heating or cooling systems and insulation of walls or roofs. The obligation schemes will remain an important market based policy instrument in view of achieving the new savings obligation for the period 2021- 2030[94].

Regarding decarbonisation, the EU Emissions Trading System (EU ETS) and the EU Effort Sharing Regulation (EU ESR) covering non ETS sectors form the core regulatory framework set in place to reach the consecutive emissions reduction targets. This is complemented with legislation ensuring that emissions and removals from Land Use, Land Use Change and Forestry (LULUCF) are at least neutral and sectoral regulations that set $CO_2$ emission standards for

[94] For the period post 2020 annual energy savings obligation of 0.8% of final energy consumption are to be pursued see the section 2.2.3.

passenger cars and vans, regulate emissions of F-gases, and increase the deployment of renewable energy.

Regarding renewables in particular, Member States are implementing their national renewable energy action plans (NREAP) and are nearly all on track to deliver their 2020 national binding targets. By implementing these renewable energy plans Member States reduce emissions, increase the indigenous energy supply, create new jobs, and drive innovation and technological and industrial development. At the same time, renewable energy requires that more 'intelligent' transition infrastructure is put in place and that energy systems are integrated on a larger scale throughout Europe, which in turn requires more coordination and synchronisation across Member States to ensure the internal market functions properly and energy resources flow efficiently between Member States. High shares of renewables requires additional actions in terms of sectoral integration of energy supply and demand, with contributions from the transport sector, heating and cooling or industrial processes. Such integration will take place through the development of decarbonised energy vectors, including electricity but also newer vectors like for instance hydrogen. A strong reflection of the interest of the Member States in this area is the Hydrogen Initiative launched by the Austrian presidency and signed in Linz in September 2018[95].

Regarding research & innovation, whilst in the EU private investments constitute around 80% of R&I spending, national and EU R&I programmes complement and add steer, also fostering efficiency and cooperation among stakeholders when embarking on the large projects for the development and demonstration of new technologies, materials and processes needed for the energy transition.

Better governance and policy planning: Integrated National Energy and Climate Plans will streamline many of the previously existing planning, reporting and monitoring requirements will promote coherent progress towards EU-level targets and policies. The National Plans will address, in a transparent manner, national targets, objectives and contributions across all five Energy Union dimensions from 2020 onwards. National Energy and Climate Plans will also include policies and measures underpinning the delivery of those targets, thereby allowing for a close political monitoring of progress towards targets and of interactions between different policies. A solid analytical framework should explore and illustrate the impacts of proposed targets policies and measures. The Plans will also promote a broader engagement of EU general public and stakeholders on Member States long term energy and climate priorities and enhance coordination between Member States in their policy planning efforts.

### *2.3.2 Additional national policies*

Some policies are not explicitly required under the EU acquis and while well aligned with the EU climate and energy policies, they are largely dependent on national considerations. The most notable examples are the coal phase-out, nuclear power deployment/phase-out and carbon tax as well as urban planning. In the transport sector, a wealth of measures has been adopted at national level to incentivise modal shift and the uptake of alternative fuels, including electro-mobility: purchase subsidies, registration tax benefits, ownership tax benefits, company tax benefits, VAT benefits, local incentives and infrastructure incentives. Also forest and land policies which are important components of decarbonisation strategies are mostly in Member State competences.

Coal phase-out

[95] Non-binding, this initiative still shows a strong support to hydrogen as an enabler of the energy transition: storage, sector coupling, injection in gas network, use by the industry or for the production of synthetic fuels: https://www.hydrogeneurope.eu/sites/default/files/2018-09/The%20Hydrogen%20Initiative.pdf

Ten EU Member States have announced coal phase-out and European utilities represented in EURELECTRIC have recently announced their intention not to invest in new coal plants after 2020[96]. While decarbonisation is a very important consideration for them, there are also other drivers. In the EU, coal consumption has fallen by 34% since 1995 and production by 53%. Thus the EU coal import dependency has increased (to 40%) even though its share in total EU energy mix has decreased to 15%. Russia still provides 30% of EU hard coal imports, including 100% of imports by Estonia and Lithuania, 97% by Greece, 94% by Latvia, and smaller share for Poland. Thus there are not only climate reasons but also security of supply reasons to reduce EU coal consumption. The recent national announcements of coal power plants phase-out is expected to lead to further reduction of coal demand, with repercussions for gas, renewables and nuclear, and to contribute to the reduction of overcapacity in the power generation system. Mitigating social repercussions, especially when related to national coal-mining activities, will be facilitated by the "Coal Regions in Transition" platform[97], a policy instrument that will support development of the accompanying strategies required for the transition.

Nuclear power

The EU Treaty allows each Member State to decide on its energy mix[98], including on the role of nuclear which represented 26% of EU power production in 2016[99]. The countries which plan to keep or develop nuclear energy as one of their energy sources share the view that it can contribute to energy security, competitiveness and cleaner electricity. Both the Energy Union Strategy[100] and the European Energy Security Strategy[101] stressed that Member States that decide to use nuclear energy need to apply the highest standards of safety, security, waste management and non-proliferation as well as diversify nuclear fuel supplies.

At the end of 2017, 126 nuclear power reactors were in operation in fourteen Member States[102] [103]. New build projects are envisaged in ten Member States, with four reactors already under construction in Finland, France and Slovakia. Other projects in Finland, Hungary and the United Kingdom, are under licensing process, while projects in other Member States (Bulgaria, the Czech Republic, Lithuania, Poland and Romania) are at different stages of preparation. The United Kingdom has announced its intention to close all coal-fired power plants by 2025 and to fill the capacity gap mainly with new gas, biomass and nuclear power plants. On the other hand, some national energy policies have fixed a ceiling for the share of nuclear in their respective range of energy generation sources (e.g. France), others (e.g. Germany and Belgium) have decided to gradually phase-out from nuclear while other Member States have never used nuclear energy.

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[96] EURELECTRIC (2017), European Electricity Sector gears up for the Energy Transition, https://cdn.eurelectric.org/media/2128/eurelectric_statement_on_the_energy_transition_2-2017-030-0250-01-e-h-E321F960.pdf

[97] European Commission (2017) https://ec.europa.eu/energy/en/events/conference-coal-regions-transition-platform

[98] Lisbon Treaty, Article 194, paragraph 2 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:12012E194&from=EN

[99] European Commission (2018), Statistical Pocketbook 2018 https://ec.europa.eu/energy/en/data-analysis/energy-statistical-pocketbook

[100] COM(2015) 80

[101] COM(2014) 330

[102] IAEA (2018), Nuclear Power Reactors in the World, Edition 2018 https://www-pub.iaea.org/books/IAEABooks/13379/Nuclear-Power-Reactors-in-the-World

[103] These Member States are Belgium, Bulgaria, the Czech Republic, Finland, France, Germany, Hungary, the Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

The importance of long-term operations is expected to increase in the coming years, and by 2030 the majority of the fleet would be operating beyond its original design life. Long-term operations are expected to represent the majority of nuclear investments in the short to medium term. Regulatory approval has been already granted for operational lifetime extension of certain nuclear power reactors in some Member States (e.g. Hungary and the Czech Republic). Decisions on operating lifetimes depend on current and forecast electricity market conditions and sometimes also on social and political factors. Such decisions are subject to a strict and comprehensive safety review by the competent independent national regulator, and as a basic requirement the highest safety standards have to be implemented[104].

Carbon taxation

Some Member States have adopted systems that levy taxes related to $CO_2$ emissions. There is lot of heterogeneity in term of scope and implementation of these policies across the Member States. Most commonly, these taxes target the transport sector either by applying registration or circulation taxes based on vehicle emissions or transport fuel taxes based on the carbon content or the efficiency of the fuel. Several Member States have broadened the scope of fuel carbon taxes to other sectors than transport.

## 2.4 Regional cooperation

In many policy fields, regional cooperation fosters synergies and complementarities across Member States as well as with neighbouring countries. It is very important in the context of energy and climate policies, considering, for example, the need to pull common resources for financing research and innovation, building infrastructure, development of large projects such as renewable energy in the North or Baltic Sea or facilitating the access to financing for capital-intensive projects. It is thus highly relevant for the Energy Union, and will certainly help the clean energy transition in the medium and long term. Whether the EU applies a single European scheme (e.g. the EU ETS), adopts legislation or fosters and coordinates cooperation amongst energy regulators, including for instance on agreeing on the necessary rules for electricity trading and grid operation in the respective regional groups defined under the EU Network Codes and Guidelines, the lesson is that coordination, cooperation and integration brings clear mutual benefits in this policy field.

Against this background, the Governance of the Energy Union Regulation requires Member States to engage in regional coordination both in the preparation and the implementation of their National Energy and Climate Plans. Regional coordination also required in the context of infrastructure planning and the joint development of projects of common interest.

A number of regional cooperation fora dedicated to energy issues are already set-up and will undoubtedly play a role in the clean energy transition process. Such fora include the Baltic Energy Market Interconnection Plan (BEMIP), the Central and South-Eastern Europe Connectivity (CESEC), the Central-West Regional Energy Market (CWREM), the North Seas Countries' Offshore Grid Initiative (NSCOGI), the Pentalateral Energy Forum, Interconnections for South-West Europe and the Euro-Mediterranean Partnership.

Further, the contribution of transnational initiatives like Macro Regional Strategies should be fully exploited notably to build the political momentum necessary for scaling-up. There are currently four EU Macro-Regional Strategies concerning 19 EU Member States and 8 non EU countries which cover the following macro-regions: the Baltic Sea Region, the Danube Region,

[104] COM(2017)237 final

the Adriatic and Ionian Region, and the Alpine Region. They have shown the importance of strengthening cooperating among Member States for maximising synergies by acting at transnational level, pooling resources together and should lead to efficiency gains.

Cooperation with non-EU partners is also taking place, including with the Energy Community contracting parties[105], members of the European Free Trade Association[106] and, when appropriate, with other third countries.

## 2.5 Action agenda by regions, industry and civil society

One of the key achievements of the 23rd Conference of Parties presided by Fiji Islands was the concept of "Grand Coalition of all Stakeholders" that goes beyond the COP 20 Paris-Lima Call for global climate action stakeholders to record their voluntary action[107]. The Grand Coalition includes states, local governments, business, faith-based organisations and citizens to join forces in fighting climate change. A pre-released chapter of the UNEP Emissions Gap report 2018[108] shows that additional emissions reduction made so far by non-state actors are still quite limited: in the order of 0.2-0.7 $GtCO_2$ per year by 2030 compared to full NDC implementation. The low level of available data and lack of consistent reporting limit a more comprehensive overview. However, global climate action, if realised to its full potential, could deliver additional emissions reduction to current policies in the range of 15-20 $GtCO_2$ annually in 2030, which is a considerable contribution to closing the gap. EU stakeholders have been at the forefront of these developments[109].

### *2.5.1 Regional actors*

Regional governments and cities, with their impact on economic, spatial, environmental planning and energy provision challenges, are increasingly drivers of the energy transition and becoming resilient. The Covenant of Mayors for Climate and Energy initiative[110], where local governments voluntarily commit to implementing climate and energy objectives, has already 7,383 EU signatories (as of 1 October 2018), representing in total 198 million citizens of the EU. A recent analysis of the local climate plans of 885 representative EU cities concluded that close to 66% of them have a climate mitigation plan and 26% have adopted adaptation plans[111]. The EU initiative is mirrored on the global level by the Global Covenant of Mayors for Climate and Energy[112].

Furthermore, the Urban Agenda for the EU[113], where cities, Member States, the Commission as well as other EU institutions and actors collaborate within the intergovernmental framework,

[105] Includes (as of September 2018): Albania, Bosnia and Herzegovina, FYR of Macedonia, Georgia, Kosovo, Moldova, Serbia and Ukraine, https://www.energy-community.org/
[106] Includes: Iceland, Liechtenstein, Norway, and Switzerland, http://www.efta.int/
[107] UNFCCC (2017), UN Climate Change Conference 2017 Aims for Further, Faster Ambition Together, https://unfccc.int/news/un-climate-change-conference-2017-aims-for-further-faster-ambition-together
[108] UN Environment (2018), Bridging the emissions gap – The role of non-state and subnational actors https://wedocs.unep.org/bitstream/handle/20.500.11822/26093/NonState_Emissions_Gap.pdf?sequence=1&isAllowed=y&stream=top
[109] UNFCCC (2017), Yearbook of Global Climate Action 2017, http://unfccc.int/tools/GCA_Yearbook/GCA_Yearbook2017.pdf
[110] https://www.covenantofmayors.eu
[111] D. Reckien et al., How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28, Journal of Cleaner Production, 26 March 2018, https://www.sciencedirect.com/science/article/pii/S0959652618308977?via%3Dihub
[112] https://www.globalcovenantofmayors.org /
[113] https://ec.europa.eu/futurium/en/urban-agenda

reinforces the urban dimension of relevant EU policies. The Agenda is being implemented through Partnerships aimed at achieving better regulation, better funding and better knowledge for cities in Europe. Through the agreed joint actions, the Partnership on Climate Adaptation aims to enhance the capacities of European cities in addressing and adapting to the impacts of climate change, and the Partnership on Energy Transition will contribute to the development of smarter and more integrated energy systems in European cities that are secure, resilient, affordable, clean and sustainable. Several other Partnerships, such as Urban Mobility and Air Quality, contribute to tackling the climate and energy challenge as well.

For regional governments, initiatives such as the Under 2 Coalition[114] are important as they actively reach out to their global members to draft 2050 pathways to set a dedicated goal of reaching less than 2 $tCO_2eq$/capita by 2050, equivalent to 80% below 1990 levels. 200 jurisdictions globally have already committed to this long-term goal. Against this background, the EU Governance Regulation facilitates the involvement of regional and local actors in the definition of national energy and climate priorities.

### *2.5.2 Sectoral actors*

Industries in Europe and their sectoral representatives have recognised the necessity of becoming more sustainable and substantially reducing GHG emissions by 2050. Private actors, large companies and sector associations are increasingly reporting on how to significantly reduce EU greenhouse gas emissions in the coming decades (see section 6.3). A record of just over US$74 billion of Green Bonds were issued in the first half of 2018.[115] There are many existing case studies of companies voluntarily implementing emission-reduction measures: for instance in order to achieve Heineken's sustainability target along its supply chain, Austrian brewery Göss has shifted entirely to using renewable and reusable energy sources, getting rid of its $CO_2$ emissions [116]. Eni has created the world's first green refinery,[117] in 2013 DHL came forward with Street Scooter, its own electric delivery van[118], and Siemens aims to achieve a worldwide net-zero carbon footprint by 2030.[119] Industry responses to the public consultation (see section 7.1) show a considerable evolution of their position in the last decade. For instance, 43% of private business supported achieving a balance between emissions in the EU by 2050 and 37% a reduction of 80-95%. Equally, there is a wealth of scenario studies done by different industry sectors on a variety of pathways. In contrast to the preparations for the roadmap in 2011, stakeholders tend to start from an 80% reduction target. More dominance is given to solutions involving electrification, hydrogen, but also circular economy and lifestyle changes.

### *2.5.3 Citizens and civil society*

Citizens have started to act both individually and collectively much more decisively on climate change which reflects the fact that climate change has become a concern for the overwhelming

[114] https://www.under2coalition.org/
[115] UN Environment (2018).
[116] Heineken (2018), Carbon-neutral brewing dream a reality for Göss https://www.theheinekencompany.com/sustainability/case-studies/carbon-neutral-brewing-dream-a-reality-for-goss
[117] ENI (2018), From oil to biomass, https://www.eni.com/en_IT/innovation/technological-platforms/bio-refinery.page
[118] DHL ( 2018), StreetScooter opens second manufacturing facility in Düren http://www.dhl.com/en/press/releases/releases_2017/all/streetscooter_opens_second_manufacturing_facility_in_dueren.html
[119] Siemens (2018), Siemens is going carbon neutral https://www.siemens.com/global/en/home/company/sustainability/decarbonization/carbonneutral.html

majority of them – see for example recent Eurobarometer results[120]. Fighting climate change as a part of safeguarding natural resources for future generations and as an essential element of their quality of life has for a long time been a concern for large part of European society. This has recently been magnified as awareness of scientific findings have grown and consumers have become more conscious about the carbon footprint of their actions. It is now clear that consumer choice can have an impact creating new markets as well as pressure on industry to adapt their offers allowing for more sustainable products coming to market. Already 1.5 million households in Germany produce their own energy for self-consumption through solar panels[121]. Consumer expectations[122] and the prospect of a substantial market prompt companies from all sectors to introduce renewable energy guarantees, carbon offset programs or low carbon products (in terms of their production chain).

Multiple examples can also be found in the field of urban mobility – certainly also because in this case decarbonisation has very quickly visible co-benefits such as better air quality, less noise or in sum more "liveable" cities. This is why citizens take actions themselves and support initiatives at the local level. For instance, the city of Milan has adopted its Sustainable Urban Mobility Plan in April 2018 with measures such as traffic reduction and shared mobility as core elements. A new shared “free floating” system, operated by cars, bikes and scooters, is fully integrated and supports both individual mobility and local public transport. As a consequence, the number of alternatives to private cars has risen: nearly 3,000 shared cars (27% fully electric) and more than 600,000 subscribers, 4,650 bikes, 12,000 free-floating shared bikes and 100 fully electric shared scooters[123]. Measures such as reduced traffic operation in city centres or even overall traffic reduction, banning polluting vehicles from accessing the city centres, bike rental services together with development of secure biking paths and shared mobility/"mobility as a service" are now core elements of the strategy applied by many cities in Europe.

It is clear that the clean energy transition and the achievement of net zero GHG emissions in the European economy can only happen with citizens’ buy-in. Consumer choice will increasingly become complementary to technological change and often a pre-condition for technology change to happen. Further work will be necessary to increase the transparency about products and services’ carbon footprint and thus capitalise on current consumer awareness. Organised civil society will play a key role in the further development of consumer awareness and providing the motivation for lifestyle change.

[120] 2017 Eurobarometer survey, see https://ec.europa.eu/clima/citizens/support_en
[121] Eurobserver (2018), Photovoltaic barometer 2018, https://www.eurobserv-er.org/pdf/photovoltaic-barometer-2018-en/
[122] https://ec.europa.eu/clima/citizens/support_en
[123] ELTIS (2018), Shared mobility enabling MaaS in Milan’s SUMP, http://www.eltis.org/discover/case-studies/shared-mobility-enabling-maas-milans-sump

# 3 IMPACT OF CURRENT POLICIES BEYOND 2030

## 3.1 Policies and assumptions

The EU and its Member States have put in place a set of policies that will already strongly impact the EU's transformation up to 2030 and will continue to do so afterwards with the ambitious energy and climate targets as recently agreed (see section 2.2). This section assesses what the impact of those policies will be up to and beyond 2030.

For the purpose of this assessment, a baseline scenario (referred to below as "the Baseline") was developed to reflect the current EU decarbonisation trajectory based largely on agreed EU policies, or policies that have been proposed by the Commission but are still under discussion in the European Parliament and Council.

It largely builds on the Reference scenario 2016 (referred to below as "REF2016")[124] but also presents an update on a number of key elements detailed in Annex 7.2.2. The Baseline keeps the macro-economic projections, fossil fuels price developments and pre-2015 Member States policies as implemented in REF2016. On the other hand, it incorporates an update of technology assumptions as conducted under the ASSET project[125] as well as several major recently agreed pieces of legislation as well as recent Commission proposals. A new element is also that the Baseline, includes projections all the way to 2070, as a way to start reflecting on potential pathways in the second half of the century. Most importantly, the Baseline also projects the achievement of energy and climate 2030 targets[126] as agreed by June 2018 as well as a continuation of policies impacting non-$CO_2$ emissions.

The aim of the Baseline is to illustrate the impact that current climate and energy policies and goals would have on long-term energy and GHG evolution. It thereby offers a basis for comparing different long-term pathways consistent with targets limiting global warming to well below 2°C or 1.5°C. The Baseline has been specifically built for the purpose of the development of the long-term strategy. It does not reflect specific Member State policies adopted as of 2015, and it was not possible to consult with Member States to verify that current or updated policies as being developed under the national energy and climate plans are adequately represented.

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[124] The "EU Reference Scenario 2016 – Energy, transport and GHG emissions - Trends to 2050" publication report describes in detail the analytical approach followed, the assumptions taken and the detailed results,
https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

[125] Modelling scenarios for development of the energy system is highly dependent on the assumptions on the development of technologies - both in terms of performance and costs. While these assumptions have been traditionally developed by the modelling consultants, based on a broad and rigorous literature review, the Commission is increasingly seeking a review of these technologies by stakeholders to make them even more robust and representative of the current projects as well as experts' and stakeholders' expectations. This is why a dedicated project was launched by the Commission in early 2018 to ensure robustness and representativeness of the technology assumptions in model PRIMES by reaching out to relevant experts, industry representatives and stakeholders, who are in possession of the most recent data in the different sectors. The project run was concluded in July 2018 and its final report (including the finalised technology assumptions) is available here: https://ec.europa.eu/energy/en/studies/review-technology-assumptions-decarbonisation-scenarios

[126] The 2030 targets are: at least 40% GHG emissions reduction compared to 1990; with 43% GHG emissions reduction in ETS sector compared to 2005 and 30% GHG emissions reduction in effort-sharing sector compared to 2005; at least 32% renewable energy share in final energy consumption and at least 32.5% reduction in both primary and final energy consumption compared to (2030 projections established in) 2007 Baseline – see more details on EU policies in section 2.2.

## 3.2 Energy supply and demand

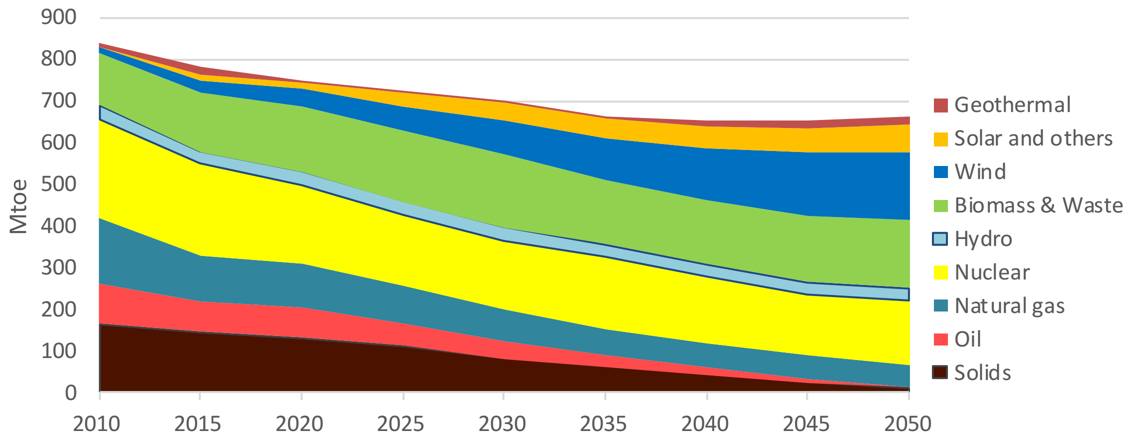
### *3.2.1 Energy supply*

The EU energy supply projections evolve both in terms of its overall level and the energy mix. Comparing primary energy consumption (PEC) projections to its historical 2005 levels, the Baseline achieves 26% reduction in 2030 (reflecting achievement of 2030 target), 35% reduction in 2050 and there are no further reductions by 2070 as continuous effect of energy efficiency policies is counterbalanced by effects of economic growth on energy consumption.

The first component of EU energy supply - energy production is projected to decrease by 28% in 2050 (compared to 2005). The fossil fuels production falls by 88% and renewable energy production (chiefly from wind, solar, biomass and waste) more than doubles in the same time - driven by the 2030 renewable energy target and competitive renewable technologies costs. The nuclear energy production, although slightly decreasing, would still keep an above 10% share of the energy mix.

The second component of the EU energy supply - net fuel imports will decrease by some 33%: from some 980 Mtoe in 2005 to 670 Mtoe in 2050-70. This decline in the Baseline happens chiefly because of reductions in fossil fuels and, to a smaller extent, and post 2030 only, renewable energy (biomass) imports. While energy efficiency measures mostly target natural gas consumption, it is the competitiveness of wind and solar technology that chiefly drives their higher penetration and thus reductions in the demand for biomass (including from imports). As a result, the EU's fossil fuel import dependency moderately decreases (from 52% in 2005 to 50% in 2050).

**Figure 7: Primary energy production in the Baseline**



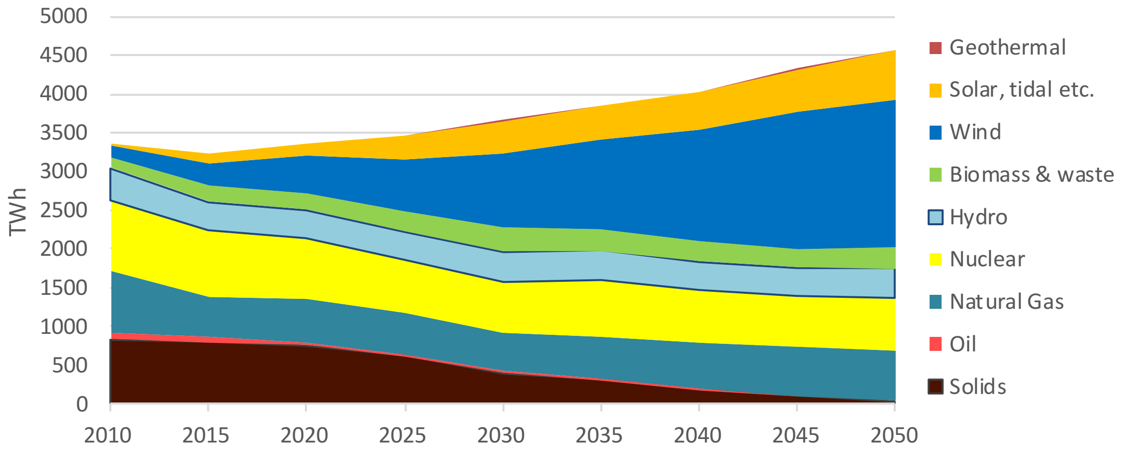

*Source: Eurostat (2010, 2015), PRIMES.*

Looking already on the transformation sector, overall electricity generation is growing strongly throughout the projection period. Electrification of demand is led by electrification of heating and cooling (notably with heat pumps) and a continuous increase of IT, leisure and communication appliances in the residential and tertiary sectors. The transport sector is also projected to drive upwards demand in electricity with the further electrification of the rail and the gradual penetration of electric vehicles[127].

[127] The advent of connected and automated mobility will also lead to increased deployment for IT and thus greater demand of electricity but this will rather be reflected in the services sector.

The EU power generation mix changes considerably in favour of renewables with the increase in wind being the most spectacular. By 2050, 73% of the electricity is generated from renewable resources, while nuclear and natural gas maintain their role in the power generation mix. By contrast, electricity produced from oil and solids becomes marginal (see Figure 8).

**Figure 8: Gross electricity generation in the Baseline**



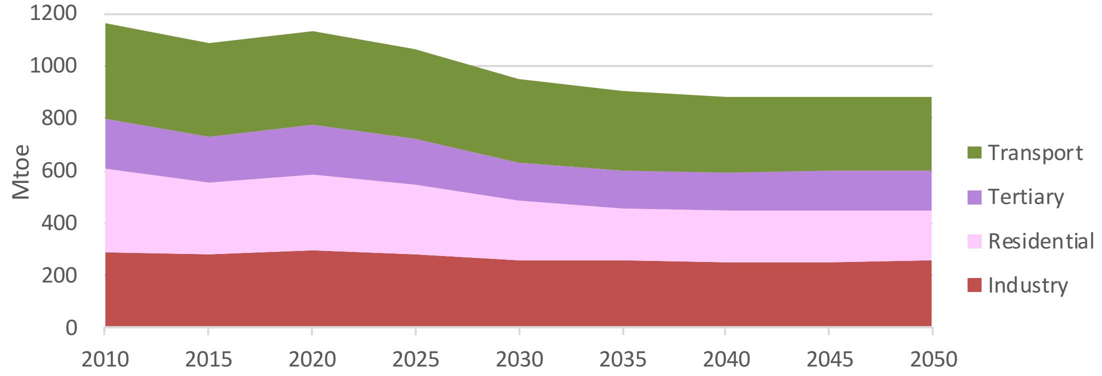

*Source: Eurostat (2010, 2015), PRIMES.*

### *3.2.2 Energy demand*

The final energy consumption (FEC) in the Baseline decreases by 26% between 2005 and 2050 due to moderation of final energy demand. This moderation of demand is most significant in the residential sector (38% reduction in 2050 compared to 2005). In industrial sector, 23% reduction in 2050 compared to 2005 is achieved but savings plateau post 2030. In transport, 24% reduction is achieved but, conversely to industry, there is an acceleration in savings post 2030. Finally, in tertiary sector (combining services and agriculture) the reduction in 2050 is the smallest (10%).

The changes in energy mix, driven by less demand for fossil fuel contrasted with an increasing use of electricity (Figure 9) also help to reduce overall levels of demand. These trends reflect the significant role of energy efficiency with ambitious 2030 targets and the implementation of dedicated EU legislation, notably the energy Efficiency Directive (EED), the Energy Performance of Buildings Directive (EPBD), the Ecodesign and energy labelling legislation, $CO_2$ emissions standards for light duty vehicles and for heavy goods vehicles and other initiatives adopted recently that increase the efficiency of the transport system.

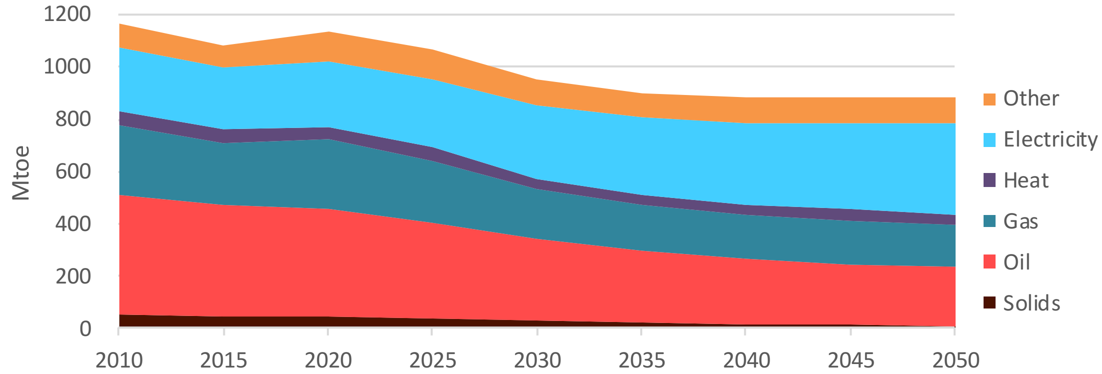
**Figure 9: Final Energy demand by sector**




*Note: "Tertiary" includes the energy consumed in the agricultural sector.*

*Source: Eurostat (2010, 2015), PRIMES.*

**Figure 10: Final Energy demand by fuel/energy carrier**




*Note: "Other" includes biomass and waste.*

*Source: Eurostat (2010, 2015), PRIMES.*

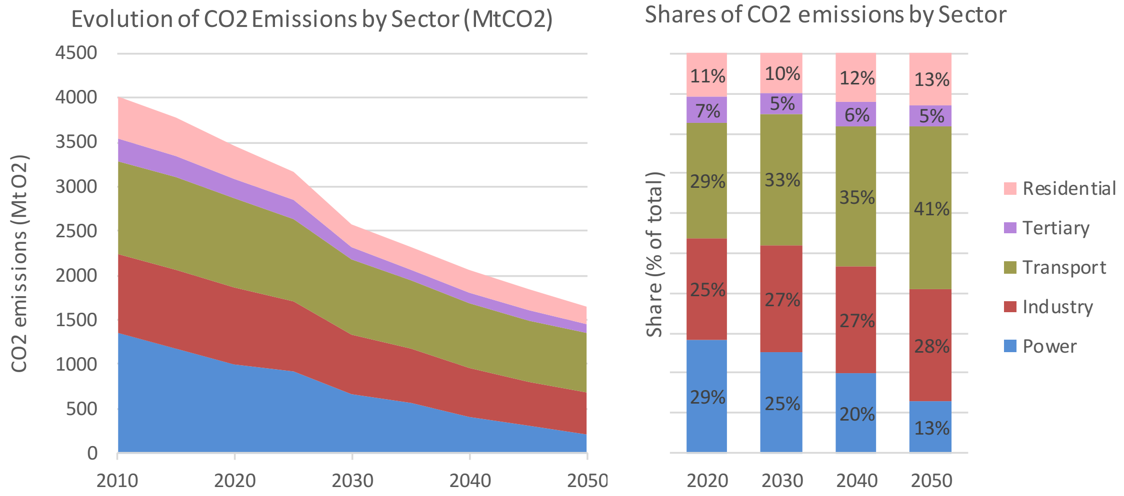
## 3.3 $CO_2$ emissions

The $CO_2$ emissions are projected to decrease steadily towards 2050, mainly supported by very substantial reduction in the power sector and more generally in sectors covered by the EU Emissions Trading System, for which the Baseline assumes a continuation of the reduction of the ETS cap with 2.2% per year, as implied by the current legislation. By 2050 the emissions reduce to just above 1600 $MtCO_2$ (Figure 11), this is a 65% reduction compare to 1990 level.

Overall, the main drivers for the decarbonisation are the increasing energy efficient in all sectors, in particular in industry, as well as the penetration of renewable energies.

Notwithstanding the transport sector becoming the largest source of $CO_2$ from 2020 onwards, fuel efficiency gains driven by standards and transport policies significantly reduce (by 38%) transport emissions between 2005 and 2050.

**Figure 11: Carbon dioxide emissions by sector**



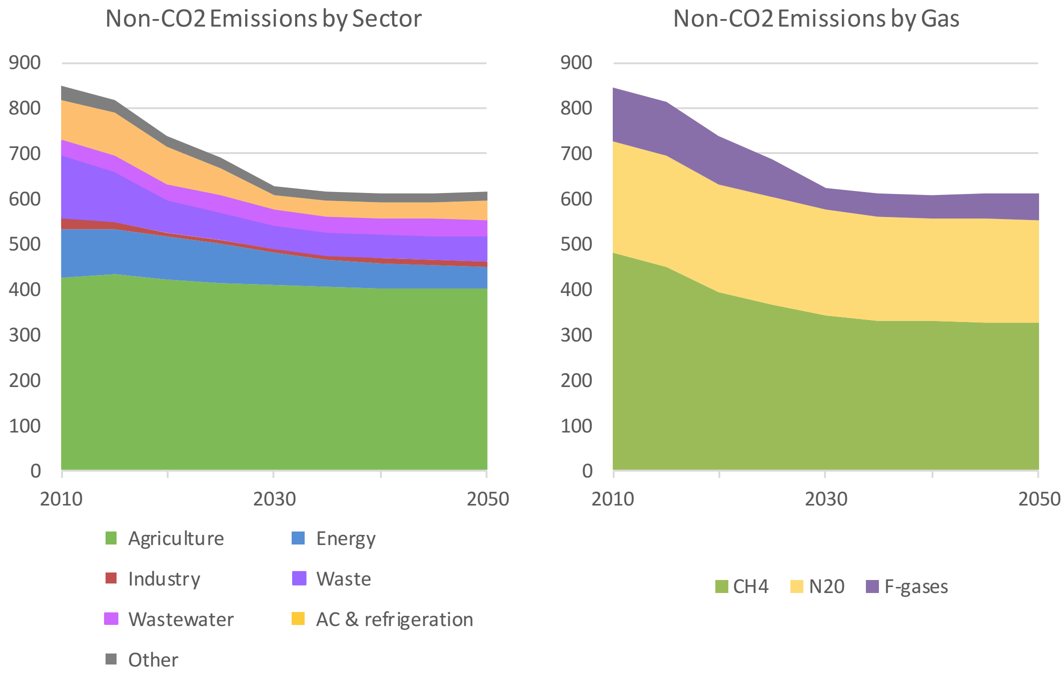

*Note: "Tertiary" includes the energy consumed in the agricultural sector.*

*Source: PRIMES.*

## 3.4 Non-$CO_2$ emissions

Non-$CO_2$ emissions are projected to reduce by 50% in 2050 compared to 1990. Since most of the legislation related to non-$CO_2$ emissions targets the pre-2030 period, the level of emissions flattens after 2030 and even increase slightly beyond 2050 (Figure 12).

**Figure 12: Baseline projections of non-$CO_2$ emissions by sector and by gas ($MtCO_2eq$)**




*Source: GAINS.*

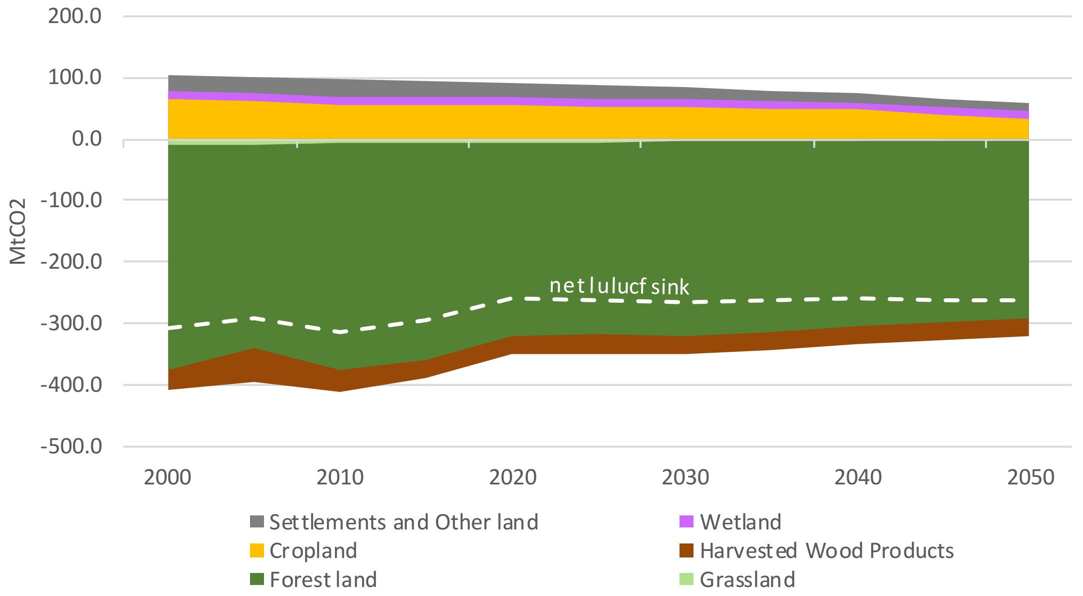
The reduction by 2050 will be the strongest for methane in absolute terms compared to 2005 (215 $MtCO_2eq$) and significant in percentage of 2005 levels (40%). F-gas emissions will reduce substantially until 2030 (50%) thanks to strict rules on Air Conditioning and refrigeration (Figure 12).

From a sectoral perspective, most sectors of the economy, with notable exception of agriculture, that are emitting non-$CO_2$ gases today are expected to significantly reduce their emissions, especially by 2030. With demand for natural gas decreasing as well as coal mining activities reducing, energy related non-$CO_2$ emissions continue to decrease.[128] Full implementation of EU waste legislation would see emissions for waste continued to reduce. Similarly, F-gas emissions are declining mainly as result of the new F-gas regulation, even though it could be counterbalanced after 2030 by the further increase in cooling needs. In the agriculture sector emissions are projected to remain stable in the absence of further mitigation incentives or changes in amount and type of agriculture goods produced.

## 3.5 Land use and forestry

The land use and forestry sector keeps its role of net carbon sink in the Baseline (Figure 13). However, the sink is projected to decrease from about 300 $MtCO_2$ in 2015 to 260 $MtCO_2$ in 2050 due to the ageing of the forest and an increasing mobilisation of forest biomass, mainly for material use (industrial roundwood, sawnwood, wood panels, paper, paperboard)[129].

**Figure 13: Evolution of the emissions and removals from land use, land use change and forestry**




[128] Going beyond this effect, specific emissions mitigation measures will also be needed to further reduce methane leakages in a decarbonised energy system. Indeed, due to the higher global warming potential of methane, as little as 3% leakage along the natural gas supply chain can cancel out the greenhouse gas emission benefits of natural gas vs. coal in power generation, see also IEA (2017), World Energy Outlook, https://www.iea.org/weo2017/

[129] While it has not been investigated as a part of analytical work for this assessment, there is also a possibility that climate change impacts (droughts, forest fires) would have some impacts on viability of forests as carbon sinks.

*Source: GLOBIOM & G4M.*

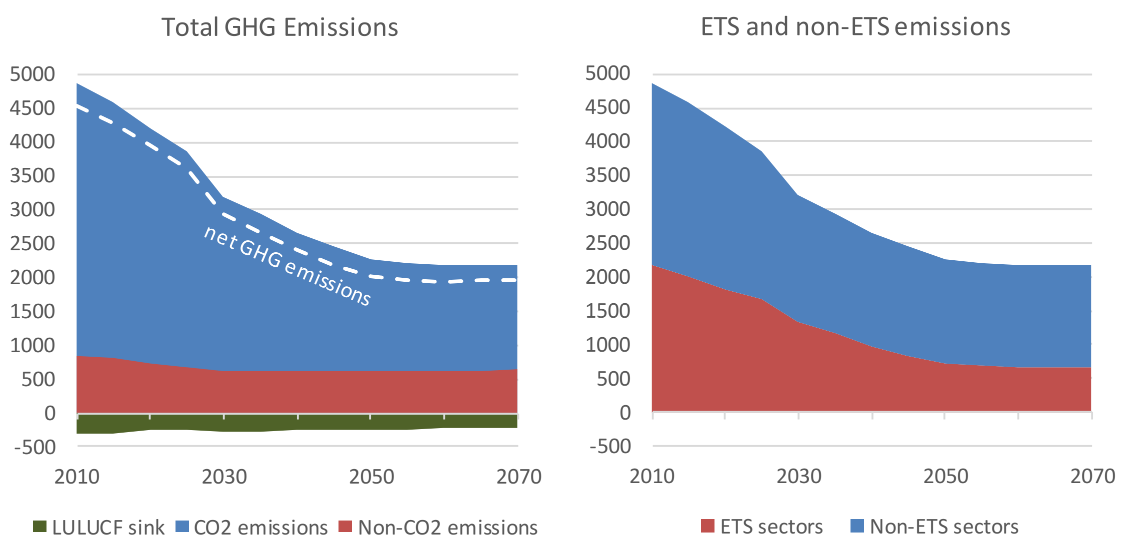
## 3.6 Total GHG emissions

Excluding the LULUCF sinks, the total GHG emissions in 2030 for the Baseline scenario is estimated at -46% of 1990 level, reducing further by 62% in 2050. Including LULUCF sink[130], net GHG emissions actually reduce by 48% by 2030 and by 64% by 2050 compared to 1990.

Reaching the 2030 renewables and energy efficiency target, both ETS and non-ETS targets are overachieved in 2030 (respectively 49% and 36% GHG emissions compared to 2005, see Figure 14). The over-achievement in the ETS by 2030 would result in increased surpluses of allowances. The Market Stability Reserve (MSR) has actually been designed to address such situations, absorbing such surpluses above a threshold (set in the legislation at 833 million allowances). Beyond 2030, scarcity will increase again due to the continued linear reduction factor. The evolution of the carbon price will depend on many variables, including expectations about future scarcity. In the Baseline, an ETS carbon price at EUR 28 per tonne of $CO_2$ (in 2013 prices) in 2030 contributes to the achievement of the Energy Efficiency and Renewable Energy targets.

After 2030, the Baseline assumes that, in the non-ETS sectors, there are no further drivers beyond market forces (e.g. rising future fossil fuel prices, more competitive renewable sources) and the continued impact of currently adopted policies such as $CO_2$ standards for vehicles or energy performance standards for products and appliances and for new buildings as of 2021 to further reduce energy and consequently emissions. Similarly a number of policies related to non-$CO_2$ emissions continue to impact on post 2030 emissions such as waste and F-gas legislation.

**Figure 14: Total GHG emissions and split ETS/non-ETS ($MtCO_2eq$)**




*Note: non-ETS emissions do not include LULUCF emissions.*

*Source: PRIMES.*

[130] Net GHG emissions add to the GHG emissions the so called unaccounted LULUCF sink, as reported in the EU's GHG inventory to the UNFCCC.

# 4 SECTORAL AND ECONOMY WIDE LOW CARBON AND ENERGY TRANSFORMATION PATHWAYS

## 4.1 Overview and scenario description

Section 4 looks at how sectors and the economy as a whole can decarbonise. Sections 4.2-4.5, describe how technology and other options (notably lifestyle changes and consumer choices) can transform the energy system and reduce greenhouse gas emissions. Sections 4.6-4.8 look at sectors outside energy, as well as natural or technological options to remove and sequester $CO_2$ from the atmosphere. Section 4.9 discusses the aggregate impact on emission levels at the economy wide level, while section 4.10 gives economic elements associated to the transition.

All sections discuss in detail different technologies and options and their associated challenges and opportunities based on a comprehensive literature review. They explore alternative views on the mitigation options. Technologies considered can be found in the mainstream research and innovation from academia or stakeholders, but do not include very innovative options with low technological readiness. The analysis was complemented by modelling, mainly using the PRIMES-GAINS-GLOBIOM model suite and by developing multiple and differentiated scenarios. Particularly for industry, a second model was used – FORECAST – to complement PRIMES.

It should be emphasised that long run uncertainties around the success of technologies are very large. Baseline and decarbonisation scenarios are precisely that: scenarios. Technological progress, consumer choices and regulation can lead to different results. While the modelling exercise has been performed to the highest quality standards, one should interpret the modelling results with caution and bear in mind that all models, independently of their complexity, are stylized approximations of reality. A description of models used, scenarios, assumptions and limitations of the modelling exercise can be found in Annex 7.2.

The PRIMES-GAINS-GLOBIOM model suite includes all sectors and GHG gases, covering not only $CO_2$ emissions related to energy combustion, but also $CO_2$ process emissions (emissions due to a chemical reaction), absorptions and emissions of $CO_2$ of the land use sectors (forestry and agriculture mainly), non-$CO_2$ emissions of all sectors with largest sectors being the agriculture, energy, waste and industrial sectors (including F-gas applications).

This modelling set up is especially useful to look in detail at the interactions between energy sectors as well as the interactions of the energy system with other relevant sectors such as industry, waste, agriculture and land use[131]. The assessment also looks at how the low carbon and energy transformation impacts international aviation and maritime sectors, given that such transformation impacts these two sectors just like any other energy consuming sectors. The standard PRIMES-GAINS-GLOBIOM set-up includes international aviation and is as such always included when referring to overall economy wide results in the section 4. International maritime has not been fully included in the modelling set-up in this analysis. While the inland navigation sector, covering inland waterways and national maritime, is an integral part of all decarbonisation scenarios, the international shipping has been treated separately. In section 4.4 a sector specific assessment is made of the international maritime sector and what it would take to decarbonise the sector and/or the bunker fuels sold in the EU.

[131] Electricity production from technologies deployed in seas and oceans is represented in the modelling, but third generation biofuels from algae and food production from marine resources is not.

This dedicated modelling exercise of the Commission, based on the revised state-of-the art technology assumptions and robust modelling tools, allows to present an economy wide but yet sectoral- and technology-specific overview of the impacts on greenhouse gas emissions, as discussed in section 4.9, while focusing on specific options and pathways and accounting for interdependencies among the sectors. Modelling results are also contrasted with a thorough literature review. The associated macro-economic analysis (section 4.10) was elaborated using three models: the GEM-E3, E3ME and QUEST models.

In general, this model-based quantitative analysis explores eight economy wide scenarios achieving different levels of emissions reduction. The scenarios cover the potential range of reductions needed in the EU to contribute to the Paris Agreement's temperature objectives of between *the well below 2°C*, and *to pursue efforts to achieve a 1.5°C temperature change*. As explained in section 1.1, this is translated into a reduction for the EU in 2050 (compared to 1990) of between 80% (excluding LULUCF) and 100% (i.e. achieving net zero GHG emissions).

Various sectoral options are explored as possible pathways to reduce GHG emissions: moderation of the demand (be it via energy efficiency[132], as a consequence of circular economy or lifestyle changes), technological options to decarbonise energy supply (mainly by fuel-switching to alternative zero carbon/carbon neutral carriers such as electricity from RES, hydrogen, e-fuels), as well as the use of negative emissions. These scenarios are contrasted to the Baseline projections presented in Section 3.

The scenarios project a gradual, yet significant, change from current situation. They all incorporate a wide, albeit varying, portfolio of mitigation options. Considering the inertia of the energy system and the economy as a whole, the resulting projections begin to differ towards 2050 and increasingly thereafter.

Three categories of scenarios are explored.

The first category addresses the *well below 2°C ambition*, aiming for GHG emissions reduction levels in 2050 of around 80% compared to 1990[133]. Five different scenarios are assessed in this category, considering differentiated portfolios of decarbonisation options. All scenarios integrate strong improvement in energy efficiency and developments of renewable energy, as well as improvements in transport system efficiency, which goes well beyond the assumptions of the Baseline scenario. On top of this, three of these scenarios are driven by decarbonised energy carriers and examine the impacts of switching from the direct use of fossil fuels to zero/carbon-neutral carbon carriers, namely electricity (ELEC), hydrogen (H2) and e-fuels (P2X), in order to meet the prescribed level of ambition. The other two scenarios examine how stronger energy efficiency measures (EE) or the transition to a more circular economy (CIRC) can deliver the desired emissions reduction.

Although no restrictions are placed in any technology or fuel, each scenario is assumed to have certain advantages in facilitating the uptake of some specific technological pathway. For instance, the circular economy scenario (CIRC) assumes standardisation of recyclable material and improved systems for waste collection, while the hydrogen scenario (H2) assumes timely deployment of the necessary hydrogen infrastructure and distribution of hydrogen also via the gas grid.

The second category consists of one scenario, which serves as a bridge between the other two main scenario categories explored. It combines the actions and technologies of the five scenarios

[132] With digitalisation being a strong enabling factor.

[133] GHG reductions of 80% are reached excluding the LULUCF sector. Including the LULUCF carbon sink in the analysis results in overall reductions increasing on average by 4 percentage points.

of the first category into a sixth scenario (COMBO), without reaching though the level of deployment of each technology as in the first category. All pathways are assumed to be available and a GHG reductions can be achieved through all of them. This results in net GHG emissions reduction (including LULUCF) in 2050 close to 90% compared to 1990. The scenario aims at identifying how far we can go in emissions reduction combining technological solutions and options assessed in the scenarios achieving 80% GHG emissions reduction, with small reliance on negative emissions technologies and without changes to consumer preferences.

All scenarios of the first and this second category continue to undertake efforts to reduce emissions after 2050, resulting in a decreasing trend in GHG emissions towards net zero GHG emissions.

The third category of scenarios achieves even stronger emissions reduction, reaching net zero GHG emissions by 2050 and thus *pursuing efforts to achieve a 1.5°C temperature change*. In this scenario category, remaining emissions that cannot be abated by 2050 need to be balanced out with negative emissions, including from the LULUCF sink. One scenario (1.5TECH) aims to further increase the contribution of all the technology options, and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage (BECCS) in order to reach net zero emissions in 2050. The second scenario (1.5LIFE) relies less on the technology options of 1.5TECH, but assumes a drive by EU business and consumption patterns towards a more circular economy. Similarly, the increase in climate awareness of EU citizens translates in lifestyle changes and consumer choices more beneficial for the climate. These include a continuation of the trend by EU consumers towards less carbon intensive diets, the sharing economy in transport, limiting growth in air transport demand and more rational use of energy demand for heating and cooling. Both scenarios have additional incentives to enhance the LULUCF sink, but this incentive is much more stronger in the 1.5LIFE scenario.

A sensitivity analysis was included, presented in section 4.7.2, looking into the impacts on biomass requirements. It builds on scenario 1.5LIFE, (i.e. with already a more circular economy, changing consumer preferences and a high incentive to enhance the LULUCF sink), while also putting a strong focus on technology options other than biomass based ones. This sensitivity tries to capture how net zero GHG emissions could be achieved while limiting biomass demand increases. This scenario is referred to as 1.5LIFE-LB. If not explicitly mentioned, all results shown in section 4 refer to the standard 1.5LIFE scenario.

Table 1 provides a summary of the scenarios, illustrating their main characteristics. For more detailed information related to the modelling set up, as well as the description and assumptions related to the scenarios, see section 7.2.

**Table 1: Overview of main scenario building blocks**

| Long Term Strategy Options | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Electrification (ELEC)** | **Hydrogen (H2)** | **Power-to-X (P2X)** | **Energy Efficiency (EE)** | **Circular Economy (CIRC)** | **Combination (COMBO)** | **1.5°C Technical (1.5TECH)** | **1.5°C Sustainable Lifestyles (1.5LIFE)** |
| **Main Drivers** | Electrification in all sectors | Hydrogen in industry, transport and buildings | E-fuels in industry, transport and buildings | Pursuing deep energy efficiency in all sectors | Increased resource and material efficiency | Cost-efficient combination of options from 2°C scenarios | Based on COMBO with more BECCS, CCS | Based on COMBO and CIRC with lifestyle changes |
| **GHG target in 2050** | -80% GHG (excluding sinks)<br>["well below 2°C" ambition] | | | | | -90% GHG (incl. sinks) | -100% GHG (incl. sinks)<br>["1.5°C" ambition] | |
| **Major Common Assumptions** | • Higher energy efficiency post 2030<br>• Deployment of sustainable, advanced biofuels<br>• Moderate circular economy measures<br>• Digitilisation<br>• Market coordination for infrastructure deployment<br>• BECCS present only post-2050 in 2°C scenarios<br>• Significant learning by doing for low carbon technologies<br>• Significant improvements in the efficiency of the transport system. | | | | | | | |
| **Power sector** | Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations. | | | | | | | |
| **Industry** | Electrification of processes | Use of H2 in targeted applications | Use of e-gas in targeted applications | Reducing energy demand via Energy Efficiency | Higher recycling rates, material substitution, circular measures | Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC) | COMBO but stronger | CIRC+COMBO but stronger |
| **Buildings** | Increased deployment of heat pumps | Deployment of H2 for heating | Deployment of e-gas for heating | Increased renovation rates and depth | Sustainable buildings | | | CIRC+COMBO but stronger |
| **Transport sector** | Faster electrification for all transport modes | H2 deployment for HDVs and some for LDVs | E-fuels deployment for all modes | Increased modal shift | Mobility as a service | | | • CIRC+COMBO but stronger<br>• Alternatives to air travel |
| **Other Drivers** | | H2 in gas distribution grid | E-gas in gas distribution grid | | | | Limited enhancement natural sink | • Dietary changes<br>• Enhancement natural sink |

## 4.2 Energy supply

### *4.2.1 Energy supply options*

The energy system is responsible for close to 80% of total GHG emissions in the EU[134]. The bulk of these emissions are due to fossil fuels combustion, which represented 75% of the total GHG emissions in 2015. This share increase to 77% adding fuel combustion emissions from international bunkers.

Reducing GHG emissions from the energy system is therefore a necessary condition for the EU to achieve the Paris commitments. As demonstrated in sections 2 and 3, transformation of the energy system is already under way and it is bringing positive effects in terms of decoupling economic growth from the energy consumption and GHG emissions.

Technology options for further decarbonising the energy sector are, to a large extent, available on the market. Without the need of breakthrough technologies, further reduction of emissions from combustion can be achieved either by replacing fossil fuels with carbon-free energy sources or by capturing their emissions by carbon capture and storage or utilisation (CCS and CCU) technologies[135].

#### 4.2.1.1 Key carbon-free energy sources

The current carbon-free energy sources are renewables and nuclear (based on nuclear fission).

Renewable sources known today, either in the form of electricity, heat or fuel are: wind, solar (solar thermal and solar photovoltaic), geothermal energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. There is a strong consensus in research that renewables will play a key role in decarbonisation pathways and when asked to rank the importance of energy technologies in the clean energy transition**,** stakeholders in the public consultation indicated that renewable energy was the most important technology (see section 7.1).

The largest primary source of renewable energy is solar energy[136], which can be used for both power generation and heating[137]. Solar electricity generation capacity has grown considerably recently, from almost no installations in 2000 to almost 100 GW in 2016, being responsible for 3.4% of the EU electricity production (estimates of 3.7% in 2017[99]). In terms of system integration, the EU is already leading globally with Greece and Italy being the only two large electricity-consuming countries where solar PV reached or exceeded 7% of annual electricity production[99]. Solar photovoltaics is one of the technologies that has seen the greatest developments since 2011, with cost reduced by around 70% at global level. Now a cost-competitive source of electricity, it is experiencing widespread deployment in buildings, infrastructure, consumer products, and more recently vehicles. Solar photovoltaics can be used to produce electricity locally, and the EU is leading globally for the deployment of solar panels with

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[134] The energy sector represents close to 80% of total GHG emissions when including emissions from international maritime and aviation (and more than 75% of total GHG emissions when excluding emissions from international maritime and aviation).

[135] The capture and injection of $CO_2$ is being used in enhanced oil recovery-related activities, but has hardly been deployed in the power sector.

[136] See for instance: Moriarty, P., Honnery, D. (2012). What is the global potential for renewable energy? Renewable and Sustainable Energy Reviews. Volume 16, Issue 1, January 2012, Pages 244-252 https://doi.org/10.1016/j.rser.2011.07.151

[137] JRC (2018), Potential of solar energy in Europe

the highest share of solar rooftop per capita. New developments in both production and operational processes are increasing efficiencies, product lifetime and capacity factors (e.g. thanks to solar tracking panels). Concentrated solar power is another solar energy source in which the EU is a global technology leader, and which has the potential to produce both heat as well as dispatchable power[138]. Europe is also the second largest market for solar heating, and it is a global leader in the deployment of solar heating for district heating and cooling systems.

Wind power produced around 11.5% of electricity in 2017 and accounted for around 55% of newly installed capacity[139] [140]. In terms of installed capacity, wind power is now the second largest, quickly closing in on gas[141]. Continuous innovation in the wind sector has led to higher capacity factors[142] (meaning also that turbines can work with lower wind speeds) and reduced production cost. The EU is a global leader in the integration of wind power with Denmark, Portugal and Ireland reaching in 2016 wind power penetration levels of respectively 44%, 21% and 20%[143], followed by another ten EU Member States. Offshore wind is an almost exclusive European development, which has rapidly developed into a competitive renewable energy source with a record of 3.1 GW installed in 2017. However, competition from abroad is increasing and EU manufacturers will have to reinforce their competitiveness in the coming years to keep their leadership. The resource potential for wind energy in Europe is very high. According to WindEurope, offshore wind could meet the EU's electricity demand[144] while on-shore wind could meet almost twice as much[145]. However, the actual long-term deployment of wind, and the possibility to access the full theoretical resource, will be highly dependent on competing land or sea-bed uses, including with agriculture, forestry and fishing, biodiversity conservation, tourism, transport activity or military uses. In addition, in order for offshore wind to operate in deeper waters, such as the Iberian coast and the Mediterranean, turbines will need to be floating rather than fixed to the ocean floor. Solid progress is being been made in this respect[146] and there is a pipeline of projects that will lead to the installation of 350 MW of floating capacity in European waters by 2021. This will need to accelerate afterwards.

Globally, electricity produced from solar and wind energy has shown the highest growth rates of all generation technologies over the past years. However, both solar photovoltaics and wind power remain variable sources that can only produce when solar or wind resources are available.

Biomass accounts for more than half of all renewable generation and it has recently seen significant growth. Moreover, the technology solutions are being developed to expand its use in power generation, buildings and industrial heating as well as transport. Biomass-fired power

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[138] A global outlook for solar thermal electricity suggests that deployment levels in the EU could range between 5 and 35 GW by 2030. SolarPaces, Greenpeace, ESTELA (2017). Solar thermal electricity. Global outlook 2016.

[139] WindEurope (2018), Wind in power 2017.

[140] EUROSTAT (2018), Gross electricity production from all fuel sources (GWh).

[141] In 2017, solar PV and wind accounted for 76% of all new capacity additions in Europe (with only 9% of other renewables added).

[142] See for instance the DOE Wind Technologies Market report 2017: in the USA "average 2017 capacity factor among projects built from 2014 through 2016 was 42%, compared to an average of 31.5% (..) from 2004 to 2011 and 23.5% (..) from 1998 to 2001" https://emp.lbl.gov/sites/default/files/2017_wind_technologies_market_report.pdf

[143] European Commission (2018). Energy statistical datasheets. https://ec.europa.eu/energy/en/news/get-latest-energy-data-all-eu-countries

[144] Between 2600 TWh and 6000 TWh under 65 EUR/MWh according to WindEurope (2017).

[145] JRC (2018), Wind potentials for EU and neighbouring countries, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109698/kjna29083enn_1.pdf

[146] the Portuguese Windfloat has been operated for five years, the new Hywind farm has been installed off Scotland and a French industrial partnership will launch the Floatgen turbine in the Atlantic.

plants are fully dispatchable and account for around 6% of EU electricity production in 2017[147]. Biomass is also the major renewable source for heating, accounting for 24% of all commercial heating production in the EU in 2017[147], and biofuels accounted for 3.8% of transport fuels in 2016. There were also more than 17000 biogas installations and around 450 biomethane installations in the EU in 2015, accounting for more than 8 GW of electricity production. In combination with CCS, energy from biomass can also produce negative emissions (see sections 4.2.1.2 and 4.8). Accounted as carbon-neutral, the use of biomass in the energy sector is expected to increase significantly in decarbonisation scenarios at global level[148 149]. However, it also raises questions about availability and trade-offs with air pollution impacts and conflicting land uses, with potential impacts on food security, biodiversity and its availability as material, as it is increasingly identified as attractive feedstock for the bio-based sector (see section 4.7.1.3).

Hydropower is the oldest form of renewable electricity production in the EU, accounting for around 10% of current electricity production. Hydropower stations can also be used to store electricity in times of oversupply by using the excess electricity to pump water into their reservoirs. Due to geographical conditions, its growth potential in Europe is limited, apart from small hydropower[150 151]. Yet, new improvements in turbine efficiency and re-powering could still contribute to additional electricity production. Its long-term reliability will depend on the evolution of climate conditions.

Geothermal energy for both electricity and heat production is currently a marginal option in EU's energy mix accounting for 0.2% of electricity production and 0.4% of commercial heat production[152]. There are a number of ongoing demonstration projects in the EU either to use low-temperature heat in advanced district heating networks or to use ultra-deep geothermal drilling for power generation. Estimates of its future potential are currently highly uncertain (although possibly very high[153 154]) and technical challenges and costs can limit its attractiveness. Although potentially contributing to a decarbonised energy system in the long run, this technology is not expected to experience a large scale deployment in the coming decades.

With 71% of the globe surface and regular tides and currents, oceans constitute a possible future energy resource, notably for the EU, which possesses the largest Exclusive Economic Zone[155].

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[147] EUROSTAT (2018). Gross electricity production from all fuel sources, GWh

[148] IPCC (2018), Special Report on Global Warming of 1.5°C http://www.ipcc.ch/report/sr15/
The report sees the global contribution of biomass to primary energy increasing by 2050 in most 1.5°C scenarios compared to 2010 (interquartile range for low or no overshoot scenarios is +123% to +261%).

[149] From 50 EJ/year today to 75-280 EJ/year in 2050 and more beyond, depending on the scenario and the model, in: Bauer, N., Rose, S.K., Fujimori, S. et al. Climatic Change(2018). Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. https://doi.org/10.1007/s10584-018-2226-y

[150] K. Bódis, F. Monforti, S. Szabó (2014), Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data, Renewable and Sustainable Energy Reviews, Volume 37.

[151] Stream Map (2012), Small Hydropower Roadmap, Condensed research data for EU-27, http://www.5toi.eu/wp-content/uploads/2016/11/HYDROPOWER-Roadmap_FINAL_Public.pdf

[152] EUROSTAT (2018). Gross electricity production from all fuel sources, GWh.

[153] WEC (2016), World Energy Resources 2016, https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Geothermal_2016.pdf. This report sees a potential of between 10 to 100 current capacity worldwide, equivalent to a production between 750 to 7500 TWh.

[154] GEOLELEC (2013), A prospective study on the geothermal potential in the EU, http://www.geoelec.eu/wp-content/uploads/2011/09/D-2.5-GEOELEC-prospective-study.pdf. This study identifies a potential of 4000 TWh for Europe alone, with an economic potential in 2050 of 2600 TWh.

[155] https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/docs/body/eu-and-international-ocean-governance_en.pdf

Wave energy, tidal stream, tidal range, ocean thermal conversion or salinity gradient devices could generate important quantities of electricity[156] and some of these technologies are on the cusp of commercial deployment. Furthermore, EU's outermost regions could use seawater air conditioning for cooling purposes. The EU is a global technology leader in ocean energy technologies. Gearing up these will require overcoming a number of barriers, in terms of costs decrease but also, like for offshore wind, anticipating potential conflicting uses of sea, seabed and coastal areas. The Roadmap produced by the EU's Ocean Energy Forum, which gathered industry, regulators and researchers, defined four actions to kick-start this activity from demonstration to production: (1) EU scheme for validation of sub systems and prototypes, (2) EUR 250 million Investment Support Fund, (3) EUR 50-70 million insurance and guarantee fund, and (4) integrated programme of measures to de-risk planning measures.

Nuclear energy (based on nuclear fission) is a well-established large-scale zero-carbon technology in power generation. Despite high construction costs (also linked to strict safety regulations), public acceptance issues in some Member States (demonstrated also in the results of the public consultation) and increasing competitiveness of other energy sources, the share of nuclear in the power production is 26% in the EU. It is expected to play a role at global level in mitigation scenarios. For instance IAEA (2018)[157] sees a possible doubling of global nuclear capacities by 2050, and IPCC (2018) [158] sees similar increases in capacity in 2050 in 1.5°C scenarios compared to 2010, albeit growing less fast than other zero carbon renewable energy sources. Being used traditionally as baseload, the economics of this option could be affected in a context of increasing role of renewables[159]. In some countries, nuclear power plants are operated in a more flexible way for instance through load following and frequency control[160] [161] [162].

Nuclear can play a role in reducing the dependence on fossil fuel energy imports in Europe. Although most nuclear fuel is imported from outside the EU, the supply is well-diversified, and fuel can be stockpiled in reserves worth 2-3 years of consumption, minimising the impact of any short-term disruptions. Although nuclear power could contribute in those Member States that opt

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[156] JRC (2016), Ocean Energy Status Report 2016, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jrc-ocean-energy-status-report-2016-edition.
Apart from the mature tidal range technology, ocean energy concepts are still in the demonstration phase. Currently announced projects sum up to about 1 GW for the early 2020s.

[157] IAEA (2018), Climate change and nuclear power, https://www-pub.iaea.org/books/IAEABooks/13395/Climate-Change-and-Nuclear-Power-2018.

[158] IPCC (2018), Special Report on Global Warming of 1.5°C http://www.ipcc.ch/report/sr15/
Interquartile range (for low or no overshoot scenarios) is +91% to +190% in 2050 compared to 2010.

[159] NEA, OECD (2012), Nuclear energy and Renewables - System Effects in Low-carbon Electricity Systems, https://www.oecd-nea.org/ndd/pubs/2012/7056-system-effects.pdf.

[160] IAEA (2018), Non-baseload Operations in Nuclear Power Plants: Load Following and Frequency Control Flexible Operations, https://www-pub.iaea.org/books/iaeabooks/11104/Non-baseload-Operation-in-Nuclear-Power-Plants-Load-Following-and-Frequency-Control-Modes-of-Flexible-Operation

[161] In addition, flexibility in electricity generation from nuclear can be enhanced by the development of small modular reactors (SMRs). Small Modular Reactors (SMRs) are defined as reactors with an electrical output lower than 300 MWe. SMRs have been first considered by the nuclear industry for commercial deployments with the aim to ensure the supply of energy to communities with little access to other sources or to address the difficulties of financing a large nuclear power plant. Nevertheless, in recent years, with large new nuclear projects advancing slowly, an increased presence of variable sources in the energy mix and the progressive decentralization of the grid, opportunities in smaller scale nuclear power reactors have become again under analysis. In SMRs design, attention is paid in particular to the capacity of the reactor to rapidly respond to the changes in the required power output.

[162] FTI Energy (2018), Pathways to 2050: role of nuclear in a low-carbon Europe, https://www.foratom.org/2018-11-22_FTI-CLEnergy_Pathways2050.pdf

for it, to an efficient decarbonisation of the power system, nuclear investments currently remain a challenge in the EU, due to the important up-front costs on the one hand and less certain electricity market prices on the other hand[163] [164].

#### 4.2.1.2 Carbon capture and sequestration/utilisation

Another option that could play a role on the path towards decarbonisation and the one that could maintain participation of fossil fuels in the energy mix is carbon capture and sequestration/use (CCS and CCU)[165] [166]. CCS and CCU are technically feasible for most large point sources (power and $CO_2$- intensive industry). So far, some 37 large scale CCS projects (mostly related to oil and gas recovery activities)[167] and a number of commercial pilot CCU projects[168] are on-going around the world in varying stages of development, while several planned projects have been abandoned due to uncertain economic performance. Uncertainties on the long-term behaviour of carbon storage as well as public acceptance issues (demonstrated also in the results of the public consultation) have also hindered a proper uptake of this technology in the EU, with some Member States having effectively banned it on their territory. Finally, capture rate above 90% appears difficult and very costly to achieve[169], meaning CCS used with fossil fuels currently does not achieve full decarbonisation.

Until recently, CCS efforts were mainly targeted at the power sector, but lately its role in reducing emissions also in industry has also been recognised. It has the advantage that it can be easily integrated into existing energy systems, significantly reducing GHG emissions, which is the reason it is often referred to as a bridging technology. Moreover, in many decarbonisation scenarios it continues to play an important role in the long term, where a share of fossil fuels remains in the energy mix for decades to come. This is due, to a large extent, to the role of natural gas as a transition fuel and the use of gas and oil used in power plants balancing the electricity sector or used as feedstock in some industrial processes. The valorisation of captured $CO_2$ as raw material for carbon-based products/feedstocks or even e-fuels could also contribute to a cost-effective transition in the industrial sector.

Importantly, while these technologies currently lack of incentives for large-scale implementation[170], CCS and CCU lie in the critical path for scenarios where negative emissions

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[163] MIT (2018), The Future of Nuclear Energy in a Carbon-Constrained World, an interdisciplinary study, http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

[164] OECD NEA (2018), The Full Costs of Electricity Production, https://www.oecd-nea.org/ndd/pubs/2018/7298-full-costs-2018.pdf.

[165] Bui et al, (2018), Carbon Capture and Storage (CCS): the way forward, Energy & Environmental Science, This article provides a detailed overview of the role of CCS in meeting climate change targets.

[166] ZEP (2017), Future CCS technologies, http://www.zeroemissionsplatform.eu/news/news/1665-zep-publishes-future-ccs-technologies-report.html

[167] Global CCS Institute (2018), Projects Database, https://www.globalccsinstitute.com/projects/large-scale-ccs-projects

[168] SCOT project (2016), Database of $CO_2$ utilisation projects, http://database.scotproject.org/projects.

[169] Global CCS Institute (2018), $CO_2$ capture at gas fired power plants, https://hub.globalccsinstitute.com/publications/CO2-capture-gas-fired-power-plants/

[170] See also IPCC Special Report on Global Warming of 1.5°C, section 2.4.2.3.

would be needed. Section 4.8 discusses further negative emissions and the possible role of biomass associated with CCS (BECCS)[171].

Nevertheless these technologies face a number of challenges, especially related to costs, but also markets, standards and established practices. In particular for CCU, the findings of various studies[172] [173] so far confirm the complexity of the subject and the uncertainty relative to the associated climate mitigation potential, since it encompasses a large variety of applications and situations.

#### 4.2.1.3 Electricity and heat

Deployment of carbon-free energy sources in power generation makes electricity a carbon-free energy carrier. As it is a versatile carrier usable for most of the final energy uses, many scenarios see increasing electrification of final energy demand in all sectors: industry, transport and buildings.

The anticipated electrification and the more decentralised deployment of renewable power generation will require reinforced and smarter electricity networks to make the best of the renewable resources allocation over the European territory[174].

Transporting electricity produced by increasingly dispersed sources calls also for the organisation of consumption and storage in a more decentralised way. Some long-term scenarios suggest that about 83% of all EU households could be actively supporting the deployment of renewables, either by producing energy themselves or by providing the flexibility services[175] thus requiring decentralised network. At the same time, important segments on both energy production (e.g. offshore wind farms which can reach capacities comparable to conventional sources) and the consumption side (e.g. energy intensive industries) are likely to remain centralised, which indicates that future electricity network will have to accommodate both centralised and decentralised elements.

Not only density of the network but also increased interconnection capacities will be needed if electricity networks are to match growing renewable energy supply and electricity demand over ever larger geographical distances. High Voltage Direct Current (HVDC), which generates less transport losses, could play an increasing role in the connection of offshore wind farms and help establishing a pan-European electricity 'super-grid'[176].

Integration of variable wind and solar energy requires flexibility of the rest of the system. This includes fast reacting generation sources on the supply side, storage or demand response. EU experience has shown that market mechanisms provide liquidity and flexibility necessary on the

[171] Negative emissions could be obtained by using bioenergy with CCS ("BECCS"): see Luderer et al. (2018), Residual fossil $CO_2$ emissions in 1.5–2 °C pathways, *Nature Climate Change*, Volume 8, pages 626–633 (2018), https://doi.org/10.1038/s41558-018-0198-6

[172] Group of Scientific Advisers (2018), Novel Carbon Capture and Utilisation Technologies, https://ec.europa.eu/research/sam/index.cfm?pg=ccu.

[173] Ramboll (2018), Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, forthcoming, https://ec.europa.eu/clima/events/stakeholder-event-carbon-capture-and-utilisation-technologies-technological-status_en

[174] COM(2017) 718

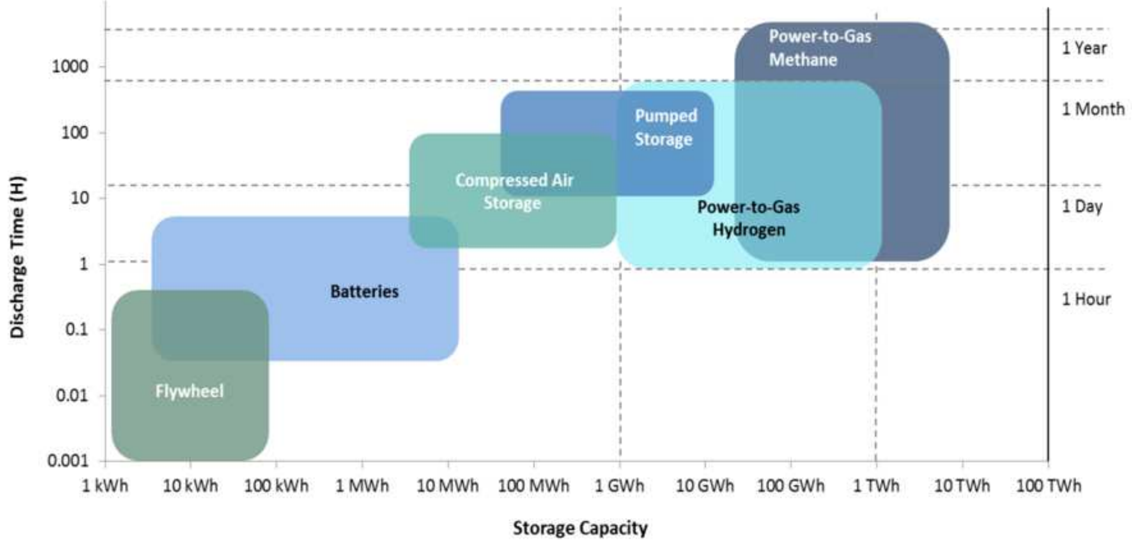
[175] CE Delft (2016), The potential of energy citizens in the European Union, https://www.cedelft.eu/publicatie/the_potential_of_energy_citizens_in_the_european_union/1845.

[176] Friends of the Supergrid (2016), Roadmap to the Supergrid Technologies – Update Report, https://www.friendsofthesupergrid.eu/wp-content/uploads/2013/07/Supergrid-Technological-Roadmap-2016-FINAL1.pdf

power market, and that market-based instruments, such as auctioning, bring down costs for renewables generation significantly. The ongoing digitalisation of the energy grids can help activating decentralised flexibility resources[177].

Electricity and thermal storage solutions are developing fast both in laboratories but also on the market. Different technological solutions compete for storing electricity over timeframes between fractions of seconds and seasons (Figure 15).

**Figure 15: Overview of different electricity storage technologies**




*Source: European Commission (2017), Energy storage – the role of electricity*[178].

The most noticeable recent evolution is the rapid improvements of batteries, in particular of lithium-ion type[179] [180]. A range of alternatives are being developed, including Power-to-Heat stored in in aquifers[181], Power-to-Hydrogen that can be stored in dedicated reservoirs and retransformed into electricity or used directly as a fuel, Power-to-Gas and Power-to-Liquid technologies[182] or even Power-to-Ammonia[183] that can be stored and used as a fuel in power plants or in maritime applications (see section 4.4).

Distributed Heat is another energy carrier that today accounts for 4% of final energy consumption. It is today mostly delivered by large CHP plants, mostly for district heating and is largely based on fossil fuels. It represents only around 10% of final energy consumption for

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[177] SWD(2017) 425 and 3rd PCI list, smart grid projects.

[178] SWD(2017) 61 final

[179] Li-ion batteries have become a key option for electrifying transport and are also increasingly as stationary electricity storage. They can be found both behind the meter, storing PV electricity for up to several hours, as well as in the form of larger centralised units providing frequency control.

[180] JRC (2018 upcoming), Li-ion batteries for mobile and stationary storage applications - Scenario assessment on growth and costs.

[181] Liuhua Gao et al. (2017), A review on system performance studies of aquifer thermal energy storage, Energy Procedia, Volume 142, https://doi.org/10.1016/j.egypro.2017.12.242 .

[182] SWD (2017) 61. This Commission Staff Working Document discusses the different storage options at greater length.

[183] Institute for Sustainable Process Technology (2017), Power to Ammonia, Feasibility study for the value chains and business cases to produce $CO_2$-free ammonia suitable for various market applications, http://www.ispt.eu/media/ISPT-P2A-Final-Report.pdf

heating[184], while 90% of heating is from self-production and is not directly accounted for in energy statistics. Whilst absolute heat production levels have been relatively stable since 2000, the share of renewables in the heating sector has increased from 11% in 2005 to 15% in 2010 and to 19% in 2015. Studies estimate that there is the potential to expand district heating and cooling to supply 50% of the heat demand[185], including 25–30% using large-scale electric heat pumps[186].

#### 4.2.1.4 New energy carriers

In addition to electricity, new carriers are being considered in energy and industrial applications where it is difficult to replace fossil fuels, in particular because of the chemical and physical properties sought. Hydrogen ($H_2$) and its carbon derivatives obtained by reaction with $CO_2$ like e-gas (e-$CH_4$) and e-liquids are considered as possible options for decarbonisation of transport, buildings or industry. These new carriers, to be themselves considered as carbon-free, will have to rely in particular on availability of carbon-free electricity. The results of public consultation indicate that these new fuels are recognised by citizens as technologies that could play a role in the clean energy transition.

Hydrogen can gradually take the role of an energy vector beyond its potential role as a chemical storage of electricity. It could replace natural gas as an energy fuel per se (albeit often with energy efficiency losses) for heating purposes or in transport (used with fuel cells) and as feedstock for industrial applications (e.g. steel industry, refineries, fertilisers). Hydrogen is already a common input to some industry processes (notably in chemicals) but currently produced via steam reforming using fossil fuels as input (mostly natural gas) and thus leading to $CO_2$ emissions. In the decarbonised future, hydrogen obtained from electrolysis using decarbonised electricity is the preferable option, including "green" hydrogen obtained from renewables. "Blue" hydrogen obtained from steam reforming of natural gas coupled with CCS may also play a role, provided the inherent constraints of CCS are lifted. In particular, in a power system largely based on variable renewable sources, hydrogen could be produced at times of low electricity demand providing additional flexibility. If needed in large quantities, hydrogen could also be produced by nuclear electricity or even might be imported from regions with potentially low cost renewable energy production[187] [188].

Hydrogen can be blended with natural gas so as to make use of the existing gas transport infrastructure up to 15% (or 20% in the future) by volume[189]. An upgrade of this infrastructure network would be needed to accommodate higher levels of hydrogen, even more so for pure

[184] Heat is estimated to represent 50% of the EU final energy consumption.
[185] Paardekooper et al. (2018), Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps, http://vbn.aau.dk/files/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps..pdf
[186] David et al. (2018). Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems, https://doi.org/10.3390/en10040578
[187] BCG & Prognos (2018), Climate paths for Germany, https://www.bcg.com/en-be/publications/2018/climate-paths-for-germany-english.aspx https://bdi.eu/publikation/news/klimapfade-fuer-deutschland/ (full study in German)
[188] Prognos (2018), Status und Perspektiven flüssiger Energieträger in der Energiewende https://www.mwv.de/wp-content/uploads/2018/06/Prognos-Endbericht_Fluessige_Energietraeger_Web-final.pdf
[189] See the FP6 EC research project NaturalHy: https://cordis.europa.eu/project/rcn/73964_en.html

hydrogen where a renewed network is likely to be needed[190] [191]. Hydrogen can also be stored at large scale, e.g. in salt caverns and other facilities.

Hydrogen could also be converted to synthetic hydrocarbons by reacting, using electricity, with $CO_2$. The emissions of such "e-fuels" will depend on the source of electricity and, to be fully accounted as carbon neutral, the source of $CO_2$ will have to come from biomass or Direct Air Capture (DAC)[192] or biomass.

E-fuels have the advantage that, once produced, these are exactly the same molecule as natural gas or oil, and can be distributed via existing transmission/distribution system and used by existing installations/applications.

Finally, another option being explored is the processing of hydrogen to ammonia, which is a versatile product, easier to transport and to store, that could be used in industry or as energy storage and energy carrier (e.g. possibly in transport)[183] [193].

However, these technologies are not ready for large-scale deployment yet, and are still characterised by low efficiency and high current production cost estimates[194].

#### 4.2.1.5 Sector coupling

Sector coupling refers to linking the energy (electricity, gas and heat), transport and industrial infrastructures with a view to increase the penetration of renewable energy sources and decarbonise the economy. Energy storage and sectoral integration would have the potential to make the energy transition faster and more cost-effective. Common to all analyses is the finding that many of the energy technologies, infrastructures and sectoral systems can further optimise their contribution to decarbonisation when coupled/integrated, allowing the best possible use of the available resources, the avoidance of stranded assets, and the best information base for decisions on investments. Integration impacts the energy system at several levels: physical and communications (i.e. technologies, infrastructures), functions and services (e.g. for business, for consumers), market (regulation, transactions). Coupling also means that action in one sector is heavily dependent on other sector(s). For instance, decarbonisation of heating via electrification will not happen unless power generation decarbonises.

This integration will build on the interdependency of energy transformation sectors (power, heating, production of new fuels) with industry, mobility, buildings sector, and other energy-using activities. Several possibilities for sector coupling have been already identified – see Figure 16.

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[190] See NREL report (2013) "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues" https://www.energy.gov/sites/prod/files/2014/03/f11/blending_h2_nat_gas_pipeline.pdf

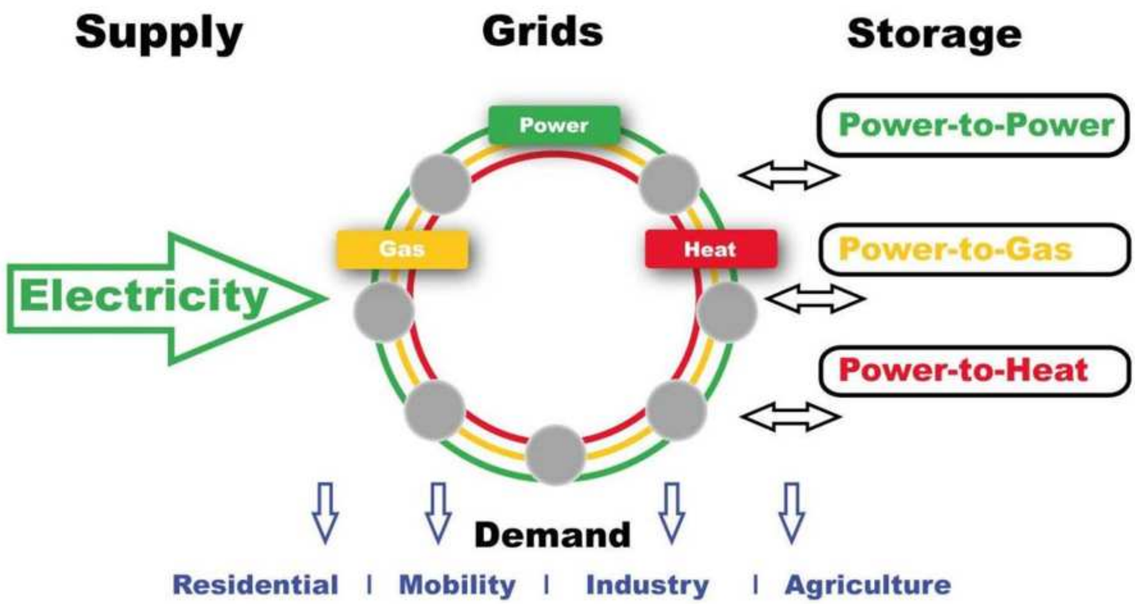
[191] Another possibility for a "decentralised" distribution system of hydrogen is the use of trucks - More precisely hydrogen tube trailers, which transports compressed hydrogen (180-250 bar) in steel tubes. Each trailer can transport about 280-720 kg of hydrogen.

[192] If the $CO_2$ comes from a fossil source (for instance captured from a gas or coal-fired power plant), then the burning of the e-fuel will result in $CO_2$ emissions, even though the overall carbon footprint of the energy chain is decreased (the same unit of $CO_2$ would be associated to the production of electricity and the e-fuel, for instance).

[193] Science (2018), Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon, DOI:10.1126/science.aau7489

[194] Close to 2500 EUR/t for e-methane to well above 3000 EUR/t for e-petrol, i.e. more than 5 times the fossil fuel alternatives, see also: https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

**Figure 16: Integration of energy vectors**




*Source: European Commission (2017)* [195].

Beyond the energy sector, the economic system will also increasingly rely on the further integration with natural resources used, industry and agriculture. Digitalisation and a smart regulatory framework will be key enablers allowing a system-level management. The energy sector coupling will in particular help the integration of larger contributions of variable renewables whose energy, after transformation, can be stored and distributed in new fuels.

Additional argument for sector coupling using e-fuels is that most of today's energy network infrastructures (electricity, gas, heating and cooling, liquid fuels) will still be operational in 2050. There is clearly a rationale of making use, during the transition, of the large existing gas (and oil) infrastructure that is able to carry and store substantial amounts of energy, including by potentially upgrading it for the use of biogas or hydrogen. In the longer run, there may be trade-offs between, on the one hand, managing simultaneously multiple networks and, on the other hand, operating only one extended power grid[196].

#### 4.2.1.6 Role of energy efficiency

Although technological development of supply-side carbon-free options will be a key and direct contributor to the decarbonisation of the energy system, it must act in synergy with the evolution of energy demand.

First of all, the actual capacity for deployment of supply-side options will be influenced by the absolute quantity of future final energy demand. On the one hand, low level of demand might hinder technologies at lower technology readiness levels to reach the scale required to reduce costs. On the other hand, in trying to supply a high level of demand, supply-side options might reach their maximum economic potential, be it related to raw resources (land or new materials for instance) or to system management (power grid stability for instance). Most likely the decarbonised energy carriers will have high costs (notably e-fuels) and thus reducing demand for them has direct economic benefits.

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[195] SWD(2017) 61 final. Energy storage - the role of electricity.

[196] PÖYRY (2018), Fully decarbonising Europe's energy system by 2050, http://www.poyry.com/news/articles/fully-decarbonising-europes-energy-system-2050

Secondly, reducing final energy demand and improving overall energy system efficiency (that will translate into reducing of primary energy demand) is often a cost-effective measure for GHG emissions reduction, able to deliver further socio-economic and environmental goals, using available and accepted technologies with a significant potential across different sectors of the economy.

That is why in the context of clean energy transition, "energy efficiency first" is a central principle applied to policymaking, planning and investment in the energy sector. It requires considering the potential value of investing in energy efficiency in all decisions about energy system development, not only on the supply side but also in homes, offices, industry or mobility. The principle aims to treat energy efficiency as the “first fuel” – a source of energy in its own right, in which governments can invest ahead of other more complex or costly energy sources, following the "save before you build"[197] logic. Applying this principle will help improving Europe’s ability to create a less costly, jobs-rich, low-carbon energy system.

For these reasons, introducing energy efficiency improvements whenever they are more cost-effective is therefore a "non-regret" or "first" option. This question is investigated further in the sections dedicated to developments in final energy sectors (sections 4.3, 4.4 and 4.5).

### *4.2.2 Energy supply results*

The section 4.2.1 above presents a comprehensive overview of the energy supply options for the clean energy transition[198]. In order to showcase the respective roles and potentials of options as well as their interplay, a quantitative analysis using energy system modelling was performed by the Commission. The modelling results are presented below and contrasted with a literature review.

#### 4.2.2.1 Primary energy consumption and energy mix

Before analysing the roles of respective energy sources, it is important to note that the "energy efficiency first” principle is present in all scenarios and drives down final energy consumption (see section 4.2.2.2), which, in turn, will decrease primary energy consumption. In fact, already with the policies assumed in the Baseline, primary energy consumption[199] is substantially reduced (35% in 2050 compared to 2005 - building on 26% reduction in 2030 reflecting the 2030 target).

In addition to final energy consumption, the evolution of primary energy mix will also have an impact on overall primary energy consumption due to uptake of renewables in power generation (wind and solar) and moving away from fossil fuels. Also (in some scenarios), the uptake of carbon neutral e-fuels (e-gas and e-liquids) and hydrogen whose production is energy (electricity) intensive will have an important impact on primary energy consumption.

The EE and CIRC scenarios achieve the highest reductions in primary energy consumption in 2050 (compared to 2005): 50% and 45%, respectively), driven by efficiency developments on the final energy consumption across all sectors and circular economy impacts on energy consumption in transport and industry respectively. On the other end, the P2X scenario (achieving only 22%)

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[197] European Climate Foundation (2016), Efficiency First: A New Paradigm For The European Energy System Driving Competitiveness, Energy Security And Decarbonisation Through Increased Energy Productivity. https://www.raponline.org/wp-content/uploads/2016/07/ecf-efficiency-first-new-paradigm-eruopean-energy-system-june-2016.pdf.

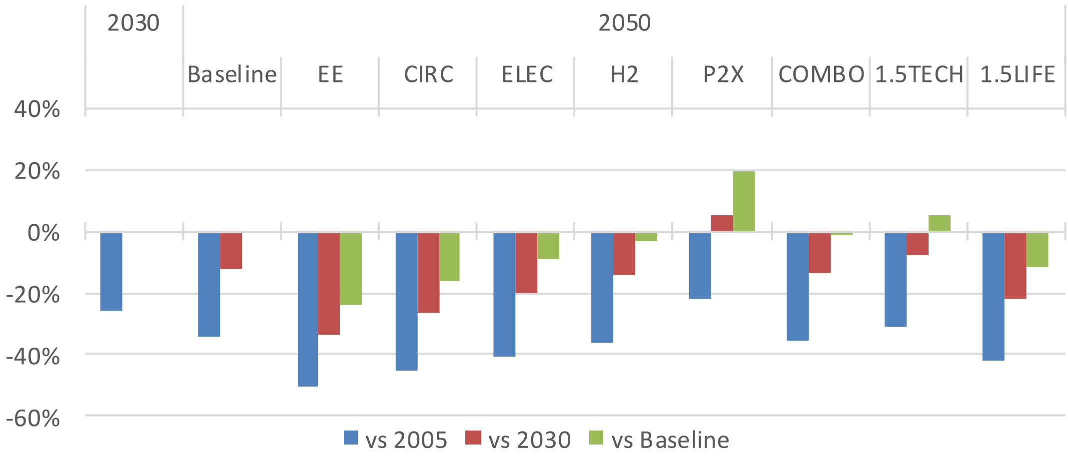
[198] Without yet being fully exhaustive as some longer-term options have not been discussed (see for instance fusion energy discussed in section 5.4.1)

[199] Gross Inland consumption excluding non-energy consumption.

makes an intensive use of e-fuels, which require large amounts of electricity to be produced. The other scenarios, including those with higher GHG reductions achieve reductions in-between (32% to 42%), i.e. close to the Baseline situation, see Figure 17. In case of 1.5°C scenarios this is the effect of combining deep savings in the final energy consumption with increased electricity needs for production of e-fuels and hydrogen.

These results indicate well the trade-off between efficiency loss and versatility of decarbonised e-fuels that could potentially replace seamlessly the fossil fuels as well as the likely dilemma of creating the right scale of e-fuels/hydrogen consumption: too small uptake would hamper technology learning, while large deployment would entail substantial additional needs on the supply side.

**Figure 17: Changes in primary energy consumption in 2050 (% change)**




*Source: Eurostat (2005), PRIMES.*

The projected energy mix (Gross Inland Consumption, see Figure 18:) clearly shows the deployment of a new energy system based primarily on renewables, moving away from fossil fuels. Those fossil fuels that remain in the system are, to a large extent, assigned to non-energy uses, i.e. used as raw material in the industry (e.g. to produce plastics).

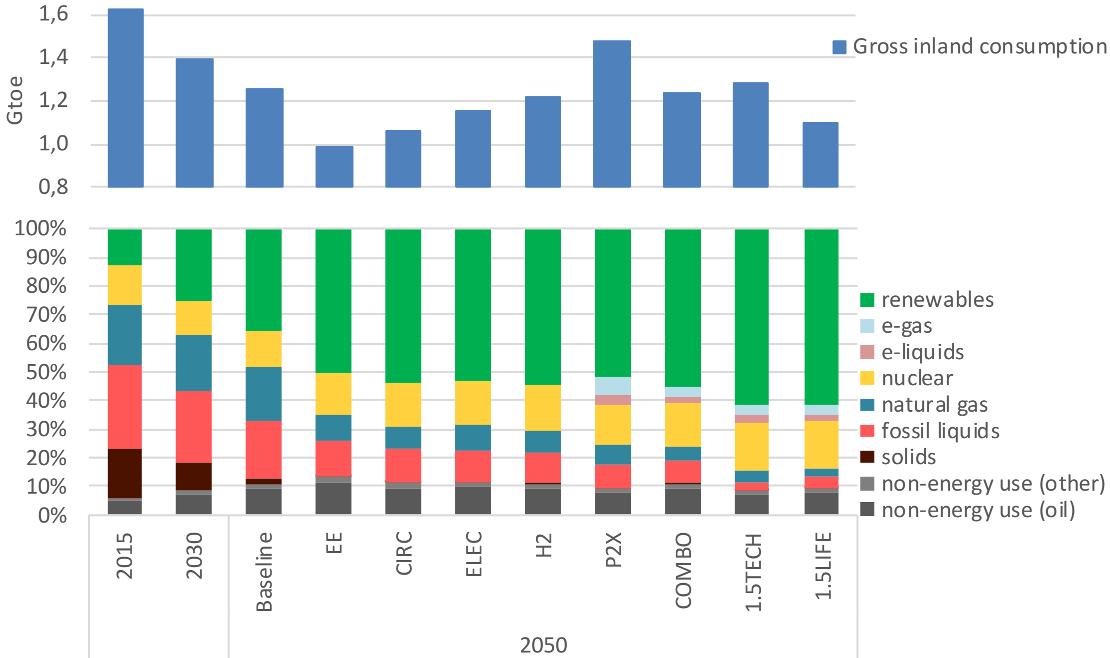
It is noteworthy that by 2050 solids virtually disappear from the energy system, including in the Baseline.

The share of fossil oil (excluding non-energy use) also declines very strongly already in scenarios achieving 80% GHG reduction: from 30% in 2015 to 25% in 2030 to, in 2050, between 12% (EE) and 8% (P2X). The amount of fossil oil in the EE scenario is slightly lower than in other scenarios achieving 80% GHG reduction, but the percentage is higher because total final energy consumption in the EE is lower than other scenarios due to the higher energy efficiency. The sharpest decreases happen in the 1.5°C scenarios due to a combination of use of several zero carbon or carbon neutral fuels/energy carriers, notably in transport (see section 4.4.2). This is because the scenarios include the most ambitious $CO_2$ efficiency for light duty vehicles[200] and, in the case of 1.5LIFE, the additional effect of lifestyle changes shifting mobility to low energy options. Around half of the remaining fossil oil in the decarbonisation scenarios achieving 80% GHG reduction is actually used as a raw material in industry, and in the scenarios with highest GHG reductions, most of remaining fossil oil is used as raw material. In several scenarios (P2X,

[200] Zero $CO_2$ emissions from the new fleet is assumed for 2040 already

COMBO, 1.5TECH and 1.5LIFE), fossil oil used as energy is partially substituted by e-liquids and they account for 2-4% of gross inland consumption[201] (see 4.2.2.4).

**Figure 18: Gross inland consumption**




*Source: Eurostat (2015), PRIMES.*

The share of natural gas (excluding non-energy uses) decreases slowly from 21% in 2015 to 20% in 2030, and then by 2050 more sharply in the decarbonisation to between 7%-9% in the 80% GHG reduction scenarios, and 3%-4% in the stronger reduction cases. Importantly, natural gas is, in several scenarios (P2X, COMBO, 1.5TECH and 1.5LIFE), partially substituted by e-gas, which then represents 4%-6% of the gross inland consumption in 2050.

Overall, the decreasing roles of fossil oil and natural gas in the energy mix will contribute to improving the security of energy supply of the EU (see also sections 4.2.2.4 and 4.2.2.5).

Studies from third parties draw a very mixed picture on the future role of natural gas in Europe. The range goes from natural gas meeting 19% of primary energy demand in the Equinor Renewal scenario[202], to 15% in the Shell Sky scenario[203], 10% in the IEA ETP B2DS[204] scenario and 1% in the Öko Vision Scenario for the European Union[205]. The meta study by Trinomics (2018)[206] on

[201] By convention, e-gas and e-liquids are accounted for in the gross inland consumption, thus, when they develop, decreasing the relative weight of primary energy from "conventional" energy sources (for instance, in particular, in the P2X case).

[202] Equinor (2018), Energy Perspectives, Long-term macro and market outlook, https://www.equinor.com/en/news/07jun2018-energy-perspectives.html

[203] Shell (2018), Sky scenario, Meeting the goals of the Paris Agreement - an overview, https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html

[204] IEA (2017), Energy Technology Perspectives 2017, https://www.iea.org/etp.

[205] Öko-Institut (2018), The Vision Scenario for the European Union 2017 Update for the EU-27, http://extranet.greens-efa-service.eu/public/media/file/1/5491

[206] Trinomics (2018), The role of Trans-European gas infrastructure in the light of the 2050 decarbonisation targets. http://trinomics.eu/wp-content/uploads/2018/11/Final-gas-infrastructure.pdf
The study identifies three "storylines": electrification of transport and heating, decarbonisation of gas through biomethane and synthetic methane, decarbonisation of gas through "green" hydrogen.

the role of gas infrastructure in the light of energy decarbonisation target identifies various storylines of replacing natural gas by decarbonised gas in the EU energy mix.

The share of nuclear energy in gross inland consumption (14% in 2015), which is relatively stable over time in the Baseline, slightly increases in the decarbonisation scenarios to 14%-17% in 2050, corresponding to energy supply close or only slightly below 2015 level (213 Mtoe in 2015 vs. 144 Mtoe in EE to 213 Mtoe in 1.5TECH in 2050).

In contrast the share of renewables increases in a spectacular manner, from 13% in 2015 to 25% in 2030, and then to 36% already in the Baseline in 2050. Renewables represent more than half the gross inland consumption in all decarbonisation scenarios in 2050, ranging from 51% (EE) to 62% (in both of 1.5°C scenarios).

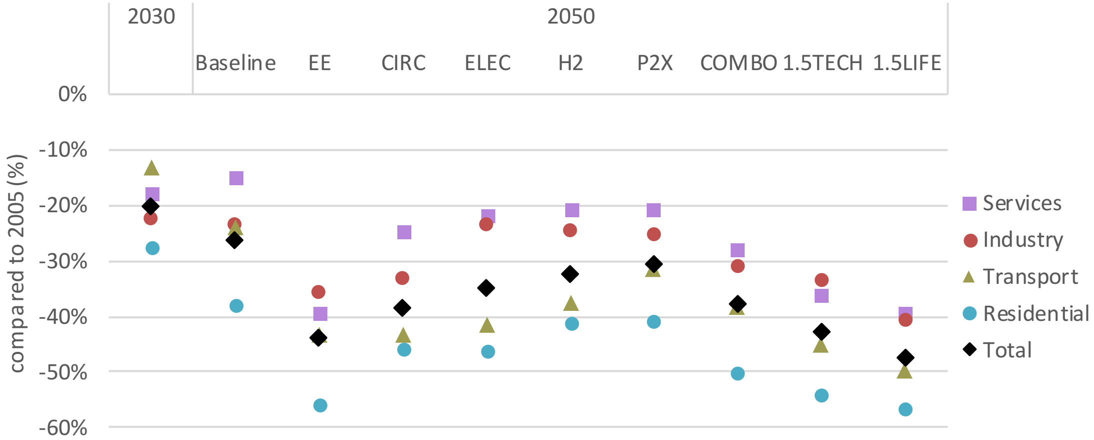
#### 4.2.2.2 Energy demand as a driver for energy supply requirements

Already in the Baseline the final energy consumption is substantially reduced and the 2030 target on energy efficiency (32.5% reduction compared to 2007 Baseline) already translates into a 20% reduction compared to 2005 (also achieved in all decarbonisation scenarios). The reductions compared to 2005 go up to 26% in 2050. At that time horizon, the reduction of final energy demand in the decarbonisation scenarios ranges from 30% (P2X) to 44% (EE) among scenarios achieving 80% GHG reductions and up to 47% (1.5LIFE) among scenarios with higher GHG reductions. The least reductions are achieved in scenarios with alternative zero-carbon/carbon neutral energy carriers (ELEC, H2 and P2X) enabling reaching decarbonisation objectives with lower reduction of the demand. The EE and CIRC scenarios achieve stronger reductions of final energy demand, mostly in residential and industrial sectors - respectively. Among scenarios that achieve higher GHG reductions only 1.5LIFE has higher reductions than EE (47%) as it builds on all technology solutions but also couples them with consumer choice that further reduces energy demand. Other studies show final energy demand reduction by 2050 ranging from as little as 19% (Shell Sky scenario[203]) to levels similar to the findings of this analysis: 43% (IEA ETP B2DS[204] scenario) or even 56% (Öko-Institut[207]).

Such significant reductions of the final demand confirm the large potential for energy demand moderation and opportunities for the development of dedicated industries and services. Attention will have to be paid, though, to implement such reductions early and gradually to avoid bottlenecks (for instance on access to capital or labour force, in particular regarding renovation of buildings, see section 5.1.2) that would prevent full deployment by 2050.

[207] Öko-Institut (2018), The Vision Scenario for the European Union, 2017 Update for the EU, Project sponsored by Greens/EFA Group in the European Parliament, https://www.greens-efa.eu/en/article/document/the-vision-scenario-for-the-european-union-7659/

**Figure 19: Changes in sectoral final energy consumption (% change vs 2005)**




*Note: "Services" includes here the agriculture sector.*

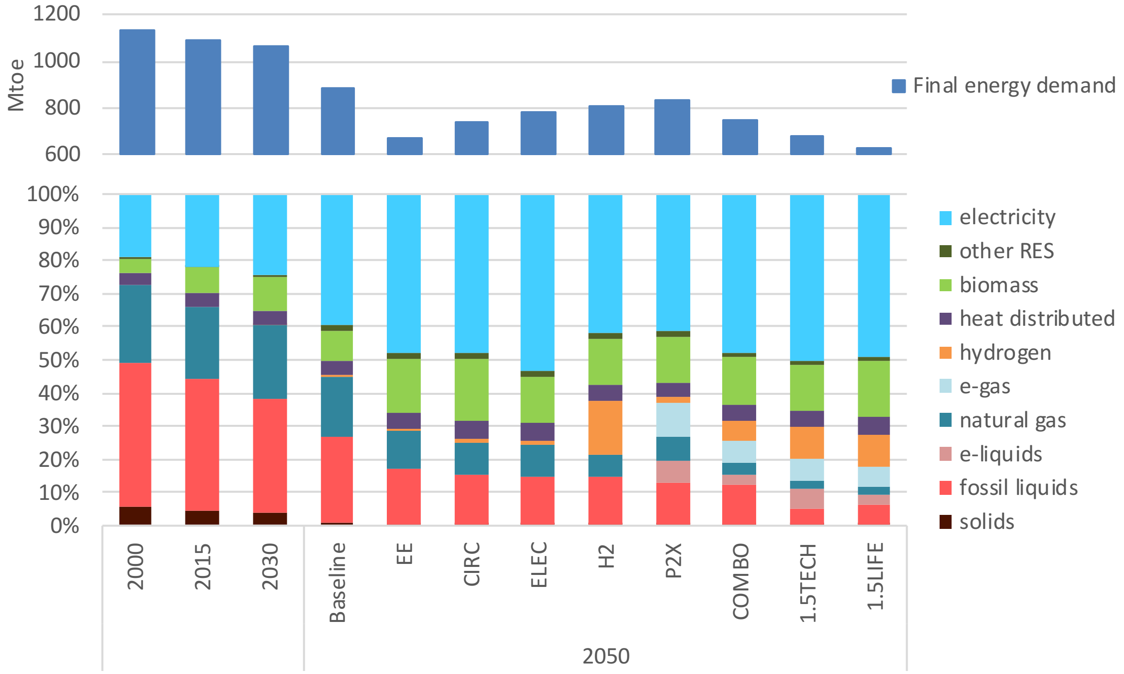
*Source: Eurostat (2005), PRIMES.*

Comparing sectors, residential has the sharpest energy consumption reductions (in 2050 compared to 2005) in most scenarios. Transport then follows, due to the substitution of highly inefficient ICE vehicles by electric vehicles and systemic energy efficiency gains. Industry and services tend to have comparatively lower energy reductions as both sectors grow according to assumptions on macroeconomic growth.

Final energy demand by sector is analysed in more detail in each of the sectoral sections: buildings (comprising residential and tertiary sector – see section 4.3.1.6), transport (section 4.4.2) and industry (section 4.5).

The overall fuel mix in final demand also changes significantly and the specific drivers are described for each of the sectors. Looking at overall picture the following trends can be noticed. First of all, solids, already marginal in 2030 disappear by 2050 and that already in the Baseline. Fossil liquids and natural gas remain in the system but their quantities are substantially reduced. In these scenarios where e-fuels develop (P2X, COMBO, 1.5TECH and 1.5LIFE), fossil liquids and natural gas are partially substituted by e-fuels: e-liquids represent 3%-7% of the final demand in 2050 whereas e-gas that represents 7%-10% of the final demand in 2050.

**Figure 20: Share of energy carriers in final energy consumption**




*Source: Eurostat (2000, 2015), PRIMES.*

Electricity becomes the dominant energy carrier and its shares grows strongly in all scenarios, from 22% in 2015 to 29% in 2030 and then in 2050 ranging from 41% (P2X) to 53% (ELEC) with the scenarios achieving highest GHG reductions situated within this range. The ELEC scenario by its construction drives the highest shares of electricity whereas in P2X scenario electricity competes with e-fuels. These rates are consistent with other studies, like Eurelectric (2018)[208] that shows electrification rate of the final demand in 2050 ranging from 38% (80% emissions reduction) to 60% (95% emissions reduction).

Biomass and waste also increases its share in all decarbonisation scenarios, partially driven by increased advanced biofuels penetration but also use of biogas. Biomass and waste thus represent between 14% (H2) and 19% (CIRC) of final demand in 2050 with the scenarios achieving highest GHG reductions situated within this range. H2 scenario has the lowest shares due to penetration of hydrogen in gas distribution as well as in high temperature applications in industry and in freight transport (both otherwise dependent on biomass).In CIRC, the high share is partly driven by low overall final energy consumption and partly because of higher availability of biomass due to reduction in industrial production (as a raw material) as well as improved management and collection of organic waste and biomass cascading, leading to the use of biomass as a feedstock for the production of biogas in local bio-refineries. Other types of renewables that produce direct renewable heat, notably solar thermal, geothermal and ambient energy[209] have only very limited penetration in all decarbonisation scenarios[210].

Distributed Heat supply in final energy consumption keeps the share it holds in 2015 (4%) over the period up to 2050 and it mainly reflects district heating for buildings and distributed industrial

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[208] Eurelectric (2018), Decarbonisation pathways for the European economy, https://cdn.eurelectric.org/media/3172/decarbonisation-pathways-electrificatino-part-study-results-h-AD171CCC.pdf.

[209] Formerly hydrothermal and aerothermal.

[210] The development of geothermal and solar thermal energy, individually or in district heating and cooling has not been in depth explored in the decarbonisation scenarios.

heat (mostly delivered from co-generation) using as energy sources biomass, geothermal heat and electricity since the fossil fuels disappear post 2030. It is noteworthy that the share of heating supplied through district heating and combined heat and power in the industrial sector increases by some 50% in most decarbonisation scenarios, although the absolute supply levels only grow moderately. In the buildings sector, distributed heat supply decreases with increased energy efficiency and electrification (compared to 2030).

Applying the Renewable Energy Directive formula[211], the renewables share in (gross) final energy consumption would grow from the target of 32% in 2030 to between 67% and 84% in 2050 in scenarios achieving 80% GHG reductions and up to 100% in 2050 in the both 1.5°C scenarios. E-fuels and hydrogen, when produced with renewable electricity, are also counted as renewables.

#### 4.2.2.3 Power sector

In line with earlier analyses of the Commission, electricity demand increases significantly by 2050 in all decarbonisation scenarios. Among scenarios achieving 80% GHG reduction, the ELEC scenario displays the highest growth, with final demand of electricity being 75% above 2015 level and the EE scenario the lowest (36% increase) as increased energy efficiency counterbalances the effects of electrification (see Figure 19). The scenarios with higher GHG reductions lie within this range, except for 1.5LIFE which shows only 30% increase due to combined penetration of e-fuels and effects of consumer choice.

Increased electrification takes place in most sectors compared to levels achieved in 2030. In 2050, transport sees the most spectacular development of electricity use, which multiplies in the ELEC and 1.5TECH scenarios up to 10 fold compared to 2015 and 4 fold compared to 2030 (see also section 4.4). Residential and industry also go through increased electrification, respectively increasing electricity use in 2050 (compared to 2030) by up to 31% in residential and up to 50% in industry (in ELEC). The further penetration of electricity in the tertiary sector is more limited – up to 24% (in ELEC), even showing a slight decrease in the EE and 1.5°C scenarios, where electrification is counterbalanced by energy efficiency improvement in this sector.

There is a consensus across studies that electricity consumption will further grow in Europe. The growth over the period 2030 - 2050 ranges between 12% in the IEA ETP B2DS[204] and 66% in the Shell Sky scenario[203].

[211] Directive 2009/28/EC

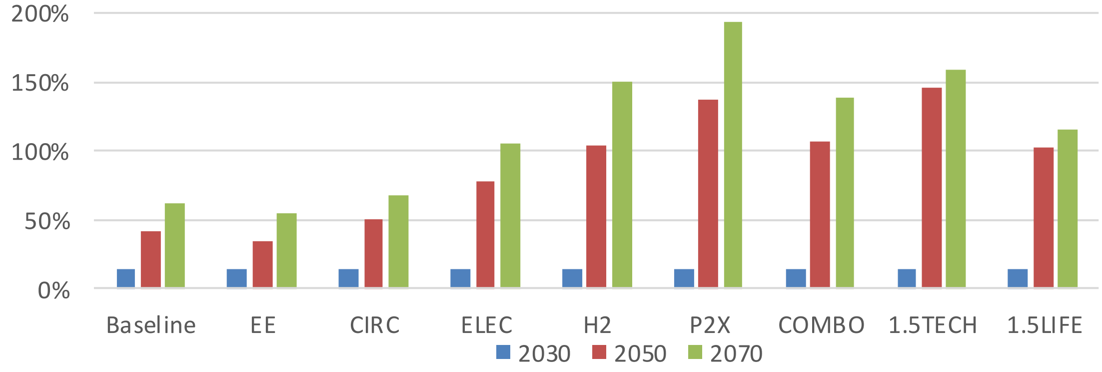
**Figure 21: Changes in final electricity consumption in 2050 compared to 2015**


*Note: left graph: % change compared to 2015 for total, residential, services and industry; right graph: ratio between 2050 and 2015 for transport.*

*Source: Eurostat (2015), PRIMES.*

In addition to increased final demand of electricity, the development of e-fuels also create a new need for electricity supply. As a consequence of both changes in the final energy demand and (in some scenarios) the production of e-fuels, the gross electricity generation in 2050 compared to 2030 increases strongly, ranging from 18% (EE) through 57% (ELEC) and to 109% (P2X, which reflects large e-fuels production) among scenarios that deliver -80% GHG reduction. Scenarios with higher GHG reductions also experience uptake of e-fuels, and thus higher electricity production needs, notably 1.5TECH that sees the highest deployment of e-fuels, hydrogen and electricity combined that lead to 116% growth in gross electricity generation. The changes are even more remarkable if compared to 2015 as shown in Figure 22.

**Figure 22: Increase in gross electricity generation compared to 2015**




*Source: Eurostat (2015), PRIMES.*

In all scenarios, the additional electricity demand is satisfied by production using resources from the EU territory, mostly local wind and solar, but also nuclear, usually considered as a secure source of supply[212] [213]. In some scenarios, biomass (mostly grown in the EU – see section 4.7.2)

[212] Although Uranium is imported, fuel can be stockpiled for 2-3 years in advance, minimising the impact of any short-term disruptions.

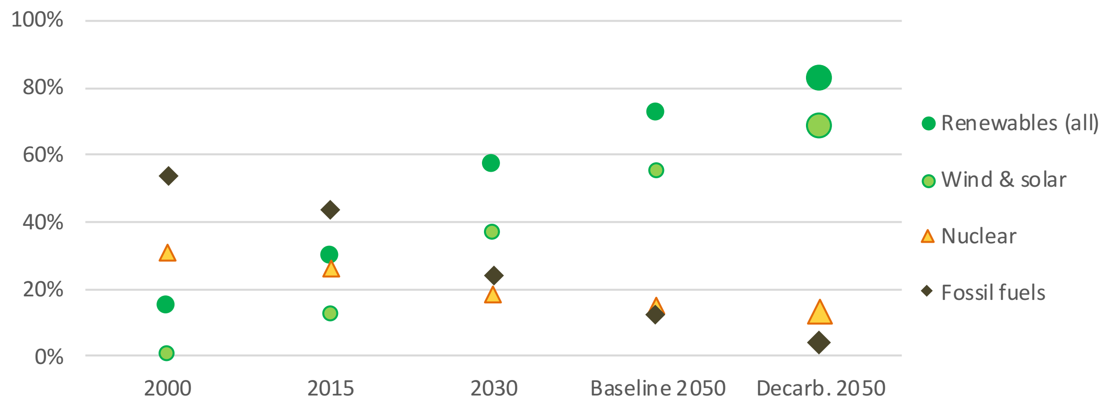
[213] The modelling does not fully take into account the implications for the import of raw materials. This issues is discussed in more detail in section 5.6.1.2 of this document.

also plays a role. But it is important to note that the modelling work cannot capture all possible issues related to availability of land, public acceptance or competitiveness of EU-located production versus imports of electricity, hydrogen and e-fuels that would be likely to develop as scale of the electricity production increases.

The changes in electricity generation mix illustrate the strong shift towards carbon-neutral energy sources (Figure 23), in a context of overall increase in electricity production as described above.

Fossil fuels, which represented 43% of the electricity production in 2015, become marginal contributors the decarbonised power system. In fact, by 2050, natural gas is the only fossil fuel left in the mix, with a share (of the production) falling from 16% in 2015 to 12% in 2030[214] and then in 2050 to between 5% (P2X) and 1% (EE, CIRC) and the scenarios achieving highest GHG reductions that lie within this range. It can be noted that the use of biogas[215] in the power system develops, and, with a consumption between 22 and 45 Mtoe in 2050 in the decarbonisation scenarios, comes closely on par with natural gas is several of the decarbonisation scenarios (see section 4.2.2.4).

**Figure 23: Shares in power generation**




*Notes: 1. The shares of renewables, nuclear and fossil fuels sum to 100%. Wind & solar is a component of renewables. 2: The "Decarb. 2050" points are the averages across all decarbonisation scenarios per category. These scenarios provide very similar power mix in 2050, with renewables ranging from to 81% to 85% (wind & solar alone from to 65% to 72%), nuclear from 12% to 15% and fossil fuels from 2% to 6%.*

*Source: Eurostat (2000, 2015), PRIMES.*

Conversely to fossil fuels, renewables become increasingly competitive, and their deployment is facilitated by the possibility of storage in hydro-pumping, stationary and mobile (in EVs) batteries and, indirectly, in hydrogen and e-fuels as well as via demand side response. Storage is increasingly the principal way of integrating the renewables in the power system as thermal generation declines over time. The amount of electricity yearly stored that in 2050 increases in the scenarios some 10 times compared to 2015, while at the same time demand for electricity,

[214] In the medium term (up to 2030) the amount of gas used in power generation depends on the interplay of electricity demand, deployment of renewables and other policies, such as the coal phase out announced by several Member States. In the context of the Long Term Strategy, these policies are not modelled as exogenous assumptions but they are endogenously driven by ETS carbon prices, which lead to a significant reduction of power generation from solids by 2030 and 2035. The impact on gas demand of the announced phase out of coal plants could be different than projected by the model in 2025 and 2030, but this is expected to have little impact on decarbonisation in 2050.

[215] Biogas is accounted for as biomass (renewable) in the energy balance.

including for production of e-fuels (where applicable), increases between one third and nearly 1.5 times and while electricity from renewables increases between roughly 3 and 6 times over the same period. The considerably increased storage systems, including the power-to-X units, operate following a pattern that help increasing the renewables, as they charge electricity when these are abundant and discharge when they are lacking.

The share of renewables in gross electricity generation is very similar across scenarios getting to 81%-85% in 2050 (compared to 57% in 2030 and 30% in 2015[32]) and remaining at this level afterwards. This finding falls within the range of studies assessed, which gives, for the EU, value from slightly above 75% in 2050 (IEA ETP B2DS[204] and Shell Sky scenario[203]) to an almost fully renewables power system (IRENA's global energy transformation[216], Greenpeace Energy Revolution[217] and the Öko-Institut Energy Vision[207]). It is also consistent with the values found in the IPCC Special Report on 1.5°C, which gives renewable share in electricity globally ranging from 69% to 87% in 2050 at global level[218].

Among renewables, wind is clearly the dominant technology, representing in 2050 51-56% of the power production in all decarbonisation scenarios. This is a spectacular growth from 26% in 2030 and 9% in 2015. These scenarios follow WindEurope's "high" scenario up to 2050 where the offshore proportion of electricity generated moves from 12% in 2017 to 36% already by 2030 which would mean about 20% of installed capacity offshore. Other decarbonisation studies see wind shares below 30% (Shell Sky scenario[203]) or above 60% (Öko-Institut Vision EU28[207]). The share of solar[219] grows up to 15-16% in 2050 in the decarbonisation scenarios, from 11% in 2030 and 3% in 2015. Views on the possible contribution of solar in the EU electricity generation in 2050 cover a broad range between 10% (IEA B2DS[204]) up to 33% (Shell Sky[203] [220]). Both wind and solar drive the development of renewables, and reach together some 70% of the power production in all decarbonisation scenarios, compared to 37% in 2030.

Additionally, some studies have looked at the role that households, collectives, small and medium-size enterprises (SMEs) and public entities may play in the production of renewable electricity. One of these studies suggests that up to 1500 TWh (equivalent to 32% of electricity production in the baseline scenario) of solar PV and wind power could be produced by these stakeholder groups by 2050[221].

The share of biomass and waste remains quite stable across scenarios and over the period (7-8% in scenarios achieving 80% GHG reductions and up to 10% in 1.5TECH scenario that develops significantly BECCS. These figures are in line with other studies, which see the share of biomass power generation between 8% (Shell Sky[203]) and 12% (Greenpeace Energy Revolution[217]).

The nuclear share in 2050 remains rather fairly similar across all scenarios (12-15%, compared to 18% in the 2030 projection and 26% in 2015). Other studies see the role of nuclear anywhere between the current share and no contribution. The Nuclear Illustrative Programme (PINC)[222] sees the nuclear share slightly higher than this analysis, between 17-21% of the total generation

[216] IRENA (2018), Global energy Transition – A Roadmap to 2050, http://www.irena.org/publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050

[217] Greenpeace, GWEC and Solar Power Europe (2015), energy [r]evolution – a sustainable world energy outlook, https://elib.dlr.de/98314/1/Energy-Revolution-2015-Full.pdf.

[218] Interquartile range for no or low overshoot 1.5°C scenarios.

[219] Combined in this reporting with tidal and other types of renewables

[220] Breyer et al. (2018), Solar photovoltaics demand for the global energy transition in the power sector, https://doi.org/10.1002/pip.2950 . This publication analyses in detail selected EU countries and sees PV shares ranging from 26% to 35%.

[221] CE Delft (2016). The potential of energy citizens in the European Union.

[222] COM(2017) 237

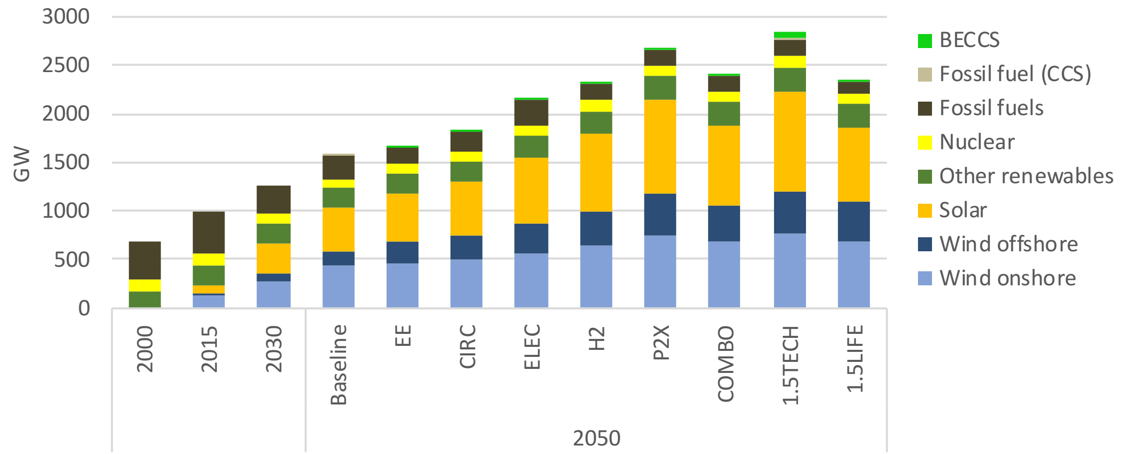
in 2050, in a business-as-usual scenario. A study by FTI Energy on behalf of FORATOM[162], the European nuclear trade association, sees three scenarios with installed capacities in 2050 ranging between 36 and 150 GW. The Shell Sky[203] and IEA ETP B2DS[204] scenario project the nuclear generation roughly stable in absolute terms and representing 11% of the total electricity production in the Shell Sky[203] scenario (due to a high growth of the electricity production), against 25% in the IEA B2DS[204] scenario. Studies by Greenpeace[217] and Öko-Institut[207] exclude the option to reinvest in nuclear energy and phase out the technology by 2050.

Finally, it has to be noted that hydrogen is only marginally used in power generation (some15 Mtoe in the H2 scenario), and that e-gas or e-liquids are virtually not used in this sector. Hydrogen provides important services as a chemical storage (see Figure 26).

The overall net installed electricity capacities reach in 2050 between some 1700 GW (EE) to some 2700 GW (P2X) and even some 2800 GW (1.5TECH), hence almost doubling of 2015 level (985 GW) or increasing even more. It also represents a substantial increase compared to 2030: from 30% (EE) to 110% (P2X) and to 120% (1.5TECH). Such a massive growth will certainly represent an investment challenge but also an opportunity for the rejuvenation of the power generation infrastructure and for development of economic activity and supply chains in Europe.

In addition to higher electricity needs, be it for final energy demand or for e-fuels production, the growth in capacity is explained by the growth in renewable energy, and most notably wind and solar, which display lower capacity factors than traditional generators.

**Figure 24: Power generation capacity**




*Source: Eurostat (2000, 2015), PRIMES.*

The deployment of renewables is even more visible looking at power production net installed capacities (Figure 24). The highest increase of renewables capacity takes place in scenarios deploying hydrogen and e-fuels.

Wind capacity increases in 2050 from some 140 GW in 2015 and some 350 GW in 2030 to between some 700 GW (EE) and some 1200 GW (P2X) in scenarios achieving 80% GHG reduction and 1.5TECH scenario goes slightly higher to over 1200 GW, meaning a further doubling to tripling compared to 2030, which corresponds to annual installation of some 30 GW (EE) to over 50 GW (1.5TECH) between 2030 and 2050 (see Figure 25), hence exceeding in most scenarios the average pace observed over 2000-2015 for the *entire* power capacity (31 GW/year). Onshore wind would represent close to two thirds of total wind capacity in 2050 (92% in 2015): from 460 GW (EE) to 760 GW (1.5TECH).

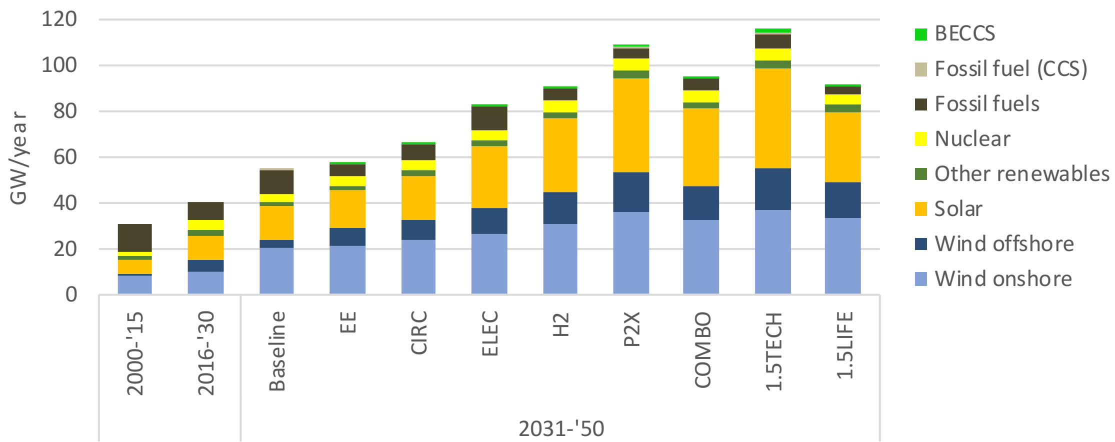
The solar capacity that starts from smaller base today shows also a spectacular growth, from 95 GW in 2015 and some 320 GW in 2030 to between some 500 GW (EE) and 970 GW (P2X) in 2050 for scenarios achieving 80% GHG reduction and up to some 1000 GW in the 1.5TECH scenario, hence respectively showing increases between some 50% and 200% and up to 220% compared to 2030. This corresponds to annual installations of almost 20 GW (EE) to over 40 GW (1.5TECH) between 2030 and 2050. Wind and solar alone represent 53% of total net capacity installed by 2030, and between 71% (EE, CIRCC) to 80% (P2X, COMBO and 1.5°C scenarios) by 2050.

Other renewables (mostly hydro and biomass) go through more modest development. Biomass capacity from 60 GW in 2030 either stabilises (in EE) or grows very moderately - up to 83 GW (P2X).

The weight of fossil fuel-fired capacity in the total power mix decreases over time. Gas-fired capacities (that can use both natural gas or biogas) decrease compared to 2015 (220 GW), ranging in 2050 from 141 GW (P2X) to 226 GW (ELEC) in scenarios achieving 80% GHG reductions, and decreasing up to 100 GW in the 1.5LIFE scenario, of which some 30% is associated with CCS. Coal-fired capacities progressively get out of the power mix, with about 20 GW only left in all scenarios except for 1.5TECH scenario, where 38 GW capacity is still present. The solid fuel plants that operate in 2050 are burning biomass and/or are applying CCS, whereas the not converted coal plants are in majority used for reserve purposes. Oil-fired capacities virtually disappear already in 2030, with less than 5 GW still installed in all scenarios, which are used either in specific applications in industry (e.g. burning industrial by-products) or serving reserve purposes. The average running hours of fossil fuel-fired capacities decline significantly in all decarbonisation scenarios.

Nuclear installed capacity in 2050 is only slightly lower than current level (99-121 GW versus 122 GW in 2015), and, in all cases, higher than both the 2030 projection (97 GW) and the Baseline in 2050 (87 GW).

**Figure 25: Newly installed power generation capacities**



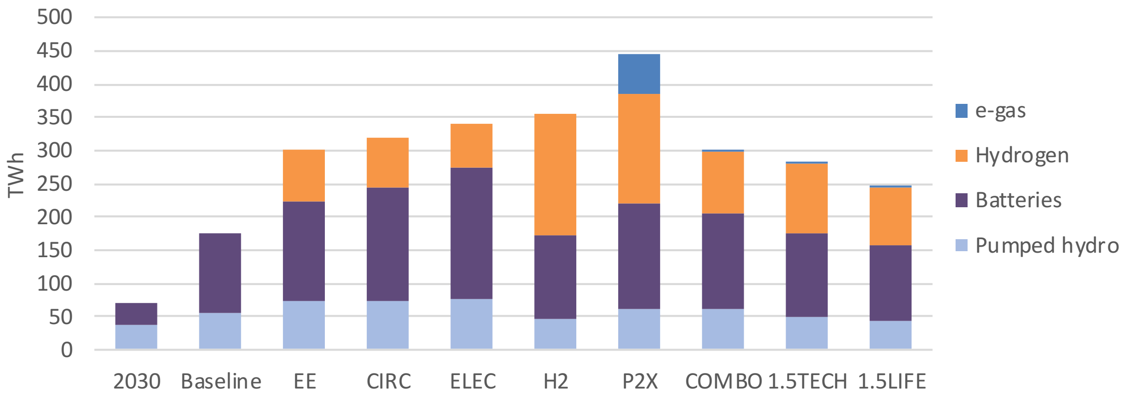

*Note: newly installed capacities using fossil fuels in 2031-2050 are almost exclusively gas-fired.*
*Source: PLATTS (2000-2015), PRIMES.*

In 2050, the role of CCS for power generation is very limited in all scenarios as competitive wind and solar, as well as biogas, hydrogen, batteries and biomass are available in sufficient quantities to balance electricity system. In 2050, CCS plays a noticeable role only in 1.5TECH, where it reaches 5% of the total net electricity generation (mostly because of biomass power generation to generate negative emissions), with 66 GW of total capacity equipped with CCS installed. In other scenarios, the share of CCS in net electricity generation is around 0.1-0.5% and capacities range between 1 to 5 GW. The situation changes by 2070 as bigger role of this technology to fully decarbonise the power sector and of BECCS to generate negative emissions is then expected. The balance of carbon capture and storage or utilisation for e-fuel production is discussed in greater detail in section 4.8.

As a result of the changes described above, the power sector[223] has only very small residual emission left in 2050 between some 10 $MtCO_2$ (EE) and 110 $MtCO_2$ (P2X) and even negative emissions (some 140 $MtCO_2$) in 1.5TECH. The larger amounts of $CO_2$ emissions in the power sector in the P2X (and closely after H2) scenarios are due to the high amounts of electricity needed for e-fuels production and the difficulties to balance such a large system without emissions generated by gas plants with CCS (which emit a small fraction of the $CO_2$ produced). In 2070, all decarbonisation scenarios except for 1.5LIFE generate negative emissions in electricity sector in order to contribute to continuing emission reductions . Other studies show emissions in the power sector ranging from close to zero (Shell Sky scenario[203]) to negative emissions (IEA ETP B2DS[204]). This illustrates that, while CCS technology for mitigation of emissions might not be currently attractive, it is critical for achieving net-zero emissions, as required to reach the 1.5°C goal of the Paris Agreement.

As already mentioned above, while electricity supply grows, electricity storage plays an increasingly prominent role in all decarbonisation scenarios (Figure 26).

**Figure 26: Electricity storage in 2050**




*Source: PRIMES.*

The use of conventional/"direct" storage, in the form of pumped hydro or stationary batteries, increases in all scenarios, from about 30 TWh today, some 70 TWh in 2030 to between some 170 TWh (H2) and 270 TWh (ELEC) in 2050 among scenarios achieving 80% GHG reductions while scenarios achieving higher GHG reductions have use of some 160-200 TWh. For all scenarios approximately less than 30% of this storage comes from pumped hydro and roughly 70%from stationary batteries. The highest conventional/"direct" storage takes place in the scenarios where e-fuels do not deploy (ELEC, EE and CIRC) in final demand sectors.

The e-fuels sold to the final demand sectors have the possibility to be stored in conventional facilities, which allows producing them at times of high availability of renewables and, in this way, reducing the needs of storage for the system. This is an "indirect" storage of electricity, which is not easily measurable and is not included in the total storage.

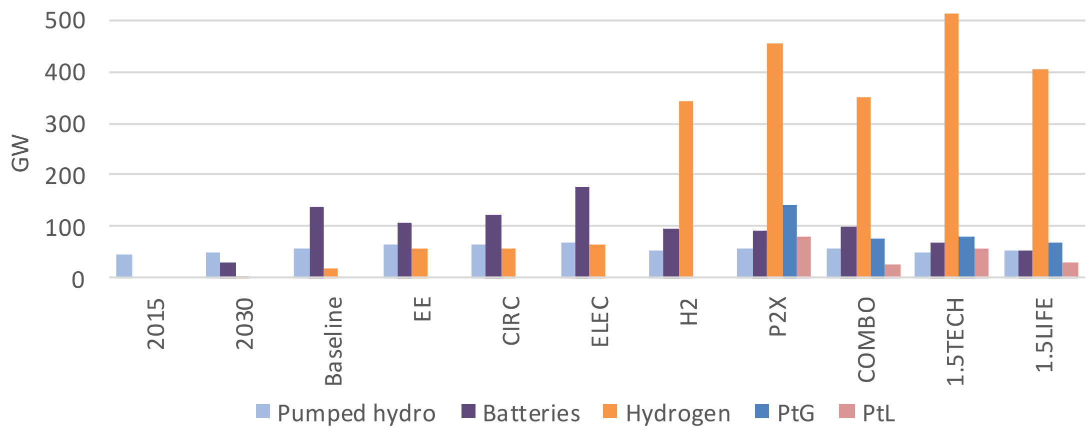
[223] For calculation of GHG emission combined with district heating.

However, it is possible to measure the explicit storage of electricity using hydrogen and e-fuels, which is also included in the scenario projections. This storage (so-called chemical storage of electricity) produces hydrogen and e-fuels at times of abundant energy (typically from wind and solar) and uses them at times of scarce energy (from wind and solar). In the context of explicit chemical storage, the power system, and not final demand consumers, use hydrogen and e-fuels. The chemical storage in 2050 ranges between some 65 TWh (ELEC) and 220 TWh (P2X) and scenarios achieving higher GHG reduction lie in this range. The total (stationary) storage explicitly used in the power system (i.e. hydro-pumping, stationary batteries and chemical storage, including the indirect storage effects of producing e-fuels for the final consumers) ranges from some 250 TWh (1.5LIFE) to 450 TWh (P2X). In addition, the large deployment of batteries vehicles (– see section 4.4) will also play a role as a storage capacity for electricity.

Figure 27 shows the development of capacities of storage and of e-fuels production. In terms of conventional/"direct" electricity storage, pumped hydro storage grows only slowly from 51 GW in 2030 (that is close to the 2015 level) up to 70 GW (ELEC). Stationary batteries would play a larger role in the future, growing from 29 GW in 2030 (from negligible amounts today) to between 54 GW (1.5LIFE) and 178 GW (ELEC), in general having higher deployment in those scenarios without significant development of e-fuels (EE, CIRC and ELEC). In the three scenarios that achieve the highest GHG reductions the needs for this type of storage are the lowest as they develop strongly both hydrogen and e-fuels – see below.

The production of new energy carriers would induce a very large deployment of electrolysers to produce the hydrogen for direct use as well as hydrogen as feedstock for the e-fuels. The capacity ranges from 57 GW (EE, CIRC) to 454 GW (P2X) in the scenarios achieving 80% GHG reductions, and up to 511 GW (1.5TECH) in the scenarios achieving higher GHG reductions. This deployment is accompanied, in scenarios where e-fuels deploy in final demand, by development of capacities of power-to-gas (71-142 GW) and power-to-liquids (28-79 GW) which, in both cases, are the highest in the P2X scenario while being more moderate in the three scenarios that achieve the highest GHG reductions.

**Figure 27: Electricity storage and new fuel production capacities (2050)**




*Source: Eurostat (2015), PRIMES.*

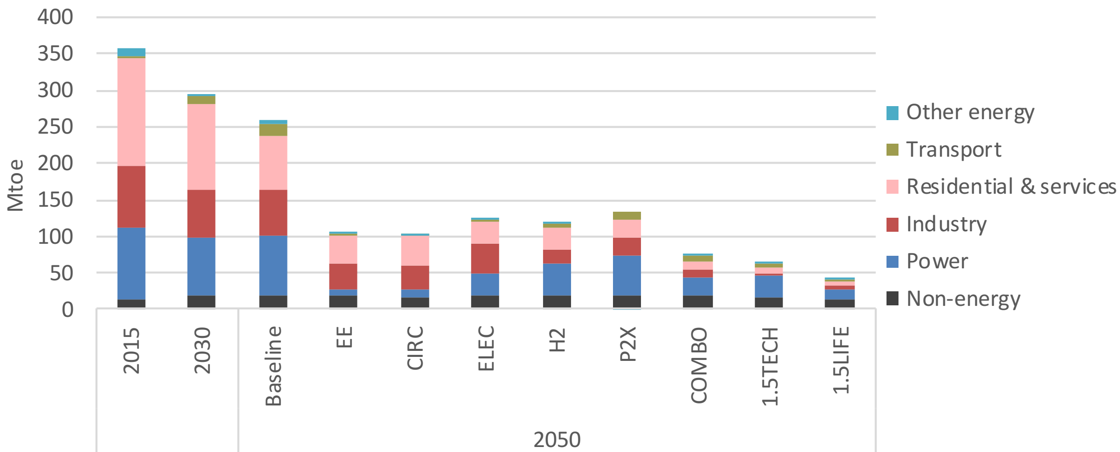
4.2.2.4 Gas sector and new energy carriers

Decarbonisation analyses show a large uncertainty on the role of gas in the long term. This uncertainty is definitely a challenge for planning the energy transition and in particular, for planning the future of the gas infrastructure.

In the long term, unabated emissions from natural gas become increasingly incompatible with the climate targets. Depending on the sector, natural gas can be replaced by carbon-neutral forms of gas (biogas, e-gas) or possibly by hydrogen, which can substitute some traditional uses of gas (e.g. in buildings heating) but which cannot be used in all industrial applications.

First of all, the consumption of natural gas (excluding non-energy use) is expected to be severely reduced by 2050 in all scenarios (Figure 28), from 345 Mtoe in 2015 to 273 Mtoe in 2030 and then in 2050, in scenarios achieving 80% GHG reductions, to between 87 Mtoe (EE, CIRC) and 109 Mtoe (P2X) and to less than 54 Mtoe in the scenarios achieving higher GHG reductions. In most cases, the power sector is key in the remaining natural gas consumption (associated with CCS in the stronger reductions cases), except in the EE and CIRC scenarios. Interestingly, looking at overall Gross Inland Consumption, in the decarbonisation scenarios a significant remaining part of natural gas consumption relates in fact to non-energy needs (organic chemistry).

**Figure 28: Consumption of natural gas by sector**




*Note: "Residential and services" also includes agriculture.*

*Source: Eurostat (2015), PRIMES.*

The EU natural gas production, which stands at 108 Mtoe in 2015, is expected to decline to some 30 Mtoe by 2050 in scenarios achieving 80% GHG reductions and even below 15 Mtoe in 1.5°C scenarios[224], still fulfilling a large part of the remaining needs. As a consequence of declining demand for fossil gas, net imports of natural gas are expected to decrease, from 247 Mtoe in 2015 to some 220 Mtoe in 2030, and then further down by 2050 (see section 4.2.2.5). The 80% GHG reductions scenarios require noticeably higher quantities of net natural gas imports by 2050 (from 98 Mtoe to 120 Mtoe) than scenarios achieving higher GHG reductions, which limit the natural gas net import to as low as 47 Mtoe (1.5LIFE). The reduction of natural gas imports has significant impacts on the security of supply and reduction of fossil fuels imports bill, which is further described in section 4.10.4.

In addition to natural gas production, biogas[225] is increasingly used in decarbonisation scenarios (Figure 29) as it is fully interchangeable with natural gas and its combustion is considered carbon-neutral[226]. The whole consumption[227] of biogas[228] would increase from 16 Mtoe in 2015

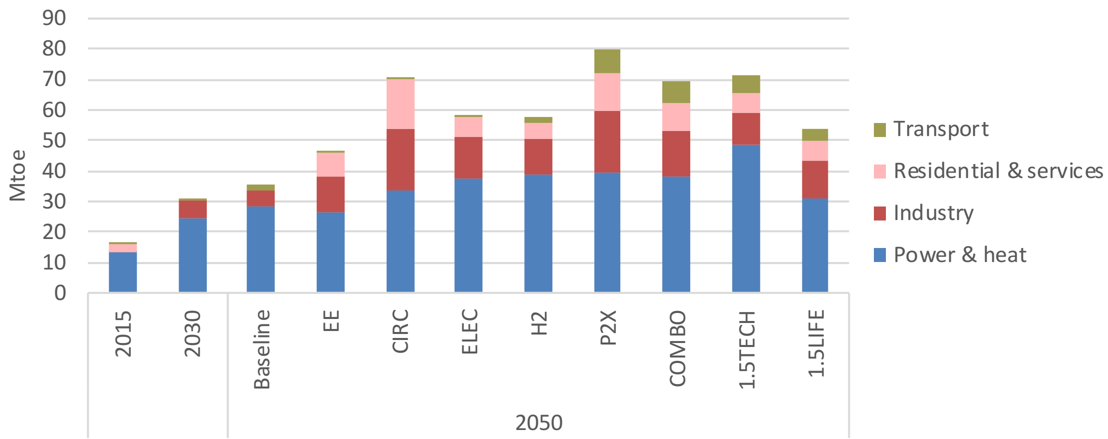
[224] Assuming that in context of declining demand for natural gas, prices of import would be more competitive and thus the level of production projected in the Baseline will not be maintained.

[225] In this quantitative analysis "biogas" actually includes both biogas and biomethane.

[226] Just as biomass and waste, where it is classified in energy balances.

to some 30 Mtoe in 2030 and then range between 45 Mtoe (EE) and 79 Mtoe (P2X) in 2050, and is mainly used in the power and industry sectors. These projections are in line with other studies that also see a potential for increased contribution of such type of gas in the EU energy system. For instance, the Green Gas Grids Project[229] estimated that a production of 48–50 bcm of biogas, i.e. close to 45 Mtoe[230], (including raw biogas, upgraded biogas and syngas) could be achieved by 2030, out of the technical potential of 151 bcm (close to 135 Mtoe), hence more than tripling the current production level. The Gas for Climate study[231] expects biogas to reach up to 98 bcm/year in 2050 (close to 88 Mtoe), hence about 20-25% of current levels of natural gas consumption.

**Figure 29: Consumption of biogas and gas from waste by sector**



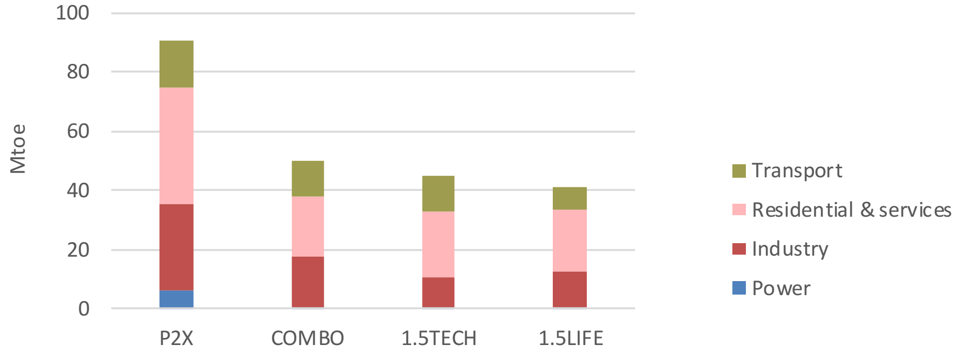

*Note: "Residential & services" also includes agriculture.*

*Source: Eurostat (2015), PRIMES.*

Among scenarios explored in this analysis achieving 80% GHG reduction, e-gas develops only in the P2X case (91 Mtoe in 2050 and 130 Mtoe in 2070) and in the strongest emissions reduction scenarios albeit there more moderately (around 40-50 Mtoe). In these scenarios, the e-gas is chiefly used in the buildings (to substitute the high natural gas demand showing in the Baseline), closely followed by energy needs in the industry where it enables seamlessly to conduct processes that today can only be performed with natural gas. Transport makes a smaller use of e-gas, although it represents about 21% of the energy use in heavy goods vehicles and around 4% of the fuel mix in inland navigation; its use in passenger cars is limited (see section 4.4.2).

[227] Biogas is assumed to be produced entirely in the EU.
[228] Also including minor quantities of gas from waste.
[229] GreenGasGrids project (2014), http://www.greengasgrids.eu/index.html.
[230] Using a conversion factor from bcm to Mtoe of 0.9.
[231] ECOFYS (2018). Gas for Climate - How gas can help to achieve the Paris Agreement target in an affordable way. https://www.gasforclimate2050.eu/files/files/Ecofys_Gas_for_Climate_Feb2018.pdf

**Figure 30: Consumption of e-gas by sector in 2050**

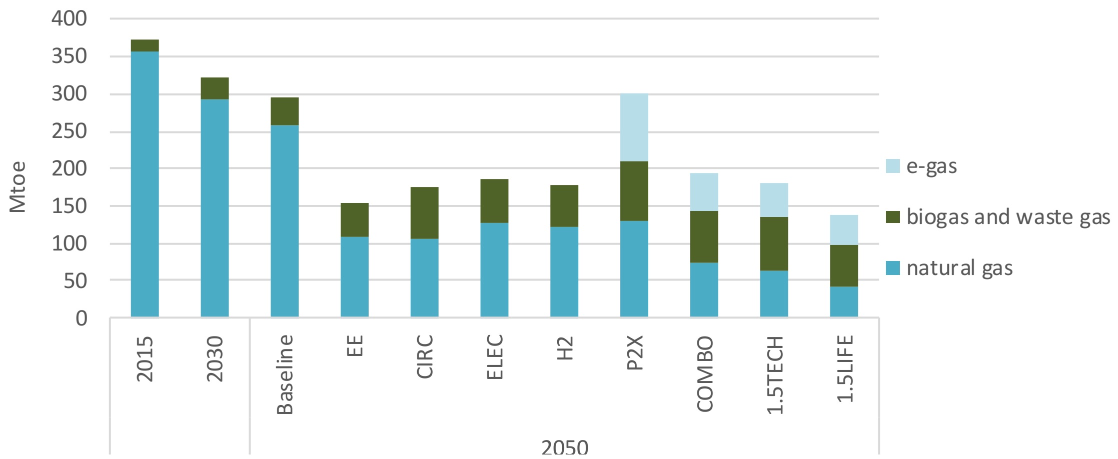



*Note 1: e-gas does not develop in the other scenarios (Baseline, EE, CIRC, ELEC, H2).*
*Note 2: "Residential & services" also includes agriculture.*

*Source: PRIMES.*

Summing up the developments for natural gas, e-gas and biogas, in the Baseline scenario, total gas consumption (covering all gas types) stands at some 320 Mtoe in 2030 and declines only slightly thereafter (compared to some 370 Mtoe in 2015 and some 450 Mtoe at its peak, in 2005). In the decarbonisation cases, the total consumption in 2050 (Figure 31) varies from some 300 Mtoe (P2X, which projects the highest quantities of e-gas) to some 150 Mtoe (EE, which reduces overall energy demand with energy efficiency measures). The scenarios that achieve higher emissions reduction scenarios lie in this range, as they see a more moderate substitution of natural gas by e-gas, complemented by a substantial role of biogas but also high levels of energy efficiency as well as circular economy and consumer choice curbing the overall energy demand for 1.5LIFE. The projections indicate that the development of both e-gas and biogas could play a key role in making the best use of the existing EU natural gas infrastructure in a decarbonised energy system.

**Figure 31: Total gas consumption per gas type**

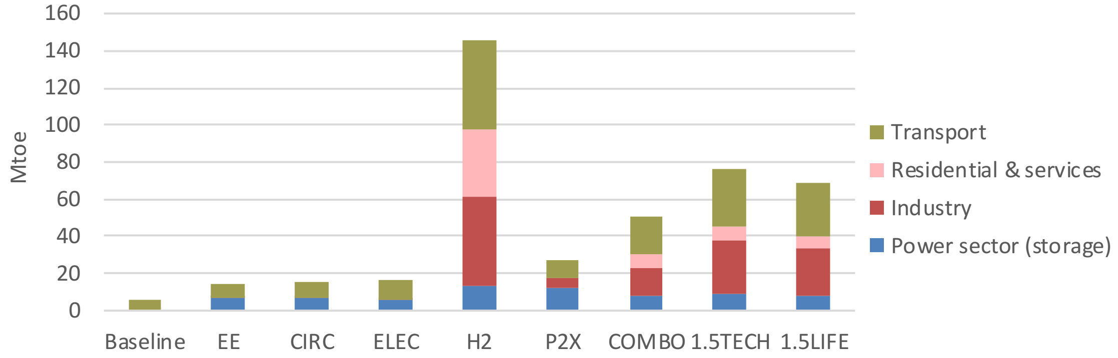



*Source: Eurostat (2015), PRIMES.*

In addition, and as a complement to methane molecules, hydrogen is also expected to play a role in the future energy system. Although no major technological breakthrough took place over the last decade, the costs lowered and new pilot projects were launched, while the industry increasingly sees bigger role for hydrogen in its decarbonisation visions and pathways. This is why different deployments of hydrogen were explored in the decarbonisation scenarios.

In the Baseline, hydrogen use develops only as a niche application for road transport (amounting to a few Mtoe). It increases (to some 15 Mtoe) further in the EE, CIRC and ELEC scenarios as an electricity storage option to absorb higher volumes of variable renewables (see Figure 26) and in transport. However, large scale deployment takes place (up to some 150 Mtoe in 2050 and 210 Mtoe in 2070 in H2 scenario and up to 80 Mtoe in 2050 in 1.5TECH) as soon as consuming technologies are available (i.e. fuel cell vehicles) and competitive (in final energy demand), and when the full portfolio of options needs to be deployed, i.e. in the 1.5°C scenarios.

**Figure 32: Consumption of hydrogen by sector in 2050**




*Note: "Residential & services" also includes agriculture.*

*Source: PRIMES.*

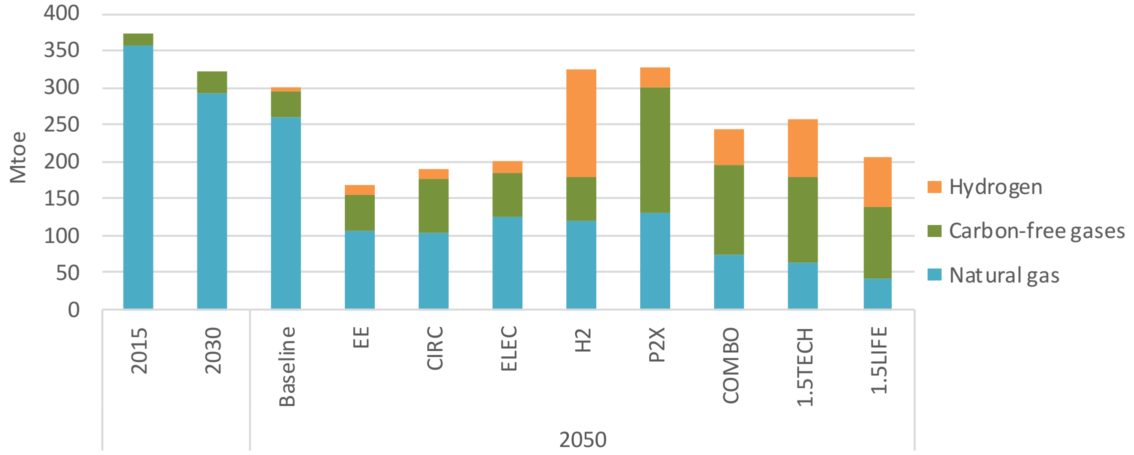
The use of hydrogen develops in industry (see section 4.5.2), transport (mostly for heavy duty vehicles, which do not have the option of electrification unless covering only short distances - see section 4.4.2) and, to a lower extent, in buildings (with heating equipment consuming hydrogen blended with gas).

Hydrogen is also assumed to be produced in the EU. Clearly, building the necessary production assets – be it for hydrogen or e-gas production and upgrading the gas infrastructure (in case large quantities of hydrogen are to be distributed) in the light of currently high costs and nascent demand would be a challenge from the industrial policy perspective. Studies indicate that some areas within the EU could be well suited to production of hydrogen/e-gas be it because of abundant production of renewables (e.g. offshore in the North Sea or, in general, close to grids giving access to diversified and big amounts of renewables) or proximity to nuclear power stations or close to industrial buyers.

When combining all gaseous fuels (natural gas, biogas, e-gas and hydrogen), Figure 33 shows two very different patterns: on the one hand, in those scenarios where the hydrogen, and the e-gas, does not develop because of a lack of consumption market, gaseous fuels are roughly halved compared to today. Conversely, in a context where large-scale end-uses of hydrogen and/or a corresponding chain of new fuels would take place, the total consumption of gaseous fuels would actually be close to current levels (in scenarios H2, P2X). In the 1.5°C scenarios and COMBO, where energy efficiency and new consumption habits limit further energy needs, the consumption of gaseous fuels would lie in-between at around 200-250 Mtoe.

Comparing total demand for gaseous fuels, these results are roughly in line with the study by Trinomics[206] on the role of European gas infrastructure in the light of 2050 decarbonisation, which expects the demand for these fuels[232] to decrease compared to today in the case of strong electrification ("storyline 1"), but to stabilise (even slightly increasing) in the case of high developments of carbon-free gases ("storyline 2") or hydrogen ("storyline 3").

**Figure 33: Consumption of gaseous fuels**

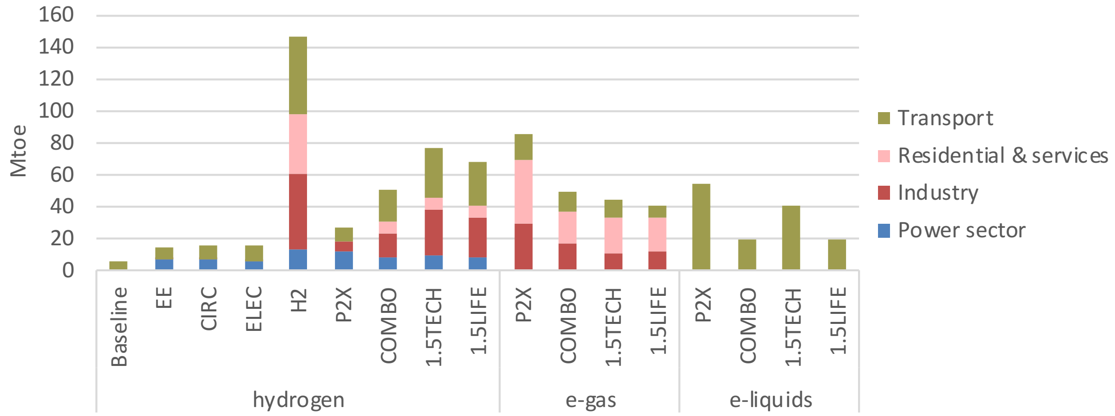



*Note: "carbon-free" gases refer to e-gas, biogas and waste-gas.*

*Source: Eurostat (2015), PRIMES.*

The future decarbonised energy system could also make use of e-liquids, i.e. more complex synthetic hydrocarbons also derived from hydrogen in the same way as e-gas, using $CO_2$ from carbon-neutral sources. Such fuels could develop in the transport sector, which appears particularly difficult to decarbonise. Their deployment reaches up to 54 Mtoe in 2050 (and stabilises afterwards) in the P2X scenario (whereas they are absent from all other scenarios that achieve a 80% emissions reduction). The e-liquids are also present, at smaller scale, in the scenarios that achieve higher GHG reductions (some 20-40 Mtoe).

**Figure 34: Consumption of new fuels by sector in 2050**




*Note: Baseline, EE, CIRC, ELEC and H2 scenarios do not produce e-gas or e-liquids.*

*Source: PRIMES.*

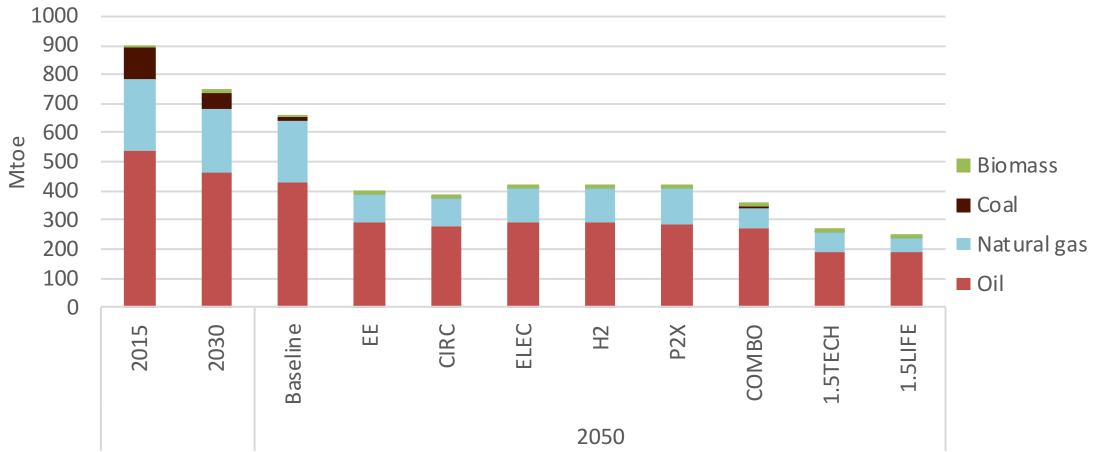
[232] A noticeable difference is that the Trinomics (2018) study anticipates the disappearance of natural gas, entirely substituted by other gaseous fuels, unlike the modelling analysis of this document.

#### 4.2.2.5 Energy imports

Security of supply is a political priority and one of the five dimensions of the Energy Union Strategy. Although the import of fuels is not necessarily an security problem, the magnitude and the nature of, in particular, oil and gas imports (sometimes coming from a limited number of suppliers or via limited number of routes) raise specific energy security and, sometimes, even wider geopolitical issues. Energy efficiency or other ways of limiting energy demand (circular economy and lifestyle change) as well as switching to domestically produced low-carbon energy vectors can contribute to reducing energy imports[233].

Net fossil fuels imports, in volumes are expected to decrease already by 2030 to close to 730 Mtoe, versus some 900 Mtoe in 2015. The trend is pursued in the Baseline case, which would see a decrease to about 650 Mtoe in 2050, 28% lower than the current level. The decarbonisation scenarios lead to further decrease, with volume of fossil fuels imports ranging from some 370 Mtoe (CIRC) to 410 Mtoe (P2X) in the scenarios reaching -80% emissions reduction (hence a reduction of fossil fuels imports of 54% to 58% compared to 2015). The fossil fuels imports volumes would be close to 350 Mtoe in the COMBO case and about 250 Mtoe in the 1.5°C scenarios, i.e. more than 70% decrease of fossil fuels imports compared to 2015. It is clear that ambitious energy efficiency measures and strong decarbonisation go in hand with deeper reductions of imports.

**Figure 35: Energy imports**




*Source: Eurostat (2015), PRIMES.*

Looking at fuels separately:

- Coal consumption virtually disappears from the EU energy system already in the Baseline and in 2050 and thus there is no longer need for imports.
- Imports of oil reduce only very slowly in the Baseline. In the decarbonisation scenarios, however, compared to 2015, they decrease in 2050 between close to 50% (in all scenarios reaching -80% emissions reduction) and nearly 65% in the 1.5°C scenarios. These scenarios combine the use of all alternative zero carbon or carbon neutral fuels and, in case of 1.5LIFE the benefit from lifestyle changes that induce changes in mobility patterns (also as part of circular economy measures).

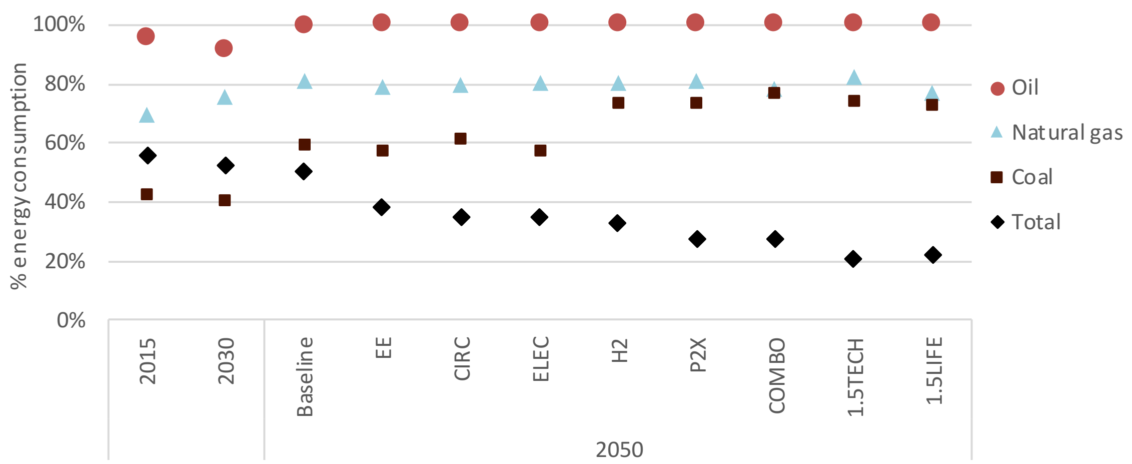
[233] Reducing the overall scale of imports also diminishes the magnitude of potential disruptions of the economy because of supply severance or price shocks.

- While imports of natural gas are only slightly reduced in the Baseline, they significantly reduce in all decarbonisation scenarios. Indeed, compared to 2015, in 2050 they are between 51% (P2X) and 60% (EE) lower for scenarios achieving 80% GHG reductions. The least reductions happen in the P2X (and closely after ELEC) scenarios because of higher gas consumption for balancing purposes in the power sector. The strongest reduction scenarios (COMBO, 1.5TECH and 1.5LIFE) lead to the highest gas import decreases - up to 81% reduction compared to today's levels is projected in 1.5LIFE thanks to impact of all technologies combined and consumer choice.
- Imports of (sustainable) solid biomass are kept limited in all scenarios at 4% to 6% of the solid biomass used for bioenergy by 2050. This assessment did not look into the effects and impacts on greenhouse gases beyond the EU if impact of biomass would be increased to meet EU demand.

A detailed analysis on the monetary values of future EU energy imports in different decarbonisation pathways can be found in section 4.10.4.

As a result, the dependency of the total EU energy consumption[234] on energy imports (mostly fossil fuels), which only reduces from 55% in 2015 to 52% in 2030, falls afterwards to between 27% and 38% in the 80% GHG reduction scenarios (highest in EE, which radically lowers the demand), 27% in the intermediate level of reductions (COMBO) and further in the net zero emissions scenarios where only 20% of the energy needs are imported.

**Figure 36: Energy import dependency**




*Note: the rate is calculated by dividing the net imports per fuel by the sum of the gross inland consumption and of the energy use in international bunkers for that fuel. The Total data series corresponds to the ratio of imports to gross inland consumption.*

*Source: Eurostat (2015), PRIMES.*

The decarbonisation scenarios explored in this document assume that decarbonised energy carriers (electricity, hydrogen, e-gas, e-liquids) would all be produced within the EU. However, as it is the case today for oil, natural gas and biofuels, hydrogen and e-fuels could actually be globally traded commodities and imported from regions with comparatively cheaper, abundant renewables.

If these fuels were to develop as large contributors to future EU energy needs in a decarbonised economy, imports option could help reduce the cost of the transition as well as possible pressure

[234] Including international bunkers.

on domestic resources (land, sea) linked to large-scale deployment of renewables. Abundant, globally traded zero-carbon/carbon neutral fuels could thus be an economic opportunity but they do create a risk of new types of dependency, possibly affecting EU's energy security.

Finally, it must be mentioned that other dimensions of energy security have not been explored in detail in this analysis. Other factors need to be considered, including the role of fuel stocks or interconnectors[235], as well as anticipating new threats to energy supply (e.g. cyberterrorism on critical energy infrastructures, unpredictable weather patterns) and new forms of dependencies, for instance on raw material imports stemming from new technologies development (see section 5.6.1.2) or on foreign investors investing in EU critical assets or technology to use them to the detriment of the EU's security (see section 5.6.1.3).

### *4.2.3 Transition enablers, opportunities and challenges*

The options and results described in the sections above clearly show that decarbonisation of energy supply is possible with existing technologies but of course these technologies have to further evolve in terms of their performance and costs so as to scale up their deployment, underlining the importance of a dedicated industrial policy. The supply of the raw materials needed for these developments (for e.g. batteries, the electricity grid, digitalization or wind power) will need to be secured (see section 5.6.1.2), making also sure that the climate impact over the life cycle of products does not lead to climate impacts elsewhere.[236]

The technology development (both in terms of new, carbon neutral fuels and energy efficiency) is clearly the main enabler for the transition while the costs and constraints associated to large scale technology deployment are the key challenge. Becoming a key actor on fast expanding global markets for low carbon technologies and services is also one of the most promising opportunities for the European industry. Developing such a production capacity will also avoid replacing the current dependency on fossil fuel imports by a dependency on new technologies. Europe is leading in many low carbon technologies today but this is not the case for some, like solar PV production and batteries. Regaining leadership and seizing the first-mover advantage in new technologies notably hydrogen, e-fuels, advanced bio-fuels production on a very competitive global market would require supporting domestic excellence in research, creating the necessary conditions for innovation to materialise and reinforcing cooperative programmes for the development of technology (see section 5.4). While many decarbonisation technologies are expected to become competitive on their own, some small-scale and emerging ones might still require financing support.

This analysis shows that the most important single driver for a decarbonised energy system is the growing role of electricity, both in final energy demand and in the supply of alternative fuels, which will be mostly met by renewables, and in particular by wind and solar electricity. A key challenge, which lies partly in the domain of technology and partly in regulatory field, is therefore the paradigm shift from electricity production following demand to a largely meteorologically driven production. The future energy system will have to rely on much higher balancing capacities, including:

[235] The internal market infrastructure will in the future likely also concern hydrogen, $CO_2$ and e-fuels in addition to electricity, as it will be cost-efficient to share the resources and productions of the new fuels in the EU given that the Member-States are differently endowed with RES.

[236] See the EU Raw Materials Initiative: https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en

- better interconnections on all grid levels, extending pan-European, national electricity grids and connection to extra EU areas with high renewable potential that would improve the match between supply and demand and unlock the potential of large offshore wind farms (e.g. in the North Sea) or solar energy (e.g. in the south of Europe);
- more storage, helping to match demand and supply over multiple time frames;
- deeper demand response;
- as well as flexible generation units.

Electricity production, transportation and storage will require proper financing and possible adaptation of tariff schemes, notably as the utilisation rate of some infrastructure might decrease, while still playing a critical role to guarantee security of supply. Once technologies have reached sufficient maturity, initial support schemes can be phased out EU wide in a coordinated way, so that investment decisions are made based on market signals.

The future of nuclear energy, will also depend on both the technological developments and the regulatory field. Nuclear will face the challenge of decommissioning of the units at the end of their economic life-time and developing a permanent solution for nuclear waste disposal as well as construction of new plants in line with the highest safety standards.

Importantly, while there are opportunities for centralised storage (including new solutions of storage in e-fuels), there will likely be also the opportunities for flexible consumers (individual ones if representing large demand or those collectively offering their capacities through aggregators) and producers of electricity who can be integrated through increasingly digitalised networks, allowing peer-to-peer trading of electricity. Options for storing and converting both electricity and heat are multiple but will all require a more integrated approach to the relevant infrastructure. A fiscal level playing field across the EU would facilitate the deployment of such solutions.

Storage of electricity in sectors other that power itself, for instance in the transport sector, is an example of sector coupling, which is currently considered as very promising option. It is crucial that sectors do not work in isolation and those consuming the energy can rely on the supply side to deliver decarbonised fuels (bio-fuels, electricity, hydrogen, e-fuels).

The significant increase in power generation capacity and the need to develop further infrastructure for energy carriers to go from supply regions to consumption areas also means that spatial planning could be an important challenge. Engaging with citizens and local authorities, addressing in synergy other local environmental challenges, will be essential to deploy in due time the necessary infrastructure.

The regulatory framework to facilitate this major change in energy market structure and operation is under construction already but of course more work will be needed and some challenges might only emerge with the scaling-up of the new energy system. The EU will need to build on the current regimes of cooperation across Transmission System Operators and Distribution System Operators to facilitate necessary investment and market opening in the most cost effective manner. The European manufacturers and service providers would then need to set standards for the ongoing convergence between the energy and the IT industries – setting such standards first in the EU could be then an opportunity for the global leadership.

Finally, the role of gas requires further consideration since scenarios considered in this analysis see large differentiation in its use at 2050 horizon. Natural gas currently plays an important role in balancing the electricity system and has many applications in final energy consumption. The full decarbonisation of the energy system will challenge this role as it can only have place if coupled with CCS, a technology itself facing challenges. In the future, decarbonised gaseous fuels (biogas, but also hydrogen and e-gas) could provide clean energy to industry, buildings and transport without loss of utility and providing longer use of existing natural gas infrastructure. Today the economics of such energy carriers is uncertain, with costly investments and a need for predictable levels of demand as well as regulatory certainty. Conversely, the fact that they fit very well with Europe's existing infrastructure and could be developed by Europe's existing (chemical) industry creates an opportunity to gain technological leadership.

## 4.3 Buildings

### *4.3.1 Buildings options*

Buildings, comprising the residential (60% to 85% of floor area across Member States) and services sectors, currently represent the highest share of final energy consumption in the EU. Energy consumption in buildings serves multiple purposes: heating & cooling, operation of appliances, water heating and cooking. Emissions in this sector have been declining only very slowly as the majority of the energy needs are still covered by fossil fuels (mostly natural gas).

Options to reach long-term reduction of energy use and associated $CO_2$ emissions are explored below.

#### 4.3.1.1 Energy performance of the building shell

The role of thermal insulation has, for a long time[237], been considered as crucial in the future evolution of energy consumption in buildings and fulfilling the GHG emissions reduction objective.

First of all, new buildings can be designed and constructed with high-performance thermal insulation. However, buildings built today will only represent 10-25%[238] of the buildings stock in 2050 and thus the overall energy performance of the stock will be largely determined by the capacity to renovate and (significantly) improve the energy performance of the existing buildings. While the efficiency of new buildings has steadily improved over time, most of Europe's existing building stock has yet to improve insulation performance, which will have to go through energy performance-targeted renovation.

Currently, about 35% of the EU's buildings are over 50 years old and almost 75% were built before energy performance standards existed. It has been estimated[239] that up to 97% (i.e. all buildings built before 2010) needs partial or deep renovation to comply with the long-term strategy ambition. This will imply a more than doubling of the renovation rate of the building stock by 2050, from the today observed 1%-1.5% yearly rate to at least 3%. Taking advantage of technological progress (e.g. ICT and smart-building technologies) policies should aim at

[237] In the EU, 2010 has been in this respect a turning point as (i) the EPBD was adopted and (ii) the global financial crisis put the housing sector, and in particular the renovation of the existing stock, in the political focus because of its growth-enhancing role, see: Housing Europe position paper: http://www.housingeurope.eu/resource-1096/decarbonisation-of-the-building-stock-a-two-front-battle. Also, already the 2011 Roadmap gave a key role to the energy performance improvements in the building stock.

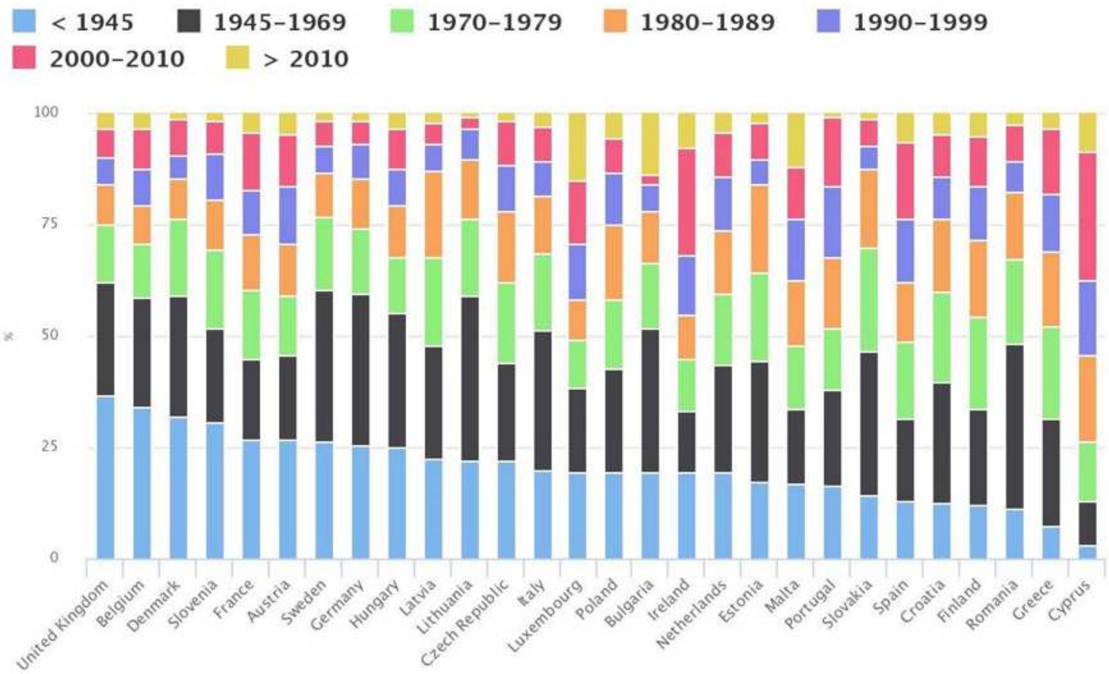
[238] BPIE (2017), State of the building stock, http://bpie.eu/wp-content/uploads/2017/12/State-of-the-building-stock-briefing_Dic6.pdf

[239] ECOFYS, Politecnico di Milano / eERG, University of Wuppertal, Towards nearly zero-energy buildings, Definition of common principles under the EPBD (2012), https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf

increasing the depth of renovation. Measures should be targeted towards the worst performing segments of national building stocks, including demolition and replacement by new buildings.

The average age of existing buildings and the share of new buildings are in fact good indicators of the overall efficiency of the building stock. Figure 37 gives the distribution of age classes in the EU building stock per Member State, showing that most of the stock was built before 1990.

**Figure 37: Breakdown of residential building by age category (2014)**



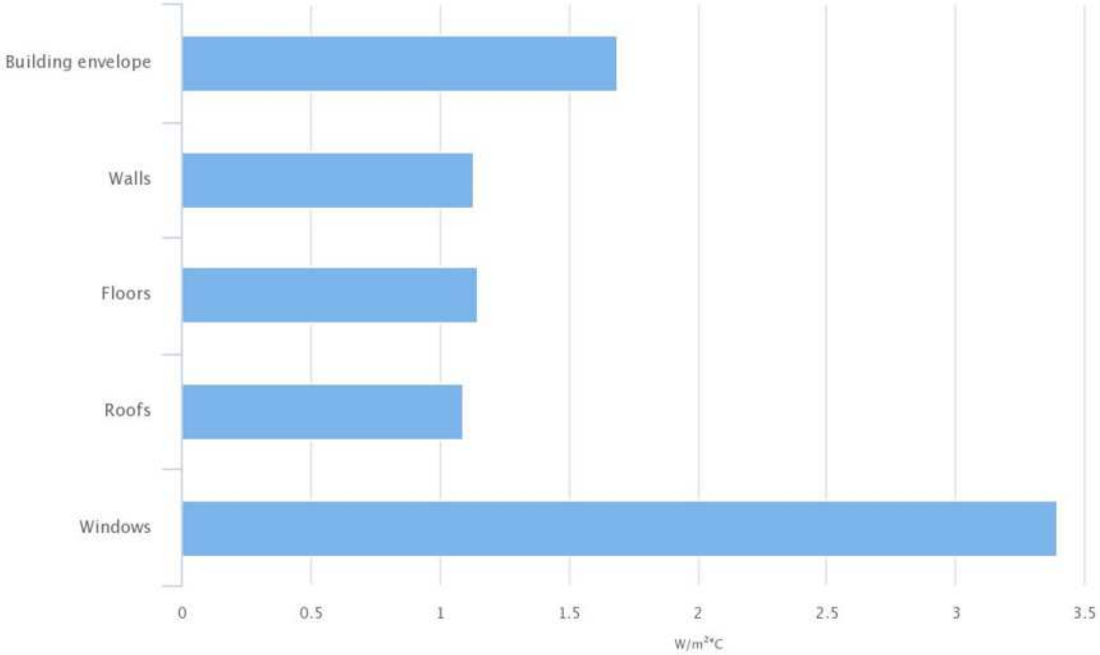

*Source: Building Stock Observatory*[240].

Of all the energy consumed in buildings, most is used for space heating, hot water production and cooling. In Europe's residential building stock, 71% of all energy is used for space heating alone. Heat demand in buildings depends in fact on the insulating properties of the building shell. The performance of the building shell and of its different elements can be expressed in U-value[241], shown in Figure 38.

[240] https://ec.europa.eu/energy/en/eu-buildings-factsheets

[241] The U-value (a short name for the heat transfer coefficient) is a way to measure heat loss through a building shell element. It is measured in W/m²°C expressing the heat transfer of the building envelope in watts per square meter (per degree of temperature difference between the inside and outside). A low U-value indicates low heat losses and a high level of insulation.

**Figure 38: Average U-value per building element (2014)**




*Note: average over the building stock.*

*Source: Building Stock Observatory*[242].

Insulation materials could highly impact the overall energy performance of buildings. Although the thermal properties and performance of the traditional building insulation materials have significantly improved over the years, new innovative emerging insulation solutions with similar or higher performances are expected to be adopted by the market in the future. The European thermal insulation market is expected to grow on average at a rate of 2.8% per year until 2019 with higher rates in central and eastern European countries[243]. Today, the largest potential for insulation materials in building applications is dominated by materials such as mineral (stone and glass) wool and organic fossil fuel-derived plastic foams such as polystyrene and polyurethane. Regarding windows, it is estimated that 85% of glazed areas in Europe's buildings are outdated[244], either single glazing or early uncoated double glazing.

The important challenge is that renovations have a very diverse as well as scattered nature and encounter multiple market failures. These barriers include diversity and fragmentation within the building value chain, split incentives between landlords and tenants, insufficient knowledge about the advantages of renovation, inefficient and complex renovation processes, a lack of deep renovation packages, insufficient and costly financing options, unclear energy or environmental requirements in renovation grants or procurement processes, low progress in performance guarantees.

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[242] https://ec.europa.eu/energy/en/eu-buildings-factsheets

[243] JRC (2018), Competitive landscape of the EU's insulation materials industry for energy-efficient buildings, https://ec.europa.eu/jrc/en/publication/competitive-landscape-eu-s-insulation-materials-industry-energy-efficient-buildings

[244] TNO (2011), Built Environment and Geosciences – Glazing type distribution in the EU building stock – TNO report TNO-60-DTM-2011-00338.

#### 4.3.1.2 Efficient equipment

The uptake of efficient energy consuming equipment in buildings (for heating/cooling, for water heating and cooking and all domestic and tertiary sector appliances) has for a long time been identified as a powerful driver in reducing energy demand, and this trend is confirmed by more recent analysis[245].

The first eco-design regulations that act precisely on the performance levels of equipment date back to the early 1990s and have been regularly revised to introduce more ambitious performance standards while new categories of products are being constantly added. The eco-design regulations are facilitated by other policies, in particular energy labelling, that ensure accurate and useful consumer information and address the remaining market barriers and behavioural biases. Together with energy labelling, Ecodesign regulations now cover over 25 product groups and are estimated to deliver annual energy savings of over 600 TWh in 2030. This represents 30% more savings on top of those already to be achieved by 2020 (1918 TWh), which are equivalent to the annual primary energy consumption of Italy.

Considerable unit-consumption improvements have been achieved recently in lighting, and for large appliances like refrigerators, freezers, washing machines, both thanks to evolving technologies and regulations[246], but an untapped potential still exists[247] [248] [249] and some end-uses are expanding.

While at global level appliances and space cooling energy consumption are still the two fastest-growing end-uses in buildings[250], in the EU the trend is partly different since energy consumption of large appliances and lighting[251] is declining and the relative importance of smaller appliances[252] and devices is increasing in aggregate as the number of electricity-using products increases and their functionality expands[253]. On the other hand, electricity demand for air

[245] IEA (2018), Energy Efficiency 2018, Analysis and outlooks to 2040

[246] For example, when the first energy label for dryers in was introduced in 1995, the highest performance level, the "A" tier, was set at a level that products then sold on the market could not achieve. This aspirational tier, along with financial incentives, motivated manufacturers to introduce new heat pump drying technology into the European market, so that sixteen years later heat pump dryers accounted for 40% of the market share (IEA; 2016), Achievements of appliance energy efficiency standards and labelling programs. A Global Assessment.

[247] IEA (2016), Achievements of appliance energy efficiency standards and labelling programs. A Global Assessment

[248] Climate Tracker (2018), A Policy Spotlight On Energy Efficiency In Appliances & Lights Could See Big Climate Gains

[249] For instance, in the "decarbonised building scenarios" in CLIMACT (2018) the average energy efficiency of appliances improves by 2.0% a year up to 2020, then by 2.9% a year up to 2030. The yearly improvement is then considered to only 0.1% from 2030 to 2050. See Climact (2018), Net Zero By 2050: From Whether to How, https://europeanclimate.org/wp-content/uploads/2018/09/NZ2050-from-whether-to-how.pdf

[250] IEA (2018), Energy Efficiency 2018, Analysis and outlooks to 2040

[251] Looking more in details at lighting, technology for light sources keeps evolving, thereby improving energy efficiency. In 2008, prior to the entry into force of the current Ecodesign and energy labelling Regulations, there were 9.2 billion light sources operating in EU28, consuming 330 TWh/a of electricity. LED technology, which is for almost all applications the most energy efficient lighting technology that exists, has had a rapid uptake on the EU market: from 0% of sold lamps in 2008 to 22% in 2015. In addition, the average energy efficiency of LEDs quadrupled[251] between 2009 and 2015, and prices dropped significantly: compared to 2010, in 2017 a typical LED lamp for household use was 75% cheaper and a typical LED lamp for offices was 60% cheaper.

[252] E.g. computers, televisions and displays, coffee makers, phones and tablets home security systems, etc.

[253] Thomas S. (2018), Drivers of recent energy consumption trends across sectors in EU28 - Energy Consumption Trends Workshop Report.

conditioning is increasing also in the EU because of hotter weather than usual and due to a wider diffusion of cooling appliances.

The efficiency of heating and cooling installations[254] deserves specific attention given that space heating represents both the largest share in energy consumption in buildings and the highest potential for efficiency gains as well as for the transition towards more sustainable and decarbonised solutions[255].

.The energy consumed by heaters could be progressively significantly reduced, thanks to replacement of the most inefficient segments with more efficient alternatives, which range from condensing boilers to heat pumps in combination with better controls and smarter packages of heaters (e.g. combinations of several heating systems). By 2030, with current policies in place, it is estimated that their annual energy consumption could be reduced by 48% in comparison to 2015 with a share of electrical appliances (i.e. mainly heat pumps) which is expected to have increased to 28%[256].

#### 4.3.1.3 Fuel switch in heating and cooling

Reduction of the energy consumption through increased insulation and more efficient equipment is already well under way in the EU and so is the use of renewable energy for heat generation, while low carbon energy vectors for heating & cooling (electricity, but also new vectors like hydrogen or e-gas) are a relatively newer option.

Today, the most common technologies using renewable sources to deliver heating and cooling services in buildings are solar thermal, geothermal, biomass boilers and ambient energy. Public consultation results clearly indicate that citizens are familiar with such options and willing to switch to them[257]. Geothermal energy is available everywhere in Europe and the extent of geothermal deployment is limited only by the demand for heat. According to some assessments, around 45% of all heat demand can be covered from geothermal by 2050[258], and around 25% of the European population is located in regions that are suitable for geothermal district heating and cooling[259]. Solar thermal is a widely used low-cost technology for domestic hot water in Southern Europe, and solar-heated buildings and solar district heating systems have been successfully demonstrated in Central Europe (both in detached houses and multi-family buildings). According to some assessments, geothermal energy and solar thermal could supply 133 Mtoe in 2050

[254] Heating and cooling appliances are covered by a number of Regulations under the Ecodesign and Energy Labelling Framework. These Regulations aim to improve the environmental impact of these appliances, by setting minimum energy efficiency requirements and where relevant requirements on sound and emissions (e.g. $CO_2$, NOx, OGC, PM) requirements. The heating products covered by Ecodesign and Energy labelling measures represent approximately 70% of the building load in the EU, the products that are not covered are district heating and very large appliances.

[255] The primary energy efficiency of heating appliances ranges from approximately 30% for open fire places to 300% for the most efficient heat pumps. The average primary energy efficiency of the installed heating products was 60% in 2010 and increased to 66% in 2015. Central space heaters are the most common heating equipment, and amounted to 120 million installed units in the EU in 2015, i.e. 50 million more than in 1990. The average primary energy efficiency of these boilers was 67% and they consumed 1850 TWh/a of primary energy to meet a heating load of 1240 TWh/a. The energy input consisted of fossil fuels (84%) and electricity (16%)

[256] European Commission (2017), Ecodesign Impact Accounting, Overview Report 2017.

[257] Comparing the responses regarding improving thermal integrity of buildings and the use of renewable energy sources, fewer respondents indicate that they have already done the latter but the number of those willing to undertake any of them as a priority is almost equal.

[258] European Technology Platform on Renewable Heating, Common Vision for the Renewable Heating and Cooling Sector in Europe, 2011

[259] GEODH, Developing geothermal district heating, page 21, http://geodh.eu/

leading to an energy saving of 217 Mtoe[260]. High Coefficient of Performance (CoP) heat pumps are key to utilise geothermal and ambient energy (aerothermal and hydrothermal) and have already significant market shares in several countries in Europe[261]. These technologies can be used in individual units of small capacity or in district heating and cooling in larger capacities[262] [186]. Provided they become increasingly efficient and decarbonised, district heating and cooling networks have significant potential to facilitate the integration of various renewable heat and cold sources, including surplus renewable power generation by offering storage and balancing services to the electricity grid.

The deployment rate of renewable heat (also in the industrial sector) currently stands at 19% in the EU but varies among Member States and in terms of technologies deployed. For example, biomass provides more than 50% of heating and cooling demand in the building stock and urban infrastructure in Croatia and Bulgaria, and more than 40% in Portugal and Latvia. Heat pumps provide 27% of heating in the Swedish building stock, and more than 10% in Finland and Italy. In Cyprus, 29% of heating demand in building sector is provided by solar thermal[263].

The specific options for the fuel switch from fossil fuels to zero-carbon/carbon-neutral energy vectors must be looked into detail as the optimal heating and cooling supply option is determined by specific local circumstances in function of the availability of local renewable resources, the presence or feasibility of energy infrastructures, buildings' technical systems and their links with the broader energy system. Renewables can be used alone or in hybrid systems combining several types of fuels in individual buildings or in decentralised district systems based uniquely on renewables. Electrification of heating in buildings through heat pumps is an important component of the decarbonisation of heating and cooling, provided the electricity supply is decarbonised.

Likewise, district heating and cooling networks have a demonstrated potential to help deliver a wide range of renewable energy sources, including surplus renewable electricity, into buildings, particularly in cities. The switch to district heating would require dedicated infrastructure and sectoral integration and the district heating sector would need to become increasingly efficient and decarbonised. District heating and cooling systems currently supply about 10% of EU's heating and cooling demand but there is a potential to expand them to supply 50% of the heat demand[185], with 25–30% of the heat potentially supplied using large-scale electric heat pumps[186] [264] [265]. Innovations in low-temperature, more efficient district heating and cooling infrastructure could even further expand the potential use of low-carbon options[266].

Changes would also be required if buildings use hydrogen and e-gas, whose supply challenges and opportunities are described in section 4.2.

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[260] European Technology Platform on Renewable Heating, Common Vision for the Renewable Heating and Cooling Sector in Europe, 2011

[261] European Heat Pump Market and Statistics Report, 2017, EGEC Geothermal Market Report, 2017

[262] IEA (2018) Renewable heat policies, https://www.iea.org/publications/insights/insightpublications/Renewable_Heat_Policies.pdf

[263] Eurobser'ER (2017), Solar thermal and CSP barometer, https://www.eurobserv-er.org/category/all-solar-thermal-and-concentrated-solar-power-barometers/

[264] JRC (2016), Efficient District Heating and Cooling systems in the EU, Case studies analysis, replicable key success factors and potential policy implication, http://publications.jrc.ec.europa.eu/repository/handle/JRC104437

[265] The town of Gram in Southern Jutland Denmark is an example of expanding solar district heating. It provides the town's 2 500 inhabitants with a heat production capacity of 20 GWh/year and 62% of the heat needs (with the help of seasonal storage), the rest being supplied from heat pumps, electric boilers, CHP and gas back-up boilers, see [264].

[266] Lund (2018). Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective, https://doi.org/10.5278/ijsepm.2017.12.2

As investigated in detail in the study "Sectoral integration"[267], hydrogen-based heating technologies have not until now been in focus in the European debate on the decarbonisation of the heating sector. However, multiple technologies exist that have been applied in international – mostly Asian – markets: fuel cell micro-CHP, direct flame combustion boiler, catalytic boilers and gas-powered heat pumps. In Europe, the fuel cell programme has led to first demonstration projects with the goal to install 50 000 systems with a subsequent commercial roll-out. The relatively high investment costs are still a challenge for this technology today, and the fact that they currently run on natural gas limits their contribution to decarbonisation. In the future, hydrogen-fuelled heating could play a bigger role, especially in off-grid areas, where there are a limited number of flexibility sources that can ensure the balance in the heating system.

E-gas, once produced, is exactly the same molecule as natural gas, and can be distributed via existing distribution system and used by existing installations. Therefore, from the final consumer perspective the only difference with natural gas will be most likely the cost (on the one hand natural gas supply cost and possible related $CO_2$ emissions pricing, vs. e-gas production cost).

All these options will need to be available and developed especially that heating and cooling is expected to remain the largest source of final energy demand in Europe. Decarbonising its supply is of vital importance to the EU’s wider climate and energy objectives in the coming decades.

#### 4.3.1.4 Smart buildings

Digitalisation is shaping Europe’s energy system transformation in enabling the shift towards a highly distributed, networked, and dynamic grid, which leads to the creation of technology-rich platforms such as integrated distributed energy resources and smart and connected buildings.

Smart buildings are capable to effectively adapt operation to the needs of the occupants, while ensuring optimal energy performances and being able to interact with energy grids[268]. ICT integrated to technical building systems, in particular building automation and control systems, will be complementary to the other measures that impact buildings’ energy efficiency and quality, e.g. building insulation. Smart technologies in buildings can contribute to optimising the technical building systems’ operation (in particular, but not only, heating and air-conditioning systems), to facilitate the use of renewable energy sources, and to improve demand-side management while guaranteeing comfort and environmental quality. Multiple studies and demonstration projects have confirmed the high potential of building smartness for energy efficiency and effective maintenance and operation of technical building systems[269] [270] [271] and the

[267] ASSET project (2018), Sectorial integration long-term perspective in the EU energy system, https://ec.europa.eu/energy/en/studies/asset-study-sectorial-integration

[268] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

[269] The European Standard EN 15232 distinguishes between four efficiency classes from A to D and defines the energy saving potential resulting from building automation and control. Such systems could achieve savings in thermal use of up to 30% in non-residential buildings and 20% in residential buildings, and in electricity use up to 13% and 8% respectively.

[270] Results of the iSERV project (2011-2014) suggest saving potential “of over 33% […] in some buildings, with average savings over 9% looking possible. Savings in non-electrical energy use will be on top of this reduction”. http://www.iservcmb.info/sites/default/files/results/overview/iSERV-factsheet_FINAL.pdf, consulted August 2018.

[271] The study Smart Readiness for Buildings suggests that between 4.3 and 5.2 Mtoe energy savings could be achieved thanks to further promotion of smart technologies in buildings in 2030. https://smartreadinessindicator.eu/milestones-and-documents (consulted August 2018).

results of public consultation prove that consumers have an interest in such technologies. Recent assessments showed in particular that smart technologies could lead to significant reductions of the energy consumption for space heating and space cooling[272].

Smart buildings can also interact dynamically with the energy system, supplying energy flexibility to the grid by dynamically managing demand and optimizing the use of local on-site energy production (e.g. electricity from PV panels) and relying, when available, on on-site storage capacities (both stationary and embedded in appliances and vehicles). Buildings thus become an active, manageable part of the energy system in transition, contributing to enhanced flexibility.

Smart buildings also lead to additional benefits for building users and consumers:

- by enabling feedback from buildings and systems, they allow building users to make better decisions on indoor parameters management and appliances and systems use, contributing to achieving an optimal balance between users' needs fulfilment and energy consumption minimisation;
- energy consumption is decreased and energy bills are lowered by optimizing the management of energy[273] [274] [275]. Impacts on energy bills are particularly marked with time-based and dynamic pricing schemes, by leveraging the increased flexibility of smart buildings[276];
- comfort and well-being can be enhanced thanks to accurate indoor environment monitoring and facilitated user interactions, such as for instance supporting independent living of elderly people[277] [278];

[272] Up to 30% for heating: see (SWD (2016) 414 final).

[273] D. Lee, C.-C. Cheng (2016), Energy savings by energy management systems: A review, Renewable and Sustainable Energy Reviews 56, p 760-777. This recent review analysed the outcomes of more than 300 cases of Energy Management Systems concluded that Building Energy Management Systems led to average yearly savings of more than 16%, and Energy Management Systems for equipment to average savings of 39% for lighting and 14% for HVAC.

[274] A. J. Morán et al (2016), Review and analysis of results from EU pilot projects, Energy and Buildings 127 128-137). This recent study based on the assessment of 105 pilot buildings from 18 European projects highlighted the role of ICT solutions in achieving energy savings of more than 20% (Information and Communication technologies (ICTs) for energy efficiency in buildings).

[275] American Council for an Energy-Efficient Economy (2017), Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings, http://aceee.org/research-report/a1701. The American Council of Energy gives average energy savings of 23% in office buildings after the installation of smart building technologies (lighting control, Remote HVAC - Heating Ventilation and Air Conditioning – control system).

[276] Energy flexibility is key to benefit from such pricing schemes. In particular, the combination of renewable energy sources and electricity storage can dramatically decrease the consumption of electricity delivered from the grid. A recent study showed that, for a two-storey residential building, the combination of PV panels with an electric vehicle could decrease the amount of electricity required from the grid of 68% on average and resulted in a reduction of up to 62% of the electricity bill. (M. Alirezaei, M. Noori, O. Tatari (2016), *Getting to net zero energy building: Investigating the role of vehicle to home technology*, Energy and Buildings 130 465-476)

[277] Y. A. Horr et al (2016), Occupant productivity and office indoor environment quality: A review of the literature, Building and Environment 105 369-389.
Indoor environmental quality (IEQ) has a great impact on the well-being of building users'. It has for instance a significant influence on productivity in tertiary buildings. This case study also suggested productivity gains from smart energy and comfort management strategies of up to $1000 per year per person, while reaching energy saving objectives.

[278] R. Al-Shaqi, M. Mourshed, Y. Rezgui (2016), Progress in ambient assisted systems for independent living by the elderly, Springer Plus 2016 5:624.).
According to this study, smart homes can also support independent living of elderly people.

- maintenance is also made easier, more reliable and more cost-effective thanks to analytics algorithms that process monitoring data from the building automation and control and technical building systems[279].

Finally, smart buildings can also be beneficial for the decarbonisation of the transport sector, as they facilitate the management of recharging infrastructure in car parks[280], in particular where smart charging capabilities are available, which in turn contributes to the uptake of electric (battery or plug-in hybrid) vehicles.

#### 4.3.1.5 Nearly zero-energy buildings

Drawing on all technological solutions, from 2021 onwards, all new buildings in the EU will have to be nearly zero-energy buildings (NZEBs), that is to say buildings that have very high energy performance and which (limited) energy consumption is mostly covered by energy from renewable sources[281] [282]. To achieve this level of performance, NZEBs will have to combine the best of energy-efficiency and smartness, relying on energy-efficient envelope components, high-performance technical building systems, and smart technologies and ICT.

#### 4.3.1.6 Societal and consumer choices

In addition to technology solutions for buildings decarbonisation that are described above, the domain of the consumer choice (facilitated by recent technology progress, notably digitalisation) also offers promising contribution with options such as better control of indoor temperature or partial heating of the house. Other types of behavioural change relate to "circular economy" family of measures such as sharing office space or reducing the number of appliances (because, again, of sharing). Finally, different urban planning while it would have the biggest impact on mobility (reducing the trajectories in daily commuting) could have also an impact on reduction of energy consumption per dwelling.

### *4.3.2 Buildings results*

The evolution of energy demand in buildings (both residential and tertiary) displays significant differentiation across scenarios, depending on whether the emphasis of the pathway is on the decarbonisation of the supply or on further reduction of the energy demand.

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[279] A study by Schneider Electric based on a report from the Federal Energy Management Program (US) highlights that current practices tend to favour reactive maintenance approaches, while predictive maintenance approaches are the most efficient and can save up to 20% per year on maintenance and energy costs: (Schneider Electric White Paper, Predictive Maintenance Strategy for Building Operations: A Better Approach, https://www.fmmagazine.com.au/wp-content/uploads/2015/03/Predictive_Maintenance-SE_asset.pdf.

[280] The revised Energy Performance of Buildings Directive [268] includes requirements on the installation of electric vehicle recharging points in buildings' car parks.

[281] This requirement is laid down in the Energy Performance of Buildings Directive [268] and will apply in the European Union, see https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings/nearly-zero-energy-buildings

[282] ECOFYS, Politecnico di Milano / eERG, University of Wuppertal, Towards nearly zero-energy buildings, Definition of common principles under the EPBD (2012), https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf

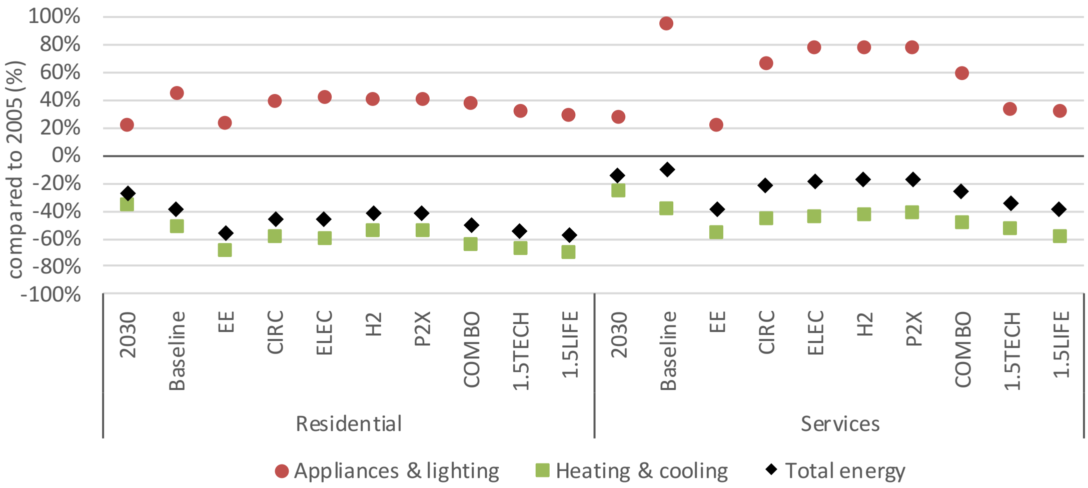
4.3.2.1 Moderation of energy demand

Buildings, combining the residential and services sectors, make currently the largest final energy consumption in the EU, representing about 40% of the total in 2015. The uptake of buildings insulation, targeting in particular energy use for space heating, the most important single energy use in buildings, is expected to lead to a decline of this energy demand.

On the one hand, the socio-economic activity drivers of these sectors are expected to push energy demand up over time. The number of dwellings as well as their average size are projected to gradually increase[283], while the services sector is expected to contribute to future economic growth, increasing its share in EU GDP to 71% in 2050 (vs. 68% in 2015).

Despite these trends that push energy consumption upwards, the final energy consumption in buildings is actually projected to reduce, due to the action of policies that will already result in noticeable results by 2030, with final energy demand reducing by 28% and 12% compared to 2005 in residential and services, respectively. Looking at the Baseline scenario, by 2050 the reductions would be 38% in residential sector and 8% in services (compared to 2005) as economic growth in the services sector would be a strong countervailing force.

**Figure 39: Evolution of the energy consumption in buildings in 2050 (compared to 2005)**




*Note: "Heating and cooling" includes space heating, water heating, cooking and air cooling.*

*Source: Eurostat (total sectoral energy consumption in 2005), PRIMES.*

In the residential sector, the 80% GHG reduction scenarios would lead to energy consumption in 2050 reduced by between 41% (P2X, H2) to 56% (EE) below 2005 level. Stronger reductions are achieved in EE which has, by construction the strongest action in terms of renovations and equipment performance, lower in H2 and P2X where decarbonised energy vectors allow keeping relatively higher levels of energy demand. The scenarios achieving higher GHG reductions reduce most, achieve up to 57% reductions in 1.5LIFE, which benefits from technological deployment complemented by consumer choice.

Importantly, the different end-uses show very different patterns. In all decarbonisation scenarios, except EE and in the two 1.5°C scenarios, electrical appliances increase their consumption over time due to the multiplications of consuming goods in households, which are only moderated in

[283] It should be, however, also considered that the trend for 1-2 person households will strengthen in EU too thus moderating the increase in surface of dwellings. See OECD (2012), The Future of Families to 2030 and GFK 2014 IFA Press Conference Home Appliances 25-04-2014.

EE and 1.5°C scenarios by ambitious energy efficiency measures (that would, in practice, require even more stringent eco-design or similar measures) in this respect. It has to be noted that little differentiation across scenarios is assumed in terms of useful energy demand of appliances since, as a principle, the same level of services are sought across all scenarios (e.g. laundry, cooking, ICT applications)[284]. While in the Baseline, by 2050 the residential appliances would be increasing their final energy demand by 46% compared to 2005 (20% compared to 2030), EE scenario keeps the increase to half that (or 1% increase only compared to 2030) and the 1.5°C scenarios keep the increase to 30-32% compared to 2005 (+6-8% compared to 2030). Other scenarios see an increase of around 40% (15% compared to 2030), lower than in Baseline but still significant. Moderation of final energy demand of appliances also happens in services sector. Energy consumption by appliances in the services sector would increase in the Baseline by 96% in 2050 compared to 2005 (54% compared to 2030), whereas the EE scenario would achieve 22% reduction compared to 2005 (5% reduction compared to 2030) and the 1.5°C scenarios would keep the increase to 34% (5% compared to 2030). Other scenarios show increases in the range of 60-80% compared to 2005 (25-40% compared to 2030).

Conversely, the useful energy demand[285] for space heating[286] (see Figure 40) reduces in all decarbonisation scenarios and in both residential and services sectors, mainly as a result of increased insulation of buildings and in 1.5LIFE, also due to a behaviour focusing on rational use of energy.

Combined with better performing equipment, this leads to significant reductions of energy use for heating and cooling in the residential sector reductions compared to 2005, ranging between 53% (H2, P2X) to 67% in EE and even 69% in 1.5LIFE. It can be noticed that scenarios that develop significant quantities of decarbonised energy carriers have lower reductions in the heating & cooling needs.

Results in the services sector follow the same logic. Reductions of actual energy demand for heating and cooling in services (Figure 39) are lower than in the residential sector, because of growing economic activity of the sector, but still range from -41% to -57% compared to 2005 (-22% to -43% compared to 2030).

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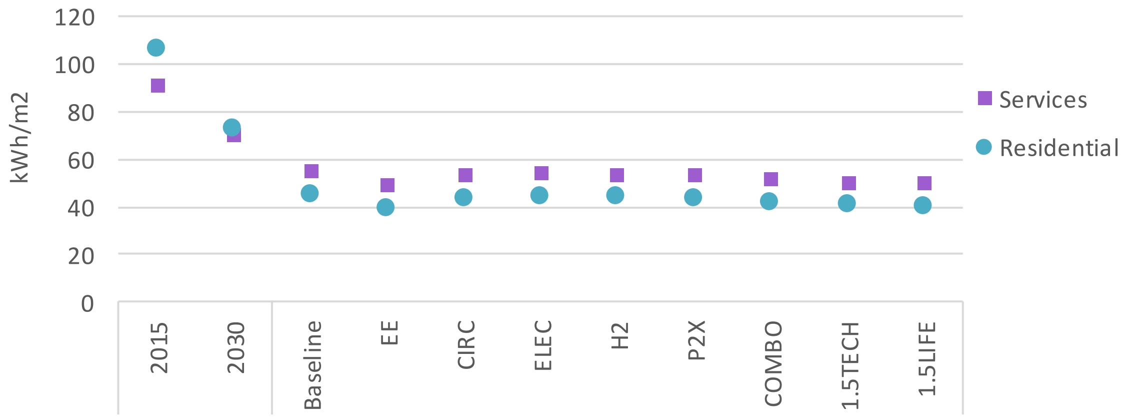
[284] The relationship between the macroeconomic and demographic drives with useful energy demand is the same across the scenarios. However, the degree of energy efficiency effort, which varies by scenario influences the useful energy that final demand has to meet. The influence is small for residential appliances but stronger for appliances and electrical equipment in the services sectors, where there exists potential of optimizing useful energy from appliances via control systems. Nonetheless the impacts of scenario differentiations on useful energy remain small.

[285] The "useful energy for space heating" is the actual end use of energy, estimated as the final energy for space heating net of the efficiency losses of the different heaters, and thus removing the effects of the changing fuel mix.

[286] The analysis is done at constant climate over time. The possible effects of a warming climate on energy needs for heating and cooling is not represented – see for instance on this topic: JRC (2014), Climate Impacts in Europe, The JRC PESETA II Project (doi:10.2791/7409); and JRC (2018), Climate Impacts in Europe, Final report of the JRC PESETA III project (doi:10.2760/93257). https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/climate-impacts-europe

**Figure 40: Useful energy consumption for space heating in buildings**




*Source: PRIMES.*

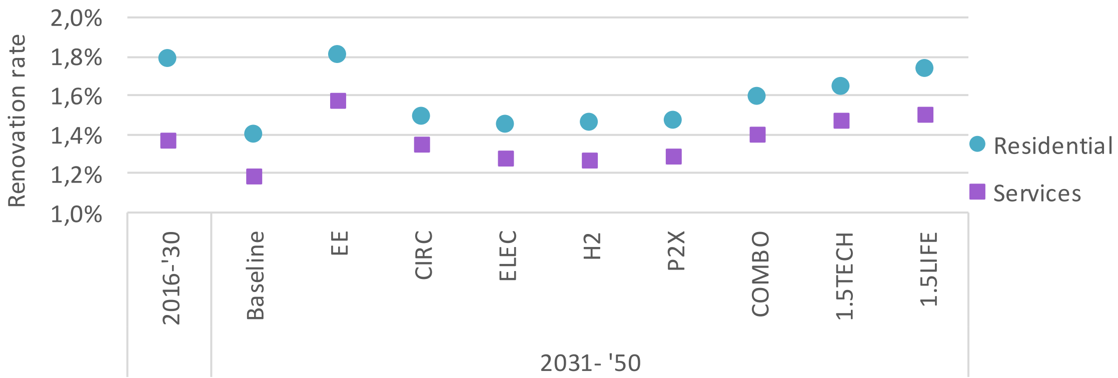
These projections clearly show that energy efficiency remains the key enabler for decarbonisation of buildings across all scenarios. These figures are higher than the reductions seen in other studies: the Öko-Institut Vison EU[205] scenario, the IEA Energy Technology Perspectives[204] (B2DS scenario) and the Shell Sky[203] studies report buildings' final energy consumption savings of 37%, 21% and 13% respectively between 2030 and 2050.

The improvement in terms of energy use for heating and cooling is due, to a large extent, to the improvement of the thermal integrity of the building shell, which comes along with the upgrade of heating appliances to more efficient and performing ones, both through the penetration of very efficient new buildings (as required by the EU legislation) but mainly through renovation of old buildings – the second trend having bigger effect due to very small rate of new constructions that has been observed historically and has not been accelerated in the scenarios in this analysis.

In fact, the Baseline and all decarbonisation scenarios apply existing measures under the EPBD Directive, which require new buildings to be nearly-zero in terms of energy consumption as of 2021. As important as they are, the contribution of such buildings constructed from 2021 to 2050 are projected to represent only 23% of the stock of residential dwellings in 2050, and 28% of surface in services. Consequently, sizable effects on the total stock will mainly happen through a renovation programmes that apply to the largest quantity of buildings and that lead to serious improvement of their energy performance. In reality there are multiple barriers to wide-spread buildings renovations notably access to finance, split incentives and likely bottlenecks if the construction sector has to step up its activity very significantly and this in a short time (as most ambitious scenarios with this respect would require). The model captures such non-market barriers to renovation, but the scenarios assume that policies, before and after 2030, also aim at removing the barriers. As a consequence, the projections include in the scenarios higher renovation rates and higher depth of energy-related renovation than observed historically.

The projected renovation rates (Figure 41) differ across scenarios. By construction[287], the EE scenario displays the highest rates among the 80% GHG reductions scenarios: 1.8% in the residential sector and 1.6% in the tertiary sector in the period 2031-50, against close to 1.5% and 1.4%, respectively, in the other cases with 80% reductions of GHG emissions. The higher GHG reductions scenarios are in-between this range with 1.7-1.8% in the residential sector in and 1.5-1.6% in the services sector.

**Figure 41: Average yearly renovation rate**




*Source: PRIMES.*

As explained above, the performance of the scenarios differs also in terms of energy-related depth of renovations pursued – whose projections are differentiated among scenarios. Again, the EE and the scenarios that achieve the highest GHG emissions reduction pursue mostly medium to deep renovations (including intervention on walls, windows, roof and basement), compared to the other scenarios where light to medium renovations (i.e. intervention on windows and roof) have a higher share. The different depth of renovations results in differing energy savings achieved from refurbishment. These savings (average annual values for 2031-50) vary in the residential sector from 55% (ELEC) to 62% (EE) and the scenarios that achieve the highest GHG reductions lie close to EE scenario performance. In the services sector, these savings vary from 51% (ELEC) to 58% (EE) and the scenarios that achieve the highest GHG reductions also lie close to EE scenario performance.

Higher renovation rates and deeper renovation translates into higher investment needs for buildings in the EE scenario than for others – see Table 10 of section 4.10.1.

Beyond renovation rates and improvements in the energy performance of heating and cooling equipment and appliances, the buildings automation, control and smart systems (BACS) (or "smart buildings") also contribute to the demand reduction. The savings achieved from BACS[288] in the scenarios analysed drive reduction of useful energy demand, notably in the services sector as described above. The projections are, however, more conservative regarding the similar effects in the residential sector, in contrast to several studies and demonstration projects that indicate larger potential for energy consumption reductions. In light of these studies, a “smart building” could thus partially reduce the need for possibly costly stringent renovation. It is also an opportunity to further involve and empower the consumers – especially if "smart building" is

[287] Both renovation rates and depth of renovation (described in section below) are outcome of modelling and are driven by energy efficiency (shadow) values. The values are standard modelling technique that enables to reflect the intensity of (yet to be defined) future energy efficiency policies.

[288] Assumptions in the scenarios are based, among others, on the1st technical study on the Smart Readiness Indicator that analyses the impacts of BACS on building energy efficiency along the classes defined by standard EN-15232.

coupled with management of own production (from renewables) and possibly storage (for example in an electric vehicle).

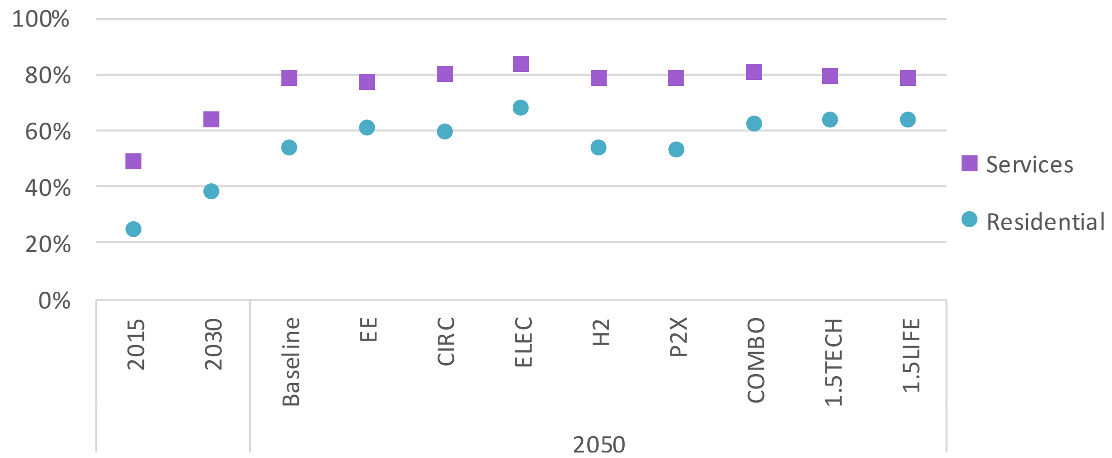
Finally, consumer choice can also have a significant impact on the energy needs in buildings and contribute further into the reduction of energy demand from buildings in the 1.5LIFE scenario. Other studies indicate much higher impact that could be achieved but also then requiring change that would have higher impact on lifestyle and thus perhaps lower acceptability such as sharing office space and different organisation of service buildings, lowering of indoor temperature, sharing of common spaces in blocks of flats, upper limits to the size of dwellings and different city planning[289].

The increasing built-in intelligence of appliances and buildings will help automate and optimise energy consumption decisions and actions (for instance switching off lights or adjusting room temperature set points according to time and presence patterns), thereby increasing the overall energy efficiency in buildings. However, despite this improved technological assistance, it is also clear that raising "energy awareness / literacy" of consumers will continue to be vital to ensure the full efficiency potential is actually exploited.

#### 4.3.2.2 Changes in the fuel mix in heating and cooling

Concerning the fuel mix, the trend that emerges the strongest (already in the Baseline scenario) is that buildings will experience a rapid growth of electrification. The share of electricity in services buildings will increase from 50% today to between 83% (ELEC) and around 80% in all other decarbonisation cases by 2050. The growth in residential buildings is also spectacular, with a share more than doubling between 25% today and 2050 where it ranges from 53% (P2X) to 68% (ELEC) and 63% in 1.5°C scenarios.

**Figure 42: Share of electricity in final energy demand buildings**




*Source: Eurostat (2015), PRIMES.*

It is clear that the electrification of space heating (by, in particular, greater role played by heat pumps using different technologies) is an important driver of this dynamics, especially in residential buildings. Also increasing penetration of appliances (only to some extent moderated by energy efficiency measures) described in previous chapters drives up electricity demand.

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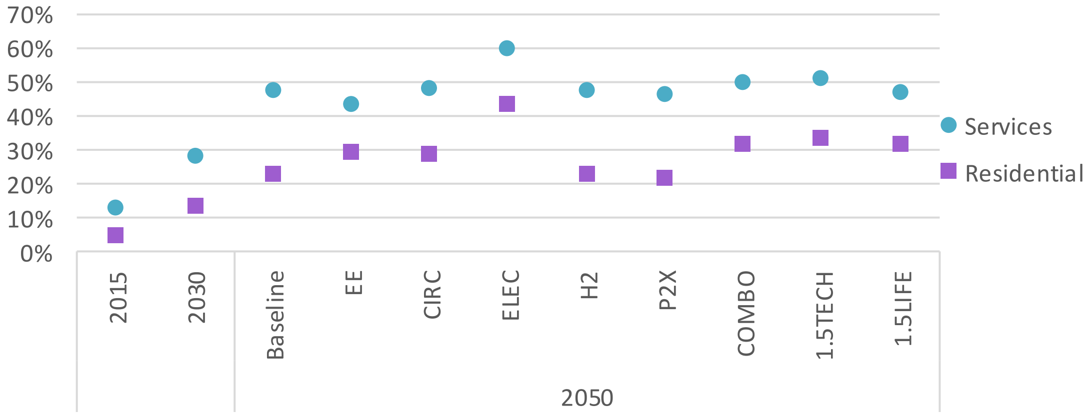
289 See, among others, the study of European Climate Foundation "Net Zero By 2050: From Whether To How"

In order to separate these two trends, one can look at penetration of electricity in space heating only (cooling being already today mainly powered by electricity). In the residential sector electricity share in heating grows from 14% in 2030 to 22-44% by 2050. The trend is stronger in services buildings, as electricity share for space heating grows from 29% in 2030 to reach 44%-60% in 2050, strongly dependent on the technological pathway. In both sectors, the highest levels are reached in the ELEC scenario (where the number of dwellings equipped with electrical heating systems, notably heat pumps, is multiplied tenfold compared to 2015 and would represent some 2/3 of all the dwellings) and in the scenarios with highest GHG reductions. Electrification of heating is the lowest (but still strongly growing from levels known today) in scenarios where alternative energy carriers develop (H2, P2X).

**Figure 43: Share of electricity in space heating in buildings**



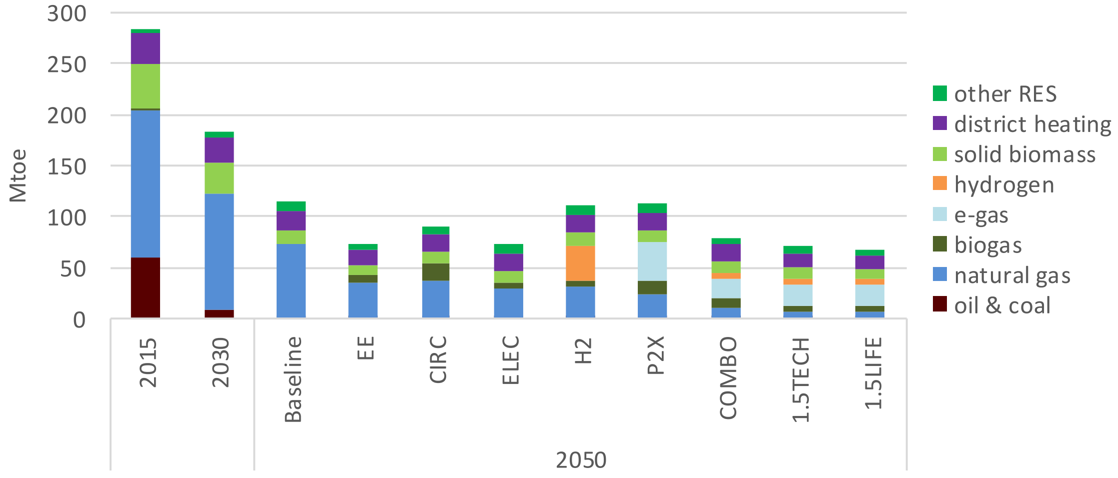

*Source: PRIMES.*

The range on electrification of buildings found in other studies is fairly wide, with for instance the Shell Sky scenario (74%) being close to this analysis findings, while the IEA ETP B2DS[204] scenario is more pessimistic with electricity reaching 35% of residential final energy demand. Eurelectric (2018)[290] shows rates from 45% (80% emissions reduction case) to 63% (95% emissions reduction case).

With the higher penetration of electricity, and an overall reducing demand, the consumption of other fuels decline accordingly (Figure 44). These fuels are used only for heating purposes: space heating, water heating or cooking.

[290] Eurelectric (2018), Decarbonisation pathways for the European economy, https://cdn.eurelectric.org/media/3172/decarbonisation-pathways-electrificatino-part-study-results-h-AD171CCC.pdf.

**Figure 44: Non-electricity fuel consumption in buildings.**




*Source: PRIMES.*

Gaseous fuels (natural gas, biogas, e-gas and hydrogen) represent the bulk of remaining consumption in final energy consumption albeit falling from the 31% share achieved in 2030 to between 12% (ELEC) to 23% (H2 and P2X). The shares projected by 1.5°C scenarios lie in this range. Natural gas, maintains some consumption in scenarios achieving 80% GHG reductions: between 8% (P2X) to 15% (EE) of total energy consumption in buildings but is marginal (3% share) in 1.5°C scenarios. Natural gas is, to a large extent, substituted by e-gas in all scenarios where this option deploys (P2X, COMBO, 1.5TECH and 1.5LIFE), and to a lesser extent by biogas and hydrogen, depending on the scenario. Other studies find natural gas contribution to energy demand in buildings ranging from 10% (IRENA's global energy transformation[216]) to 21% (IEA ETP B2DS[204]). Those that see the energy system fully based on renewable energies in 2050 make no more use of natural gas.

Distributed heat roughly maintains its share from 2030 with 5-6%of total energy demand in buildings across all decarbonisation scenarios. Solid biomass, used in modern stoves (to limit related air pollution) and biogas play a role too. Total of biomass has rather stable shares compared to 2030 (9%) and across decarbonisation scenarios, between 8% and 12% of the total energy demand in buildings. Other studies see a much higher share for biomass in buildings between 10% (Shell Sky[203] scenario) and 25% (Öko-Institut Vision EU[205]). Finally, solar thermal and geothermal heat represents marginal shares of the energy consumption. Coal and oil both disappear from the energy consumption in buildings.

The share of renewables in heating and cooling increases considerably in all scenarios. The "RES H&C" share, as defined by Renewable Energy Directive (and that covers also industrial heat – see section 4.5.2), increases from 19% in 2015[291] to 32% in 2030 to between 55% (ELEC) and 68% (P2X) in scenarios achieving 80% GHG reductions. Noticeably higher shares are even reached in both 1.5°C scenarios, with 79% for 1.5TECH and 78% for 1.5LIFE. As comparison, in IRENA's global energy transformation[216], the share of renewables in heating and cooling grows to 65% in the industry sector and 75% in the buildings sector. As explained in the section 4.2.2.1, the e-gas and e-hydrogen that are produced with renewable electricity also count as renewable energies.

[291] Eurostat (2018), SHort Assessment of Renewable Energy Sources (SHARES), https://ec.europa.eu/Eurostat/web/energy/data/shares

As a result of such significant moderation of energy demand and fuel switch towards carbon-free carriers, the GHG emissions in buildings decrease substantially. In the Residential sector, GHG emissions are in 2050 reduced between 87% (CIRC) and 91% (P2X) (compared to 2005) and nearly completely in 1.5°C scenarios. In the services sector, GHG emissions are in 2050 reduced between 88% (EE) and 93% (P2X) (compared to 2005) and nearly completely in the 1.5°C scenarios. The unabated emissions come from the remaining natural gas blended in gas distribution. To sum up, the existing technology options enable buildings to fit in the -80% GHG reduction objective by 2050 and, especially if complemented by moderate lifestyle changes, to go beyond and contribute to the net-zero objective in 2050.

### *4.3.3 Transition enablers, opportunities and challenges*

Energy efficiency improvements in the building sector have a robust base to start with: the EPBD and the EED provide the right regulatory basis and incentives to ensure the construction of near-zero emissions buildings across sectors and to spur ambitious renovations even beyond 2030 since there is no sunset clause on energy efficiency obligations). In addition, EU energy labelling and eco-design rules have steered both consumers and industry to pay more attention to the energy consumption of appliances and buildings, in their consumption choices, but also in business' industrial design and strategic product development.

While the fundamental approach has been put in place, there remains still a number of challenges for future development considering also that demographic and welfare changes (pushing consumers to seek increasing comfort levels) will have an impact on energy demand.

First of all, the pace of renovations has to increase significantly, which can be a challenge for the construction sector and the production of materials that it uses. In the results of the public consultation, it is clear that energy related renovations are desired by majority of respondents. Technological challenges, however, exist in terms of delivering even more efficient materials at prices affordable for all consumers. In addition, the current pay-back times in terms of renovations can still be discouraging for lower-income owners or landlords, which is likely to prove even more difficult with an ageing population and in general the renovations are more difficult to envisage for the tenants as also shown in the results of public consultation. Finally, these very highly-performing materials and affordable for construction and insulation will be needed at a very large scale, if the increased renovation rates are to be met and the energy savings delivered.

As regulatory requirements on buildings become more and more stringent on a number of aspects (not only energy consumption but also on urban, social, cultural, safety, resource efficiency, noise, etc. aspects), this will have a combined impact on the investment levels, operational and maintenance costs. In addition, the level of maturity of local markets in terms of services supply and access for new entrants will influence the investment and operational costs for the property owners and building occupants.

Within buildings, appliances will continue to need to improve their efficiency, to continue to do more with less energy and cutting edge IT solutions would need to be integrated to reap all the benefits – again at the cost affordable for all consumers.

A critical development entailing both challenges and opportunities will be how buildings, appliances and the energy system "talk" to each other for example through Internet of Things[292] applications and reflected by the smart readiness/communications aspect of energy systems in

[292] https://ec.europa.eu/digital-single-market/en/internet-of-things

buildings. The ultimate goal of smart buildings being synchronisation of consumption with both consumer and local energy system needs, including in particular mobility needs and the development of electro-mobility (see section 4.4), which will require adequate charging infrastructure and a proper integration of energy flows at buildings levels.

Here again, the EU has already started to address the issue – requirements for smart meters in households or smart readiness indicators for buildings introduce technology into the households and also raises awareness of consumers as to the new role they are able to play in managing their energy demand. While opportunities for energy savings (and also storage) and potential of technology to develop as a part of digitalisation wave are significant, the uptake of such solutions will very much depend on the ease of their use. Therefore, smart technologies, for instance minimally managed on smart phones, will need to evolve in line with users' acceptance.

Besides technology development, it will remain a key challenge to convince the consumers to embark on these possibilities and become more active participants in the energy markets. Today smart building technology is perceived as promising but costly and depending on infrastructure and network improvements, or even simply burdensome and paying off only in the long run. The public consultation shows the lowest support to smart meter option among all options that allow reducing energy consumption and related $CO_2$ emissions in buildings.

## 4.4 Transport

### *4.4.1 Transport options*

Transport represents around a third of the final energy consumption in the EU. The currently dominant transport technologies rely on liquid fossil fuels. This is projected to only gradually change under current trends and policies by 2050. Greenhouse gas (GHG) emissions from the sector, including emissions from maritime and aviation bunker fuels, have been on the rise, except during the period 2007-2013, when emissions decreased due to a combination of factors (i.e. improvements in energy efficiency, the impact of the economic crisis and a subsequent period of high oil prices).

The 2011 White Paper on Transport and the 2016 EU low-emissions mobility strategy have already shown[293] [294] that an integrated system approach is required to put the transport sector on a sustainable path. Central elements of such approach include action on overall vehicle efficiency, promoting low- and zero emission vehicles and infrastructure, and the long-term switch to alternative and net-zero carbon fuels for transport, against the backdrop of a fundamental increase of the efficiency of the transport system - by making the most of digital technologies, smart pricing and further encouraging multi-modal integration and shifts towards more sustainable transport modes. This section focuses on the central elements of the integrated system approach and presents the options available across different transport modes.

#### 4.4.1.1 Low- and zero emission vehicles, vehicle efficiency and infrastructure

A strategic approach to low emissions mobility needs to fully exploit the potential for improving vehicle efficiency, in both conventional and alternative fuels vehicles. Engine efficiency improvements, aerodynamic improvements and drag reduction, engine hybridisation of various forms, as well as plug-in hybridisation and range extension, will continue to play a role.

[293] COM (2011) 144, White Paper Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system.
[294] SWD(2016) 244, A European Strategy for Low-Emission Mobility.

Important gains can still be made through a radical rethink of vehicle and vessel design, including light-weighting of vehicles, or the use of sails as an auxiliary power source in shipping. Significant gains are also possible in aircraft efficiency.

The uptake of low- and zero-emission vehicles will need to accelerate over the coming years and decades. Battery electric vehicles are themselves a strong enabler of efficiency of energy use for vehicle propulsion, as well as offering novel vehicle design possibilities. Falling battery prices are expected to facilitate the uptake of these vehicles, although as discussed in section 5.6.1.2, the necessary supply of raw materials needs to be secured. Advances on battery and fuel cell developments need to be complemented by strong action to accelerate the roll out of appropriate recharging and refuelling infrastructure in the Union, on the Trans-European Transport Network (TEN-T) and beyond, to ensure full coverage of all transport networks. Electricity can also be delivered via catenary lines and pantograph systems, such as in rail, tram, and metro systems or possibly through road electrification[295]. Accelerated emissions reductions in the whole electricity system, including the production of hydrogen, will further amplify the benefits of low- and zero-emission vehicles (see section 4.2).

#### 4.4.1.2 The use of alternative and net-zero carbon fuels

There is no single fuel solution for the future of low-emission mobility - all main alternative fuel options are likely to be required, but to a different extent in each of the transport modes. In addition, the interplay between vehicles powertrains and fuels is expected to become more diverse in the long term. Electricity and hydrogen will be used in dedicated powertrains. Furthermore, for those transport modes where the deployment of zero emission vehicles is unfeasible due to energy density requirements or technology costs, carbon neutral fuels (i.e. advanced biofuels and biomethane, as well as e-fuels) can be deployed for use in conventional vehicle engines. For instance, if, in a transitional phase, were gas to be used as a fuel for shipping, it could be gradually decarbonised.

In the case of advanced biofuels and biomethane, $CO_2$ emissions are offset through the initial growth of biomass in case of sustainable biomass. However, as discussed in section 4.7, land constraints imply that they should be deployed only in those transport modes or means where they are necessary.

E-fuels (e-liquids and e-gas) represent a promising alternative but their lifecycle $CO_2$ emissions will depend on the source of the $CO_2$ used to produce them; in case of biomass or direct air capture of $CO_2$ this can result in carbon-neutral fuels (see also section 4.2.1.4). With e-fuels requiring significant amounts of electricity for their production and the uncertainty regarding the pace of their cost reduction, the transport modes where they would be deployed need to be carefully considered.

An important advantage of both e-fuels and advanced biofuels is their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure.

#### 4.4.1.3 Improving the efficiency of the transport system

In addition to vehicles and fuels, substantial emission reductions are possible through optimising the transport of people and goods across modes. Connected, cooperative and increasingly automated mobility solutions offer unprecedented opportunities in this context to complement

[295] Siemens (2017), eHighway – Innovative electric road freight transport. https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/mobility/road/electromobility/ehighway/documents/ehighway-2017.pdf

good public transport services. Seamless, user-centric door-to-door multi-modal solutions are already possible, supported by Intelligent Transport Systems and multimodal travel information services. The deployment of Cooperative Intelligent Transport Systems offers significant potential[296]. More generally, digitalisation is already reshaping the transport sector, leading to strongly improved logistics across transport modes[297]. Data sharing, enhanced traffic management and increased cooperation between relevant authorities, as well as with private actors, could enable the provision of services that can contribute to low emissions mobility. How far these innovations would make a difference depends on how services are provided, and how they impact on user behaviour.

On freight, alternatives to road (rail, waterborne transport) could be pursued more effectively, to realise the potential of multimodal transport and modal shift[298]. Rail freight would need to become more competitive compared to road transport, by eliminating operational and technical barriers between national networks, and by fostering innovation and efficiency. In addition, a stronger international coordination of rail freight operations would have an important impact in terms of cost reduction, thanks to minimisation of delays, an increased priority of freight trains and an overall reduction of time related costs. Support for intermodal connections, digitalisation and automation of shipping has the potential to increase the competitiveness of waterborne transport. Extending charging to all vehicles categories and transport network could be instrumental for improving the efficiency of the transport system.

A completed core and comprehensive Trans-European Transport Network, notably the Core Network by 2030 and the Comprehensive Network by 2050, would allow for the optimal use of transport modes, with rail and waterborne transport being attractive means for medium distance passenger trips between cities in the EU, as well as for international freight traffic. As the transformation of the various transport modes will take time, the use of the least polluting modes needs to be optimised. Rapid capacity increase in rail is needed, and could be supported by the effective deployment of European Railway Traffic Management System (ERTMS). It would allow growth in commuting, long-distance travel and the development of effective freight corridors. Alternatives to flights for short-to-medium distances (typically with high-speed railway connections) are alternatives where available to reduce emissions because air transport is harder to decarbonise. Finally, multimodal last-mile logistics can contribute to lower $CO_2$ emissions though zero-emission transport modes such as electric vehicles, cargo bikes, electric barges etc., as well as promoting joint delivery of goods using urban consolidation centres.

#### 4.4.1.4 Societal and Consumer choices

Consumer choices influence much of transport development. In the end, it is the consumer who decides. But consumer choices are strongly influenced by government policies and business offerings.

In terms of future policy design by *governments*, internalising the externalities of transport through road charging would increase social welfare. Enhanced implementation of the user/polluter pays principle and public incentives, including subsidies, would make sustainable

[296] A first milestone was reached with the adoption of the EU Strategy on Cooperative Intelligent Transport Systems (COM(2016)766 final).

[297] Proposal for a Regulation on electronic freight transport information (COM/2018/279 final) and Proposal for a Regulation establishing a European Maritime Single Window environment and repealing Directive 2010/65/EU (COM/2018/278 final)

[298] Proposal for a Directive amending Directive 92/106/EEC on the establishment of common rules for certain types of combined transport of goods between Member States (COM(2017) 0648 final); Shift2Rail Initiative.

infrastructure and greening of assets financially viable and promote modal shift. To level the playing field between different transport modes, external costs would need to be internalised in all of them. In addition, dynamic pricing could reduce congestion in both road and rail transport with positive effects on $CO_2$ emissions.

An accelerated implementation of the EU policy framework[299] and its further development for Cooperative Intelligent Transport Systems (C-ITS) technologies will mark the first step towards connected, cooperative and automated mobility in the EU, where data represent sort of "new mode of transport". Public authorities need to ensure integrated, long-term sustainable and socially just urban[300] and spatial mobility planning[301], improving the convenience and availability of active modes (walking and cycling) and public transport[302]. Public procurement of clean fleet solution could help build market momentum for low- and zero-emission transport solutions. In addition, eliminating operational and technical barriers between national rail networks and fostering the competitiveness of waterborne transport would increase the potential for modal shift.

For *business* digitalisation will increasingly offer solutions to replace physical transport needs by more advanced, secure and easy-to-use tools for videoconferencing and telepresence. While face-to-face contact cannot be replaced in all cases, there are large opportunities for saving time and money, as well as reducing the corporate carbon footprint. This is particularly important in the case of business air travel. In addition, large-scale fleet operators will shape much of the transition to zero-emission mobility, both in view of accelerating uptake of zero-emission vehicles, but also of innovative vehicle-to-grid and grid-to-vehicle solutions.

From the *consumer perspective*, the development of mobility as a service needs to be based on a truly multi-modal approach, involving collective/public transport, shared vehicles and bikes. It would need to make use of zero-emission vehicles, with higher occupancy rates for the average vehicle (currently low at 1.5 passengers per car). Under such conditions, it would result in higher energy efficiency and lower emissions. At the same time, it could reduce the amount of time cars are not used, resulting in a lower vehicle fleet and thus improving materials efficiency throughout the whole supply chain of the road transport system.

Vehicle automation is quickly proceeding. What is needed however is to ensure that the direction is right, leading to emissions reduction in transport, and limiting rebound effects. For example, there is a risk that vehicle automation would increase the demand for mobility or willingness to spend time in traffic, with adverse environmental effects as a consequence. Other trends like online shopping could reduce transport demand but could also increase it, and teleworking can reduce traffic, but also encourage fewer but longer commutes. Hence automation and connectivity need to go hand in hand in order to achieve overall system efficiency improvements.

Consumers can also make *conscious choices* to take the environmental impact of transport into account. In an urban context, choices for active modes such as walking and cycling could be encouraged, alongside shared, collective and public transport. For long distance travel, high

[299] COM (2016) 0766 Final

[300] International Resources Panel (2018) The Weight of Cities: Resource requirements of future urbanization http://www.resourcepanel.org/reports/weight-cities

[301] The concept of sustainable urban mobility planning, promoted by the Commission, is the tool to render transport operations of municipalities more effective. The Commission's European Mobility Week complements this with the awareness-raising and dissemination that supports consumer choices towards public transport, walking, cycling etc.

[302] Larger pedestrian zones, better and safer cycling lanes and more and better access to public transport options.

speed rail (where available) and coaches could replace aviation for short/medium distances[303] (<1000 km). Improved integration of airports and the extensive rail network would further enable passengers to undertake part of, or all of, their journey via high speed rail in particular[304][305]. However, this would require appropriate incentives, as flights are often economically more attractive and/or faster than their alternatives. In addition, if consumers are conscious of environmental impacts, long distance touristic visits could be made longer but less frequent, without reducing the value of such travel.

#### 4.4.1.5 Sectoral analysis of available technologies

There is no single solution for the future of low-emission mobility. There are different modes with different needs. All technologies have their place in the years to come. All main alternative energies for transport must be pursued, with a focus on the specific needs of each transport mode.

**Road transport** is the mode where electrification is most suitable, particularly in the segments of passenger *cars and vans* but also for *buses, powered 2-wheelers* and *e-bikes*, and possibly *urban delivery*. Battery-electric vehicles represent a promising option, with fast developments being foreseen especially for cars. However, large-scale roll out of recharging infrastructure is a prerequisite. Some recent studies[306] project a breakthrough[307] in the competitiveness of battery-electric passenger cars, although more conservative estimates exist as well. It is however widely acknowledged that bridging solutions such as hybrids and plug-in hybrids would still be needed in the medium term, as well as improvements in vehicle design. Important co-benefits are visible for battery-electric vehicles, beyond socio-economic benefits of decreased pollution cost. Such vehicles will help the EU in managing the ongoing energy transition, by offering a tool to address the growing need of managing intermittent renewable energies in the grid. A system based on new, highly efficient batteries of the electric vehicles, connected onto a smart grid, fully digitised, can be used to store electricity produced from renewables when it is cheap and available, and reversely feed the power back to the grid when it is scarce and expensive. Important new business models and consumer rewards are available in such a perspective. Considering the wider environmental impacts of battery-powered vehicles, battery production and resource use play a role, with re-use and recycling of key raw materials likely to become increasingly important[308]. According to the EEA[309], life-cycle climate change impacts of battery-electric vehicles vary depending on the impacts of electricity production, with greater benefits if the electricity production is zero emission.

Hydrogen and fuel cells can play an important role in the achievement of a low-carbon road transport system, in particular in *long-distance transport, e.g. for long-haul heavy goods vehicles and coaches*, provided that the necessary hydrogen refuelling station infrastructure is deployed.

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[303] High-speed rail is considered competitive with aviation only for relatively short to medium distances (e.g. < 1 000 km) (European Commission, 2011)

[304] European Environment Agency (EEA). (31 January 2018). *'Aviation and shipping — impacts on Europe's environment' TERM 2017: Transport and Environment Reporting Mechanism (TERM) report.* EEA Report No.22/2017. https://www.eea.europa.eu/publications/term-report

[305] COM (2011) 144 final

[306] Bloomberg New Energy Finance (2018), Electric Vehicle Outlook

[307] BEUC, ElementEnergy (2016): Low Carbon Cars in the 2020's: consumer impacts and EU policy implications https://www.beuc.eu/publications/beuc-x-2016-121_low_carbon_cars_in_the_2020s-report.pdf

[308] European Parliament (2018): Research for TRAN committee: Battery-powered electric vehicles: market developments and life-cycle emissions http://www.europarl.europa.eu/RegData/etudes/STUD/2018/617457/IPOL_STU(2018)617457_EN.pdf

[309] EEA (2018) EEA Report no13/2018 Electric vehicles from life cycle and circular economy perspectives

Hydrogen produced from carbon-neutral energy, by using electrolysis or natural gas with CCS, offers well to wheel pathways, which are zero or close-to zero-emission.

Advanced biofuels, biomethane and e-fuels have the advantage of not requiring dedicated engine technologies and refuelling infrastructure; but as discussed in section 4.4.1.2 care needs to be taken on where to deploy them.

*For long haul heavy goods vehicles and coaches that travel longer distances than buses*, various fuels and powertrains can be considered: electric motors, hydrogen fuel cells, the use of biofuels and biomethane[310] in conventional internal combustion engines (ICE)[311], as well as the use of e-gas in gas-fuelled vehicles, and the use of drop-in e-liquids, which do not require any powertrain adaptation. Intermediate technologies such as hybrids are available as well. For heavy goods vehicles and coaches, in the short- and medium term, full battery electrification appears to be more challenging due to the power and range requirements. However, projects have been already put in place for full electric heavy goods vehicles, and some studies are bullish[312] on their potential, including a roadmap by Scania[313]. Development of charging infrastructure would be, however, more challenging than for cars, as electric heavy goods vehicles and coaches would require super-fast charging, or an effort to construct catenary lines and pantograph infrastructure. Hydrogen could be delivered in a decentralised fashion in the future, but future fuel cell costs are still uncertain. Advanced biofuels and biomethane are technologically feasible, but will require the necessary land. E-fuels would not require powertrain adaptation and could use the existing refuelling infrastructure, but costs and energy considerations and the origin of $CO_2$ may represent limitations. As a result, it is not yet possible to foresee a dominant technology for long haul heavy goods vehicles and coaches. The application, distance range or local context might lead to a variety of technologies and fuels being deployed.

**Rail** is an important mode for low-emission mobility, as already explained in section 4.4.1.3. Alternatives to road need to be pursued more effectively to unveil the full potential of multimodal transport and modal shift. Low-carbon electricity is a sustainable energy carrier for rail in all scenarios. Further electrification of rail would require investments in the rolling stock but also in the rail infrastructure network. The European Union railway Agency (ERA) has developed a database that shows where electrification of the network is needed.[314] As a complementary option, biofuels could be used, while hydrogen is also an option.

**Maritime and inland waterways** transport is heavily dependent on oil derivatives (more prominently for deep sea shipping than for short maritime routes and inland waterways). In addition, international shipping displays high activity growth. Short sea shipping and inland waterways is an area where the power to weight ratio may make electrification feasible, with

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[310] The Commission has already indicated that biofuels, bioliquids and biomass fuels produced from food and feed crops should gradually be limited beyond 2020. As now agreed in the recast of the Renewables Energy Directive, such biofuels use will be capped (in view of achievement of renewables 2030 target) and should be gradually phased out and replaced by advanced biofuels, including notably cellulosic ethanol and diesel and algal fuels, as well as renewable electricity based fuels.

[311] If advanced fungible bio-fuels are used no adaptation in the engine is required. First generation bio-fuels can only be blended to certain level in liquid fossil fuels.

[312] Earl et al. (2018), Analysis of long haul battery electric trucks in EU - Marketplace and technology, economic, environmental, and policy perspectives, https://www.transportenvironment.org/sites/te/files/publications/20180725_T%26E_Battery_Electric_Trucks_EU_FINAL.pdf

[313] SCANIA (2018), Achieving fossil-free commercial transport by 2050, https://www.scania.com/group/en/wp-content/uploads/sites/2/2018/05/white-paper-the-pathways-study-achieving-fossil-free-commercial-transport-by-2050.pdf

[314] The database is called RINF (Rail Infrastructure Register) https://rinf.era.europa.eu/RINF/Search

demonstration projects such as the CEF funded Port-Liner project in the Netherlands and the Horizon2020 funded E-ferry in Denmark. While solar power, wind, or other renewables can be used on board large vessels to diminish the use of high energy density fuels, these energy sources do not have the right energy density to power such vessels as their main source of propulsion. Substantial decarbonisation of this sector will therefore necessitate other energy sources such as hydrogen and ammonia[315], advanced biofuels and biomethane and e-liquids, the use of which still requires research. Hybridisation can be used as a bridge solution. Shipping can also exploit efficiency improvements: not only engine optimisation but also hull design and vessel size can bring significant improvements.

**Stylised variants for EU international shipping**

While the inland navigation sector, covering inland waterways and national maritime, is an integral part of all scenarios included in the analysis, the *EU international shipping*[316] has been treated separately. Three stylised variants were developed for the EU international shipping with the PRIMES model, using the H2 and 1.5LIFE scenarios set up. These variants include: (i) a reduction by 50% in the EU greenhouse gas emissions by 2050 compared to 2008, based on the H2 scenario (called H2Mar50 scenario hereafter), (ii) a reduction by 70% in the EU GHG emissions by 2050 compared to 2008, based on the H2 scenario (called H2Mar70 scenario), and (iii) 1.5LIFEMar, where the maritime sector forms part of an economy wide net zero greenhouse gas emissions target by 2050, based on the 1.5LIFE scenario, and it reduces emissions by about 88% by 2050 compared to 2008.

In addition, a stylised modelling exercise has been performed for international shipping at global level by JRC with the POLES-JRC model. The POLES-JRC 2C scenario illustrates a reduction by 50% in the global (i.e. not EU only) international shipping greenhouse gas emissions by 2050 compared to 2008.

Finally, **for aviation**, decarbonisation will be the biggest challenge, due to the projected growth in activity, and the fewer options available; this requires a multi-pronged approach.

E-liquids, as well as advanced biofuel, are technically more straightforward options to implement, in the sense that they are compatible with the existing infrastructure and fleet – but only once available on the market at acceptable cost. Electric hybridisation and design improvements of aircrafts will contribute to further fuel efficiency improvements. Full electric aircrafts are being developed, and the first small non-commercial planes are operating, but the potential for large full electric aircraft is yet untested and remains in an exploratory phase.

### *4.4.2 Transport results*

#### 4.4.2.1 Transport activity projections

**Passenger transport activity** is projected to increase by 16% during 2015-2030 and 35% by 2050 in the Baseline scenario. Passenger cars and vans would still contribute 69% of passenger traffic by 2030 and about two thirds by 2050, despite growing at a slower pace (12% for 2015-2030 and 26% during 2015-2050) relative to other modes. In the scenarios, the lower traffic growth is due to the slowdown of the increase in car ownership which is close to saturation levels in many EU15 Member States, wide-spread and differentiated distance-based road pricing in line with the proposed revision of the Eurovignette Directive, and shifts towards rail. Rail transport activity would grow significantly faster than for road, driven in particular by the opening of the market for domestic passenger rail transport services, and the effective implementation of the

[315] According to OECD/ITF 2018, ammonia could represent up to 70% of fuel in global shipping transport by 2035 in a 80% decarbonisation scenario: https://www.itf-oecd.org/decarbonising-maritime-transport

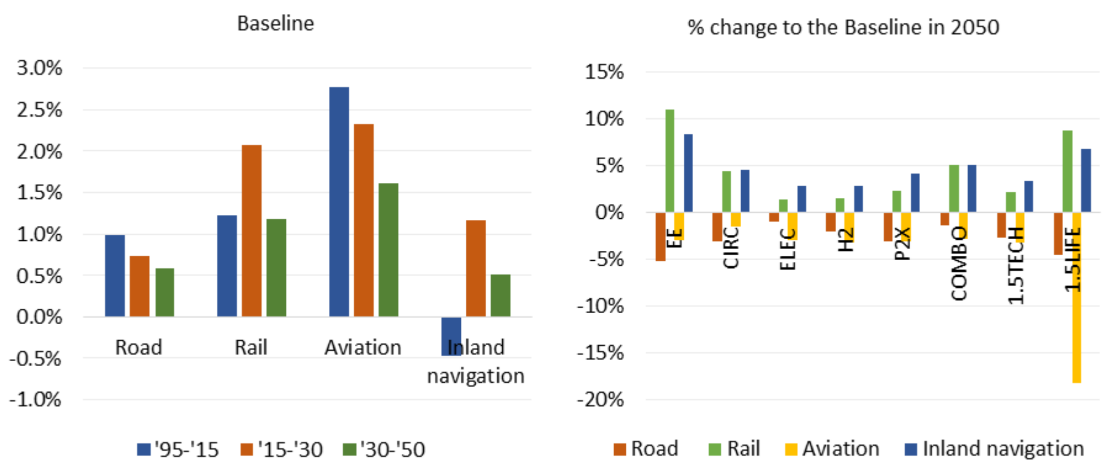
[316] Covering maritime transport between a port of a Member State to a port outside that Member State, or conversely.

TEN-T guidelines, supported by the CEF funding, leading to the completion of the TEN-T core network by 2030 and of the comprehensive network by 2050. Passenger rail activity goes up by 36% between 2015 and 2030 (72% for 2015-2050), increasing its modal share by almost 1.5 percentage points by 2030 and an additional percentage point by 2050.

Intra-EU air transport would grow significantly in the Baseline scenario (by 41% by 2030 and 94% by 2050) and increase its share in overall transport demand (by 2 percentage points by 2030 and by additional 2 percentage points by 2050). Overall, aviation activity including international extra-EU flights is projected to go up by 43% by 2030 and 101% by 2050, saturating European skies and airports. Nevertheless, there are uncertainties: the Impact Assessment accompanying the review of the EU ETS in view of the implementation of a single global market-based measure to international aviation emissions[317] used higher growth projections (from the AERO model), as well as PRIMES projections, to estimate ranges of demand for EU ETS allowances due to aviation.

The evolution of passenger transport activity by 2050 in the Baseline scenario (average growth rates per year) and in the scenarios reaching -80% to net zero emissions by 2050 (percentage changes relative to the Baseline in 2050) is provided in Figure 45.

**Figure 45: Passenger transport activity in the Baseline (average growth rates per year) and in the -80% to net zero scenarios (% changes to the Baseline in 2050)[318]**




*Source: PRIMES.*

In all scenarios reaching -80% to net zero emissions by 2050, passenger transport activity is expected to continue growing relative to 2015 (about 29-34% increase by 2050). However, active policies in place for stimulating change in the transport system and increasing its efficiency would put a brake on the expansion of activity in the scenarios reaching -80% to net zero emissions by 2050, compared to the Baseline. Among the scenarios reaching -80% by 2050, the reduction in activity is the largest for the EE scenario (above 3% in 2050 relative to the Baseline), while for the scenarios reaching net zero in 2050, the 1.5LIFE scenario projects the highest decrease (almost 5% in 2050 compared to the Baseline). Significant modal shift towards rail takes place in all scenarios driven by the gradual internalisation of external costs ("smart"

[317] SWD (2017) 31 final

[318] For aviation, intra-EU activity is reported, to maintain the comparability with reported statistics for the historical period.

pricing) going significantly beyond the Baseline, support for multimodal travel information, policies supporting the Single European Rail area (market and interoperability), digitalisation and automation of rail, support for multimodality and intermodal connections. The increase in passenger rail transport activity is the highest in the EE scenario (11% in 2050 relative to the Baseline) and 1.5LIFE scenario (close to 9% in 2050 compared to the Baseline). High-speed rail gains further share in these scenarios and is projected to undertake 235 billion more passenger kilometres in 2050 relative to 2015 in these two scenarios. In addition, measures promoting urban policies that curb pollutant emissions and increase the efficiency of transport operations drive significant shifts from private transport towards collective transport modes (i.e. buses, but also tram and metro where available) in all scenarios; in the EE and 1.5LIFE scenarios the activity of buses and coaches increases by up to 10-11% in 2050 relative to the Baseline.

The CIRC and 1.5LIFE scenarios additionally show the benefits of integrating the sharing economy and connected cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service (including shared/collective mobility). Overall, the wealth of measures improving the transport system efficiency, including the promotion of the Collaborative Intelligent Transport Systems (C-ITS), results in a 2-7% decrease in passenger cars and vans transport activity in 2050 in the scenarios reaching -80% to net zero emissions by 2050, compared to the Baseline (about 4% decrease in CIRC scenario and 6% in 1.5LIFE scenario).

Finally, the 1.5LIFE scenario assumes significant lower growth in intra-EU and extra-EU air transport activity (59% increase for intra-EU and 70% for extra-EU for 2015-2050) relative to the Baseline (94% growth for intra-EU and 104% for extra-EU for 2015-2050). A part of intra-EU air trips for leisure and personal reasons would be shifted to rail (high-speed rail, where available) and coaches and a reduction in the distance travelled for extra-EU trips would also take place. The number of the business trips would be reduced thanks to the adoption of video/tele conferencing facilities. No explicit policy instrument that would steer change in peoples' behaviour has been specified: it could be interpreted as due to rising environmental awareness, or take place in combination with strong policies.

**Freight traffic for inland modes** would grow faster than for passenger at 29% by 2030 and 53% for 2015-2050 in the Baseline scenario. The share of road transport in inland freight is expected to slightly decrease at 69% by 2030 and 68% by 2050. The activity of heavy goods vehicles expressed in tonnes kilometres is projected to grow by 26% between 2015 and 2030 (46% for 2015-2050) in the Baseline scenario, while light goods vehicles activity would go up by 25% during 2015-2030 (52% for 2015-2050). Rail freight activity grows by 45% by 2030 and 88% during 2015-2050, faster than passenger rail activity, resulting in a 2 percentage points increase in modal share by 2030 and 2 additional percentage points by 2050. Transport activity of freight inland navigation[319] also benefits from the completion of the TEN-T core and comprehensive network, the promotion of inland waterway transport and the recovery in the economic activity and would grow by 28% by 2030 and by 46% during 2015-2050. The significant growth in freight inland navigation and rail freight activity is also supported by road pricing, the revision of the Combined Transport Directive and the implementation of electronic documentation for freight transport.

The evolution of inland freight transport activity by 2050 in the Baseline scenario (average growth rates per year) and in the scenarios reaching -80% to net zero emissions by 2050 (percentage changes relative to the Baseline in 2050) is provided in Figure 46.

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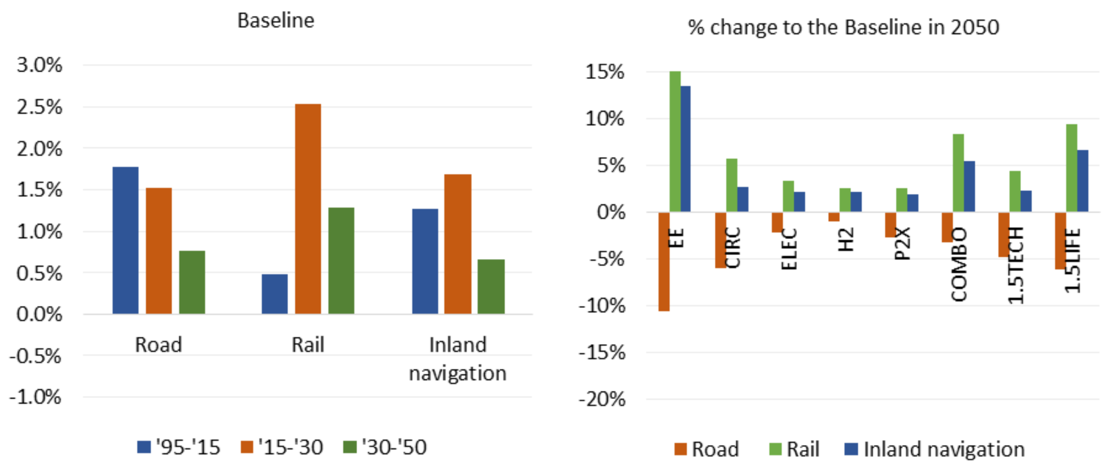
[319] Inland navigation covers inland waterways and national maritime.

**Figure 46: Inland freight transport activity in the Baseline (average growth rates per year) and in the scenarios reaching -80% to net zero emissions by 2050 (% changes to the Baseline in 2050)[320]**




*Source: PRIMES.*

In the scenarios reaching -80% to net zero emissions by 2050, impacts on total freight transport activity are also limited, and most significant for the EE and CIRC scenarios (around 2.5% decrease relative to the Baseline in 2050); impacts for all other scenarios, including those scenarios achieving more than 80% GHG reductions, are lower. Overall, freight transport activity is expected to continue growing relative to 2015 (about 49-53% increase by 2050) in all scenarios reaching -80% to net zero emissions by 2050, although at lower rates than in the Baseline. However, very significant modal shift towards rail and inland navigation (i.e. inland waterways and national maritime) takes place, beyond the Baseline, due to improvements in transport system efficiency, driven by the gradual internalisation of external costs ("smart" pricing), policies supporting the Single European Rail area (market and interoperability), rail freight corridors (RFC), digitalisation and automation of rail, support for multimodality and intermodal connections, as well as autonomous shipping and increased competitiveness of inland waterways.

Rail freight activity is projected to increase by 3-15% in the scenarios reaching -80% by 2050 relative to the Baseline in 2050, 8% in the COMBO scenario and 4-9% in the scenarios reaching net zero by 2050. The highest increases compared to the Baseline are achieved in the EE scenario (15%) and 1.5LIFE scenario (9%); overall rail freight activity would increase by around 116% and 105% for 2015-2050, respectively, in these scenarios, driven by strong policy incentives. Inland waterways and national maritime would also see a significant increase in activity relative to the Baseline (2 to 13% for the scenarios reducing by -80% by 2050, 6% for the COMBO and 2 to 7% for the scenarios reaching net zero by 2050). Similarly to rail freight, the activity would go up very significantly in the EE scenario (13%) and 1.5LIFE scenario (7%) relative to the Baseline.

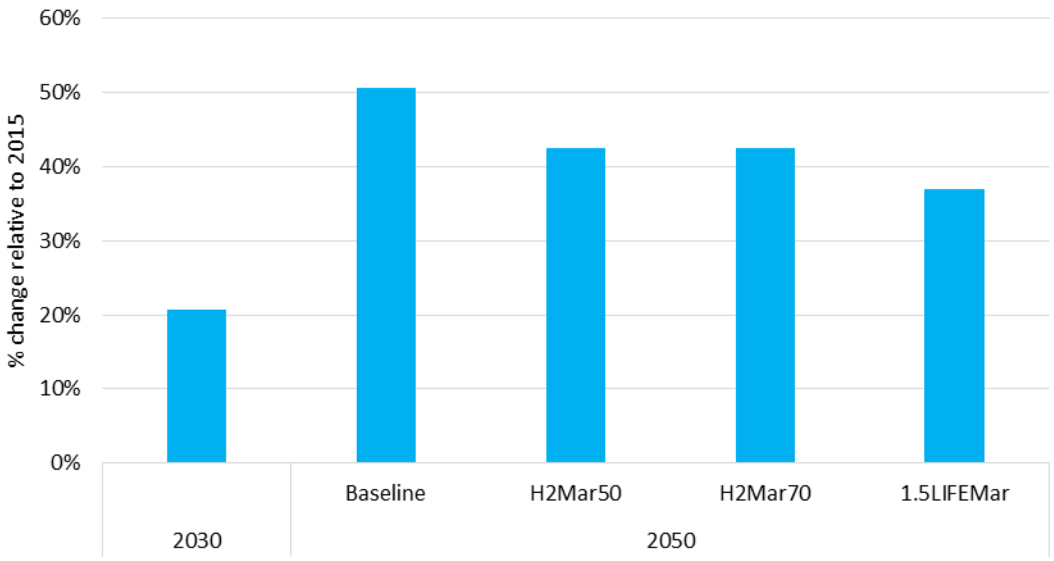
Road freight activity is projected to decrease by 1-11% in the scenarios reducing by -80% by 2050, 3% in the COMBO scenario and 5-6% in the scenarios reaching net zero by 2050 relative to the Baseline in 2050. Besides policies improving the efficiency of the transport system in all scenarios, including the promotion of the Collaborative Intelligent Transport Systems (C-ITS), improved logistics and shifts from long-distance freight to near-sourcing also play a significant

[320] Projections for international maritime are presented separately to preserve comparability with statistics for the historical period.

role in the CIRC and 1.5LIFE scenarios. Road freight activity would go down by about 6% relative to the Baseline in CIRC and 1.5LIFE scenarios in 2050, despite activity still growing by 37% relative to 2015.

**International maritime transport activity** at EU level is projected to continue growing strongly in the Baseline scenario, according to the PRIMES model, increasing by 21% during 2015-2030 and by 51% for 2015-2050, due to, for instance, rising demand for primary resources and container shipping. As explained in section 4.4.1.5, the modelling of EU international maritime has not been integrated into the main analysis of all emissions reduction scenarios. However, all three stylised variants developed for EU international maritime show lower growth in transport activity relative to the Baseline, expressed in tonne kilometres (43% for 2015-2050 in the H2Mar50 and H2Mar70 scenarios, and 37% for 1.5LIFEMar). This is due to lower imports and thus transport demand for fossil fuels in the scenarios reaching -80% to net zero emissions by 2050.

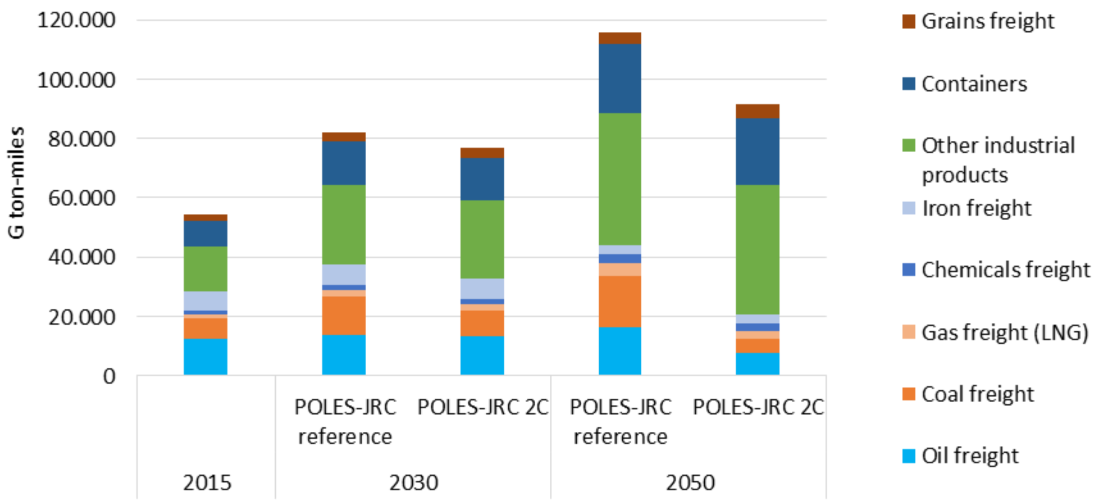
**Figure 47: EU international maritime activity in the Baseline and scenario variants**




*Source: PRIMES.*

Additional analysis for international maritime at global level has been performed by JRC with the POLES-JRC model. Global international shipping is projected to grow by 51% during 2015-2030 and 113% for 2015-2050 in the reference scenario, driven by trade in coal, gas, oil, chemicals, containers, grains and other industrial products. The POLES-JRC 2C scenario, which is a global mitigation scenario including all sectors of the economy, shows much lower growth in global shipping activity by 2050 (68% for 2015-2050) relative to the reference scenario, due to the lower trade and transport demand for fossil fuels.

**Figure 48: Projections for global international shipping activity**




*Source: POLES-JRC.*

4.4.2.2 Technology development projections by transport mode

*Road vehicle drivetrain technologies*

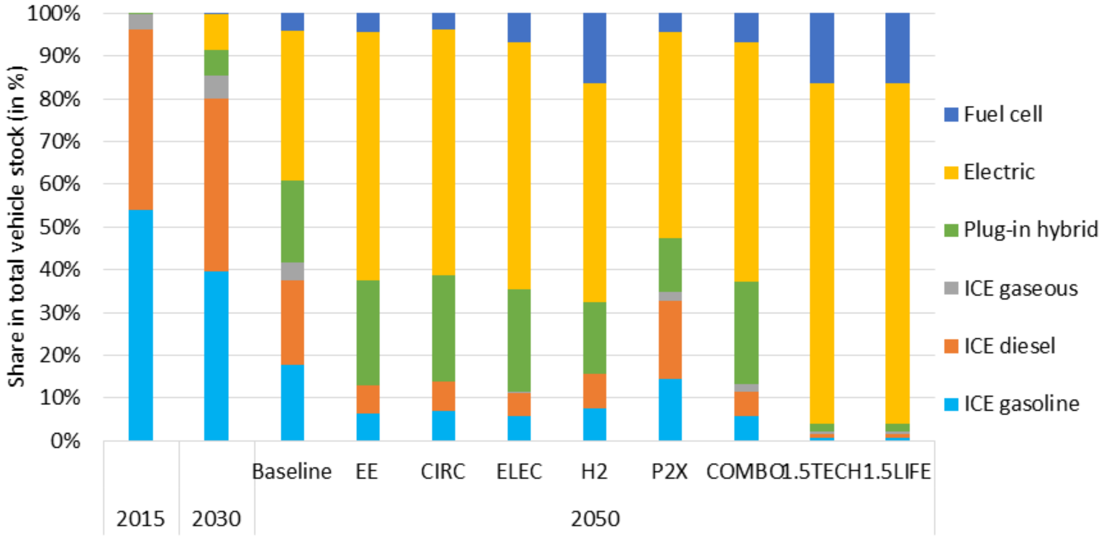
In the Baseline scenario, alternative (to internal combustion engine) drivetrains are increasingly used in road transport, driven by more stringent $CO_2$ standards for new cars and vans post-2020, $CO_2$ standards for new heavy goods vehicles post-2020, and the revision of the Clean Vehicles Directive. No further tightening of $CO_2$ standards is assumed in the Baseline post-2030; their levels remain consistent with the Commission's proposal for 2030. The increasing share of alternative drivetrains in the long run is mainly driven by the turnover of the vehicle stock, technological progress, and the deployment of the recharging infrastructure for electric vehicles and refuelling infrastructure for fuel cells.

Conventional diesel **passenger cars** would see their share declining from 42% of the total stock in 2015 to around 20% by 2050 in the Baseline, while the share of conventional gasoline cars would go down from 54% in 2015 to around 18% by 2050. The share of internal combustion gaseous vehicles (i.e. LPG and CNG) remains relatively stable by 2050, at around 4%. Conventional diesel and gasoline drivetrains (including hybrid systems that complement internal combustion engines) are gradually replaced by electrically chargeable systems (i.e. battery electric, plug-in hybrid and fuel cell vehicles), which are becoming more appealing to consumers thanks to lower costs. In the long run, battery electric vehicles become increasingly important, reaching 35% of the stock by 2050 while plug-in hybrids would represent around 19% of the vehicle stock. The uptake of hydrogen would be facilitated by the increased availability of refuelling infrastructure, but its use would remain limited in lack of additional policy incentives in the Baseline. Fuel cells would represent about 4% of the cars stock by 2050.

All scenarios reaching -80% to net zero emissions by 2050 show much higher uptake of alternative drivetrains in the car stock by 2050 relative to the Baseline. Looking at the scenarios reducing by -80% by 2050, the share of battery electric, plug-in hybrid and fuel cell drivetrains in the car stock ranges between 65 and 89% in 2050. The P2X scenario shows the lowest share of these technologies (65% in 2050) since e-liquids enable passenger cars to reduce emissions without changing the drivetrain, and ELEC the highest share (89% in 2050). In the other scenarios reducing by -80% by 2050, the remaining internal combustion engine (ICE) cars use fuels with significantly reduced carbon intensity, thanks to the blending of advanced biofuels in fossil fuels. In the P2X scenario, the additional blend of e-liquids implies lower carbon intensity for the ICE cars. The EE, ELEC and CIRC scenarios show relatively similar shares for battery electric (57-58%), plug-in hybrid (24-25%) and fuel cell vehicles (4-7%) by 2050. While EE, H2 and ELEC share more ambitious $CO_2$ standards, from 23 to 16 gCO2/km in WLTP test cycle for new cars in 2050 respectively, CIRC benefits from integrating the sharing economy and connected, cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service that benefits the penetration of electrically chargeable systems despite less ambitious $CO_2$ standards. In the H2 scenario, the faster learning assumptions for fuel cells and the large scale availability of hydrogen refuelling stations lead to higher uptake of fuel cell drivetrains (16% of car stock in 2050) to the detriment of plug-in hybrids (17% in 2050); the impact on the uptake of battery electric vehicles (51% in 2050) is more limited relative to the EE, ELEC and CIRC scenarios. In COMBO the share of battery electric, plug-in hybrid and fuel cell drivetrains in the car stock is similar to the EE, CIRC and CIRC scenarios, at around 87% in 2050 (56% for battery electric, 24% for plug-in hybrids and 7% for fuel cells); the share of internal combustion gaseous vehicles (i.e. LPG and CNG) would go down below 2% of the car stock.

In the scenarios reaching net zero by 2050, the share of battery electric and fuel cell drivetrains would reach 96% in 2050 (around 80% for battery electric and 16% for fuel cells), with $CO_2$ emissions for new cars being 0 gCO2/km from 2040 onwards, and the large scale availability of recharging stations and hydrogen refuelling stations. This outcome is also linked to the fact that in the scenarios reaching net zero by 2050 e-fuels and biofuels are used with priority in other parts of the energy system, including in transport sectors such as road freight, aviation and maritime, that have fewer options available to decarbonise. This implies that the passenger car fleet needs to be rapidly replaced by zero emission vehicles in the decades up to 2050. Plug-in hybrids would go down below 2% of the cars stock and internal combustion gaseous vehicles (i.e. LPG and CNG) below 1% of the cars stock in 2050.

**Figure 49: Shares in total cars stock by drivetrain technology in the Baseline and scenarios reaching -80% to net zero emissions by 2050**




*Source: PRIMES.*

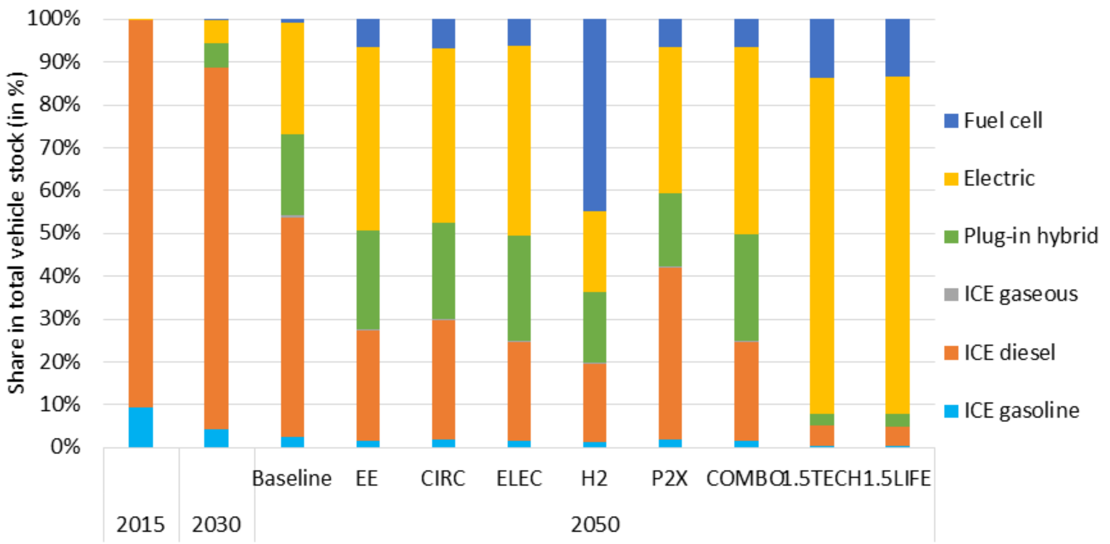
The **light commercial vehicles** fleet is currently dominated by conventional diesel powertrains (around 90% of the stock). In the Baseline scenario, battery electric, plug-in hybrid and fuel cell vehicles are projected to gain significant share by 2050 (46% of the stock), driven by the

Commission's proposal on $CO_2$ standards for new light commercial vehicles for 2030 and the availability of recharging stations and hydrogen refuelling stations. Conventional powertrains, including hybrids, would still provide around 54% of the stock in 2050.

In the scenarios reducing by -80% by 2050, electrically chargeable systems (including fuel cells) would represent 58-80% of the light commercial vehicles stock in 2050. CIRC, EE and ELEC show relatively similar shares, at 70-75% of the stock in 2050 (41-44% for battery electric, 22-25% for plug-in hybrids and 6-7% for fuel cells). In the H2 scenario, fuel cells make up to 45% of the stock in 2050 while battery electric and plug-in hybrids would represent around 19% and 16% of the stock, respectively. The P2X scenario projects lower shares for electrically chargeable systems (58% of the stock in 2050), enabled by the uptake of e-liquids. All scenarios reducing by -80% by 2050 have significant blending of biofuels, and e-liquids in the P2X scenario, that reduces the carbon intensity of fuels used in the remaining ICE light commercial vehicles. COMBO shows similar shares in the vehicle stock in 2050 as the ELEC scenario (44% for battery electric, 25% for plug-in hybrids and 6% for fuel cells).

In the 1.5TECH and 1.5 LIFE scenarios, battery electric and fuel cell vehicles would provide around 92% of the stock by 2050, with $CO_2$ emissions from light commercial vehicles being 0 gCO2/km from 2040 onwards and the large scale availability of recharging stations and hydrogen refuelling stations. As explained above, this outcome is also linked to the fact that, in the scenarios reaching net zero by 2050, e-fuels and biofuels are used with priority in other parts of the energy system, including in transport sectors such as road freight, aviation and maritime, that have fewer options available to decarbonise. This implies that the light commercial vehicles fleet needs to be rapidly replaced by zero emission vehicles in the decades up to 2050. Plug-in hybrids show shares below 3% of the stock.

**Figure 50: Shares in total light commercial vehicle stock by drivetrain technology in the Baseline and scenarios reaching -80% to net zero emissions by 2050**




*Source: PRIMES.*

Powered 2-wheelers would also benefit of electrification, around 82% of the fleet being electric in the scenarios reducing by -80% by 2050 and COMBO scenario by 2050. The only exception is the P2X scenario, which projects lower electrification of the stock (41% in 2050), enabled by the use of e-liquids as drop in fuels. In the 1.5TECH and 1.5 LIFE scenarios, electric powered 2-wheelers would represent up to 94% of the stock in 2050.

Technology uncertainties exist and future development could well result in different outcomes than those represented in the above scenarios. But for cars and light commercial vehicles, the current "conventional wisdom" regards electrification (with a more limited share of fuel cell vehicles) as a viable long term option to decarbonise these segments. This is consistent with the above PRIMES scenarios results that show very high shares of electrically chargeable powertrains for light duty vehicles (i.e. cars and light commercial vehicles) by 2050.

Other studies also show a significant take up of electric vehicles. The "New Policies Scenario" of the 2018 IEA Global EV Outlook[321], based on existing and planned policies, projects a share of battery electric and plug-in hybrids in new sales in Europe of 23% for all vehicles (except two- and three-wheelers) by 2030. The more aspirational EV@30 Scenario of the IEA shows a share of 35% in new sales for light duty vehicles, buses and trucks by 2030. By comparison, the sales share in China is projected to be higher than in Europe in the IEA scenarios, reaching 26% and 40% in the “New Policies Scenario” and EV@30 Scenario, respectively. In addition, the IEA foresees a large increase in the stock of electric two- and three-wheelers in the “New Policies Scenario”, from 300 million in 2017 to 455 million in 2030, largely in China, India and the ASEAN countries.

The Bloomberg New Energy Finance Electric Vehicle Outlook 2018[322] forecasts that given current trends, more than half a billion electric vehicles (including plug-in hybrids) on the road by 2040, representing a third of the global car fleet. By 2030, 28% of global new car sales, would be electrically chargeable, while by 2040, 55% of new car sales would be electric. China is expected to lead the transition, with Europe following. Their analysis shows that the bus fleet is likely to electrify faster than cars.

The OPEC World Oil Outlook[323] Reference Case takes a more conservative view, with electric vehicles (including plug-in hybrids) in OECD Europe by 2040 reaching 33% of new sales. OPEC also provides a sensitivity analysis in which 3 out of 5 cars sold in Europe by 2040 would be electric.

The BP Energy Outlook 2018[324] Evolving Transition Scenario (which assumes that government policy, technology and social preferences continue to evolve at the speed seen in the past) expects 15% of the global car fleet to be electric by 2040, but 30% of all vehicle kilometres to be powered by electricity, due to the increase in shared mobility. Amore radical "ICE ban" scenario is also analysed.

By contrast, a recent study by Ricardo for Concawe[325] presents scenarios showing an alternative to the “conventional wisdom” on long-term electrification. Apart from scenarios showing high penetration of battery electric vehicles, the study presents a scenario in which plug-in hybrids shares are higher, and a scenario in which low-carbon fuels (biofuels and e-fuels) are the dominant greenhouse gas reduction technology. Both scenarios result in a significant (~85%)

[321] IEA (2018) IEA Global EV Outlook - towards cross-modal electrification. https://www.iea.org/gevo2018/
This reports analyses technology, consumer behaviour, infrastructure needs and policies, for electrification across all road transport, including two- or three-wheelers, buses and HDVs.

[322] Bloomberg NEF (2018), Electric Vehicle Outlook (EVO), https://about.bnef.com/electric-vehicle-outlook/

[323] OPEC (2017) World Oil Outlook

[324] BP (2018), World Energy Outlook, https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-sector/transport.html

[325] Ricardo for Concawe (2018) Impact analysis of mass EV adoption and low carbon intensity fuels scenarios; https://www.concawe.eu/publication/impact-analysis-of-mass-ev-adoption-and-low-carbon-intensity-fuels-scenarios/

reduction of greenhouse gas emissions from light duty vehicles by 2050. In the high plug-in hybrids scenario, these powertrains would represent around 91% of the passenger car vehicle fleet in 2050. In the low-carbon fuels scenario, plug-in hybrids represent around 47% of the fleet. In terms of fuel mix, the low-carbon fuels scenario projects around 54% of biofuel use in 2050, 23% electricity use and 14% e-fuel use. However, the low-carbon fuels scenario relies on the assumption of continued strong improvements in ICE technology as well as, importantly, sufficient availability of land resources globally. On the other hand, the high plug-in hybrids scenario relies on the assumption of increased global production of Lithium or other materials for batteries.

While the pace of technology development is uncertain, there is widespread expectation that the penetration of alternative drivetrains will increase, notably that of battery electric cars. Furthermore, a successful transition to low-emissions mobility depends not only on continued improvement in technology costs but also on regulatory action, financial incentives and large scale deployment of recharging and hydrogen refuelling infrastructure.

As described in 4.4.1.5, **for heavy goods vehicles (HGVs)** the scenarios reflect the uncertain and diverse technology expectations: they show a variety of HGV technologies being used in different circumstances, depending on technology preferences, the distance travelled, the load, and the infrastructure choices that are available – see chapter on fuel mix projections below.

The heavy goods vehicles stock is currently almost entirely dominated by conventional diesel powertrains. In the Baseline scenario their share is projected to decrease significantly (to around 51% by 2050, excluding hybrids), driven by the $CO_2$ standards for new heavy goods vehicles. Gas-fuelled vehicles are projected to represent around 18% of the HGV stock in 2050 and hybrids around 29%. Overall, electric and fuel cell vehicles would only provide around 2% of the stock by 2050 in the Baseline scenario. It should be noted that the Baseline scenario keeps the $CO_2$ standards for new heavy goods vehicles unchanged post-2030, consistent with the Commission’s proposal for 2030. Further evolution is thus driven by the turnover of the fleet, technological progress and the assumed availability of refuelling infrastructure for LNG.

Looking at the scenarios reducing by -80% by 2050, hybrids would represent 22-33% of the HGV stock in 2050. Electric drivetrains (fully electric and HGVs with pantograph[326]) would provide 17-20% of the stock in the EE and ELEC scenarios, but only 3 and 6% in the P2X and CIRC scenarios, respectively. Fuel cells are projected at 15% of the vehicle fleet by 2050 in the H2 scenario, driven by the faster learning assumptions for fuel cells and the large scale availability of hydrogen refuelling stations. Gas-fuelled vehicles would represent 14% of the stock in H2 scenario and 35% in P2X scenario by 2050. At the same time, conventional diesel drivetrains, excluding hybrids, are projected to still provide 37-58% of stock by 2050 in the scenarios reducing by -80% by 2050. However, the carbon intensity of fuels would be reduced due to the blending of advanced biofuels in diesel, and in addition by e-liquids in the P2X scenario. Similarly, the blending of biomethane and e-gas reduces the carbon emissions of gas-fuelled heavy goods vehicles.[327] Thus, low carbon fuels reduce the greenhouse gas emissions of trucks, even when used in conventional drivetrains. As an example, the use of liquid biofuels in trucks by 2050 ranges from 21% in H2 scenario to 26-27% in ELEC and EE scenarios, and up to 34% in CIRC. In P2X, liquid biofuels only make up 8% of the energy demand, as e-liquids

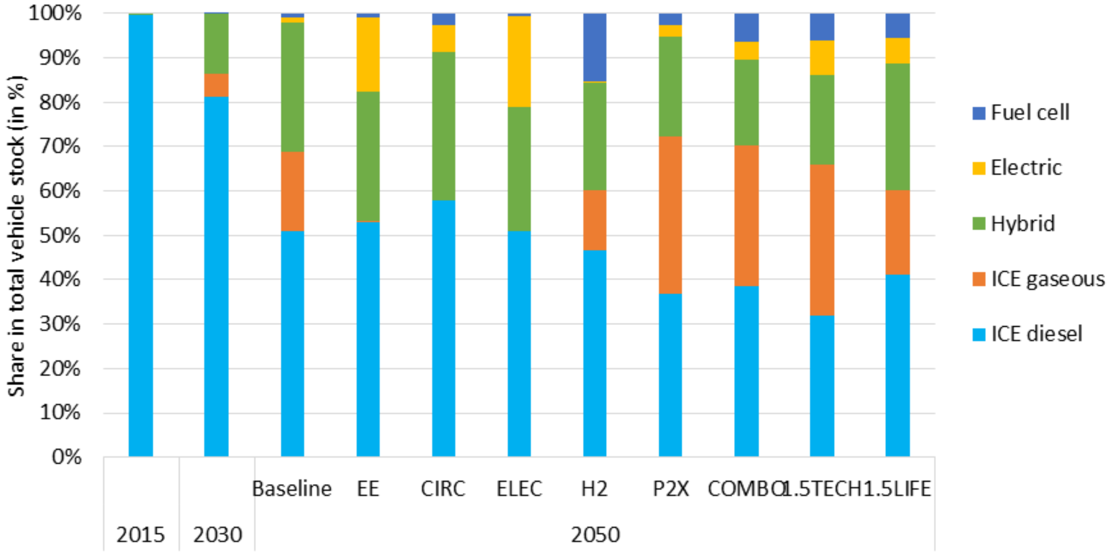
[326] The investment costs for the catenary lines and pantograph infrastructure are not considered in these scenarios. These investment costs can amount up to 2 million EUR for equipping 1 km of road (e.g. in Schleswig-Holstein).

[327] The scenarios assume that by 2050 liquefaction and gasification at small scale will be applied at a competitive cost, thus allowing refuelling hubs to develop in a widespread manner as well as liquefaction stations where blending of biogas and e-gas in gas distribution takes place.

provide around 21% of the fuel mix and gaseous fuels another 44% (of which 21% is e-gas, 9% biomethane and 14% natural gas). E-liquids and e-gas are nearly absent in the other scenarios reducing by -80% by 2050 while gaseous fuels, including biomethane, would provide around 7% of the fuel mix in the H2 scenario.

The COMBO scenario shows moderate uptake of electric drivetrains and fuel cells (around 10% of the stock) by 2050, while hybrids would represent around 19% and gas-fuelled vehicles 32% of the stock. As in the scenarios reducing by -80% by 2050, the fuel mix plays an important role in driving the greenhouse gas emissions reduction. For example, e-liquids are projected at around 11% of the energy demand of trucks, hydrogen at 14%, liquid biofuels at 16% and gaseous fuels at around 33% of the fuel mix (of which more than 15% is e-gas, 8% biomethane and 9% natural gas). In the 1.5TECH and 1.5 LIFE scenarios, as illustrated in Figure 51, the uptake of powertrains by 2050 is broadly similar to the COMBO scenario. However, the uptake of low carbon fuels in the mix, in particular of e-fuels and biofuels, is higher. Both COMBO and the scenarios reaching net zero by 2050 would require significant deployment of refuelling infrastructure for hydrogen and gaseous fuels.

**Figure 51: Shares in total heavy goods vehicles stock by drivetrain technology in the Baseline and scenarios reaching -80% to net zero emissions by 2050**




*Source: PRIMES.*

Generally, for HGVs, the PRIMES scenarios show that ICE and hybrid powertrains using fuel blends with very low carbon intensity, either liquid or gaseous, would represent the dominant technology. However, hydrogen would also play a significant role for long distance road haul and electricity in particular for urban deliveries. Given the high uncertainties, care should be taken when interpreting these results.

The IEA has analysed Scenarios for the Future of Trucks[328]. In the Reference Case, penetration of alternative drivetrains remains limited. The Modern Truck Scenario implements a large number of systemic efficiency improvements, as well as vehicle technology improvements. By 2050, drivetrains remain varied, with electrification becoming important for light trucks, especially for urban delivery, and a variety of technologies, from conventional diesel, hybrids, LPG/CNG and

[328] IEA (2017), The Future of Trucks https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf

some electrification being used for medium and long-haul heavy duty trucks. While the report states that the price of fuel cells can be brought down to become competitive, the uncertainty is still large. As in the PRIMES scenarios underpinning this strategy, no obvious technology winner appears for trucks.

However, as noted in 4.4.1.5, a recent report by Scania[329] shows battery electrification as the most cost-effective option, providing an alternative viewpoint.

**For buses and coaches**, the Baseline scenario projects significant uptake of hybrids (36%) and gas-fuelled vehicles (21%) as a share of the stock by 2050. Electric drivetrains (battery and trolleys) would represent around 5% of the fleet in 2050. However, in the scenarios reaching -80% to net zero emissions by 2050, the picture is mixed due to their different uses and technologies available. While buses are mostly used in the urban environment where electrification is a viable option, coaches travel longer distances and face similar limitations to those faced by heavy goods vehicles. For buses[330], the EE, ELEC and CIRC scenarios show almost full electrification of the vehicle fleet by 2050. In the H2 scenario fuel cells are dominant in the stock (84%) while electric vehicles (battery and trolleys) represent around 16% in 2050. However, in the P2X scenario, conventional diesel drivetrains still represent around 26% of the stock and gas-fuelled vehicles around 24% in 2050, while electric buses reach 41% of the stock by 2050. In the P2X scenario, low carbon fuels like e-gas, e-liquids, liquid and gaseous biofuels play a significant role in the greenhouse gas emissions reduction. COMBO and the scenarios reaching net zero by 2050 show shares of electric buses in the range of 79-88%, while fuel cells would represent between 3% and 14% and gas-fuelled vehicles between 6 and 8%. In addition, e-gas, e-liquids, liquid and gaseous biofuels play a significant role in reducing the carbon intensity of fuel used in ICE powertrains. For coaches, the outcome is relatively similar to that for heavy goods vehicles, although fuel cells gain significant market shares in the 1.5TECH and 1.5 LIFE scenarios.

*Rail*

For rail, all scenarios show electrification as the main option. In the Baseline scenario, around 87% of the rolling stock used for passenger rail is projected to be electric by 2050, and 77% for freight rail. This requires significant efforts, supported by the assumed completion of the core TEN-T network by 2030 and of the comprehensive TEN-T network by 2050. In the scenarios reducing by -80% by 2050 electric rolling stock would represent around 93-95% for passenger rail in 2050 and 85-88% for freight rail; rail infrastructure would need to be largely electrified by 2050 to support such significant changes[331]. In COMBO and the scenarios reaching net zero by 2050 the shares of electric rolling stock are similar to those in the EE scenario (95% for passenger rail and 88-89% for freight rail).

*Inland navigation*

In PRIMES inland navigation covers inland waterways and national maritime[332]. In the Baseline scenario, a large share of the vessels fleet (87%) is projected to be powered by liquid fuels by 2050. LNG vessels would represent around 13% of the fleet by 2050, driven by CEF funding and

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[329] Scania (2018) Achieving fossil-free commercial transport by 2050; https://www.scania.com/group/en/wp-content/uploads/sites/2/2018/05/white-paper-the-pathways-study-achieving-fossil-free-commercial-transport-by-2050.pdf

[330] The IEA Global EV Outlook points out that urban electric buses can already operate cost-competitively in regions with high diesel taxation.

[331] The investment costs for the electrification of the rail network are not covered in the modelling, but only those related to the rolling stock.

[332] This is due to the fact that a split of energy statistics between the two is not currently available.

the assumed availability of LNG refuelling infrastructure, plus the Sulphur Directive that is relevant for national maritime.

In all scenarios reaching -80% to net zero emissions by 2050, energy efficiency improvements would provide a significant contribution in decreasing greenhouse gas emissions. Energy intensity would go down by 11-13% in the scenarios reducing by -80% by 2050, 12% in COMBO and 13% in the scenarios reaching net zero by 2050 during 2015-2050, driven by technical and operational measures (e.g. engine optimisation, hull design, speed optimisation, capacity utilisation, voyage optimisation, etc.). Electrification would represent a niche market by 2050 (up to 3% of the vessels fleet in the EE and ELEC scenarios, 1% in COMBO and 3% in the scenarios reaching net zero by 2050) while fuel cell vessels are projected at around 2% of the fleet in the H2 scenario. Propulsion systems powered by liquid fuels would maintain a dominant role by 2050 (84-87% of the fleet in the scenarios reducing by -80% by 2050, 86% in COMBO and 81-84% in the scenarios reaching net zero by 2050), followed by those powered by gaseous fuels (13% in the scenarios reducing by -80% by 2050 and COMBO, and 13-16% in the scenarios reaching net zero by 2050). However, the carbon intensity of liquid fuels would decrease significantly relative to the Baseline due to the uptake of liquid biofuels (16-34% of the fuel mix in the scenarios reducing by -80% by 2050, 29% in COMBO and 34-44% in the scenarios reaching net zero by 2050) and e-liquids (37% of the energy demand in P2X scenario, 19% in COMBO and 29-48% in the scenarios reaching net zero by 2050). In addition, gaseous fuels would provide around 5-9% of the fuel mix in the scenarios reducing by -80% by 2050 and 7-9% in scenarios achieving higher GHG reduction, of which e-gas would represent around 4% of the fuel mix in the P2X scenario, 3% in COMBO and 4-5% in the scenarios reaching net zero by 2050.

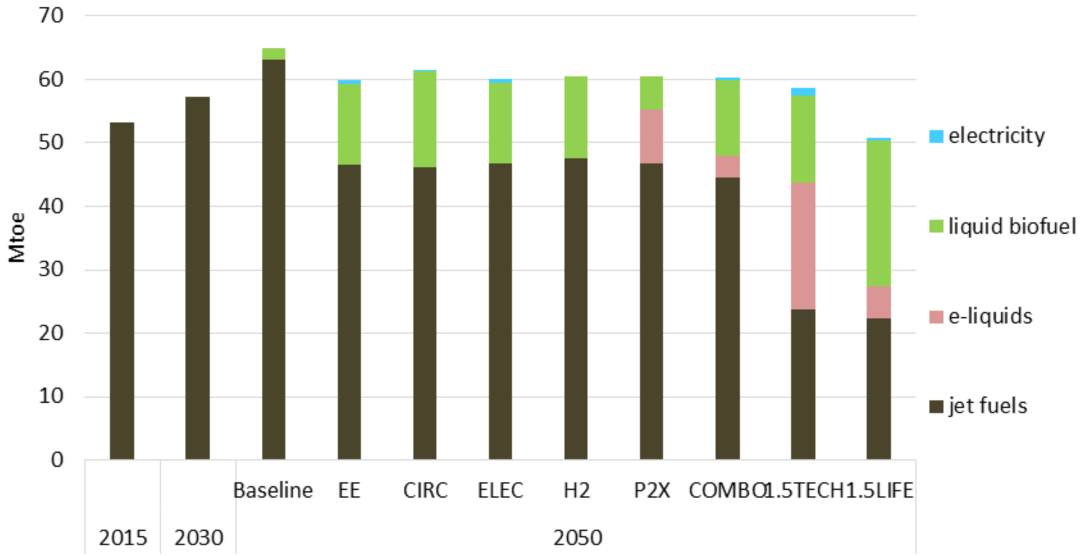
*International aviation*

Concerning EU geographical scope, as already discussed in section 4.4.2.1, in the Baseline scenario air transport activity including international extra-EU flights is projected to increase significantly (43% during 2015-2030 and 101% for 2015-2050). Energy efficiency is already a strong driver in the Baseline scenario. Energy efficiency covers a combination of measures related to aircraft technology and design, air traffic management and operations, improved occupancy rates, etc. Energy intensity of air transport in this broad sense, measured as tons of oil equivalent per million of passenger-kilometres, is projected to decrease significantly in the Baseline Scenario, by 25% during 2015-2030 and 39% for 2015-2050. In the scenarios reaching -80% to net zero emissions by 2050, energy efficiency improvements are projected to around 42% by 2050 relative to 2015.

Currently, air transport relies entirely on petroleum products. In the Baseline scenario, liquid biofuels (i.e. bio-kerosene) are projected to provide around 3% of the energy demand in air transport by 2050. In the scenarios reaching -80% to net zero emissions by 2050, liquid biofuels and e-liquids represent the main alternatives for reducing the carbon intensity of air transport fuels, with the required energy density to provide for longer distance flights, while electricity remains a niche market by 2050. In most scenarios reducing by -80% by 2050, bio-kerosene would provide 21-25% of the fuel mix in 2050 (21% in the ELEC, EE and H2 scenarios and 25% in CIRC). The P2X scenario sees a significant penetration of e-liquids, reaching 14% of aviation fuel consumption in 2050, while the share of liquid biofuels is projected to be more limited (9%). Despite the significant uptake of liquid biofuels and e-liquids in the scenarios achieving 80% emissions reductions, around three quarters of aviation fuels would still remain fossil fuel based by 2050.

In the COMBO scenario, bio-kerosene would provide around 20% of the energy demand in 2050 and e-liquids around 5%, while in the scenarios reaching net zero by 2050 much faster penetration of both bio-kerosene and e-liquids takes place by 2050, reaching 55-57% of the fuel mix (23-45% for bio-kerosene and 10-34% for e-liquids). In the 1.5LIFE scenario the significant uptake of liquid biofuels and e-liquids is coupled with a reduction in energy demand relative to 2015 (5% decrease by 2050), driven by the lower growth in transport activity and energy efficiency improvements.

**Figure 52: Aviation fuels mix in the Baseline and scenarios reaching -80% to net zero emissions by 2050 in 2050**




*Source: PRIMES.*

Electric aircraft only materialise in very small numbers in EE, ELEC and scenarios reaching net zero in 2050. However, there are some developments on full electrification of aviation ongoing, while Airbus, Rolls-Royce and Siemens are developing[333] a hybrid-electric demonstration aircraft. Hybridisation can significantly increase aircraft efficiency, for example by modifying the aircraft design to enhance the overall weight, thus reducing fuel consumption.

*International shipping*

Various studies have described technology options for the decarbonisation of the maritime sector. A literature review by Bouman et al.[334] assesses the potential of different options, described in six main groups: hull design, power and propulsion, economies of scale, speed, weather routing and scheduling, fuels and alternative energy sources. These categories are similar to the generic categories described in section 4.4.1. The authors conclude that emissions can be reduced between 33 and 77% relative to the baseline in 2050 based on current technologies, through a combination of policy measures[335]. In terms of emissions per freight unit transported, they conclude that it is possible to reduce emissions by a factor of 4-6. The figure below summarises the fleet level emission reduction potential relative to the baseline according to Bouman (2017)[334].

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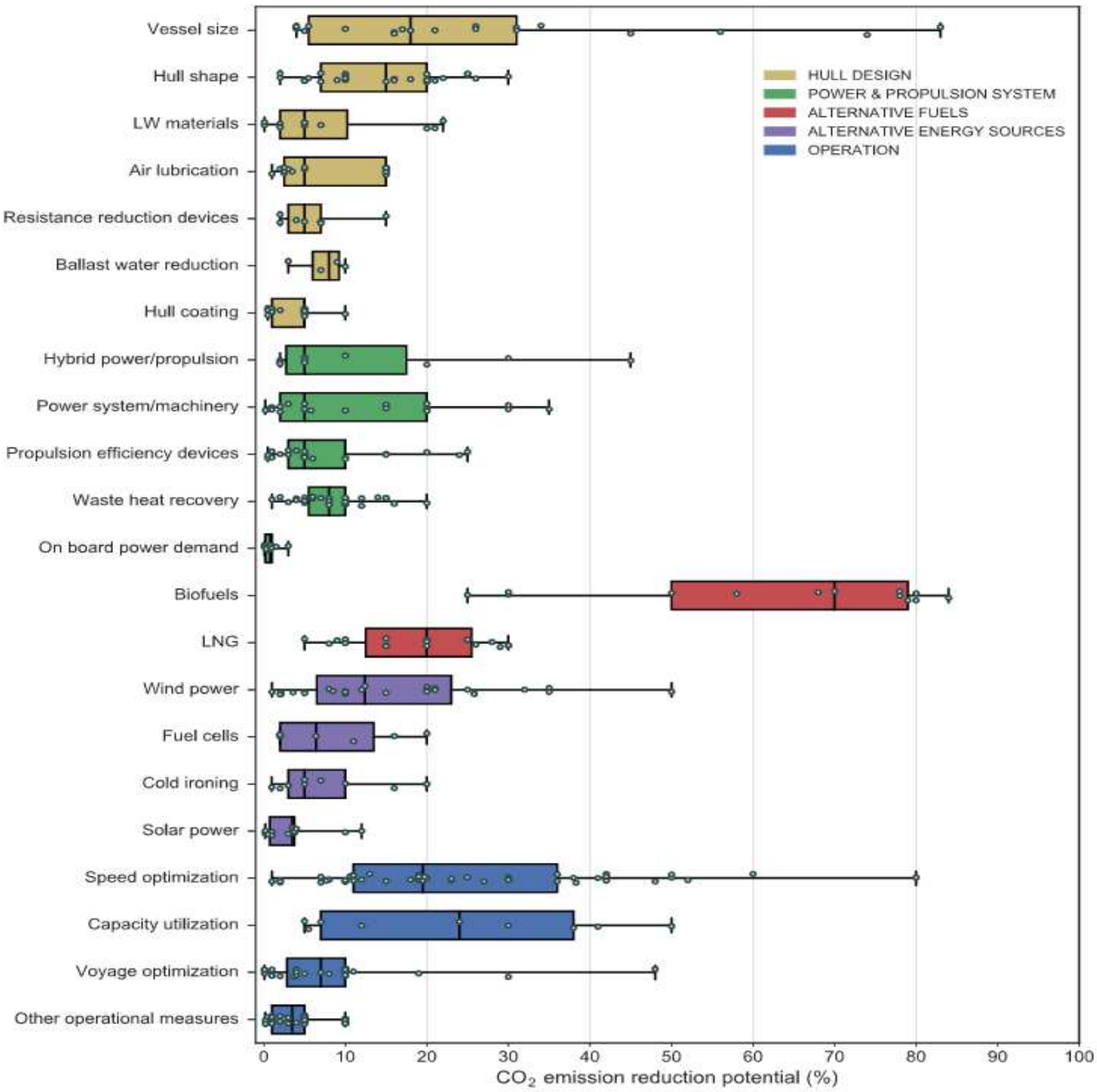
[333] Airbus (2017), https://www.airbus.com/newsroom/press-releases/en/2017/11/airbus--rolls-royce--and-siemens-team-up-for-electric-future-par.html

[334] Bouman et.al.(2017), State-of-the-art technologies, measures, and potential for reducing greenhouse gas emissions from shipping – a review, Transportation Research Part D 52, 408-421

[335] Even higher reductions are viewed as possible if nuclear power is included as an option.

**Figure 53: Fleet level emission reduction potential from individual measures**




*Source: Bouman (2017)*[334]

The OECD report on Decarbonising Maritime Transport[336] described various ambitious pathways to zero-carbon shipping. The categories of technical, fuel and efficiency measures are highly similar to those described above. The OECD also points out that a global effort to meet the goals of the Paris Agreement would lead to a reduction of demand for the maritime transport of fossil fuels. The scenarios described by the OECD lead to zero-carbon shipping in 2035, through the rapid penetration of alternative fuels, primarily hydrogen and ammonia supplemented by biofuels, operational measures, technical measures and ship size increase. These options are varied in intensity to generate different scenarios.

[336] International Transport Forum, OECD (2018), Decarbonising Maritime Transport - Pathways to zero carbon shipping by 2035, https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf

A study[337] by UMAS, UCL and Lloyds for the Danish Shipowners Association describes scenarios of various ambition levels, ranging from those achieving zero emissions by around 2035, to the least ambitious keeping shipping emissions roughly constant at the current level. In each decarbonisation pathway, there are different relative contributions from technical, operation, fuel shift, and offset purchases. Ambitious reductions are achieved through hydrogen and biofuels, in combination with low operational speeds when using fossil fuels. The report notes that hydrogen could be replaced by other zero carbon vehicle technologies, such as electrification. The different scenarios modelled show differing penetration of biofuels, hydrogen, LNG and fossil fuels, depending on ambition and assumptions made.

In the PRIMES Baseline scenario, important improvements of energy efficiency are foreseen, also triggered by the implementation of the Energy Efficiency Design Index adopted at global level by International Maritime Organisation. Energy intensity of EU international shipping, measured as tons of oil equivalent per million tonnes-kilometres, is projected to decrease significantly, by 10% during 2015-2030 and 16% for 2015-2050. The share of marine diesel oil would increase over time, while natural gas would provide around 11% of energy demand by 2050 driven by the Sulphur Directive and the assumed availability of refuelling infrastructure for LNG.

As already explained in section 4.4.1.5, three stylised variants have been run with the PRIMES model for EU international maritime, based on the H2 and 1.5LIFE scenarios. The variants drawing on the H2 scenario are assumed to achieve 50% and 70% reductions in the greenhouse gas emissions relative to 2008 (H2Mar50 and H2Mar70, respectively). In the 1.5LIFEMar scenario, international maritime is assumed to be part of an economy wide net zero greenhouse gas emissions target and reduces its emissions by about 88% by 2050 compared to 2008.

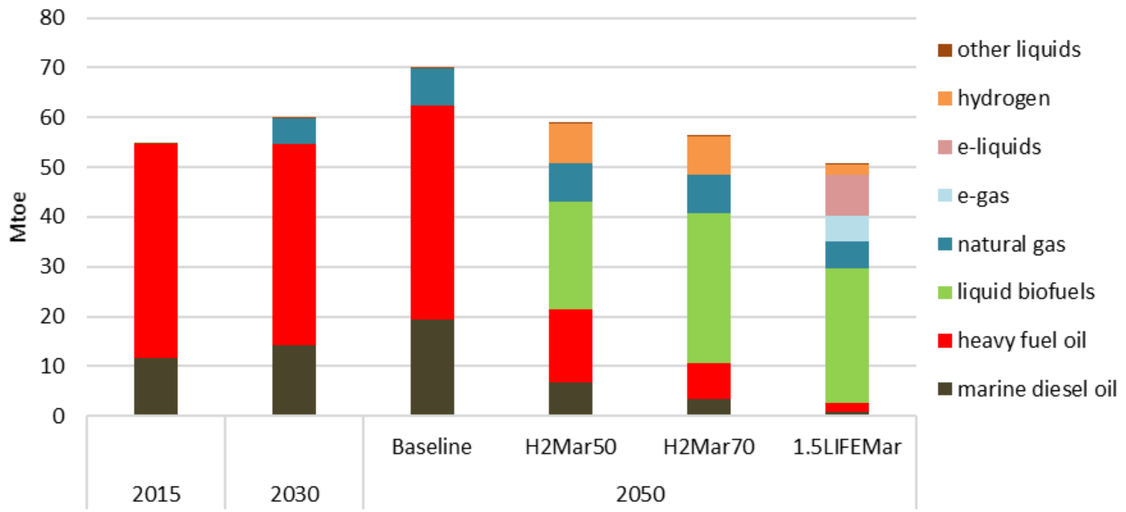
Energy efficiency is projected to provide significant contribution to the achievement of emissions reductions in all three decarbonisation variants by 2050 (25% by 2050 relative to 2015 in the H2Mar50, 28% in the H2Mar70 and 33% in 1.5LIFEMar) through e.g. technologies for propulsion, propeller, hull coating and through speed reduction.

In terms of fuels, all three variants would imply significant uptake of liquid biofuels in the fuel mix by 2050 (37% of the energy demand in H2Mar50 and 54% in H2Mar70 and 1.5LIFEMar). This implies 21-30 Mtoe liquid biofuels demand by 2050. H2Mar50 and H2Mar70 scenarios project higher uptake of hydrogen by 2050 (13-14% of the fuel mix)[338] while the 1.5LIFEMar scenario relies more on e-gas and e-liquids (10% and 17% of energy demand, respectively). Natural gas would still represent 11 to 14% of the energy demand by 2050 in all three variants (11% in 1.5LIFEMar and 14% in H2Mar70). The share of marine diesel oil and heavy fuel oil is projected to reduce significantly by 2050, especially in the 1.5LIFEMar scenario. As a result, the $CO_2$ intensity (expressed in tons of $CO_2$ per tonne-kilometre) is projected to go down by around 66% by 2050 relative to 2005 in H2Mar50, 79% in H2Mar70 and 91% in 1.5LIFEMar.

[337] UMAS, UCL, Lloyds Register (2016), $CO_2$ emissions from International shipping – possible reduction targets and their associated pathways, https://www.danishshipping.dk/en/press/news/download/News_Model_News_File/71/CO2-study-full-report.pdf

[338] E-fuels are not available in the H2 scenario and thus in the H2Mar50 and H2Mar70 variants.

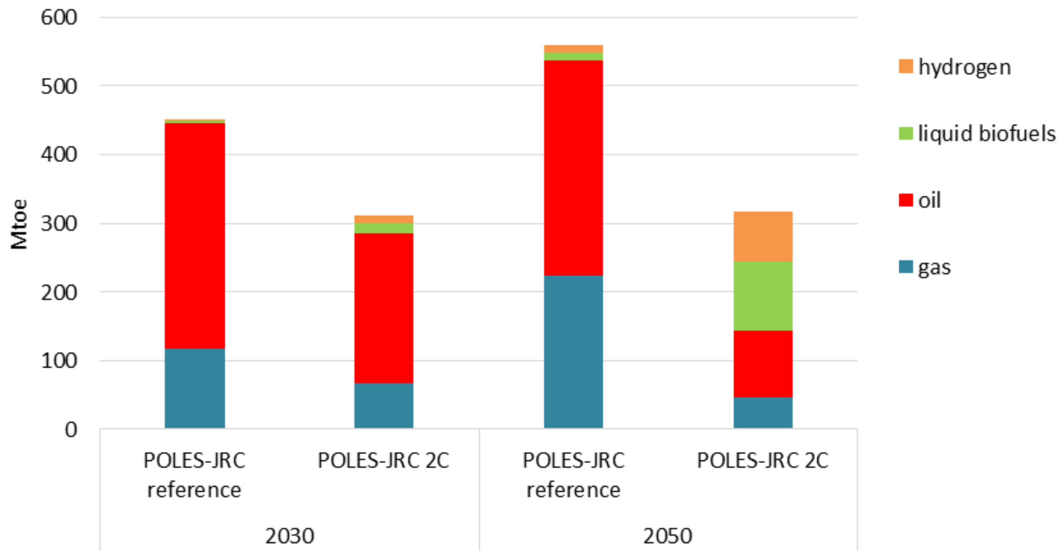
**Figure 54: EU international maritime fuel mix in the Baseline and decarbonisation variants**




*Source: PRIMES.*

The analysis of the international maritime at global level, performed by JRC with the POLES-JRC model, shows energy intensity improvements of around 14% between 2015 and 2050 (measured in ktoe/Gtonne-miles) in the reference scenario. However, the POLES-JRC 2C scenario shows higher improvements in energy intensity over time (39% for 2015-2050), which allows less reliance on liquid biofuels in terms of volume than what would have been required otherwise. By 2050, liquid biofuels would still represent around 32% of the energy demand at global level (101 Mtoe). Hydrogen is projected to provide around 23% of the fuel mix by 2050 and gas another 14%. The POLES-JRC model does not consider e-gas and e-liquids for international shipping.

**Figure 55: Energy demand of global international shipping**




*Source: POLES-JRC.*

4.4.2.3 Energy demand and fuel mix projections

The Baseline scenario shows transport energy demand[339] decreasing by 24% by 2050 compared to 2005, mainly due to the impact of the proposed $CO_2$ standards for new cars, light commercial vehicles and heavy goods vehicles on overall vehicle fleet efficiency, but also due to improvements in the efficiency of the transport system. Oil products remain dominant, providing 75% of the final energy demand in 2050, down from over 90% currently. Electricity would provide around 11% of the energy consumption by 2050, driven by the uptake of electric vehicles and further progress in the electrification of rail. Liquid biofuels would maintain a relatively stable share over time (around 6% of the fuel mix) in the Baseline, while gaseous fuels including biomethane would provide around 6% of energy demand by 2050. Hydrogen is projected to represent around 2% of the transport energy demand by 2050 in the Baseline scenario, in lack of additional policy incentives.

In the scenarios reducing by -80% by 2050, total energy demand in transport goes down between 31% (in the P2X scenario) to 43% (in the EE and CIRC scenarios) in 2050 compared to 2005, driven by more $CO_2$ efficient new cars, vans, heavy goods vehicles and buses post-2030 but also by measures increasing the efficiency of the transport system and shifts towards more energy efficient transport modes (e.g. rail). In more ambitious scenarios, higher reductions in energy demand are achieved by 2050 relative to 2005 (38% in COMBO, 45% in 1.5TECH and 50% in 1.5LIFE). Across all scenarios, larger energy savings are projected for passenger relative to freight transport. Significant savings would take place in road transport while air transport shows lower growth in energy demand relative to the Baseline. Energy demand in rail is projected to increase relative to 2005, while the energy savings in inland navigation are limited; this is due to the significant modal shift taking place from road to rail and inland navigation in all scenarios, having countervailing effects to the higher energy efficiency of these transport modes.

**Figure 56: Change in energy consumption per mode in 2050 compared to 2005**

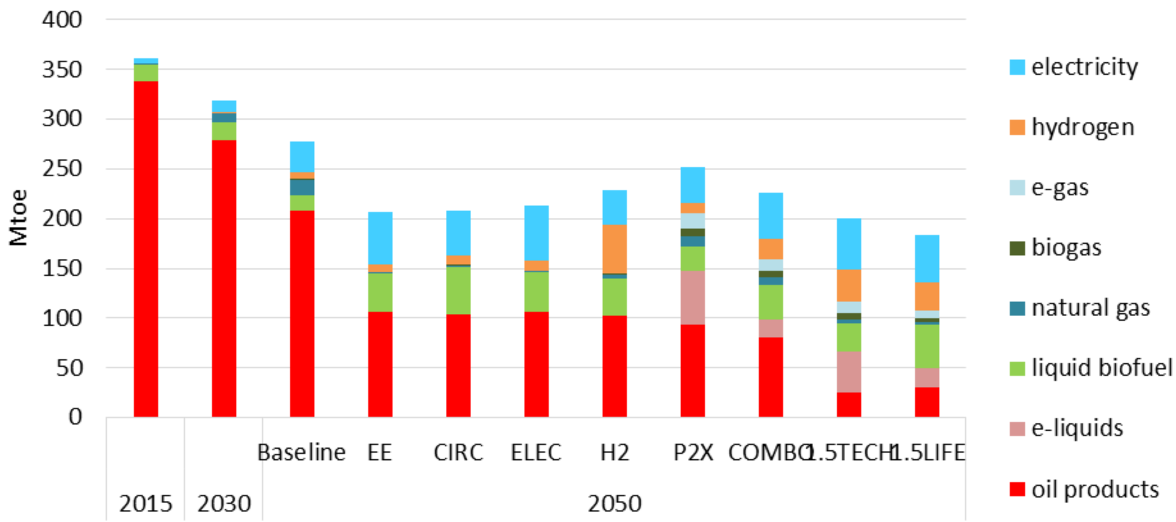

*Source: ESTAT, PRIMES.*

The strongest driver for fuel consumption reduction in transport is projected to be the electrification of the road transport sector. In the scenarios reducing by -80% by 2050, the share

339 Energy demand discussed in this section includes all transport modes except international maritime. This is consistent with the logic of the energy balances, which report international bunkers separately.

of electricity in energy demand would be between 15% (in P2X and H2 scenarios) and 26% (in EE and ELEC scenarios) by 2050, compared to 11% in the Baseline. The share of electricity is only incrementally higher in more ambitious scenarios reaching net zero by 2050, although these see electrification in passenger car transport penetrating faster. This is because in the scenarios reaching net zero by 2050, by construction also e-gas and e-liquids play a more significant role in the transport energy mix, in particular in road freight and aviation.

**Figure 57: Fuels consumed in the transport sector in 2050**




*Source: PRIMES.*

Liquid biofuels consumption is projected to increase in all scenarios, mainly driven by their use in the air transport, road freight and inland navigation sectors. While in the Baseline liquid biofuels would represent around 6% of the fuel mix in 2050, the scenarios reducing by -80% by 2050project shares between 10% (in P2X scenario) and 23% (in CIRC scenario) and the more ambitious scenarios 14-24% by 2050. Together with biomethane, the shares of liquid and gaseous biofuels would be around 13-24% in the scenarios reducing by -80% by 2050s, 18% in COMBO and 17-26% in the scenarios reaching net zero by 2050 in 2050.

The total amount of liquid biofuels used in transport is not very different across the scenarios, although the allocation between transport modes is very different. In more ambitious scenarios, the transport modes that have fewer options to decarbonise use liquid biofuels with priority and thus the other modes opt for different solutions, less based on biofuels.

E-fuels (e-liquids and e-gas) are projected to represent about 28% of the energy demand in 2050 in the P2X scenario (around 71 Mtoe), which is the only scenario reducing by -80% by 2050, that shows a significant uptake of e-fuels. In COMBO e-fuels would provide around 14% of the energy demand, while in the scenarios reaching net zero by 2050 between 15 and 26% of the fuel mix (27 to 53 Mtoe). E-gas would be mostly used in road freight and, to more limited extent, in inland navigation, while e-liquids are projected to be used in air transport, road freight and inland navigation. As previously explained, the advantage of e-liquids is high energy density but also their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure.

Similarly to liquid biofuels, the allocation of e-fuels between transport modes is different in the P2X scenario and more ambitious scenarios. In the more ambitious scenarios, e-fuels are predominantly used in transport modes that have fewer options to decarbonise like air transport, road freight and inland navigation.

Hydrogen is projected to have the highest share in transport energy demand in the H2 scenario (21% in 2050) but it is part of the transport fuel mix in all scenarios, including the Baseline (around 2%). In the scenarios reducing by -80% by 2050, except for the H2 scenario, hydrogen would provide around 4-5% of the energy demand in 2050 while more ambitious scenarios project larger shares (9% in COMBO and 15-16% in the scenarios reaching net zero by 2050).

E-fuels and hydrogen require significant amounts of electricity for their production. For e-fuels electricity is also needed for the capturing of $CO_2$. Thus, reserving the consumption of e-fuels and hydrogen for the transport modes that need them most would help limiting the power sector resources, which increase with their production and deployment.

Gas can play an important role, particularly in road freight transport and shipping as long as gradually the gas supply is decarbonised.[340] By 2050 the role of natural gas would be limited in all scenarios reaching -80% to net zero emissions by 2050 (0.5-4% of the energy demand).

As already explained, not all transport modes are able to switch to electricity. As liquid and gaseous biofuels, as well as hydrogen and e-fuels do not deliver the same type of efficiency improvements as electrification (i.e. electric engines are much more efficient than ICE ones), their relative share in total fuel consumption increases significantly by 2050. Overall, liquid and gaseous biofuels, hydrogen and e-fuels would represent about 23-44% of the energy demand in the scenarios reducing by -80% by 2050, 41% in COMBO and 56-59% in the scenarios reaching net zero by 2050 by 2050. Also accounting for electricity, their shares would increase to 48-59% of the energy demand in 2050 in the scenarios reducing by -80% by 2050, 61% in COMBO and 82-85% in the scenarios reaching net zero by 2050. Nevertheless, by 2050 projections still show some fossil fuel use in the transport sector, notably in aviation but also to more limited extent in road freight and inland navigation, underlining the challenges to decarbonise these sectors.

#### 4.4.2.4 Greenhouse gas emissions from transport

In the Baseline scenario, $CO_2$ emissions from transport, including domestic and international aviation but excluding international maritime, are projected to reduce by 19% by 2030 relative to 2005 and by 38% for 2005-2050[341]. However, relative to 1990 levels, emissions would still be 4% higher by 2030 and only 21% lower by 2050, owing to the fast rise in the transport emissions during the 1990s.

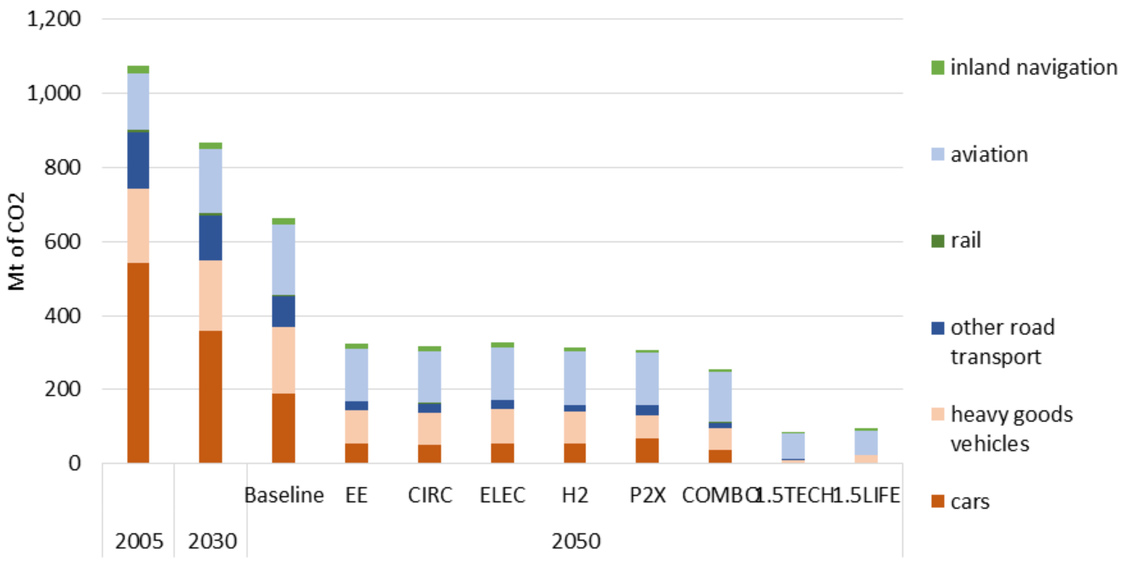
$CO_2$ emissions from passenger cars would be 65% lower by 2050 compared to 2005. For heavy goods vehicles, lower emissions reductions are projected by 2050 (10% compared to 2005). Already by 2030-2035, emissions from heavy goods vehicles and air transport together are projected to overtake those of passenger cars.

The main drivers for the emissions reductions in the Baseline are the $CO_2$ standards for new cars, vans and heavy goods vehicles, consistent with the Commission's proposal for 2030, supported by the deployment of recharging infrastructure for electric vehicles and refuelling stations for hydrogen, and by technological progress. Other policies recently proposed by the Commission would also contribute to the emissions reductions (e.g. the revision of the Eurovignette Directive, Clean Vehicles Directive, Combined Transport Directive and the assumed implementation of electronic documentation for freight transport), in particular in the freight transport sector.

[340] In the modelling, liquefied natural gas is assumed to be the main way of using gaseous fuels in transport enabled by the assumption of low cost miniature liquefaction and gasification stations, allowing blending of biogas and e-gas.

[341] This section only covers the tank to wheel emissions from transport. The $CO_2$ impact of battery production for electric vehicles is also not taken into account.

**Figure 58: $CO_2$ emissions from transport in 2050 (in $MtCO_2$)[342]**



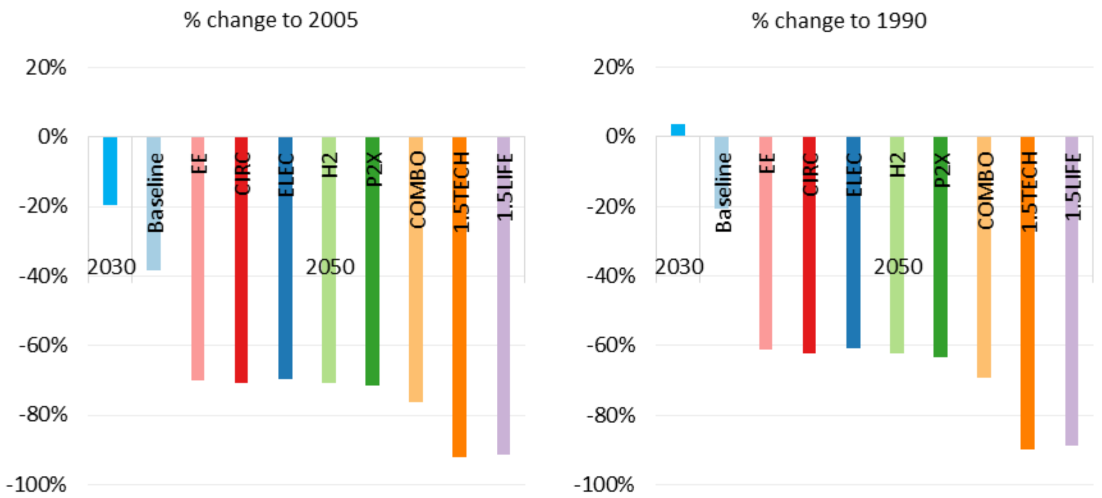

*Source: PRIMES.*

In the scenarios reducing by -80% by 2050, emissions from transport excluding international shipping would go down by 70-71% by 2050 compared to 2005 (61-63% relative to 1990). Thanks to more $CO_2$ efficient new cars post-2030 and the roll out of recharging and refuelling infrastructure, which both support electro-mobility, emissions from passenger cars are projected to decline substantially by 2050 relative to 2005 (by 87% in the P2X scenario and 90% in all other scenarios reducing by -80% by 2050). For heavy goods vehicles, emissions reductions would range between 52% (in the ELEC scenario) and 69% (in the P2X scenario). By 2040, passenger cars would only represent around 24-25% of emissions in most of scenarios reducing by -80% by 2050 (except for the P2X scenario), having been overtaken in importance by heavy goods vehicles (28-29% of emissions) and aviation (31-32% of emissions).

In the COMBO scenario emissions from transport are projected to be 76% lower in 2050 relative to 2005 (69% lower relative to 1990), while in the scenarios reaching net zero by 2050 deeper emissions reductions are achieved (91-92% relative to 2005, equivalent to 89-90% relative to 1990). In the scenarios reaching net zero by 2050, almost the entire passenger car stock would be zero-emitting by 2050. In addition, the rapid penetration of low- and zero-emission vehicles, of alternative and net-zero carbon fuels, and the significant improvements in the transport system efficiency, as described in the previous sections, results in a rapid decrease of emissions from heavy goods vehicles and aviation. In the 1.5LIFE scenario, this is complemented by significant changes in consumer preferences.

[342] Including aviation but excluding international maritime.

**Figure 59: $CO_2$ emissions from transport in 2050 relative to 2005 (left) and to 1990 (right)**[343]




*Source: PRIMES.*

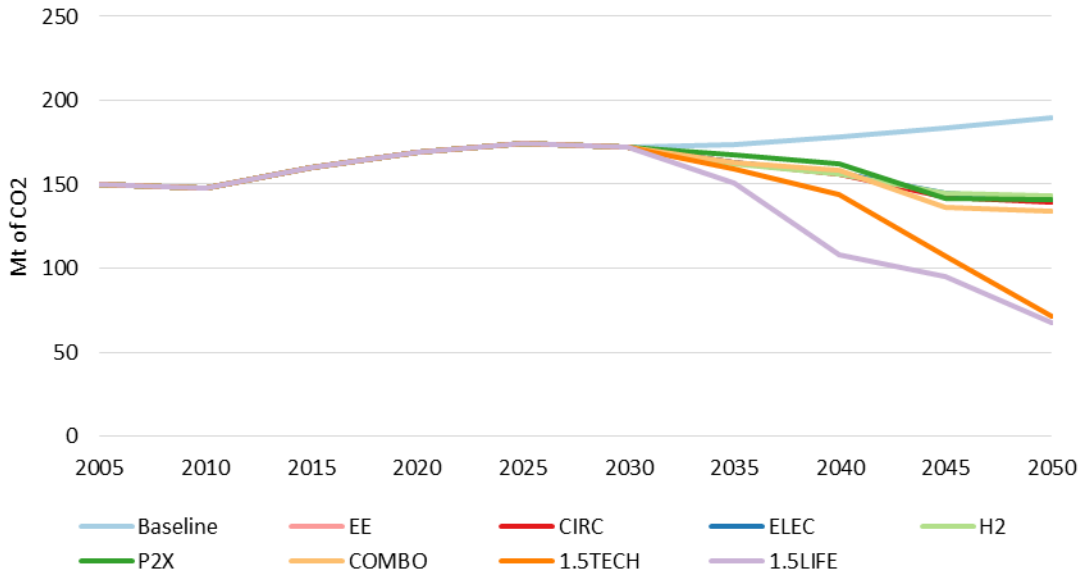
*Greenhouse gas emissions from air transport*

In the Baseline scenario, $CO_2$ emissions from air transport are projected to grow by 26% by 2050 relative to 2005. However, relative to 1990 levels, emissions would be 130% higher, due to the fast rise in the air transport emissions during the 1990s.

In the scenarios achieving 80% GHG reduction, air transport emissions would drop by 5-8% during 2005-2050 but they would still be 68-73% higher relative to their 1990 levels. In the COMBO scenario, somewhat higher emissions decreases are projected, at around 11% for 2005-2050. By contrast, both scenarios reaching net zero by 2050 show large reductions in emissions post-2035; this is mainly due to the rapid penetration of low carbon fuels (e-liquids and advanced biofuels) and lower growth in air transport activity in 1.5LIFE scenario relative to the Baseline. Thus, air transport emissions would go down by 52-55% by 2050 relative to 2005 (13-19% reduction for 1990-2050). The results are shown in Figure 60.

[343] Including aviation but excluding international maritime

**Figure 60: Air transport emissions ($MtCO_2$) in the Baseline and scenarios reaching -80% to net zero emissions by 2050**




*Source: PRIMES.*

A study commissioned for the European Parliament's ENVI Committee[344] shows that to stay below 2°C, the target for EU aviation for 2030 should not exceed 39% of its 2005 emission levels (50% below the baseline in that study) and should be 41% lower compared to 2005 emission levels in 2050. However, the study also allows for offsetting. The PRIMES results do not show such significant reductions within the sector in the scenarios reducing by -80% by 2050, but go beyond them in the scenarios reaching net zero by 2050.

In addition to the above, it should be noted that aviation is also a source of non-$CO_2$ emissions. Flights emit $NO_x$, $SO_2$, sulphate aerosols and water vapour, which have an effect when emitted at high altitude. The deleterious effects are known, albeit the exact impact and interrelationships (radiative forcing) are still debated. Research to better determine these should continue to be pursued and encouraged. So far the non-$CO_2$ effects of aviation on climate change remain virtually fully unaddressed. Exploring measures such as avoiding cloud contrail formation as well as research into aircraft avoiding sensitive climate areas, may be avenues to be explored. While currently, policies directed at aviation only address $CO_2$ emissions[345,346,347], the International Civil Aviation Organization will present for endorsement, in 2019, a Global Standard for Non Volatile Particulate Matters, and will progress in further assessing the impacts of some of contaminants, in order to evaluate the risk to human health and to further the goal of reducing emissions.

*Greenhouse gas emissions from international maritime*

[344] European Parliament DG for Internal Policies (editor) - Study for the ENVI Committee. (2015). Emission Reduction Targets for International Aviation and Shipping.

345European Parliament DG for Internal Policies (editor) - Study for the ENVI Committee. (2015). Emission Reduction Targets for International Aviation and Shipping.

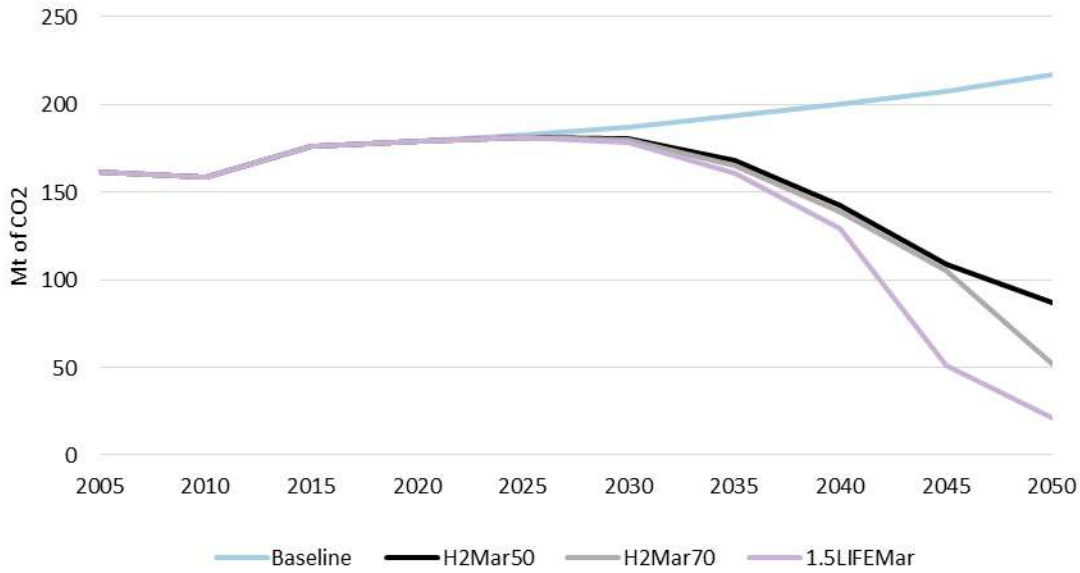
[346] Grewe, V. (23 January 2018). Climate Impact of Aviation CO2 and non-CO2 effects and examples for mitigation options.
https://www.transportenvironment.org/sites/te/files/Climate%20impact%20of%20aviation%20CO2%20and%20non-CO2%20effects_Volker%20Grewe.pdf

[347] CE Delft. (May 2017). Towards Addressing Aviation's non-CO2 Climate Impacts.

In the Baseline scenario, emissions from EU international maritime are projected to increase by 34% during 2005-2050 (equivalent to 19% increase over 2008-2050). This is mainly driven by the sustained growth in transport activity over the period and despite important improvements in the energy efficiency, also triggered by the implementation of the Energy Efficiency Design Index.

As already explained in section 4.4.1.5, the stylised variants that have been run with the PRIMES model for EU international maritime are based on the H2 and 1.5LIFE scenarios. The variants drawing on the H2 scenario are designed to achieve 50% and 70% reductions in the greenhouse gas emissions relative to 2008 (H2Mar50 and H2Mar70, respectively) while in the 1.5LIFEMar variant, international maritime is assumed to be part of an economy wide net zero greenhouse gas emissions target and reduces its emissions by about 88% by 2050 compared to 2008. When compared to 2005, the emissions reductions by 2050, are equivalent to 46% in H2Mar50, 68% in H2Mar70 and 87% in 1.5LIFEMar. The emissions reductions are driven by significant energy efficiency improvements and the uptake of advanced biofuels, e-liquids, e-gas and hydrogen in the fuel mix. The evolution of emissions from EU international maritime in the stylised PRIMES variants are provided in Figure 61.

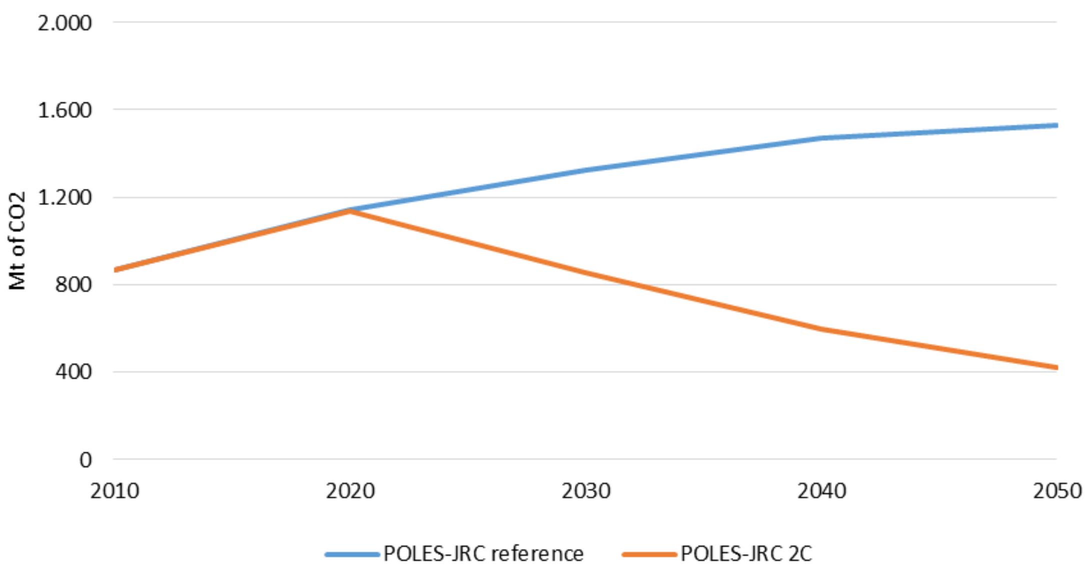
**Figure 61: Emissions reductions at EU level in the maritime decarbonisation variants**




*Source: PRIMES*

The stylised modelling exercise performed for international shipping at global level by JRC with the POLES-JRC model shows a doubling of emissions by 2050 relative to 2005 in the POLES-JRC reference scenario (83% increase between 2008 and 2050). As already explained, the POLES-JRC 2C scenario illustrates a reduction by 50% in the global international shipping greenhouse gas emissions by 2050 compared to 2008 (relative to 2005, this is equivalent to 44% decrease in emissions at global level). The emissions reductions in POLES-JRC are driven by significant improvements in energy efficiency and the uptake of advanced biofuels and hydrogen.

**Figure 62: Emissions reductions at global level in POLES**




*Source: POLES-JRC.*

The two modelling exercises above offer stylised views on the evolution of emissions from international shipping at EU and global level. They offer a broad range of alternatives and degree of ambition in terms of energy efficiency improvements and the uptake of advanced biofuels, hydrogen, e-liquids and e-gas in the fuel mix. An even broader range of scenarios, both in terms of ambition and mitigation options, is found in the other studies[348] [349] referred to above. The implementation of the initial IMO strategy on reductions of greenhouse gas emissions from ships and its subsequent review will further determine the evolution of emissions from international shipping at global level. While further work is needed to refine the approach for integrating the EU international shipping modelling results into the EU scenarios reaching -80% to net zero emissions by 2050, the importance of the maritime sector for greenhouse gas emissions and energy demand cannot be ignored.

### *4.4.3 Transition enablers, opportunities and challenges*

In the transport sector, sustained activity growth is expected in all modes. Attaining deep emissions reductions will thus require a broad range of measures, including significant improvements in transport system efficiency, building on strong modal shift, multi-modality and making full use of benefits of connected, cooperative and automated mobility[350] while at the same time triggering high deployment of low- and zero-emissions vehicles, vessels, rolling stock and aircraft and/or alternative and zero-emissions fuels.

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[348] International Transport Forum, OECD (2018), Decarbonising Maritime Transport - Pathways to zero carbon shipping by 2035, https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf

[349] UMAS, UCL, Lloyds Register (2016), $CO_2$ emissions from International shipping – possible reduction targets and their associated pathways, https://www.danishshipping.dk/en/press/news/download/News_Model_News_File/71/CO2-study-full-report.pdf

[350] Improvements in transport system efficiency also cover, among others, reinforced mobility planning. This can be also supported by measures for shifting consumer choice to low- and zero-emission modes.

Increased and targeted efforts to support R&D&I and a proper support system for deployment is indispensable to enable the transition. For example, it is clear that the development of advanced biofuels and e-fuels still needs to take large strides, as these are required in view of needed emission reductions from aviation. Therefore, in particular for transport sectors with currently limited decarbonisation options such as aviation, substantial research and innovation financing programmes will be necessary to allow for real scale demonstration of new technologies and business models.

Road transport will need to deliver substantial emission reductions. There is growing international momentum for battery-electric passenger cars and light commercial vehicles deployment. Other regions are strongly pushing this market. Europe needs to maintain its competitiveness, making it necessary to adopt an integrated approach for vehicles, infrastructures and services, putting consumer needs first. There is also progress on heavy-duty vehicles, particularly for the deployment of low- and zero-emission buses in urban areas.

For heavy duty road transport, the transition might require continued development of a mix of technologies, including battery electrification, particularly for short haul, but also advanced biofuels, hydrogen fuel cells, e-liquids and e-gas, catenary lines and pantograph systems etc. If technically and economically possible, a transition in this sector more reliant on electrification or fuel cells, rather than biofuels and e-fuels, would have benefits in terms of reduced stress on land or energy resources. On the other hand, an important advantage of both e-fuels and advanced biofuels is their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure.

In international maritime and aviation, energy efficiency will be one of the possible elements to limit the demand for low carbon fuels. However, the uptake of advanced biofuels, e-fuels and hydrogen (for maritime) will be important to enable their decarbonisation. The relatively long replacement time of the vessel/aircraft fleet in these sectors imply high risk if regulatory action is delayed. Especially in the aviation sector, the technological challenges are large.

Similarly, there is a need to accelerate modal shift: towards rail (as a largely electrified sector for long distance transport) and waterborne transport, and towards public transport or active modes (cycling and walking) in cities. However, rail freight needs to become more competitive compared to road transport by eliminating operational and technical barriers between national networks and by fostering innovation and efficiency across the board; the competitiveness of inland navigation should also be improved. In addition, a completed core and comprehensive Trans-European Transport Network is needed by 2050 to support the transformation.

New societal developments and changes in consumer choices have a large potential for improving mobility and contributing to decarbonisation. Integrating the sharing economy and connected, cooperative and automated mobility in the existing transport institutional and technical set-up, and making full use of digitalisation, automation, mobility as a service and the potential of active modes, should therefore be an important part of the agenda.

The revision of the rules on road pricing is an opportunity for the EU to address a significant part of issues concerning systemic efficiency. In all modes, there is a need for fair taxation policies and the phase-out of fossil fuel subsidies, where present.

In view of technological trends, stronger integration of transport with the energy system, with the support of ICT, is essential. Enabling smart charging for vehicle users, turning vehicles into multi-purpose assets, that generate cost savings for consumers and help the management of the energy transition, should be advanced quickly. Energy storage – both stationary and mobile - is an important enabler of future low- and zero-emission transport, as it can provide a flexible mechanism to support recharging of vehicles in cases where links with the energy grid are constrained, as well as support balancing services. At the same time, the introduction at scale of vehicle-to-grid solutions based on large scale fleets (for example in more densely populated areas) could further support the energy transition and enable new consumer services.

However, questions of market design and governance issues related to consumer rights, transparency of information, sectoral integration (energy and transport), access to data and cybersecurity are already key policy questions today. Technological lock-in needs to be avoided and infrastructures and systems need to be open and easily accessible to all consumers. Ensuring sustainability of the full (global) value chain is a policy challenge, particularly for battery development, where the EU needs to take a lead for the second generation battery development. It will require greater coordination and cooperation among public and private market actors.

Urban areas will be the centres of mobility innovation – increasing scarcity of space could become a real driver of innovation in mobility services. On the other hand, the convenience of automation poses the risk that activity will increase faster. But if well channelled, technological and societal developments could result in very large co-benefits for pollution, noise, congestion and accidents, thereby improving the quality of life, especially in cities. Transport will be most likely one of the first sectors affected by digitalisation and automation, with the large-scale arrival of self-driving vehicles – including self-driving lorries – being possible in the next decade. Full deployment of C-ITS can improve the overall efficiency of the transport system. The Commission has published a Communication on Connected and Automated Mobility[351], setting out a strategy for the EU.

New areas of business development and mobility services will open up. Europe's strong industrial base, supported by R&D&I should give it the strength to compete globally, although there is also a risk of a disruptive shift in competitiveness. Furthermore, societal challenges need to be tackled head-on. For example, employment in some professions might decrease (e.g. drivers) and the development of new technologies and services will require new skills. SMEs might not be sufficiently equipped to face these changes. Therefore, opportunities for re-training of people with obsolete profiles should be open up.

In all transport modes, market barriers and market failures such as split incentives, information gaps, lack of certainty about the future, lack of internalisation of externalities, or lack of information for consumers hinder the uptake of green technologies. But the importance of the automotive, maritime and aerospace industries in the European economy requires a readiness to be prepared for the challenges of the future.

## 4.5 Industry

### *4.5.1 Options to reduce emissions in industry*

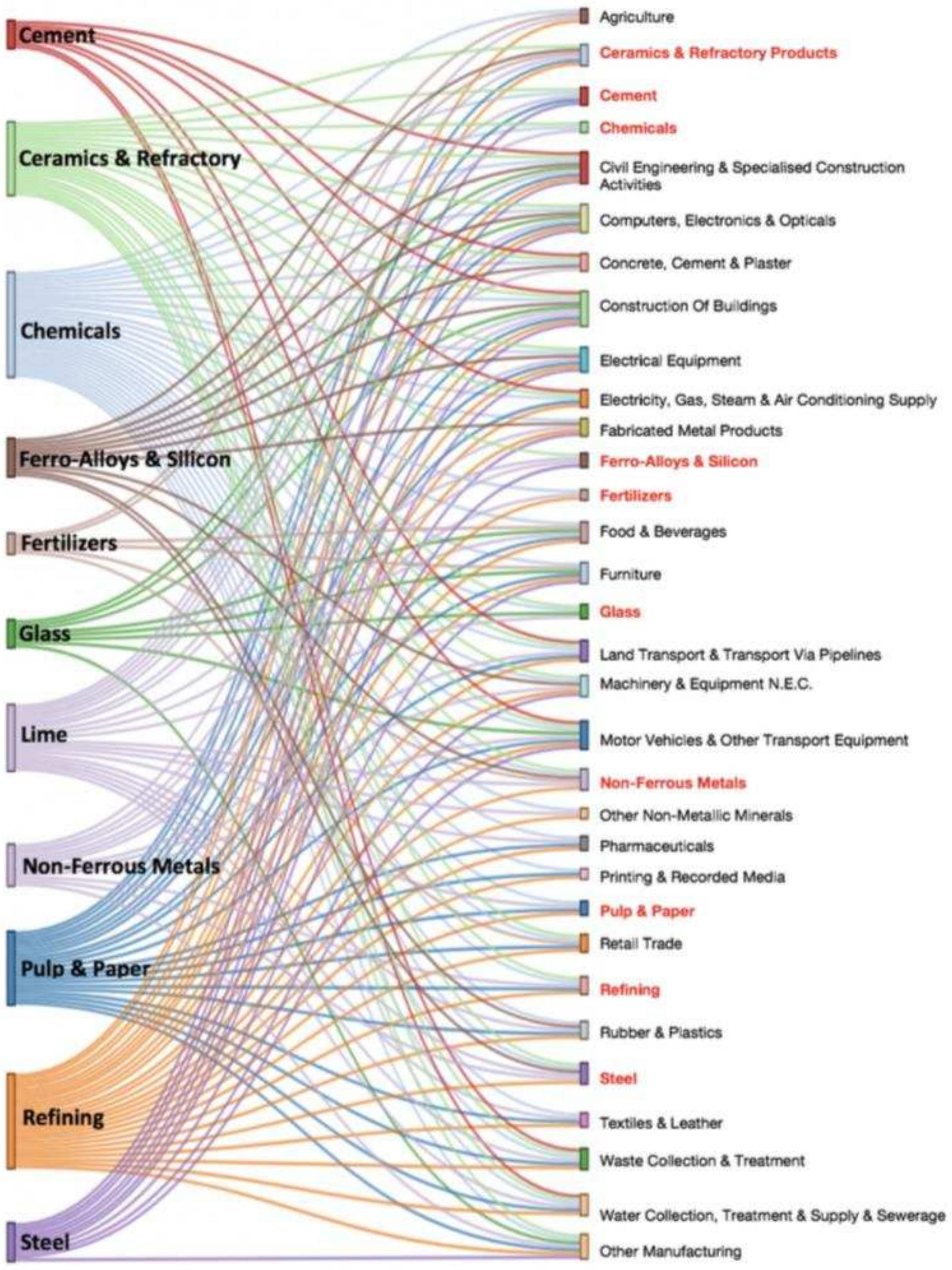
Industry is expected to continue the trend of emissions reduction and energy savings exhibited in the past few decades. However, to further and deeply reduce its emissions, especially in line with Europe's ambition for 2050, major changes need to be made in the way industry consumes energy and produces its products. There is a plethora of deep decarbonisation[352] options for industry, but no single silver bullet for all subsectors. The industrial sector is composed by many

[351] COM (2018) 283 Final

[352] The term decarbonisation is defined as reducing the amount of gaseous carbon compounds released in air as a result of economic activity and not the complete disappearance of carbon in the industrial production process, which for example is vital for the chemical industry. This is why the chemical industry prefers to use the more precise term fossilisation.

diverse subsectors, each with its own particularities arising from a variety of reasons: different energy and material needs resulting in different types, mixture, volumes and concentration of industrial effluents containing greenhouse gases.

**Figure 63: Value chain links of energy intensive industries to other sectors in the economy and other energy intensive industries**




*Source: VUB-IES*[353].

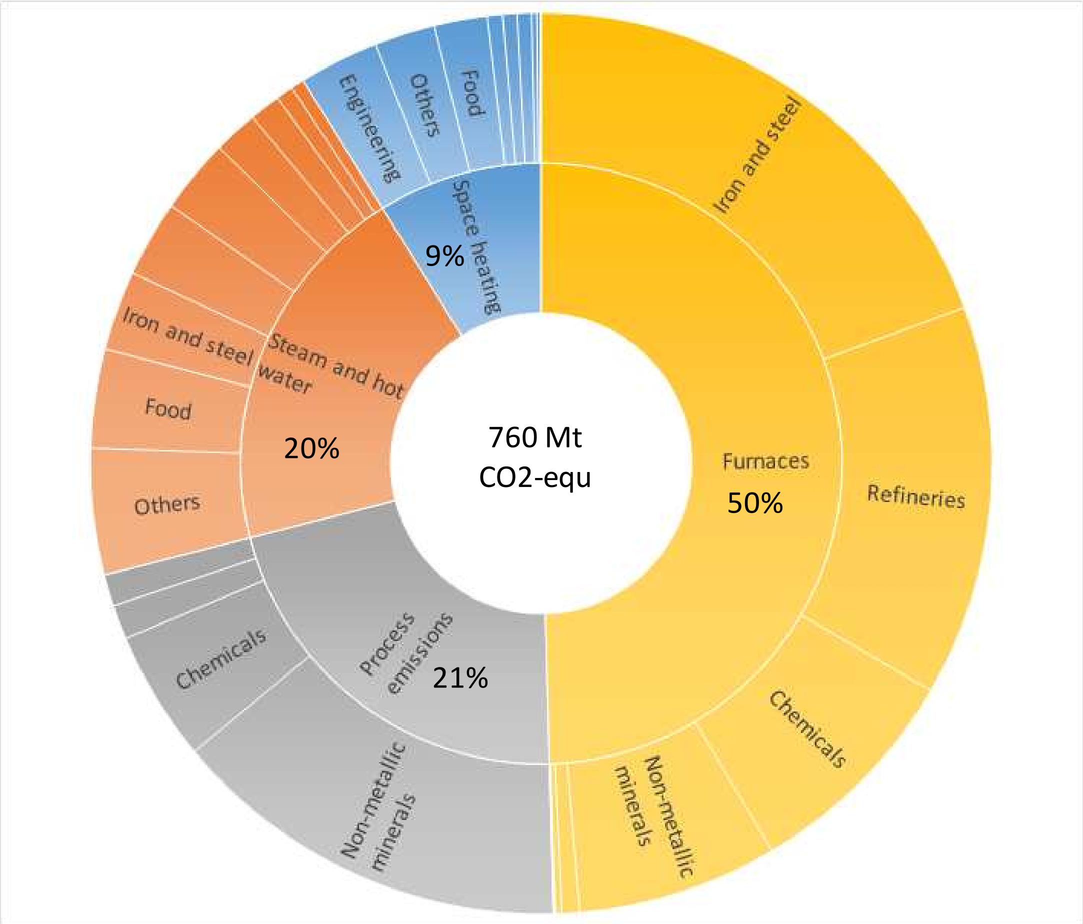
The flow of materials to and from the energy intensive industries forms an integrated network with each other and every other sector of the economy. The products from energy intensive industries are indispensable to low carbon solutions like energy-efficient buildings, decarbonised

[353] VUB-IES (2018), Industrial Value Chain. A bridge towards a carbon neutral Europe, https://www.ies.be/files/Industrial_Value_Chain_25sept_0.pdf

transport system, renewable energy and battery storage. Figure 63 depicts this interconnectedness of the value chains between energy intensive industries (EII) and other sectors.

Figure 64 shows a bottom up estimate of GHG emission in industry in 2015.[354] The pie chart excludes refineries and indirect emissions (e.g., from generating the electricity used in industry). A significant part of industrial emissions (21%) consists of process related emissions (i.e. emissions from chemical reactions other than combustion), while two thirds of industrial GHG emissions are from high-temperature process heat, either in the form of steam or hot water (20%), or from the direct firing of various types of furnaces (50%). The remaining share (9%) is due to space heating.

**Figure 64: EU 28 Industrial direct emissions by end use and sub-sector**




*Source: FORECAST.*

The complexity and multitude of solutions to reduce industrial emissions is well illustrated in the 85 pathways and technologies identified in the main sectors under the ETS, during the 2017 expert consultation for the Innovation Fund.[355] A detailed description of decarbonisation options of the EU industry can also be found in one of the reports supporting the Commission analysis,[356]

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[354] SET-Nav project (2018), Low-carbon transition of EU industry by 2050, http://www.set-nav.eu/sites/default/files/common_files/deliverables/wp5/Issue%20Paper%20on%20low-carbon%20transition%20of%20EU%20industry%20by%202050.pdf

[355] Climate Strategy & Partners (2017), Summary report: Finance for Innovation: towards the ETS Innovation Fund, https://ec.europa.eu/clima/sites/clima/files/events/docs/0115/20170612_report_en.pdf

[356] ICF & Fraunhofer ISI (2018), Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis, forthcoming

as well as in a report[353] commissioned by the Energy Intensive Industries for contributing to the European Commission's strategy for long-term GHG emissions reduction.

The latter report was commissioned following the request to Europe's EII by DG GROW in the 3rd meeting of the Commission High Level Expert Group on EII to develop a consolidated 2050 sector strategy, which would contribute to the EU's low emission strategy for 2050. It complements the individual 2050 roadmaps produced by most industries, by helping understand how their plans fit together and what are the prerequisites for the deep decarbonisation of these sectors in terms of access to clean energy (particularly electricity), raw materials, infrastructure, investments, as well as policy framework conditions.

In the following, the identified solutions are grouped in a number of broader categories.

*Energy efficiency, electrification and fuel switching*

A large part of the GHG reductions achieved up to date are a result of energy efficiency improvements.[357] Further energy use and process optimisations, for instance through the reduction of heat losses, recovery of process released heat and re-use of energy containing gaseous effluents are achievable, including by linking it to district heating systems, but seem insufficient to achieve the long term GHG reduction goals on their own. Moreover achieving these energy savings would require in many cases the replacement of major parts of existing production processes, which may not be preferable compared to changing to a radically new production process, such as the ones presented below.

Electrification of industrial heat (that relies on decarbonised electricity) is a promising emissions abatement option. There is significant potential to electrify low temperature industrial heat with heat pumps (up to approximately 100° C) or with electric boilers (below 300° C). Low temperature heat and steam production is common in several industrial sectors such as pulp and paper and the chemical sector. IEA estimates[358] that heat pumps can realistically provide 6% of the world industrial heat demand in 2040 in a cost effective way. For some applications, electromagnetic processing technologies such as electric arc furnaces, infrared heating and induction heating, present distinct advantages (e.g. controllability, precision, versatility, and efficiency). However, the potential for such applications is limited. EPRI[359] estimated that, in Europe, the economic potential of electromagnetic processing technologies other than heat pumps is approximately 15 Mtoe[360]. Further electrification is technically possible, e.g. for the production of higher temperatures, but tends to increase considerably energy consumption and cost. Further research is required to reduce costs and increase the scalability of such solutions.

Currently, energy efficiency and electrification of industrial heat and steam production seem as the most technologically mature options for further reducing energy-related industrial emissions.

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[357] This is currently supported by a series of EU regulations that set minimum energy performance requirements for energy-related products, under the framework of the Ecodesign directive. Regulations concerning electric motors, industrial fans and water pumps were adopted in 2009, 2011 and 2012 respectively. A regulation on air compressors is under preparation. Other regulations that target lighting, ventilation, heating or cooling may also positively impact energy efficiency in industry, but to a smaller extent.

[358] IEA (2018), World Energy Outlook 2018 (upcoming), https://www.iea.org/newsroom/news/2018/june/weo-2018.html

[359] EPRI (2018), Electromagnetic Processing of Materials (EPM) – Europe Industrial Electrification Potential Assessment, http://www.leonardo-energy.org/resources/1407/electromagnetic-processing-of-materials-epm-europe-industria-5ad7aba86b87f.

[360] The analysis includes Norway Switzerland and Iceland and other European countries outside the European Union. Final Energy Consumption in the EU in 2015 was approximately 275 Mtoe.

Other fuel switching options do exist, but at various levels of technological readiness; these would mainly be switching from fossil fuels to mostly biomass, but also to hydrogen and e-fuels.

Electrification of processes also has a high potential, but not horizontally across all sectors. Today it is deployed in the non-ferrous metals and chemicals industries, while some further potential exists in the chemical sector (electrochemical processes) and in the iron & steel sector (electrolysis steel, electric arc). In the cases processes can be electrified the reduction potential is very high, assuming carbon free electricity. Further research is required to increase the technology readiness of these solutions.

*Innovative low carbon processes*

Process related emissions are the inherent result of the chemical transformation of materials, the most notables one being cement production and the oxidisation of coke to produce pig iron. Alternative process technologies that use different chemical reactions for the production of the basic (or substitute) material could avoid the emission of such process related $CO_2$ emissions. Such break-through innovations[361] therefore constitute a completely new production system that would replace production processes that have been used and optimised since many decades.

An alternative way to reduce process emissions is by substituting currently used materials, based on fossil fuels, by ones with less carbon content (mainly hydrogen) or with biomass. The chemical and the refining sectors are a prime example where either biomass feedstock or hydrogen-based[362] chemical production can significantly reduce process emissions. Biomethanol and bioethanol represent the most efficient ways to use bio-feedstock in these industries[363], while biomass is a key raw material for the paper and pulp industry. Considerations though must be given to the finite supply potential of sustainable biomass and its importance as a low carbon solution also for other hard to decarbonise sectors, like transport. Similarly, hydrogen can be used to produce low carbon methanol, ammonia and other chemicals, but often requires a $CO_2$ molecule in its reaction process. Depending on the source of this $CO_2$, the production process would become less carbon intensive or even carbon neutral. The hydrogen solution though also suffers from limitations, as research is needed to decrease its production costs and further develop the associated processes, while at the same time necessary enabling infrastructure needs to be constructed. Biomass and hydrogen have also an application in the iron & steel industry.

*Carbon capture and sequestration and or use (CCS and CCU)*

The options of CCS and CCU are already described above in section 4.2.1.2, but in industry it can be also used to capture process-related emissions. CCS is regarded as a cost-effective option for the future to reduce emissions from industrial processes. The suitability of CCS technology differs across industrial processes, due to the different physical properties.

CCU could allow $CO_2$ utilisation into one or several product cycles, avoiding the use and emissions related to an equal carbon amount of fossil based resources provided that the energy

[361] As an example, in the iron & steel sector the hydrogen based direct reduction process (projects Hybrit, Salcos and H2Steel) aims using hydrogen to completely bypass the use of coal for the production of primary steel. For the cement sector, new binders – replacing clinker – can substantially reduce emissions, while at the same time allow for lower demand of heat.

[362] Hydrogen as a reactant with $CO_2$ being re-used to produce chemicals.

[363] Dechema (2017), Low carbon energy and feedstock for the European Chemical Industry, https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf

used in capturing and converting the $CO_2$ is zero carbon. Its potential applications can be quite wide, ranging from materials (chemicals and minerals) to e-fuels (in this context also called CCU fuels), but technological feasibility, public acceptance and cost-effectiveness have to be further assessed (see section 4.2.1.4). The CO2 mitigation potential of CCU needs to be assessed along the complete lifecycle of the products.

CCU based materials, in contrast to CCU fuels, have the advantage that they can be recycled at the end of life so the carbon can be again captured and re-used. Materials under advanced development are various types of plastics and building material substitutes. Their lifespan depends on the end use of the CCU product. Examples would be the application in the automotive sector (e.g. polyurethane car seat cushions) or in the construction sector (e.g. concrete building blocks). Other CCU materials are still at basic research stage, such as carbon fibres, but have the potential to displace carbon-intensive materials such as steel, aluminium and cement and reduce emissions from their production.[364] In addition, the overall lifespan of these materials can be elongated via material recycling (see discussions on circular economy).[365]

*Resource efficiency/Circular Economy*

Resource efficiency in industry means reduced raw material needs, minimisation of waste and by-products, increased recycling and material substitution. As such, it is a key part of the Circular Economy concept. Industrial and manufacturing processes can be redesigned so that material loss in the production and between the different lifecycles phases of each product or material are minimised. Improved waste management allows materials to go back into the economic cycle, thus, reducing the input of primary raw materials and the need to treat waste. The quantities of virgin material used as feedstock can reduce, part of it replaced by increased recycled and re-used material[366], which requires (with high quality waste streams) much less energy and carbon intensive processes for its processing. A part of virgin materials will come from the cascading use[367] of material and reduced material loss during the processing phase.

According to the International Resources Panel,[368] by 2050, resource efficiency policies could reduce global extractions by 28%. Combined with an ambitious climate action, such policies can reduce greenhouse gases emissions around 63%, and increase economic growth by 1.5%. A recent study from Material Economics,[369] focused on energy-intensive sectors like steel, plastics, aluminium or cement, estimates that the circular economy model could reduce European emissions by 56% (300 $MtCO_2$) annually until 2050. Globally, emissions savings could reach 3.6 billion of tonnes of $CO_2$ by year. Moreover, the production and incineration of plastics produce

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364 Innovation for Cool Earth Forum – ICEF (2017), Carbon Dioxide Utilization Roadmap 2.0, https://e-reports-ext.llnl.gov/pdf/892916.pdf

365 Ramboll (2018), Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, forthcoming, https://ec.europa.eu/clima/events/stakeholder-event-carbon-capture-and-utilisation-technologies-technological-status_en

366 The increase in the recycling rates of many materials will require removing several bottlenecks, see for example EU's Plastic Strategy, COM (2018), 28 final.

367 Ellen McArthur Foundation (2013), Towards the Circular Economy, https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf
An example provided in this report is how cascading use of material will lead to a diversified reuse across the value chain, for example cotton clothing first reused as second hand apparel, then as fibre-fill in upholstery in the furniture industry and later in cotton wool insulation for construction.

368 UNEP (2017), Resource Efficiency: Potential and Economic Implications, http://www.resourcepanel.org/reports/resource-efficiency

369 Material Economics AB (2018), The Circular Economy, http://materialeconomics.com/latest-updates/the-circular-economy

globally every year 400 $MtCO_2$. If it were possible to recycle all plastic waste, the equivalent to 3.5 billion of oil barrels per year would be saved. Recycling a million of tonnes of plastics is equivalent to the emissions of one million cars.[370]

Many of the changes required to achieve the kind of resource efficiency gains in the context of a circular economy will require changes to product design or business model of the involved industries. Industries may also be able to develop genuinely new products, with similar functionality for end users but lower emissions associated.

*Industrial symbiosis*

The partnership of industries across sectors, sharing their infrastructures and their material inputs and outputs (including waste) in the context of industrial symbiosis, is another way to optimise resource use and thereby reduce emissions. CCU can be an example of such symbiosis. Such structures are greatly enabled by the mega-trend of digitalisation, which is already increasingly penetrating industry. Taking advantage of the strong interlinkages of the different industrial sectors, intensified exchanges of material, energy and services, can enhance environmental sustainability and achieve economic benefits for all partners at the same time.[371]

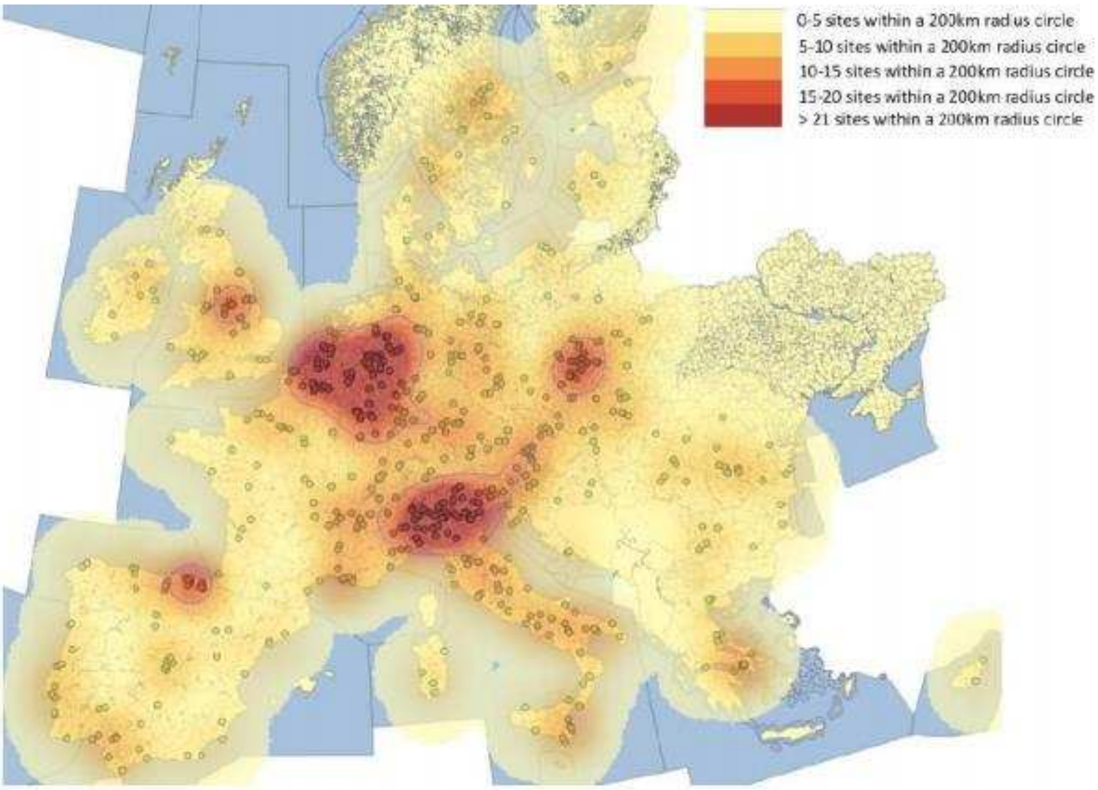
The above options may be applicable to all industrial subsectors, to only a few or even to selected industrial sites in Europe, which fulfil possible requirements of infrastructure and access to specific resources. Industrial symbiosis is more meaningful for industrial sites that are closely located to each other, in order to facilitate the exchanges of materials and resources. An effort to identify the best potential sites in Europe was performed as part of the SPIRE EPOS project.[372] All European industrial sites in the EPOS Sectors of cement, steel, refining and chemicals were mapped to systematically assess the geographic dimension of industrial symbiosis, identifying five hotspots (Figure 65).

[370] COM(2018) 28 final

[371] Trinomics (2018), Cooperation fostering industrial symbiosis: market potential, good practice and policy actions, https://publications.europa.eu/en/publication-detail/-/publication/174996c9-3947-11e8-b5fe-01aa75ed71a1/language-en

[372] https://www.spire2030.eu/epos

**Figure 65: Hotspots in term of density of industrial sites in Europe**




*Source: EPOS SPIRE Project.*

*Material substitution*

Finally, it must be kept in mind that the type of materials used in the economy will also affect the capacity of the industry as a whole to decarbonise. It is likely that the consumption patterns will move progressively towards materials that deliver equivalent services while being less energy and carbon-intensive (or even sequestrating carbon, like biomass), be it in their processing and in their use (for instance lighter products, requiring less energy to be transported). Beyond innovative technical solutions in specific industrial sectors, material substitution[373] is thus likely to contribute also to the low-carbon society.

Such options are particularly relevant for the cement sector. New binders are developed to reach reduced $CO_2$ emissions, replacing limestone. There are even binders aiming to cure with $CO_2$ instead of water, thus absorbing $CO_2$.[356] Such solutions of low carbon cements, ranging from -30% to -90% of carbon intensity, are targeting specific market segments and occasionally have niche applications, but combined they can replace a significant portion of the reference cement (Portland Cement).

### *4.5.2 The Industrial Transition*

This section collects visions, present analyses and explains the challenges on how industry can reduce its emissions. These are compared with the results of modelling performed for the Commission, using two different models, PRIMES and FORECAST.[374] As discussed in previous

[373] Climate Analytics (2016), Manufacturing a low-carbon society: how can we reduce emissions from cement and steel? https://newclimate.org/wp-content/uploads/2017/10/memo_decarb_industry_final1.pdf

[374] A detailed description of the models and the methodology followed can be found in section 7.2.

sections, PRIMES follows an energy system approach, capturing the interactions of industry with the parallel developments in the other sectors, notably the energy sector. FORECAST follows a sector specific bottom-up approach, examining in more detail the industry sector, but isolated from the other sectors. For this reason, a complementary approach was followed concerning the options examined, with PRIMES analysing more horizontal options while FORECAST focusing on more extreme technology pathways.

There is an increasing amount of evidence indicating that continuation of current efforts and policies in industry can achieve additional GHG emissions reduction by 2050, ranging between 55 to 65% compared to 1990.[375] Nevertheless, such reductions, stemming mainly from current trends (such as energy efficiency measures or structural change), foreseeable technological developments, mega-trends such as digitalisation and automation, as well as existing measures and policies, cannot deliver the desired levels of ambition.[376] [377]

As it will not be possible to reduce industrial emissions by 80% to 95% with current commercial technologies alone, innovative decarbonisation technologies should be developed and tested at a large scale to demonstrate their reliability and affordability. Intense global competition and the need for significant investments add to the challenge of decarbonising the industrial sector. Although currently there does not exist a widely accepted pathway for achieving deep reductions in industrial sector emissions, similar to the other sectors of the economy (power, transport, buildings), solutions do seem to exist. This is because European companies have been increasingly active in researching ways to decarbonise their activities[378] and finding break-through low-$CO_2$ innovations[379]. Given the long lead-time to develop new technologies and the investment cycles of industry (20-30 years), it is likely that the deep emissions reduction technologies that will be deployed by 2050 are already known today. Several recent projects and examples are demonstrating how deep decarbonisation of processing industries can happen.[380]

Achieving the reductions required for a -80% level of ambition is translated to GHG emissions reduction between 75 to 85% compared to 1990 for industry. This is found by many studies as being feasible, even by using to a large extent existing technologies, but which need to be further developed in order to be scaled and penetrate the market. Energy efficiency, increased use of sustainable biomass and electrification (with electricity increasingly produced by carbon-free sources), are technologically ready options to achieve this target.[216] [381] [382]

[375] BCG & Prognos, (2018), Climate paths for Germany, https://www.bcg.com/en-be/publications/2018/climate-paths-for-germany-english.aspx https://bdi.eu/publikation/news/klimapfade-fuer-deutschland/ (full study in German)

[376] ICF (2015), Study on Energy Efficiency and Energy Savings Potential in Industry and on Possible Mechanisms, https://ec.europa.eu/energy/sites/ener/files/documents/151201%20DG%20ENER%20Industrial%20EE%20study%20-%20final%20report_clean_stc.pdf

[377] McKinsey & Company(2018), Decarbonization of industrial sectors: the next frontier, https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability%20and%20resource%20productivity/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.a.

[378] A number of industries have already voluntarily committed to further reducing their emissions, while identifying sustainable and economically viable low carbon business cases. For example, see e.g. the European Round Table of Industrialists (ERT), https://www.ert.eu/

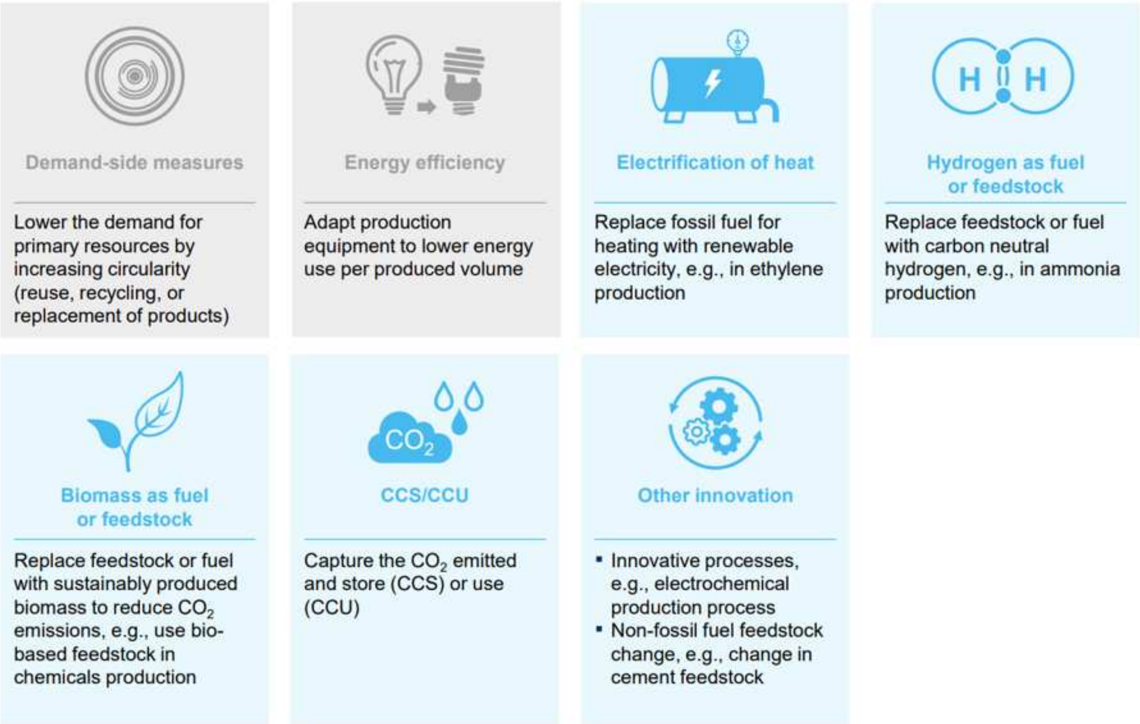
[379] VUB-IES (2018), Breaking Through. Industrial Low-$CO_2$ Technologies in the Horizon, https://www.ies.be/node/4695

[380] A more detailed presentation of these projects can be found in section 7.6.

[381] Deep Decarbonisation Pathways Project (2015), Pathways to Deep Decarbonisation, http://deepdecarbonization.org

Other pathways often considered but not yet widely deployed, relate to hydrogen (both as a feedstock and an energy carrier), clean gas, CCS and CCU and circular economy measures (Figure 66).[376] [383] Such pathways are considered feasible – and even preferable for specific industrial applications. The use of hydrogen in steel making is an example of such pathways. On the other hand, alternative technology pathways require higher investments in infrastructure (not necessarily just in industry), possible changes in existing industrial value chains and technological breakthroughs.

**Figure 66: Menu of options to decarbonise industry**




*Source: McKinsey & Company.*

Further increasing the level of ambition to be consistent with net zero GHG emissions, GHG emissions reductions in industry need to approach 90-95%, making necessary the availability of all pathways and technologies mentioned above.[384] [385] But this will likely be not sufficient, in particular to tackle the GHG emissions from the harder to decarbonise subsectors (e.g. sectors with a high share of process emissions). Most importantly, it is widely accepted that for the higher levels of ambition. CCS and CCU will be necessary to compensate the emissions for the harder to abate sectors, especially in cement and chemicals.[386] [387]

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[382] Öko-Institut (2018), The Vision Scenario for the European Union, 2017 Update for the EU, Project sponsored by Greens/EFA Group in the European Parliament, https://www.greens-efa.eu/en/article/document/the-vision-scenario-for-the-european-union-7659/

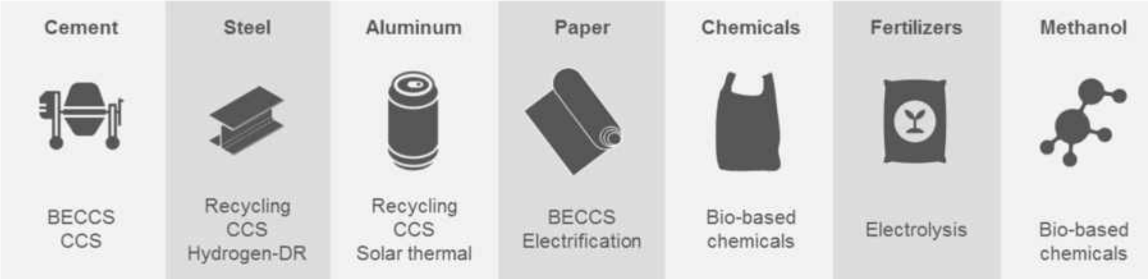
[383] Shell (2018), Sky scenario, Meeting the goals of the Paris Agreement - an overview, https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html

[384] ECOFYS (2018), Energy Transition within 1.5°C, https://www.ecofys.com/files/files/ecofys-a-navigant-company-2018-energy-transition-within-1.5c.pdf

[385] Climact (2018), Net Zero By 2050: From Whether to How, https://europeanclimate.org/wp-content/uploads/2018/09/NZ2050-from-whether-to-how.pdf

[386] CCS can also play an important role during the transition, as it would reduce the emissions of fossil fuels. Although the ambition may be to switch from fossil fuels to low carbon energy carriers, changing the energy source of industrial processes cannot take place overnight. It will require first (or at best in parallel) a decarbonisation of these energy carriers and then the investment and deployment of such

**Figure 67: Low carbon technologies used for each material in industry**




*Source: ECOFYS.*

Sector or even process specific solutions need to be applied to the more carbon intensive sectors and processes (Figure 67). Moreover the emissions reduction of the industry sector rely on the successful decarbonisation of the power and gas sectors.[376] Fuel-switching to electricity, both for industrial heat and processes, is meaningful only when electricity is produced from low carbon sources, implying the need of large investments in wind and solar power plants. Gas consumption may be reducing, but it is expected to retain an important share in the fuel mix of industry given the limited potential for electrification of high temperature processes. Therefore lowering the carbon intensity of gas used in industrial processes is critical. This can be achieved by changing the composition of gas in distribution grid and shifting from mostly natural gas to a blend of natural gas, hydrogen, biogas and e-gas.[231] Such changes would require further technology developments, as well as significant investments in energy infrastructure.

The above observations from a wide range of studies and reports are consistent with the conclusions from own modelling runs, using PRIMES and FORECAST, despite the differences in the methodologies used. It is important to underline at this point that the scenarios ran for the two models are not directly comparable, as two different approaches were followed in order to get complementing results. PRIMES scenarios achieving 80% GHG reduction are more balanced, sharing many common assumptions and developments, but promoting more a specific pathway in each case for the additional effort needed compared to the Baseline to meet the respective ambition. FORECAST scenarios are more "extreme", fully exploiting one technology pathway at a time, in order achieve about 80% reductions in industry in 2050, with the exception of one scenario combining in a cost-efficient way all solutions to achieve the same target. The COMBO scenario of PRIMES also combines the pathways, achieving though higher reductions than 80%. Both the 1.5°C scenarios of PRIMES and the one of FORECAST achieve 95% GHG emissions reduction or above. Detailed descriptions of all scenarios can be found in Annex7.2.2.

Total final energy consumption of industry[388] in PRIMES is projected to decrease between 2015 and 2050 across all scenarios, despite the projected increase in industrial output overall (Figure 68). The highest reductions (between 22-31%) are observed in the scenarios with increased energy efficiency and / or circular economy. The latter happens because the circular economy scenarios assume reduced output in certain subsectors and increased secondary production of materials (which is less energy intensive than primary). The lowest reductions in final energy

infrastructure. Given the inertia associated with these transformations and the large scale of investments required in industry, such changes cannot be expected to be observed much earlier than 2040-45.

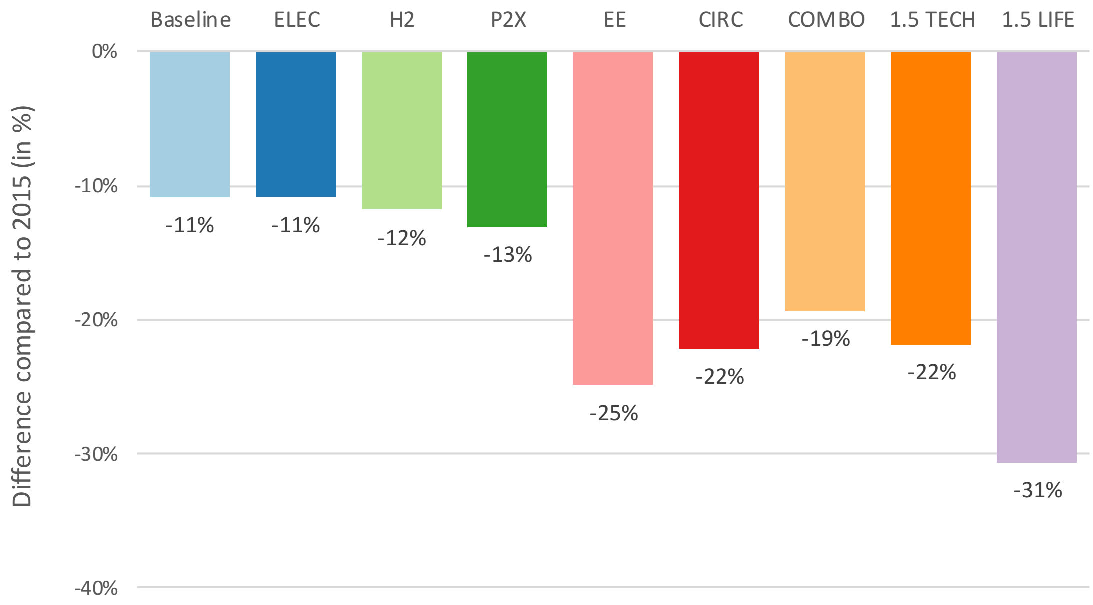
[387] Energy Transitions Commission (2017), Better Energy, Greater Prosperity, http://www.energy-transitions.org/better-energy-greater-prosperity

[388] In the context of PRIMES, the industry sector includes all subsectors except refineries, in line with Eurostat energy balances definitions. Information specifically about refineries can be found in section 7.6.6.

consumption are observed in the high electrification scenario (at 11%). This is because the focus of this scenario is the electrification of industrial heat and certain processes, which is less efficient than thermal processes in high-temperature applications; at the same time electrification reduces the potential of energy savings through heat recovery. Electricity is more efficient than thermal processes in low enthalpy heat uses, but the amount of energy demand in these uses is a fraction of total energy demand of high-temperature uses (see Figure 64).

Energy consumption is actually the same in the ELEC scenario as in the Baseline. The largest part of energy efficiency improvements for the scenarios without circular measures take place between 2020 and 2030 (around 10% compared to 2015 for all scenarios). This is mainly due to increased waste heat recovery applications, which are cost-efficient and lead to a quick improvement in energy consumption. However, the rate of energy efficiency improvements decreases after 2030, as available options shrink, with a jump in 2050 as more expensive decarbonisation options become economic.

**Figure 68: Total final energy consumption in industry by scenario compared to 2015**

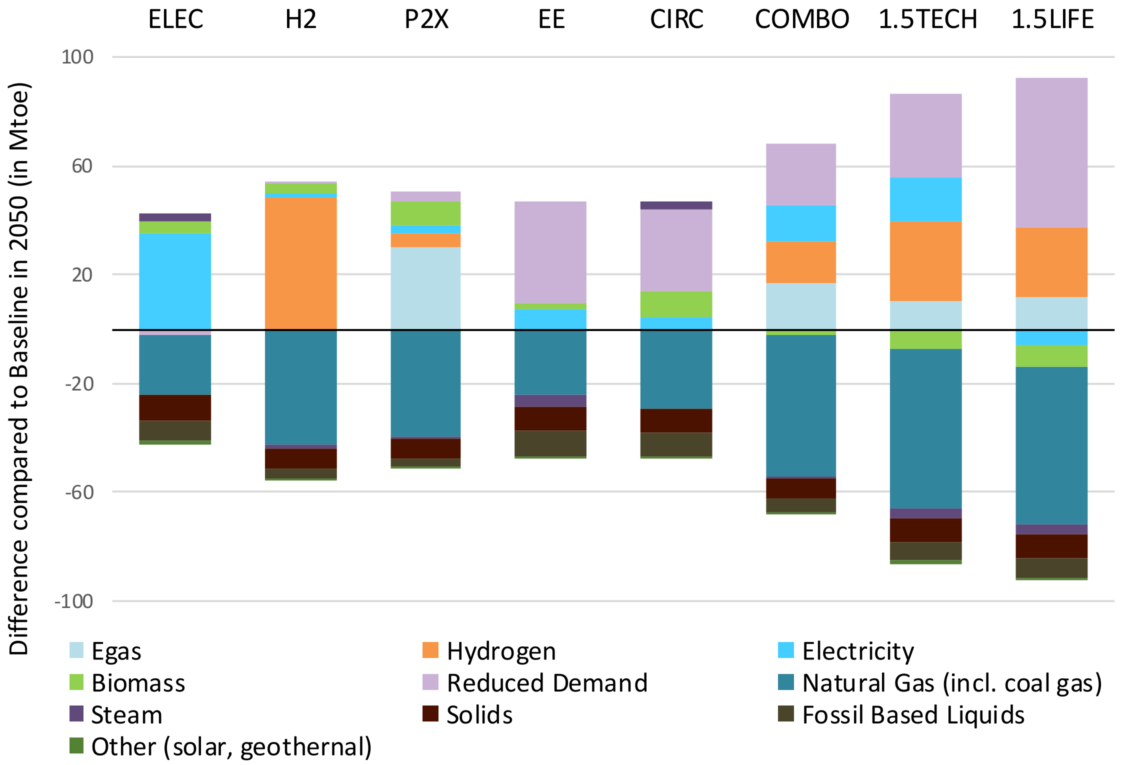



*Source: PRIMES.*

There are significant changes across scenarios in the fuel mix used in industry both for heating and for chemical processes other than combustion. In the PRIMES Baseline, natural gas is the only fossil fuel remaining in the industry final energy fuel mix with a significant share of around 24.5% (61 Mtoe). Solids and other fossil fuels account for an additional 9% (23 Mtoe). About half of the final energy demand comes from electricity and heat. Total final energy demand is 253.5 Mtoe.

In the scenarios achieving 80% GHG reduction, the share of fossil fuels is approximately halved. As can be seen in Figure 69, depending on the scenario, the reduced amount of fossil fuels is replaced by electricity (in ELEC), hydrogen (in H2), clean gas and biomass (in P2X) or reduction of demand and some electricity or biomass (in EE and CIRC). Biomass and steam broadly retain their increased levels in the Baseline, between 45-50 Mtoe in the scenarios achieving 80% GHG reductions and 35 Mtoe for the net zero GHG emissions ones, compared to 26 Mtoe in 2015, with some differences appearing depending on the pathway followed (less steam in EE and more biomass in P2X and CIRC)[389].

**Figure 69: Differences in final energy consumption in industry compared to Baseline in 2050**




*Source: PRIMES.*

Similar to what is found in other studies, for levels of emissions reduction consistent with net zero GHG emissions, PRIMES projects a significant stepping up of the effort. Addressing this challenge does not seem to require radical solutions, completely changing current way of manufacturing and doing business (though changes will be required to a certain degree). However, higher levels of ambitions will require deployment of all the options described above, including the ones that need to be further developed, and at different scales. In the net zero GHG emissions scenarios, electrification is not the critical energy carrier for further reducing emissions in industry below 80%. Similar to studies referenced above, PRIMES identifies clean gas-based solutions (using hydrogen and e-gas) as preferable for meeting the higher ambition. These solutions are combined with significant investments in CCS to capture process emissions, energy efficiency and circular economy.

Concerning emissions captured and stored from industrial processes, around 60 $MtCO_2$ are captured in most of the scenarios achieving 80% GHG reductions (excluding CIRC) and

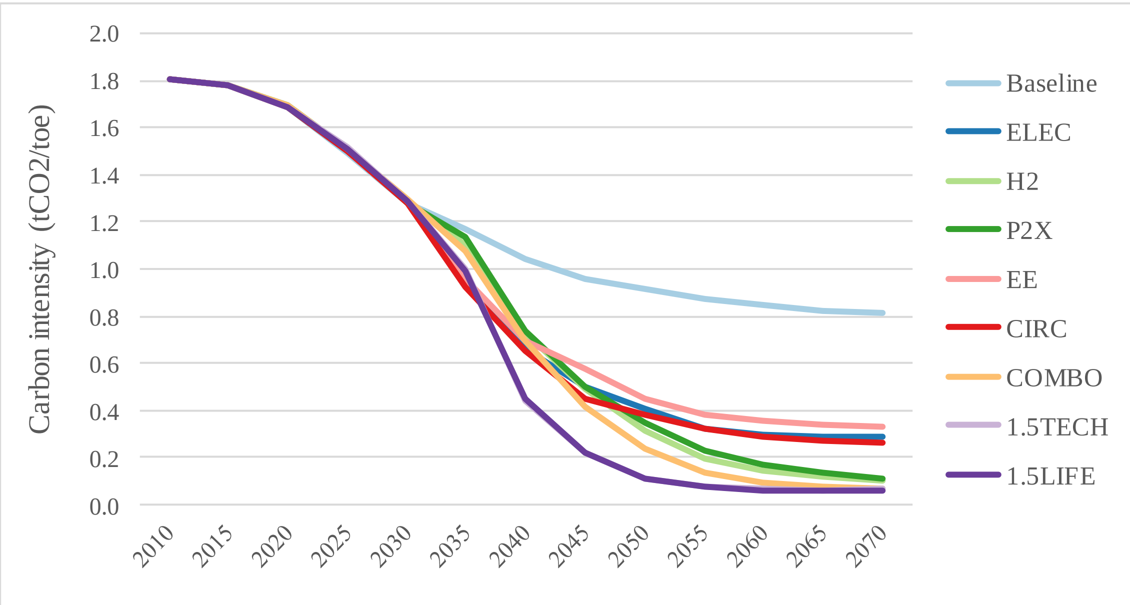
[389] In addition to the standard scenarios, a low biomass variant of the 1.5LIFE scenario has been introduced (1.5LIFE-LB) to better analyse the role of biomass in the EU economy and its impact on land resources and natural carbon sinks. Its results are discussed in Section 4.7.2. In the case of industry, biomass consumption in 2050 drops to 11 Mtoe, replaced mainly by hydrogen, but also electricity. This shows that despite the results of the standard scenarios projecting high levels of biomass consumption, there are economic alternatives to biomass; the choice of fuel will depend on the availability and relative prices of these energy carriers.

COMBO (see Table 8). In these scenarios, CCS installations appear in 2045 capturing 30 $MtCO_2$, while post-2050 the amount of $CO_2$ captured increase to 135 Mt. In CIRC, due to reduced industrial output of carbon intensive industries, only 44 $MtCO_2$ are captured in 2050, following similar increasing trends with the other scenarios. For the 1.5°C scenarios, the higher carbon prices allow the appearance of CCS from 2040, with 54 / 58 $MtCO_2$ captured (for 1.5LIFE / 1.5TECH respectively), increasing to 71 /80 $MtCO_2$ in 2050 and further to 112 / 128 $MtCO_2$ post-2050. In these two scenarios, storage of $CO_2$ in materials (plastics) also makes a presence, with 47 / 80 $MtCO_2$ stored in materials in 2050.

The projections find the industry reducing total GHG emissions (including process emissions) from 72% in ELEC up to 77% in the CIRC scenarios between 2015 to 2050, compared to only 44% in the Baseline. The rate of reductions though differs over the period 2030-2050 across scenarios, depending when the driver for emissions reduction is either introduced in large scale or exhausts most of its potential. Therefore ELEC, EE and CIRC reduce quickly emissions up to 2040, but then this trend slows down considerably for ELEC and EE (CIRC retains it). On the other hand H2 and P2X increase the pace of emissions reduction post 2040. COMBO achieves 79% reductions, while the 1.5°C scenarios around 95-98% GHG emissions reduction, all following a rather stable reducing trend over the 2030-2050 period.

While energy intensity is similar in the Baseline and in scenarios achieving 80% GHG reduction, carbon intensity is significantly lower in all decarbonisation scenarios. Figure 70 presents carbon intensity in industry for the different scenarios.

**Figure 70: Carbon intensity in industry**




*Source: PRIMES.*

Complementary to PRIMES, FORECAST was used to assess in a more detailed level more extreme pathways.[390] Four pathways were examined which focus in the deployment of single technology options: CCS, clean gas (CleanGas), bio-economy and circular economy (BioCycle) and electrification (Electric). These four pathways were then combined into two balanced pathways, one aiming to meet the 2°C ambition (Mix80) and one the 1.5°C ambition (Mix95).

[390] ICF & Fraunhofer ISI (2018), Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation, forthcoming

All scenarios have as a starting point today's best available energy efficiency techniques, as well as a certain level of recycling, material efficiency and substitution. Their key results, presented below, are coherent with PRIMES, providing also some additional insights on the extent these pathways can be used to meet the different levels of ambition[391].

In 2050, GHG emissions in industry[392] for the CCS scenario are 79% below 2015 (87% compared to 1990), with 294 $MtCO_2$ captured per year, mainly from the cement and lime production, the chemical and the iron and steel industry, reducing significantly process related emissions. Driven by energy efficiency, demand falls by 16% in 2050 compared to 2015.

The Clean gas scenario results indicate a 72% decrease of GHG emissions by 2050 compared to 2015 (82% compared to 1990), with the remaining emissions largely coming from processes that need to be dealt via other means.

In the BioCycle scenario biomass consumption both for energy uses and as a feedstock quadruples between 2015 - 2050, which would make it the dominant energy carrier. At the same time, circular economy practices reduce demand for carbon intensive products and shift part of the primary production to secondary, due to increased availability of recycled materials. The combination of circular and energy efficiency measures lead to a decrease of final energy demand by 27% in 2050 compared to 2015. The above lead to 68% GHG reductions in 2050 compared to 2015 (80% compared to 1990), with additional mitigation potential remaining in reducing the remaining fossil fuel consumption in industry.

In the Electric scenario, electricity consumption increases from 1,040 TWh in 2015 to 1,718 TWh in 2050, with industry using to a significant extent high temperature heat pumps where applicable, as well as electric steam boilers. The demand for hydrogen (feedstock and energy use) produced via electrolysis adds another 693 TWh, resulting in a total demand of 2412 TWh in 2050. Results show a shift towards electricity accelerating post-2030, when many of the technologies become available at industrial scale, with emissions dropping by 66% in 2050 compared to 2015 (79% compared to 1990). The remaining emissions are mainly process related, as well as from some natural gas still consumed in 2050.

The combination of the above solutions in Mix80 result to 71% GHG emissions reduction in 2050 compared to 2015 (82% compared to 1990), driven mainly by electrification which becomes the major energy carrier with demand doubling between 2015 and 2050 (to 2,162 TWh), including 632 TWh for hydrogen production. The combination of increased recycling, energy and material efficiency improvements reduce final energy demand by 25%, while H2 takes an important role as a feedstock. Similar to the electrification scenario, remaining emissions are related to the gas used and the process related emissions.

Finally, Mix95, building on Mix80, achieves GHG emissions reduction of 92% compared to 2015 (or equivalently 95% compared to 1990). Electricity consumption reaches 2946 TWh, of which 1539 TWh are directly used and 1407 TWh are needed for the production of hydrogen and synthetic methane via electrolysis.

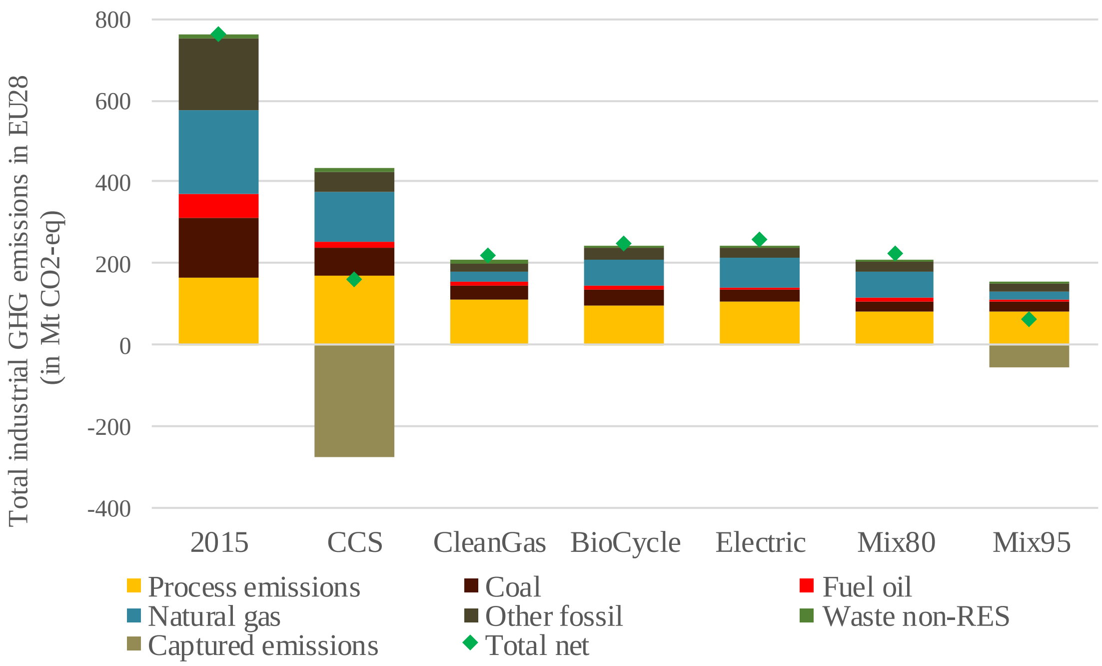
Figure 71 below gives an overview of the remaining industrial emissions in 2050 based on the scenarios of the FORECAST model. The GHG emissions, mainly coming from process related emissions and fossil fuels, are observed to decline steadily during the projection horizon in all

[391] All policy scenarios run with FORECAST can be considered 2°C scenarios except for one, which is closer to the 1.5°C ambition (scenario Mix95).

[392] Please note that contrary to PRIMES, the definition of industry in FORECAST includes refineries, Therefore care should be given when interpreting and comparing the results of the two models, especially when also considering the differences in the assumptions and scenario definitions.

scenarios, with all emission sources contributing to these reduction. However, the relative importance of process related emissions is increasing towards 2050, while other emission sources like coal, other fossils or natural gas are decreasing. In all decarbonisation scenarios, small amounts of fossil fuels are still used in 2050. Reasons are long capital lifetime, inertia in the technology stock replacement and remaining niches.

**Figure 71: Total remaining industrial GHG emissions by scenario and energy carrier in EU28**

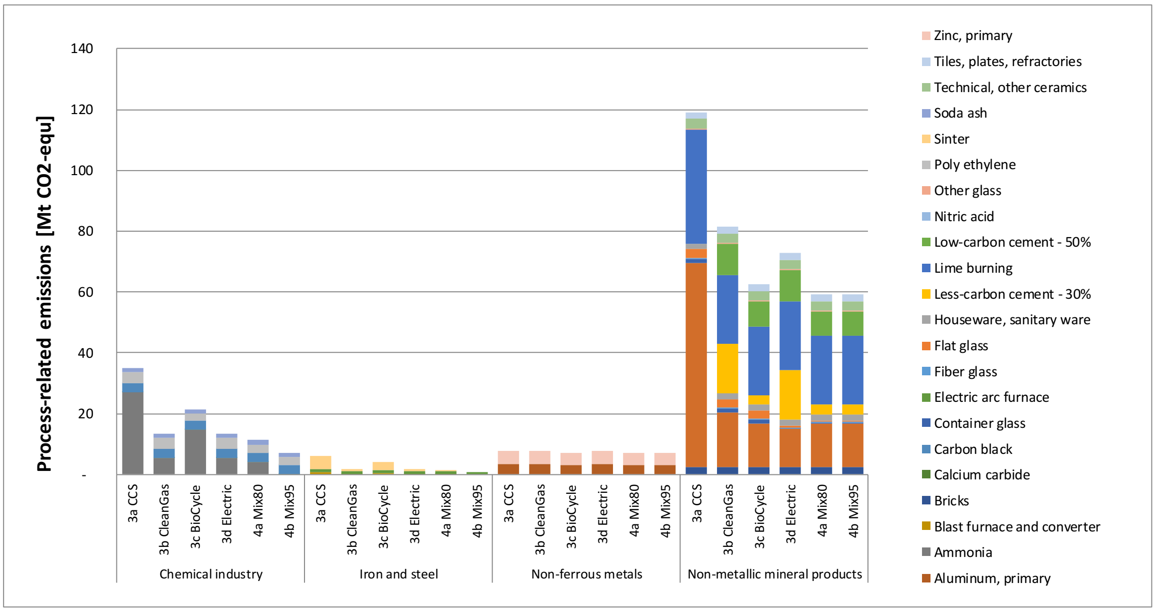



*Source: FORECAST.*

Even in the most ambitious scenario Mix95, with emissions reduction of 95% compared to 1990, the process emissions continue to resist (Figure 72). The remaining mitigation potentials to be exploited are limited. From the 62 $MtCO_2$ of remaining process emissions, about half come from smaller sources of emissions, which become important while approaching the goal of GHG neutrality. These include primary aluminium (3.1 Mt), primary zinc (4 Mt), ceramics (7 Mt), bricks (3.4 Mt) and other. CCS will most likely not be an option for all these distributed sources and thus some limited emissions are projected to remain.

The menu of options for dealing with the remaining emissions mainly includes the replacement of left over fossil fuels in all subsectors, diffusion of low-carbon production technologies towards 100% market share in steel, cement and chemicals, use of biomass in combination with CCS and enhancement the circular economy and material efficiency measures, particularly in the construction and plastics industries.

**Figure 72: Remaining (gross) process emissions by sector and process in 2050 before possible $CO_2$ capture**




*Source: FORECAST.*

A highly debated topic in the various industrial roadmaps and studies is the level of electricity demand required to the decarbonisation of industry and whether the power sector can actually provide such quantities of electricity in an economic and reliable way. The Institute of European Studies (IES) aggregated the low- $CO_2$ pathways and technology studies by industries and other sources to get an estimate of the potential future electricity demand from 2,980 to 4,430 TWh for EIIs alone, including e-fuels production in refineries (for consumption also in other sectors).[353]

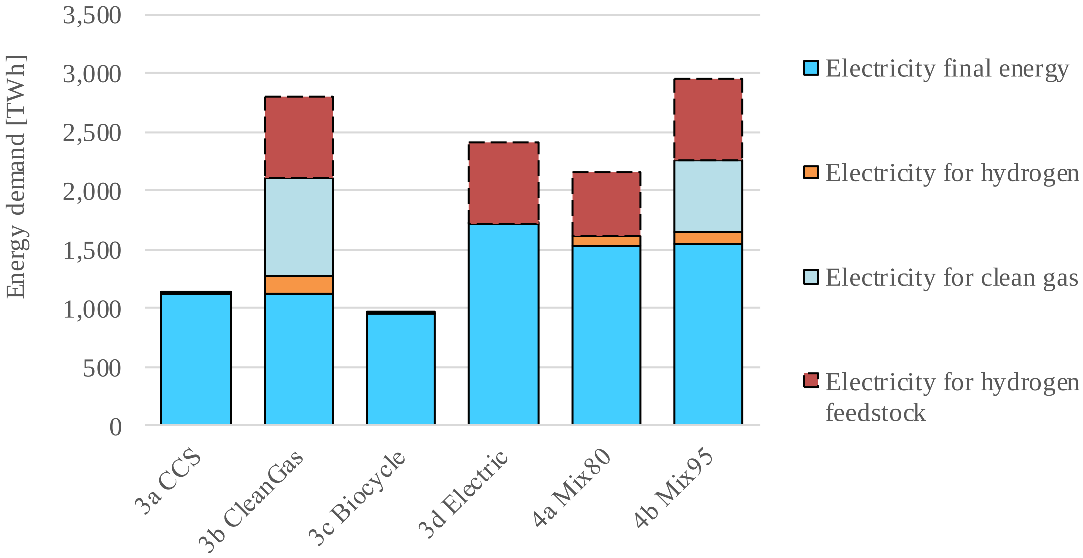
Eurelectric in a recent study estimated different levels of ambition, finding that in a 95% emissions reduction scenario, industrial demand would approach 3,000 TWh,[393] turning industry to the largest final electricity consumer in the EU.

Results from modelling done for this assessment are in line with the Eurelectric study and the estimates of IES. FORECAST, looking into more extreme scenarios for industry (including refineries), and considering also hydrogen used as feedstock for chemicals, but without producing hydrogen or e-fuels for other sectors, sees electricity demand increase to maximum levels close to 3000 TWh (see Figure 73 below).

The scenario with the highest electricity demand in industry in PRIMES is 1.5TECH. Electricity demand for industrial sectors (including refineries), as well as for the production of hydrogen and e-fuels consumed by all sectors, reach 4808 TWh, of which 1344 TWh is final electricity demand in industry, not related to hydrogen or e-fuel production.

[393] Eurelectric (2018), Decarbonisation pathways, https://cdn.eurelectric.org/media/3172/decarbonisation-pathways-electrificatino-part-study-results-h-AD171CCC.pdf.

**Figure 73: Industrial electricity demand in final energy in 2050, including production of feedstocks, clean gas and hydrogen**




*Source: FORECAST.*

Concluding, both literature review and the quantitative analysis performed using two different models indicate that technology deployment can be envisaged for the industrial sector to successfully contribute to the Paris agreement objective. It will require combining best available techniques in energy efficiency and fuel-switching with additional options like innovative low-carbon production technologies, circular economy and material efficiency, process integration[394], low carbon energy carriers and / or CCS and CCU. It also requires the full decarbonisation of the power sector, as well as the substitution of any remaining natural gas by zero carbon gases to the largest degree possible.

An approach focusing on one technological pathway, similar to the more extreme scenarios examined using the FORECAST model, would lead to economies of scale, thus reducing the costs of the respective pathway. On the other hand, such an approach has significant risks of lock-ins and exhausting the potentials of the chosen pathway, not being possible to further reduce emissions post-2050.

Combining several of the additional mitigation options, as in the PRIMES COMBO and the FORECAST Mix80 scenarios, reduces the risk of lock-ins and is still on track for deeper decarbonisation beyond 2050. The difficulty that lies in this option is how much to diversify, so the investments made over the selected pathways are still able to achieve economies of sufficient scale.

Nevertheless, the highest ambition level can only be achieved if all mitigation options are exploited, including CCS and CCU for selected process emissions, clean gas in the gas grid, circular economy and material efficiency measures. In this case the solutions become more sub-sector specific and less horizontal for the whole industry, across sub-sectors. This has interesting implications per industrial sector, further analysed in Section 7.6 for the main individual energy intensive ones.

[394] By integrating intermediate production steps combined with recycling or better internal use of generated process gases.

### *4.5.3 Transition Enablers, Opportunities and Challenges*

Europe has a strong industrial base and is a global leader in many industries, especially in high value-added product and services. It is imperative that EU's low-carbon economy transition does not hamper but further strengthen industry.

EU industry has the opportunity to become the leader in this transition, changing to more sustainable and resource-efficient business models, products and services that could then become the paradigm for other countries and regions. At the same, this would provide a competitive advantage, creating important cost savings and spurring innovation. Europe would then be able to export not only sustainable products, but also sustainable technology and business models to exploit the huge potential of the global market for low-emission solutions.

On the other hand, a number of challenges exist.[353] Existing literature makes clear that the required reductions of emissions in industry are closely linked with the need to further develop promising low carbon technologies, currently at an early stage of research, as the deployed Best Available Techniques (BAT) can deliver limited emissions reduction. Such innovations should ideally become commercialised by 2030, to allow for timely scaling and deployment across the EU by 2050.[379] Thus, more research and innovation is needed, i.e. inert anodes for the aluminium industry or direct reduced iron for the iron & steel industry. The Innovation Fund under the EU-ETS, working in synergy with EUInvest Fund and Horizon Europe, is intended to become important enabling tools in this direction, supporting industrial innovation from research to commercialisation and thus speeding up the penetration of the new technologies.[395]

Similarly, decarbonisation policies cannot be implemented and innovative solutions cannot be deployed without an extensive network of adequate infrastructure. As a minimum, there should be sufficient infrastructure about to fully support the major trends framing the energy landscape of tomorrow: electrification (including storage), use of alternative zero-carbon fuels and alternative industrial feedstocks, decentralisation/distribution, digitalisation, extreme efficiency through new materials, technologies and services, and the related new market design.

In this context, the important role of demand side actions should be carefully considered, not only in the context of unlocking the potentials for material efficiency and circularity, but also for designing markets that generate demand for innovative low-carbon basic material products. This will allow companies to make large-scale investments in production plants, particularly in first-of-a-kind and subsequent plants.

The speed of penetration of technologies and building of infrastructure is critical. Modular technologies such as photovoltaics and wind power have been very successful in large-scale penetration of the electricity markets. The penetration of industrial decarbonisation technologies will not be that straightforward, as apart from international competition concerns that slow the development of innovative environmental technologies, many industrial plants are large, tailor-made, often part of complex industrial systems and thus difficult to change while the innovative technologies themselves often are rarely suited for retrofitting. They also depend on the availability of the infrastructure as described above or reliable supply of alternative fuels and feedstocks, which is not in the hands of individual enterprises. Therefore, a "chicken and egg" situation is likely to arise. Concerted action would be needed at regional level for creating these new business networks along the technological development. Such action will also need to

[395] More broadly, in line with the Paris Agreement and the commitment to the United Nations Sustainable Development Goals, the Commission proposed to set a more ambitious goal for climate mainstreaming across all EU programmes, with a target of 25% of EU expenditure contributing to climate objectives. https://ec.europa.eu/commission/sites/beta-political/files/communication-modern-budget-may_2018_en.pdf

account for the significant regional differences in Europe in term of the existing industries, the product portfolio and the shares of the various subsectors. To facilitate concerted action roadmaps should be developed for industrial decarbonisation on local and regional levels.[377]

The considerable investments required to support the industrial transition poses another risk if not planned carefully. Furthermore, stranded assets can be created when a major discontinuity in the economic environment in which they operate takes place. The transition to a low-carbon economy can be exactly such a major discontinuity. For existing infrastructure and assets, effort must be made to identify innovative solutions for using them - or part of them - in the long-term low-carbon economy. The challenge for industrial sites to retrofit and convert many of their existing installations is that it will require significant and costly changes to the design of the plant or a process (e.g. its furnace to accommodate switching to alternative fuels). Conversely, it can also be seen as an opportunity that is rising from the timely replacement of ageing infrastructure and assets with modern, highly efficient and carefully designed ones, which are compatible with the decarbonisation targets will be an increasingly attractive one.

The above observations point to a need for a policy framework that can facilitate these investments, support innovation and incentivise all the necessary changes, without jeopardising the global competitiveness of the European industries (see Section 5.3). Considering the longevity and capital intensiveness of industry's investments and thus the inertia in replacing industrial plants, the timing of such policy actions as well as concerted industrial action becomes more important when ambition increases. Industrial investments made in the next 10 years will most likely be in place in 2050, thus it is important to ensure that proper incentives are given for low carbon investments starting as early as today.

## 4.6 Non-$CO_2$ emitting sectors

### *4.6.1 Increasing importance of non-$CO_2$ GHGs*

Approximately 18% of the GHGs emitted in the European Union in 2015 were non-$CO_2$ gases. Historically, non-$CO_2$ gases have reduced faster than $CO_2$, linked for instance to the Member States that joined the EU after substantial reforms in the agricultural sector, and the inclusion of industrial installations with relatively easy to reduce $N_2O$ emissions in the ETS as well as the development of EU waste policies. While further reduction is projected to continue in the future up to 2030 in Baseline, at least stagnation is expected after that (see section 3.4). Non-$CO_2$ emissions, notably in agriculture, will be more difficult to reduce towards zero emissions than $CO_2$.

In Baseline, the share of non-$CO_2$ gases could increase to over 25% by 2050, and up to 31%-34% in scenarios achieving 80% GHG reduction by 2050. Scenarios with net zero GHG reached in 2050 see non-$CO_2$ emissions as the only residual GHG emissions fully offset by net negative $CO_2$ emissions. Non-$CO_2$ GHGs are projected therefore to become the main source of emissions on the pathway towards net zero emissions and need to be addressed specifically.

Table 2 summarizes the contribution of the different non-$CO_2$ GHGs per sector and major source of emission in 2015. Methane ($CH_4$) and Nitrous Oxide ($N_2O$) are the two main gases, responsible for respectively 55% and 32% of the non-$CO_2$ emissions[396] of the European Union in 2015. The remaining 13% emissions are comprised of various fluorinated gases belonging to

[396] Based on a GWP 100 metric, IPCC (2007), Fourth Assessment Report, https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

hydrofluorocarbon (HFC) group, sulphur hexafluoride ($SF_6$), nitrogen trifluoride ($NF_3$) and the group of perfluorocarbons (PFC).These gases have various properties and characteristics, leading to different times of residence in the atmosphere and potentials in term of climate warming. Annex 7.5 elaborates on these aspects and addresses in particular the specificity of methane and other short-lived climate pollutants (SLCP).

**Table 2: Major sources of non-CO2 greenhouse gases in the EU in 2005**

| Sector | Major sources | $CH_4$ | $N_2O$ | HFCs | PFCs | $SF_6$ | $NF_3$ | Contribution to current EU28 non-$CO_2$ emissions |
|---|---|---|---|---|---|---|---|---|
| Energy | Energy use (power, industry, residential) | x | x | | | | | 3.9% |
| | Transport | x | x | | | | | 1.3% |
| | Coal mining | x | | | | | | 2.9% |
| | Oil and gas production | x | | | | | | 1.5% |
| | Natural gas transmission & distrib. | x | | | | | | 2.5% |
| Industry | Nitric & adipic acid, caprolactam prod. | | x | | | | | 1.4% |
| | Primary aluminium production | | | | x | | | 0.1% |
| | Semiconductor industry | | | | x | | x | 0.1% |
| Agriculture | Livestock: enteric fermentation | x | | | | | | **21.7%** |
| | Livestock: manure handling | x | x | | | | | **8.7%** |
| | Agricultural soils | | x | | | | | **22.3%** |
| | Rice cultivation | x | | | | | | 0.3% |
| | Agricultural waste burning | x | | | | | | 0.3% |
| Waste | Solid waste | x | x | | | | | **14.0%** |
| | Wastewater | x | x | | | | | 4.2% |
| Other | AC & refrigeration | | | x | | | | **11.3%** |
| | High and mid voltage switches | | | | | x | | 0.3% |
| | Aerosols | | | x | | | | 0.9% |
| | Foams | | | x | | | | 0.7% |
| | Other F-gas uses | | | x | | x | | 1.4% |
| | Other N2O uses | | x | | | | | 0.9% |

*Source: GAINS.*

### *4.6.2 Reducing non-$CO_2$ GHG emissions in Agriculture*

#### 4.6.2.1 Options to reduce emissions in Agriculture

Non-$CO_2$ emissions for agriculture have declined since 1990. But with currently available and foreseen technology and management practices, agriculture emissions cannot be fully eliminated, due to the biological processes involved and growing demand for food, feed, fibres and public goods.

Given the more restricted mitigation potential of agriculture and the multiple demands including food security, this sector is expected to make up most of the remaining sources of EU GHG emissions after 2050 in case of deep decarbonisation. Yet, there is a need in reducing agriculture's GHG emissions as much as possible to avoid having to recourse heavily on offsetting through negative emissions technologies or sink in the LULUCF sector. Mitigation action has also to avoid that agriculture production will be moved to countries with lower climate ambition, leading to carbon leakage.

The GHG emission profile of the agriculture sector reported under UNFCCC (which excludes energy consumption related emissions) is very specific, with only 2% of emissions derived from carbon dioxide (from liming of acid soils and urea applications), whereas 55% of emissions being methane ($CH_4$, from enteric fermentation and manure management) and 43% nitrous oxide ($N_2O$, from fertilizer application on soils and manure management). Agricultural activities may also emit (or sequester) $CO_2$ from soil and biomass, but these emissions are reported separately in the land use, land use change and forestry (LULUCF) sector[397] of the UNFCCC inventories.

The EU's emissions from agricultural activities amount to 430 $MtCO_2eq$ in 2016, about 10% of EU GHG total emissions. These emissions have reduced by over 20% since 1990, mainly through the reduction in livestock numbers and overall efficiency improvements in EU agriculture such as the more efficient use of inorganic fertilizers.

Broadly speaking, two strategies can be envisaged to contribute to reducing agricultural non-$CO_2$ GHG emissions from a supply side perspective:

a) Increase productivity. To meet growing and changing food demand without encouraging land conversion to agriculture will require productivity increases – the amount produced per animal or unit of land – on current agricultural land to be increased sustainably. By using less land, fewer animals and fewer fossil-based inputs (such as fertilizer and fuel) to produce the same crop, dairy and meat production, the GHG efficiency of the agricultural system is improved and overall emissions reduced;

b) Adopt innovative technology and practices that aim to reduce GHG emissions. Non- $CO_2$ emissions can be reduced through the application of a number of technical options and selection of management practices that favour climate outcomes. The main source of emissions that could be targeted this way are enteric fermentation, management of agricultural soils and manure management. All together, these sources comprise more than the 95% of the total non- $CO_2$ GHG emission in agriculture;

Actions aiming at sequestering carbon in agricultural soils and forest biomass and thus increase the EU LULUCF sink or store carbon in goods limit soil erosion and increases sustainability. These actions are complementary to non- $CO_2$ measures and discussed in section 4.7. Adaptation actions that ensure that ecosystems continue to act as sinks are also of importance. See also section 5.7 that discusses among others also interactions between mitigation and adaptation actions. The approaches can provide substantial synergies that create virtuous drivers; for example, sequestering soil carbon improves soil fertility, increases productivity, and is also associated with innovative management practice that reduces soil erosion and increases sustainability. However, if an ecosystem currently acts as a sink, its possible lack of adaptation to the future climate combined with other drivers may decrease its mitigation potential and turn it into a carbon source. Adaptation benefits are likely to emerge from many such actions and mitigation practices, too.

As such, “win–win” or "no-regret" strategies should be prioritised to the greatest extent possible. Mitigation measures that also improve food security, profitability and resilience, would be more favourable than those that have no economic or agronomic benefit, or that could hinder the application of long-term adaptation actions. For example, even a modest increase in the soil carbon pool can provide a significant contribution to improving soil fertility, water retention and agricultural productivity, which in turn fosters the availability of land for other societal needs.

Consumer preferences also impact agriculture production and associated emissions. Shifts in demand in terms of types of food consumed may lead to shifts in types of agricultural production in the EU. This would have impacts on methane and nitrous oxide emissions from animal

[397] The land use, land use change and forestry (LULUCF) sector covers the emissions of biogenic and removals of atmospheric carbon through land use activities related to forest, cropland, grassland and wetland management, or resulting from land use change between these managed lands.

farming. Similarly, a reduction in the generation of food waste in households and commercial establishments would reduce GHG emissions.

#### 4.6.2.2 Mitigation Actions

Mitigating emissions related to production in the agriculture sector is recognised as challenging, but a number of options exist already today and are well known. In aggregate they all show significant total reduction potential. However, large differences remain between studies in the potential for GHG emissions reduction of individual measures. This is illustrated in a study published by RICARDO-AEA[398] in 2016 that presents a meta-review of the main mitigation measures applicable in EU with the range of GHG emissions reduction potential reported by various stakeholders at Member State levels. The following are the main mitigation options currently available:

<u>Action to reduce emissions in the livestock sector</u>

*Enteric fermentation*

Methane emissions from livestock derive from enteric fermentation during the digestive process in the stomachs of ruminants. Different selective breeding programmes (i.e. the selection of animals with beneficial traits) with multiple objectives and selection have been shown to effectively reduce enteric methane emissions per unit of production from livestock. Two distinct strategies exist. The first approach aims to enhance the herd's overall health and fertility, while maintaining or increasing productivity, reducing the number of animals needed in the stock. The second strategy focuses on reducing methane emissions per animal, either by selecting to enhance the feed efficiency of the animals, or by selecting animals with low emitting rumen.

Other options exist or are under development for improving feed management, thereby enhancing the GHG efficiency of animal diets, for instance by enriching feed with lipids or adding limited amounts of nitrates, both of which may reduce methane emissions from digestion. Due to already high intake of nitrate in EU livestock, mitigation potentials from additional nitrate in animal diets are likely limited. Feed management improvements also includes options such as pre-processing of the feed to facilitate digestion, or precision feeding with close monitoring of the composition and timing of feeding.

*Anaerobic Digestion*

Manure, if left untreated, will emit methane and nitrous oxide emissions as well as a number of other air pollutants or GHG precursors such as ammonia. Instead, if the organic content of livestock manure decomposes in the absence of oxygen in an anaerobic digester, it will decompose into a gas mixture richer in methane. This so-called biogas can be captured. Where produced on farm this can be used to generate electricity or heat or sold to local industry. However, the way in which the biogas is produced – in particular the inputs to the digestion process in the form of type of manure and eventual additional biogenic material such as crop residues or food waste – can have significant impacts on the efficiency and cost of the process. A by-product is “digestate”, a nutrient-rich substance that is usually used as fertiliser.

Other options exist to reduce manure emissions but do not produce usable energy: Storage management, air filtering and circulation, composting, nitrification-denitrification treatment,

[398] RICARDO-AEA (2016), Effective performance of tools for climate action policy – meta-review of Common Agricultural Policy (CAP) mainstreaming (Ricardo-AEA/R/ED60006/Mitigation potential, 08/01/2016), report for European Commission – DG Climate Action.

acidification, solid separators and artificial wetlands all have shown potential to reduce greenhouse gas emissions from manure.

*Action to reduce nitrous oxide emissions from agriculture soil*

Natural microbial processes in the soil convert ammonia into nitrate and further to molecular nitrogen. While nitrogen is key to plant growth, both processes release nitrous oxide as a side product. Consequently, fertilizer and manure application to soils are the most important sources of nitrous oxide emissions in agriculture. Moreover, mineral fertilizer production is also GHG intensive. Optimizing fertilizer application rates, avoiding excess application and reducing fertilizer losses, therefore reduces GHG emissions both directly and indirectly as well as other pollutants. It is also potentially beneficial from an economic perspective for the farmer.

Precision farming applied to nutrient management refers to a technology that optimises the application of nutrients to plants, adapting fertiliser application precisely to the extent they need it. It makes use of a number of technologies such as Variable Rate Technology (VRT), Remote Sensing, Global Positioning Systems, and Geographical Information Systems (GIS), linked to farm machinery that applies inputs more precisely. Nutrient management plans are essential tools to provide baseline information on nutrient use by cropping systems.

Nitrification inhibitors refer to chemical additives that reduce the release of nitrous oxide when mineral fertilizer or manure is applied. They slow down the conversion of ammonia into nitrate and give crops a better opportunity to absorb nitrogen, which increases the nitrogen-use efficiency of the fertiliser and reduces nitrous oxide emissions due to mineral fertilisers and manure application.

Organic soils, with their larger amount of available carbon provides “feed” for micro-organisms, including those responsible for the release of nitrous oxide. Fertiliser application on organic soils therefore leads to higher nitrous oxide emissions than corresponding applications on mineral soils. Moreover, the decomposition of the organic matter releases nitrogen which leads to N2O emissions also independently of fertilizer input through the 'cultivation' itself. Since the overall area of organic soils under cultivation is relatively small in the EU, fallowing organic soils is a simple mitigation option to reduce nitrous oxide emissions related to fertiliser application, with the additional benefit that it would reduce $CO_2$ emissions related to tillage from these soils. Furthermore, specific management practices can be implemented under different specific conditions in order to minimize carbon mineralization.

Other mitigation options relate to stricter enforcement of the existing ban on open burning of field residuals as well as improved management practices for rice cultivations, both reducing methane emissions and associated air pollutants.

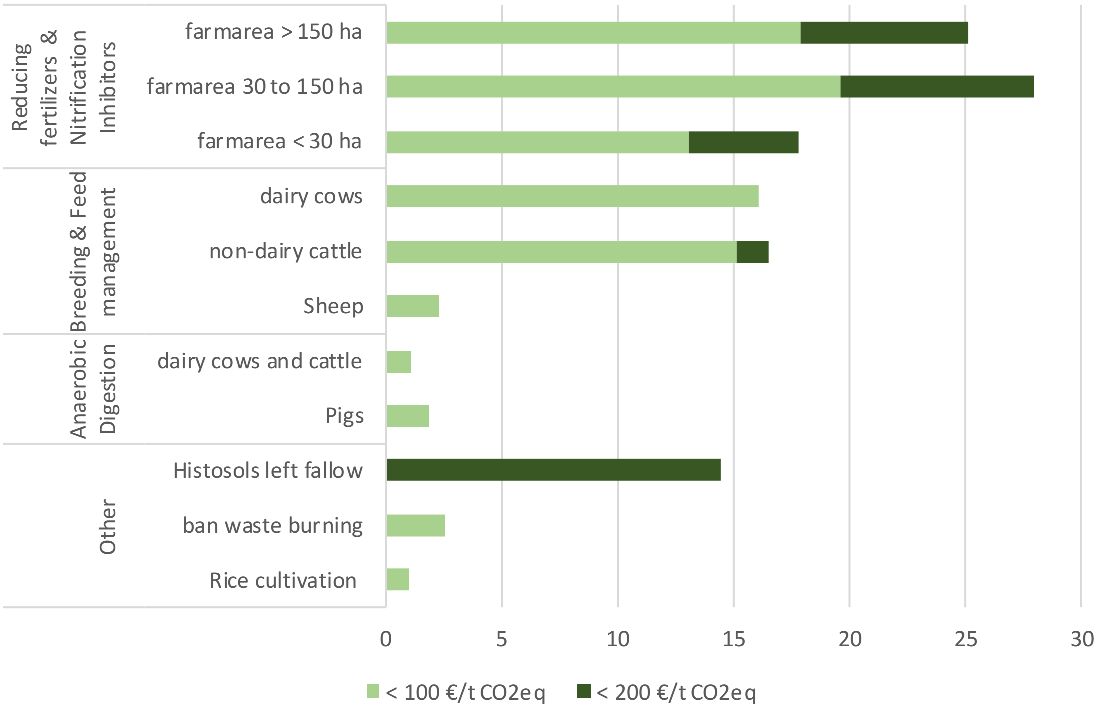
Figure 74 gives an overview of the main reduction options as represented in the GAINS model with marginal reduction costs up to EUR 200 per ton of $CO_2$ equivalent, representing in total around 130 $MtCO_2eq$ mitigation potential in 2050.

According to GAINS modelling, mitigation options with highest potential by 2050 are precision farming (low cost options such as variable rate technology), breeding for productive, healthy and fertile livestock, as well as nitrification inhibitors[399]. The estimated additional technical reduction

[399] Note that in the GAINS model, the order of technology uptake when several different technologies can be used to address emissions in a given sector, follows from the order of the estimated marginal cost of each technology. Hence, the potential from technology with the lowest marginal cost is always fully exhausted before assuming uptake of the technology with the second-lowest marginal cost. This approach leads to a fair representation of the mitigation potential and marginal cost at the sector and

potential coming from farm scale anaerobic digesters are relatively small in GAINS, this is partly because there is already a significant take-up of anaerobic digestion in the baseline projections.

**Figure 74: Example of technologies and mitigation potential in the agriculture sector**




*Source: GAINS.*

An ongoing study by JRC, EcAMPA III, making use of the CAPRI model estimated similar total non-CO2 reduction potentials in the mid-term up to 2030 than the GAINS model. The most significant reduction options in the EcAMPA study are also measures addressing enteric fermentation, manure management and soil emissions.[400]

Of note is that many of these measures, such as simultaneously breeding for enhanced productivity and healthier and more fertile animals, or precision farming, increase efficiency of the agriculture sector. Increased efficiency may make the EU agriculture sector more competitive, and thus may lead to rebound effects expanding EU agricultural production. The end effect is however uncertain as there could also be net cost impacts of these measures, which if borne by consumers through increases in consumer prices may increase competition with imported goods, thereby decreasing EU agricultural production. Depending on the origin of these imports, the overall carbon efficiency in terms of impacts on global greenhouse gas emissions would need to be evaluated in detail.

#### 4.6.2.3 Consumer preferences on food diet

European society has historically had a strong preference for red meat consumption. Statistics from FAO nevertheless indicate that a plateau has been reached at the beginning of the 90s with a

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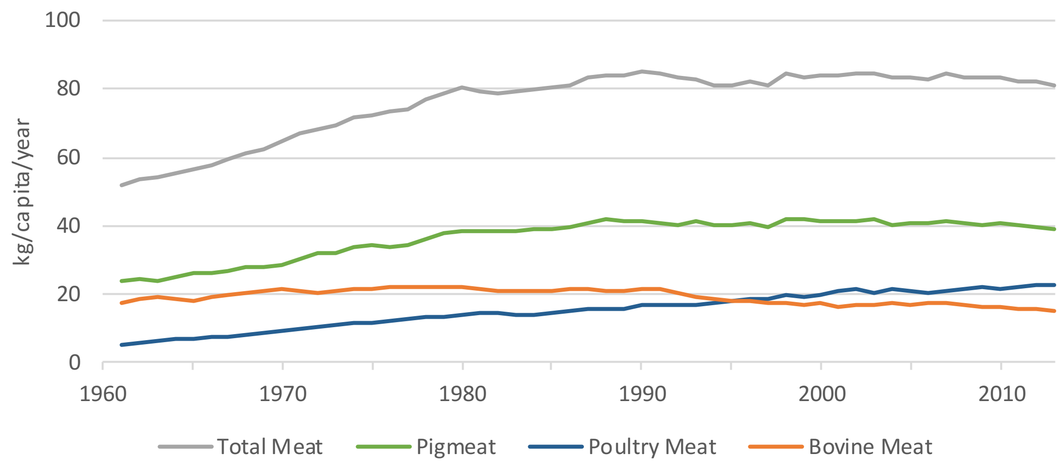
country level, however, can overstate the potential from the technology with the lowest marginal cost at the technology level.

[400] Pérez Domínguez et al. (forthcoming): An economic assessment of GHG mitigation policy options for EU agriculture (EcAMPA 3). JRC Technical Report.

stabilization of the total meat consumption per capita in the EU28 since and a decrease in overall animal products. Moreover, beef consumption in the EU declined by 31% which was offset by a +37% increase in poultry consumption.

**Figure 75: Historical EU meat consumption**




*Source: FAOstat database.*

In the Baseline used for this assessment, the assumptions on the animal based calorific consumption are the same as in the EU Reference Scenario 2016[401] (which in turn is based on the EU Agricultural outlook[402] until 2030 and FAO projections[403] for the longer term). A sensitivity analysis has been carried out in order to understand the possible implications of differing trends in consumer preferences by the EU population on greenhouse gas emissions in the next decades.

Five further scenarios were analysed with variation in the consumption of various meat, milk and egg products that see a reduction of animal based calorific consumption in the EU. Diet 5 is consistent with reaching in 2070 levels of meat consumption seen as in-line with recommended diets in a number of studies (AgCLIM50 project of the JRC[404], Bajzelj et al. (2014)[405] and Bryngelsson et al. (2016)[406]). These five scenarios also include a reduction by half in the generation of food waste in all EU Member States. This respects the objective of the Sustainable

[401] European Commission (2016), EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050 https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

[402] EU Agricultural outlook for the agricultural markets and income 2017-30 (2017) https://ec.europa.eu/agriculture/markets-and-prices/medium-term-outlook_en

[403] Alexandratos, N. & Bruinsma, J. World Agriculture Towards 2030/2050 The 2012 Revision. 160 (FAO, Rome, 2012).

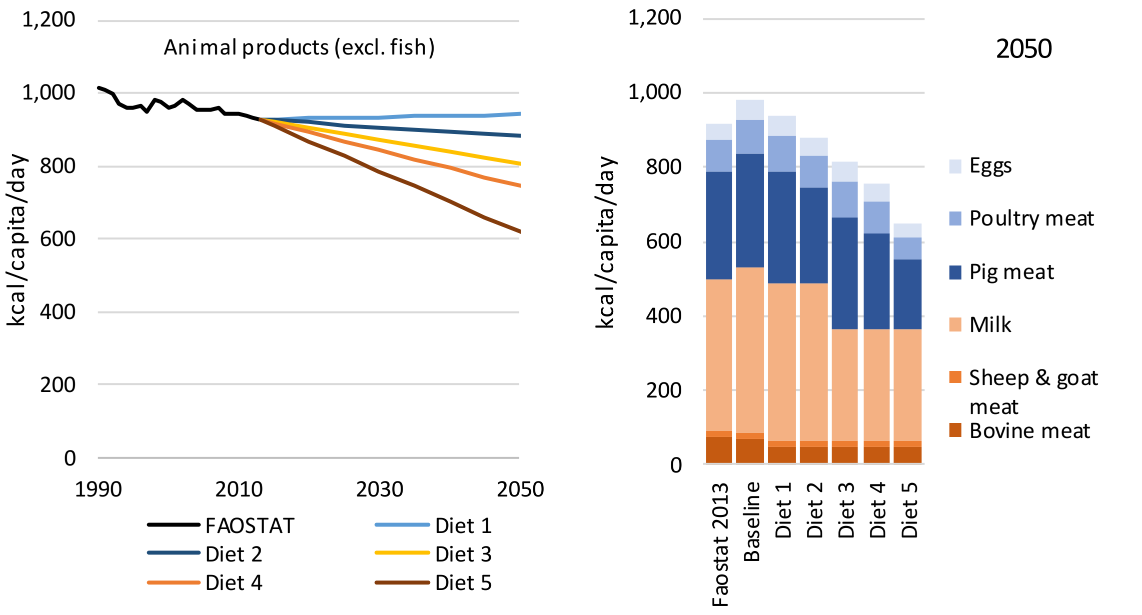
[404] AgCLIM50 (2017) Challenges of Global Agriculture in a Climate Change Context by 2050. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC106835/jrc106835_agclim50_jrc_science_for_policy_report.pdf

[405] Bajželj, B. et al. (2014), Importance of food-demand management for climate mitigation. Nature Climate Change, 4, pp.924–929

[406] Bryngelsson et al. (2016), How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture, Food Policy, Volume 59, February 2016, Pages 152-164

Development Goals adopted by the United Nations Assembly in 2015 where a target was agreed to halve per capita food waste generation at the retail and consumer levels until 2030[407].

**Figure 76: Animal based calorific consumption for different diet assumptions**



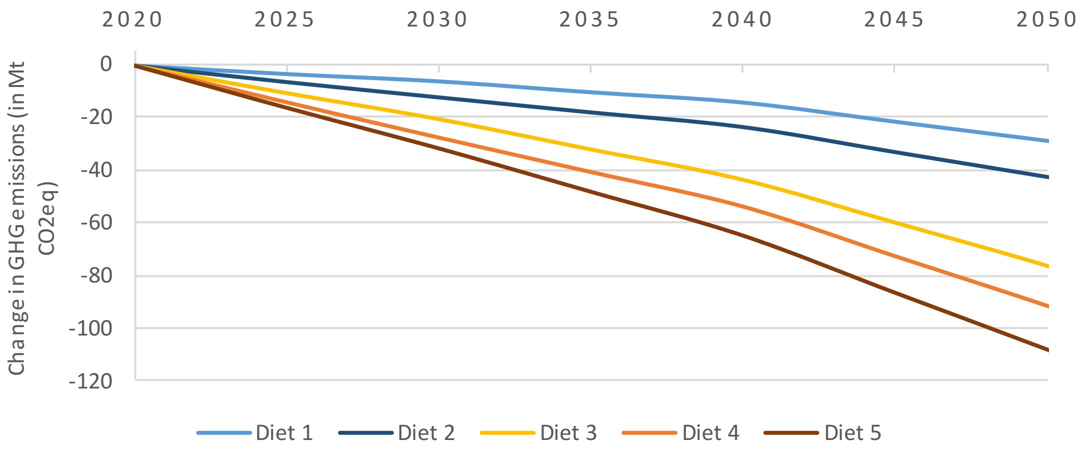

*Source: FAO.*

The results show that moderate changes in food consumption patterns will still include in each of the diets the consumption of all types of food products, even though in smaller quantities for some of them. These possible shifts could reduce significantly emissions from agriculture production. The effect in 2050 ranges from 34 $MtCO_2eq$ with Diet 1 to 110 $MtCO_2eq$ with Diet 5 and represents approximately 8% to 25% of 2015 emissions from agriculture[408]. In 2050 the transition would only be partially implemented, at full implementation in 2070 emissions could reduce by 13% in Diet 1 to 44% in Diet 5.

[407] Transforming our world: the 2030 Agenda for Sustainable Development (2015). http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

[408] Assuming that the decrease in EU animal products consumption is entirely passed on EU production levels and no increase in exports of animal products to the rest of the world takes place.

**Figure 77: Potential impacts on GHG emissions due to dietary changes**




*Source: GLOBIOM and GAINS.*

The analysis conducted in this report does not model specifically a shift towards an increase in the consumption of food products from seas, oceans and freshwater resources to substitute GHG-intensive food production processes and the potential associated benefits in terms geographic and environmental footprint. There is probably little scope for increasing the volume of seafood from capture fisheries but a possible way to increase the proportion of seafood in the human diet would be to shift toward more sustainable aquaculture. Though an increasing proportion of feed for aquaculture comes from crops, studies have shown that the land requirements to produce a given amount of protein are less than other sources.[409]

*Overall potential of GHG emissions reduction in agriculture sector*

The respective effects of technical mitigation measures, consumer preferences and their combination on levels of future emissions reduction are depicted in Figure 78.

In Baseline, with current policies in place, projected population stable and no changes in EU diets, the EU's agriculture emissions are projected to slightly decline until 2030 and then stabilize just over 400 $MtCO_2eq$ in 2050. This represents just below 10% of total 1990 EU GHG emissions and consequently a significant amount of negative emissions would be needed to reach net zero GHG emissions in the EU if agriculture emissions would remain at that Baseline level.

Applying existing technical mitigation measures to the Baseline would reduce emissions by around one third to below 300 $MtCO_2eq$. Approximately 60% of this reduction would be achieved via reduction in nitrous oxide emissions and 40% via reduction in methane emissions.

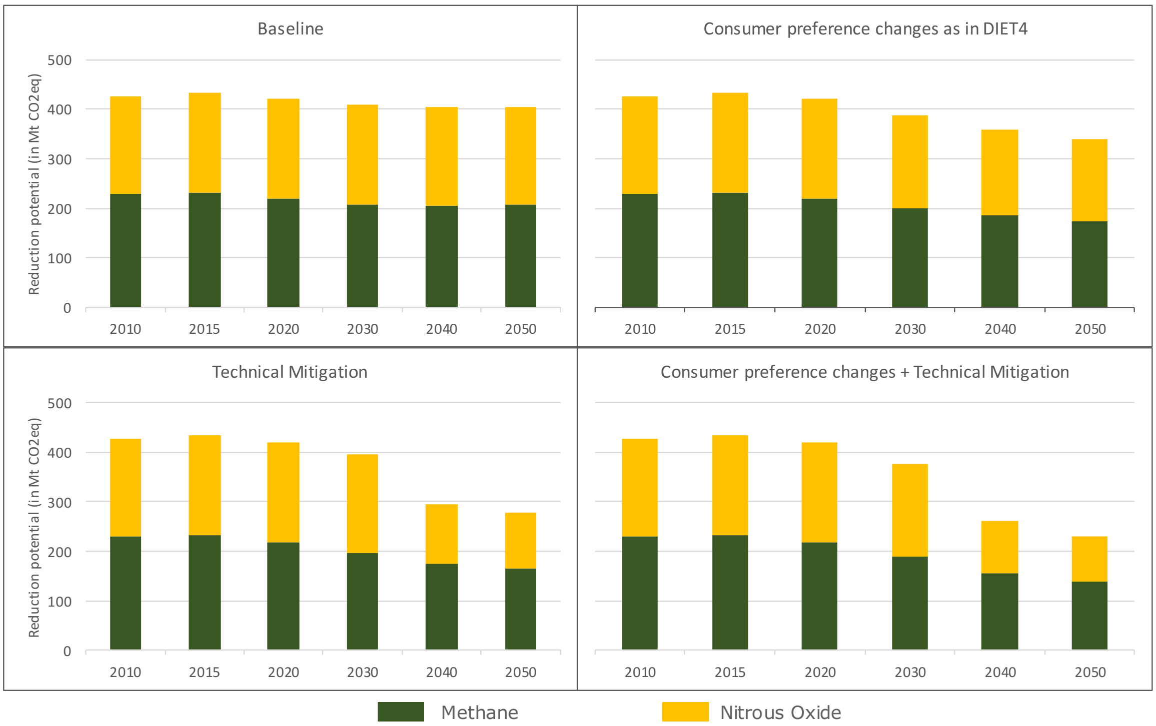
Modelling dietary change alone (Diet 4), continuing the recent observed shift in animal product consumption, shows that demand-side action could reduce emissions compared to Baseline from EU agriculture to approximately 340 MtCO2eq when export of animal products are free to increase. The emissions reduces further to 310 $MtCO_2eq$ when the EU dietary change is fully passed on EU production levels (by constraining animal products exports).

Combining both technical supply-side mitigation measures and a demand-side shift in diets, could bring down non-$CO_2$ GHG emissions from 430 $MtCO_2eq$ in 2015 to 230 $MtCO_2eq$ in 2050

[409] D. Nijdam et al (2012) The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes, Food Policy 37 (2012) 760–770

(211 $MtCO_2eq$ with dietary changes fully passed on EU production) or the equivalent of just below 5% of 1990 EU GHG emissions. Achieving this level of emissions would clearly reduce pressure on the need for negative emissions to reach net zero GHG emissions.

**Figure 78: Example of reduction potential in the agriculture**




*Source: GAINS.*

Regarding the modelling done by the PRIMES-GAINS-GLOBIOM model set up, all the scenarios achieving 80% GHG reduction or net zero GHG assume the uptake of technical mitigation measures but only the 1.5LIFE scenario assumes, in addition, a change in consumer preferences towards Diet 4.

Assumptions in yields improvement are the same in Baseline than in mitigation scenarios from a technological perspective but partial reallocation of the production to the most suitable land has a limited positive effect on average yields.[410] In order to avoid that substantial indirect land use effects affect the results of the analysis, the modelling assumptions include constraints to keep the imports of agricultural commodities at Baseline level or lower and the exports at Baseline level or higher. This prevents the risk of significant displacement of food and feed production outside Europe and allows assessing the impact of producing energy crops domestically in the context of global efforts to reduce GHG emissions.

### *4.6.3 Reducing non-$CO_2$ GHG emissions in other sectors*

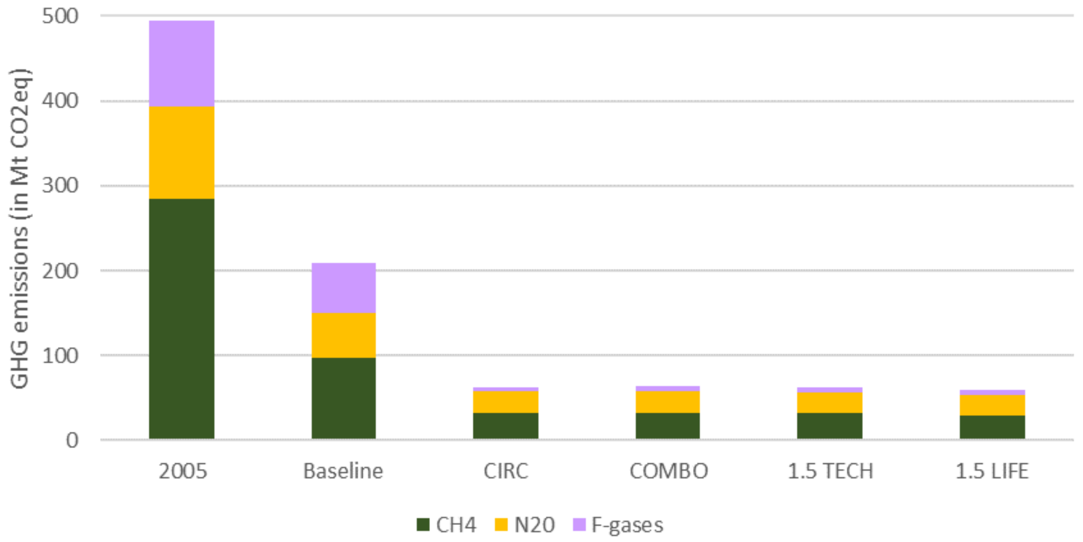
The main sources of non-$CO_2$ emissions from sectors other than agriculture are fugitive emissions from the energy sector (e.g. coal mining, oil and gas production, gas distribution, fossil

410 The model assumes that possible farmland abandonment happens firstly on less productive land, implying an increase in average yield. The fact that energy crops tend to have better yield on marginal land than food and feed crops contributes also to the increase in average productivity.

fuel power plants), emissions related to waste (solid waste, wastewaters) and F-gases from air conditioning, refrigeration and industry.

These emissions are projected to reduce by almost 60% in the baseline from approximately 490 $MtCO_2eq$ in 2005 to 205 $MtCO_2eq$ in 2050 (section 3.4). The implementation of strong GHG reductions in the energy system through transitions away from fossil fuels result in strong reductions of methane emissions from the energy system. This together with technological developments could deliver additional reductions of almost 150 $MtCO_2eq$. This means that approximately 60 $MtCO_2eq$ of non-$CO_2$ GHG would still be emitted by 2050 in sectors other than agriculture, mainly methane and nitrous oxide emissions.

**Figure 79: Reductions in non-$CO_2$ emissions in sectors other than agriculture**




*Source: GAINS.*

Largest methane reductions outside of the agriculture sector can be found in the waste sector. Existing legislation would already see a halving of methane emissions by 2050 compared to 2005. But additional technical potential exists that could further reduce these emissions by more than 50%.

Emissions in the energy sector are largely linked to emissions from fuel combustion, fugitive emissions of the transmission and distribution system and emissions from fossil fuel extraction activities. These emissions can be largely eliminated in a low carbon scenario with a combination of decreased fuel consumption and increased application of technological mitigation options. The single largest reduction in 80% GHG reduction and net zero GHG scenarios in the energy sector is achieved with the halting of most coal mining activities, but this already occurs in Baseline under existing policies. Similarly the halting of most oil extraction in the EU by 2050 results in significant reductions of $CH_4$ emissions. Additional significant reduction can also be achieved in the gas network, in part through the reduction in consumption, but also thanks to strong progress in monitoring, detection and maintenance preventing leaks.

**Table 3: $CH_4$ emissions (outside agriculture), mitigation potential by 2050 in different scenarios.**

| CH4 ($MtCO_2eq$) | | 2005 | Baseline 2050 | Remaining emissions with technical mitigation < 250 €/t $CO_2eq$ | |
|---|---|---|---|---|---|
| **Sector** | **Activity** | | | **COMBO** | **1.5LIFE** |
| **Waste** | **Total** | **192** | **68** | **25** | **22** |
| | Municipal solid waste | 87 | 29 | 14 | 11 |
| | Industrial solid waste | 33 | 18 | 7 | 7 |
| | Historical landfill of waste | 51 | 0 | 0 | 0 |
| | Industrial wastewater | 10 | 11 | 1 | 1 |
| | Domestic wastewater | 12 | 10 | 3 | 3 |
| **Energy** | **Total** | **92** | **30** | **21** | **7** |
| | Gas distribution | 18 | 11 | 8 | 2 |
| | Gas transmission | 6 | 5 | 3 | 0 |
| | Transport | 4 | 3 | 3 | 0 |
| | Biomass combustion | 6 | 2 | 2 | 2 |
| | Other combustion | 3 | 2 | 2 | 2 |
| | Production of crude oil | 15 | 3 | 0 | 0 |
| | Production of natural gas | 3 | 3 | 1 | 1 |
| | Coal mining | 36 | 1 | 1 | 0 |
| | Oil refinery | 1 | 0 | 0 | 0 |
| **Total CH4 (non-agriculture)** | | **284** | **97** | **46** | **29** |

*Source: GAINS.*

The energy sector produces small amounts of $N_2O$ emissions with fossil fuel combustion, when nitrogen in the fuel and in the air get oxidised. These reduce with reductions of fossil fuel consumption, though combustion of biofuels or e-fuels will also produce some by-products such as N2O. In waste current policies would not stop $N_2O$ emissions, and these would potentially increase, though technical solutions exist to reduce these emissions. Industrial sectors already have cut almost all emissions since the inclusion of most of the installations under the EU ETS, and some very limited remaining mitigation potential exists.

**Table 4: $N_2O$ emissions (outside agriculture), mitigation potential by 2050 in different scenarios.**

| N2O (Mt$CO_2$eq) | | 2005 | Baseline 2050 | Remaining emissions with technical mitigation < 250 €/t $CO_2$eq | |
|---|---|---|---|---|---|
| **Sector** | **Activity** | | | **COMBO** | **1.5LIFE** |
| **Energy** | **Total** | **32** | **16** | **12** | **11** |
| | Energy use | 21 | 9 | 9 | 9 |
| | Transport | 11 | 7 | 3 | 2 |
| **Waste** | **Total** | **17** | **23** | **7** | **7** |
| | Solid waste composting | 2 | 7 | 0 | 0 |
| | Domestic wastewater | 15 | 16 | 7 | 7 |
| **Industry** | **Total** | **54** | **6** | **4** | **4** |
| | Adipic acid production | 12 | 1 | 1 | 1 |
| | Caprolactam production | 2 | 3 | 0 | 0 |
| | Nitric acid production | 40 | 2 | 2 | 2 |
| **Other** | **Direct N2O use** | **7** | **8** | **3** | **3** |
| **Total N2O (non-agriculture)** | | **110** | **53** | **26** | **24** |

*Source: GAINS.*

While current F-gas legislation have already significantly reduced emissions (certainly compared to a no-policy baseline), still some 60 million ton $CO_2$eq. emissions remain in Baseline by 2050. Technical options exist to eliminate almost all, with an overall reduction of 95% in 2050 compared to 2005. Improvement in refrigeration and air conditioning technologies has by far the greatest potential to reduce F-gases emissions.

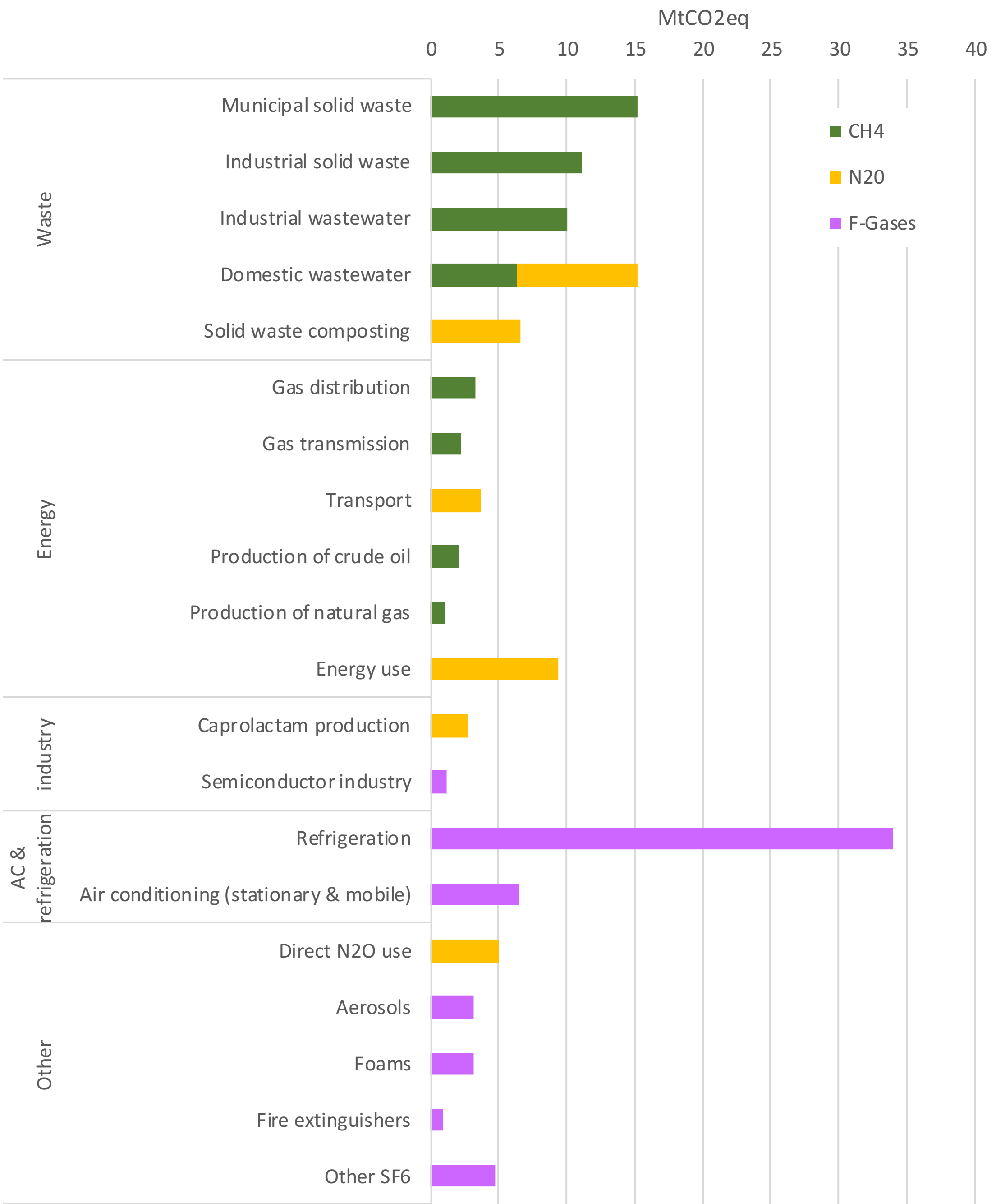
**Table 5: F-gas emissions (outside agriculture), mitigation potential by 2050 in different scenarios.**

| F-gases ($MtCO_2eq$) | | | | Remaining emissions with technical mitigation < 250 €/t $CO_2eq$ | |
|---|---|---|---|---|---|
| **Sector** | **Activity** | **2005** | **Baseline 2050** | **COMBO** | **1.5LIFE** |
| **AC & refrigeration** | **Total** | **66** | **41** | **0.3** | **0.3** |
| | Refrigeration | 40 | 34 | 0.1 | 0.1 |
| | Air conditioning (stationary & mobile) | 26 | 7 | 0.2 | 0.2 |
| **Industry** | **Total** | **11** | **6** | **5.1** | **5.1** |
| | HCFC22 production | 2 | 0 | 0.0 | 0.0 |
| | Primary aluminium production | 3 | 1 | 0.7 | 0.6 |
| | High & mid voltage switches | 3 | 3 | 3.2 | 3.3 |
| | Magnesium production & casting | 1 | 0 | 0.0 | 0.0 |
| | Semiconductor industry | 2 | 1 | 0.1 | 0.1 |
| | Other industry sources | 1 | 1 | 1.0 | 1.0 |
| **Other** | **Total** | **23** | **12** | **0.1** | **0.1** |
| | Aerosols | 7 | 3 | 0.0 | 0.0 |
| | Foams | 7 | 3 | 0.0 | 0.0 |
| | Ground-source heat pumps | 0 | 0 | 0.1 | 0.1 |
| | Fire extinguishers | 2 | 1 | 0.0 | 0.0 |
| | Solvents | 0 | 0 | 0.0 | 0.0 |
| | Soundproof windows | 2 | 0 | 0.0 | 0.0 |
| | Other SF6 | 5 | 5 | 0.0 | 0.0 |
| **Total F-gases** | | **100** | **59** | **5.4** | **5.5** |

*Source: GAINS.*

Combining all mitigation options in sectors other than agriculture across all non-$CO_2$ gases, the waste sector at large shows the largest potential on top of existing policies to reduce emissions compared to Baseline by 2050. F-gas emissions reduction in refrigeration and air conditioning follow. In the scenario assessment, all scenarios use the maximum mitigation potential for non-CO2 GHG gasses.

**Figure 80: Additional non-$CO_2$ emissions reduction potential in 2050 compared to baseline in the EU in sectors other than agriculture**




*Note: Only reduction potentials above 2 $MtCO_2eq$ are included in the chart; results from COMBO scenario*

*Source: GAINS.*

### *4.6.4 Transition enablers, opportunities and challenges*

Combining all options and actions described in the sections above indicate that strong reduction potential for non-$CO_2$ emissions exist in 2050 compared to present emission levels and can reach 2/3$^{rd}$ of 2005 levels (Table 6).

All scenarios achieve a similar maximum technical reduction potential with emissions levels of around 340 $MtCO_2eq$ in 2050. Only the 1.5LIFE scenario manages to reduce emissions further, notably with the impact of consumer food preference changes on emissions in the agriculture sector, further reducing emissions to 290 $MtCO_2eq$ in 2050.

**Table 6: Non-$CO_2$ GHG emissions compared to baseline in 2050 in different scenarios ($MtCO_2eq$).**

| 2050 | 2005 | Baseline | CIRC | COMBO | 1.5TECH | 1.5LIFE |
|---|---|---|---|---|---|---|
| **Outside Agriculture** | **494** | **209** | **62** | **64** | **62** | **59** |
| CH4 | 284 | 97 | 33 | 33 | 32 | 29 |
| N20 | 110 | 53 | 25 | 26 | 24 | 24 |
| F-gases | 100 | 59 | 4 | 5 | 5 | 5 |
| **Agriculture** | **440** | **404** | **277** | **277** | **277** | **230** |
| CH4 | 237 | 207 | 165 | 165 | 165 | 139 |
| N20 | 203 | 197 | 111 | 111 | 111 | 91 |
| **TOTAL** | **934** | **613** | **339** | **341** | **339** | **290** |
| CH4 | 521 | 305 | 198 | 198 | 198 | 169 |
| N20 | 313 | 250 | 136 | 137 | 136 | 115 |
| F-gases | 100 | 59 | 4 | 5 | 5 | 5 |

*Source: GAINS.*

Achieving this reduction potential will be important if the aim is to reach zero GHG emissions given that any remaining emissions would need to be offset by $CO_2$ removals from other activities. Therefore, the challenge is to tackle a very diverse set of sources of non-$CO_2$ emissions.

Technological alternatives are expected by 2050 for most, if not all, F-gas applications. It is important to give clear signals to industry to provide them sufficient certainty to invest in technology development to allow for a complete phase out on time.

The Governance of the Energy Union and Climate Action Regulation requests the Commission to consider policy options for rapidly address methane emissions and to put forward a Union strategic plan for methane.[411] In that context this assessment clearly indicates that for the development of any strategy towards reducing methane emissions, as requested, a limited amount of sectors are of key importance, notably agriculture, waste and energy.

Reduction in the waste sector under current policies are expected to be significant, though additional potential exist and needs to be achieved towards 2050. Therefore it is very important in the short term to ensure effective implementation of existing policies and thus attentiveness is required that Member States fully translate and implement the waste acquis. This will not only reduce $CH_4$ emissions, it will also contribute to a more circular economy, improved recycling systems will make our industrial production processes more resource efficient.

[411] COM/2016/0759 final/2 - 2016/0375 (COD). Article 16.

The largest driver for methane emissions reduction in the energy sector are reductions in fossil fuel consumption itself and associated reductions in emissions from fossil fuel extraction and distribution in the EU. The faster this transition e, the faster the emissions will decrease. Nevertheless, the gas transmission and distribution system will continue to play a role in a low carbon economy, though rather based on clean gases such a biogas and e-gas. Thus increased monitoring, detection and prevention, all fulfil an important function.

Finally the agriculture sector is by far the largest source of methane emissions. The introduction of wide-spread use of anaerobic digestion would not only reduce methane emissions, it would also provide for renewable energy. The role of feed management and feed additives has to be explored to see how methane emissions from the ruminant herd can be reduced. The former may also improve farm efficiency. Breeding systems focussed on both improving productivity and animal fertility and health in the ruminant herd can significantly increase the overall efficiency of the dairy and beef sectors, while reducing associated $CH_4$ emissions. Given the time-lag of this action, a more concerted EU wide effort well before 2050 seems preferable.

The same agriculture, waste and energy sectors are also responsible for nitrous oxide emissions. For both waste and the energy sector, most measures to reduce $CH_4$ will also reduce $N_2O$. For the agriculture, the focus for $N_2O$ reductions foremost needs to come from more appropriate fertiliser application and reduced associated $N_2O$ emissions. Excessive fertilisation is not only problematic for the environment; it can also have a negative impact on farmer's income. In this context the use of better information systems, such as the nutrient management plans or variable rate application should improve awareness of farmers and willingness to reduce fertiliser application without hurting farmers' income. Together with the introduction of further digitalisation and smart farming techniques, this could further improve farm efficiency as well as decrease $N_2O$ emissions. Subsequent options that can be explored relate to the application of novel technologies that can reduce subsequent $N_2O$ emissions after fertiliser application, which would not only reduce $N_2O$ emissions but also contribute to reducing nitrate pollution.

## 4.7 Land resources

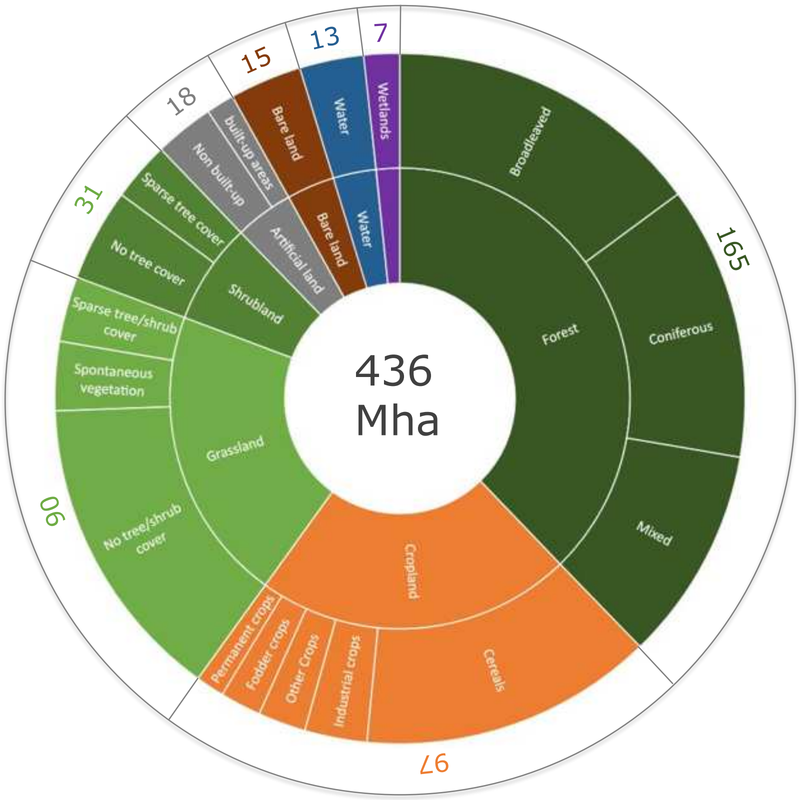
### *4.7.1 Land use options*

Land is a precious and finite resource providing goods and services essential to the well-being of our society and our economy. Land use – and the split between settlements, agriculture land, forests and natural habitats – is a major factor influencing the distribution and functioning of ecosystems and thus the delivery of ecosystem services, including those related to climate change[412]. There is a competition for the use of land, the main drivers being the production of food and feed, the development of forests and its provision of various services, the supply of bioenergy and other renewable energies and the increasing demand for housing and infrastructures.

According to Eurostat statistics, 38% of the EU land is covered by forest and 22% is cropland, 21% grassland and 7% shrubland (Figure 81). Due to differences in the definitions of land categories, the UNFCCC inventories report a larger share for cropland (28% or 127 Mha in 2016), with part of land classified as grassland in EUROSTAT database (in particular temporary grassland) is inventoried as cropland in the UNFCCC database.

[412] EEA (2015), The European environment — state and outlook 2015: an integrated assessment of the European Environment, https://www.eea.europa.eu/soer-2015/about

**Figure 81: Land cover overview in 2015**




*Source: Eurostat.*

From a $CO_2$ emissions perspective, the land use, land use change and forestry (LULUCF) sector covers the emissions and removal of carbon dioxide through land use activities related to forest, cropland, grassland, settlements, wetland and other land management, or resulting from land use change between these managed lands.

The LULUCF sector in the EU today is a net carbon sink, i.e. it removes (or sequesters) annually more carbon than it emits as GHG. According to the information reported by Member States to the UNFCCC[413], the 2016 net balance amounted to 314 $MtCO_2$ sequestered in the LULUCF sector as a whole, with 424 $MtCO_2$ net removals from forest land only offsetting the net emissions of other land cover types, in particular cropland and settlements and smaller net emissions from grassland and wetlands. Carbon tends to be lost when converting grasslands, forest or other native ecosystems to croplands, or by draining, cultivating or liming highly organic soils. Soil organic carbon tends to increase when restoring grasslands, forests or native vegetation on former croplands, or by restoring organic soils of wetlands to their native condition.

The use of natural resources can substantially affect climate, in positive or negative terms. Climate change interacts with other drivers and further exacerbates biodiversity loss and ecosystem degradation (also through droughts and forest fires), thus weakening the ecosystems' ability to capture and sequester carbon. Climate change can considerably alter natural availability, structure and function to deliver private goods and eco-system services of natural resources, including their mitigation and adaptation capacity. A sustainable enhancing of the

[413] EEA data viewer, not including N20 indirect emissions

natural resources capacity to deliver, and especially of land as being at the crossroad, will be critical in a decarbonised context.

#### 4.7.1.1 Preserving carbon from agricultural soils

In addition to the emissions of methane and nitrous oxide, EU agricultural soils release a substantial amounts of $CO_2$ emissions, 60 $MtCO_2$ in 2016 from cropland and grassland. Slowing down the soil degradation and enhancing the carbon sequestration of EU soils is a win-win strategy for climate and food security that reduces $CO_2$ emissions and, in the same time, increases the fertility and productivity of EU agricultural land. The international initiative "4 per 1000"[414], launched by France on 1 December 2015 at the COP 21, goes in this direction by encouraging the implementation of some practical actions on soil carbon sequestration and the type of practices to achieve this (e.g. agroecology, agroforestry, conservation agriculture, landscape management, etc.).

The depletion of the soil organic carbon pool is caused by oxidation or mineralization, leaching and erosion. Under the temperate European climate, most soil losses take place during a period of 20 to 50 years after conversion from natural land to arable land and a quarter to half of the soil organic carbon under natural conditions is lost at the new equilibrium.[415]

Organic soils

An effective way to reduce soil carbon losses and associated $CO_2$ emissions is to limit the use of organic soil and peatlands for agriculture production and prevent the expansion of new agricultural land on these soils. Peatlands are wetlands with a thick layer of organic soil and even if they cover only three percent of the global land area, they store 30 percent of the world’s soil carbon[416]. In 2012 the Organic soils and peatlands climate change mitigation initiative[417] was launched by FAO, the MICCA Programme and Wetlands International. The initiative is committed to reducing GHG emissions from peatlands and safeguarding other vital ecosystem services that peatlands provide.

In Europe, in the 2018 UNFCCC inventories for the year 2016, the agriculture land with organic soils is emitting on average 16 to 17 tons of $CO_2$ per hectare (less than 1 ton of $CO_2$ in average for mineral soils). Only 1.5% of the cropland is covered with organic soils but that represents 55% of the total soil emissions for cropland (Table 7). For grassland, the 3% area covered by organic soils is emitting as much carbon as the 97% grassland area of mineral soils is sequestrating carbon, making overall grassland near neutral in term of $CO_2$ emissions.

Protecting organic soils of intensive use would be beneficial from the perspective of climate action in the agriculture sector. It could be achieved by limiting or using appropriate agriculture activities on organic soils and by restoring peatlands and wetlands through the elevation of groundwater level, in order to reduce the oxidation of the organic material.

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[414] https://www.4p1000.org/

[415] FAO (2010) – SOLAW Thematic Report 4B Soil carbon sequestration, http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_04b_web.pdf

[416] FAO (2018), Mitigation of Climate Change in Agriculture (MICCA) Programme, http://www.fao.org/in-action/micca/knowledge/peatlands-and-organic-soils/en/

[417] FAO (2012), Launch of the global ‘Organic Soils and Peatlands Climate Change Mitigation Initiative, http://www.fao.org/3/a-az616e.pdf

**Table 7: EU agricultural soil emissions in 2016**

| | Cropland | | Grassland | |
|---|---|---|---|---|
| | Mineral Soils | Organic Soils | Mineral Soils | Organic Soils |
| **Area (Mha)** | 125 | 2 | 85 | 3 |
| **Total Soil Emission ($MtCO_2$)** | 27 | 33 | -41 | 41 |
| **Implied Emission Factor ($tCO_2$/ha)** | 0,2 | 17 | -0,5 | 16 |

*Source: 2018 UNFCCC inventories.*

Mineral soils

Several studies estimated soil organic carbon (SOC) emissions from mineral soils of arable land and the carbon sequestration potentials at regional and global level using either biophysical SOC models[418,419,420,421] or static SOC sequestration rates[422,423,424]. Most studies conclude that European SOC mitigation potential could contribute to reaching emissions saving. The PICCMAT project[425] estimated the carbon mitigation potential for several carbon sequestration options.

Strategies to enhance carbon sequestration in agriculture aim to increase the soil carbon pool, improving soil biological activity, as such also increasing net primary productivity (NPP), decreasing nutrient and organic carbon losses from erosion and leaching, and increasing the humification efficiency[415]. Sustainable management practices commonly recommended are[426]

- Reduced till or no-till cultivation practices that minimize soil disturbances, avoid the complete inversion of the soil horizon (i.e. ploughing) and thereby reducing the oxidation of soil carbon. Co-benefits are reduced risk of soil erosion by wind or water, and less energy required for cultivation.
- Crop residues left on the soil surface after harvest. This enables greater carbon retention in soils than removing crop residues.
- Cover crops are used to reduce the period of time that soil is left bare in order to reduce the risk of soil erosion. Catch crops are grown to reduce the duration of bare soil between

[418] Zaehle, S., A. Bondeau, T. R. Carter et al. (2007). "Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100." Ecosystems 10(3): 380-401.
[419] Yu, Y., Y. Huang and W. Zhang (2013). "Projected changes in soil organic carbon stocks of China's croplands under different agricultural managements, 2011–2050." Agriculture, Ecosystems & Environment 178(0): 109-120.
[420] Lugato, E., P. Panagos, F. Bampa et al. (2014). "A new baseline of organic carbon stock in European agricultural soils using a modelling approach." Global Change Biology 20(1): 313-326.
[421] Stefan Frank, Erwin Schmid, Petr Havlíka et al. (2015). The dynamic soil organic carbon mitigation potential of European cropland. Global Environmental Change Volume 35, November 2015, Pages 269-278
[422] De Cara, S. and P.-A. Jayet (2006). Mitigation of greenhouse gas emissions in EU agriculture: An assessment of the costs of reducing agricultural emissions and enhancing carbon sinks in agricultural soils. INSEA Final report SSP1-CT-2003-503614-Final, INRA and International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria.
[423] Schulp, C. J. E., G.-J. Nabuurs and P. H. Verburg (2008). "Future carbon sequestration in Europe—Effects of land use change." Agriculture, Ecosystems & Environment 127(3–4): 251-264.
[424] Thomson, A. M., R. César Izaurralde, S. J. Smith and L. E. Clarke (2008). "Integrated estimates of global terrestrial carbon sequestration." Global Environmental Change 18(1): 192-203.
[425] PICCMAT (2008). Deliverable D7: European quantification results. schulop, Alterra: 42.
[426] Ricardo-AEA (2016) Effective performance of tools for climate action policy - meta-review of Common Agricultural Policy (CAP) mainstreaming

harvest and the following spring in order to take up mobile nutrients, such as nitrate, and hence reduce pollution of watercourses.

- Better use of complex farming systems including mixed crop-livestock and agroforestry techniques (inclusion of trees in cropland/grassland) that efficiently use nutrient resources, enhance biodiversity and mimic the natural ecosystems perennial grasses, permanent crops and deep rotting crops.[415]

However, despite the variety of studies large uncertainties in the magnitude of SOC emissions and mitigation potential prevail[427,428]. Some studies questioned the feasibility to achieve high emissions saving through carbon sequestration[429]. Uncertainties can be attributed to gaps in our understanding of future land use change, quantification of the response of carbon sequestration to land use change[423] future level of adoption of mitigation measures, potential feedback on $N_2O$ and $CH_4$ emissions, and persistence of mitigation[430]. In addition, there is an ongoing debate about the effectiveness of conservation tillage for SOC sequestration and consequently climate change mitigation since studies mainly relied on shallow sampling depth when comparing sequestration rates of conservation and conventional tillage systems. Some recent studies conclude that, even though conservation tillage may increase surface SOC concentrations, it does not store more SOC for the whole soil profile but solely redistributes carbon in the soil[431]. Carbon stored in soils also depends on the climate and weather, which can cause emissions of carbon or reduction of the carbon sequestration potential. This raises the question on the permanence of carbon in soils, together with the issue of soil saturation.

#### 4.7.1.2 Forest carbon sink

The current carbon sink on EU forest land results from an imbalance in a dynamic forest ecosystem. Growth each year in forest biomass (gross annual increment) is larger than the quantity of biomass taken out of forests through natural mortality and disturbances, and human activities (harvests). This imbalance results in an increase in net carbon stocks of EU forests, which in turn represents the net absorptions of $CO_2$ from the atmosphere in living biomass. The information reported in the UNFCCC inventories shows limited changes in the characteristics of the EU forest over the last 25 years. The carbon sink of the total forest is stable since 1990, slightly larger than -400 $MtCO_2$, with a small increase in the biomass produced but also a small increase of the annual losses in forest biomass (harvest and natural mortality).

Typically a forest system that has no human intervention (i.e. management) will move over the long term towards a balanced state, with a likely decrease in increment and an increase in mortality, and an upper limit to the carbon stock present in above ground biomass and a limited carbon sink. Optimising the European carbon sink would therefore need action to maintain or

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[427] Emanuele Lugato, Adrian Leip & Arwyn Jones (2018). Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. Nature Climate Change volume 8, pages 219–223

[428] Paul Gosling, Christopher van der Gast & Gary D. Bending (2017). Converting highly productive arable cropland in Europe to grassland: –a poor candidate for carbon sequestration. Nature, Scientific Reports volume 7, Article number: 10493

[429] Powlson, D. S., A. P. Whitmore and K. W. T. Goulding (2011). "Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false." European Journal of Soil Science 62(1): 42-55.

[430] Smith, P. (2012). "Soils and climate change." Current Opinion in Environmental Sustainability 4(5): 539-544.

[431] Baker, J. M., T. E. Ochsner, R. T. Venterea and T. J. Griffis (2007). "Tillage and soil carbon sequestration—What do we really know?" Agriculture, Ecosystems & Environment 118(1–4): 1-5.

intensify the forest system imbalance, through increasing the forest area through reforestation or afforestation of non-forest land, the carbon density per hectare of forest with other tree species, or through stimulating faster increment by optimising harvests and smarter management practices – or a combination of all three.

Afforestation, reforestation and reduced deforestation are obvious options to increase the coverage of EU forests potential together with possible co-benefits of many other ecosystem services such as biodiversity and reduced risks of soil erosion, floods, air and water pollution. Land is nevertheless a finite resource and extending forest coverage can, if carried out over large scales, intensify the competition for land with other sectors of the economy. Afforestation for instance may displace agricultural production of food, feed, fibre or energy, and subsequently increase GHG emissions in other GHG sectors. On the other hand, it may be the most productive and viable use of some land in the EU.

Limiting or reducing the amount of wood extracted annually from forests may increase the forest carbon stock and – at least in the short to medium term – the sink. Unfortunately, it comes with the drawback of limiting the supply of biomass for energy and wood product substitution that may otherwise lower emissions in other sectors. Other forest management practices can influence overall carbon stock density. Depending on the forest type and location, intervention may improve the nutrient supply and light available to or health of standing trees, thereby stimulating growth and increasing the overall carbon stock. The progressive introduction for instance of tree species with a faster growing rate – i.e. increment – has the potential to increase the carbon density of a forest while preserving biomass flows towards the rest of the economy. Such practices need to be carried out respecting the risk of potential negative impacts on biodiversity and other ecosystems services as well as possible increased demand for water resources.

Finally, the use of the harvested wood also matters. In essence, the more it is used for durable goods replacing those produced with fossil materials, such as construction, the more effective it is in reducing the release to the atmosphere of biogenic (and fossil) carbon. This concept is captured in the LULUCF accounts as Harvested Wood Products. Although in principle this use is only a temporary storage, with the $CO_2$ still being released eventually to the atmosphere, cascading use can also reduce emissions in other sectors. An example is reduction of production of other building materials like bricks and steel, or subsequent “waste” timber being incinerated for energy production, thus reducing emissions from fossil fuels as well.

When looking at how to preserve or enhance the forest sink, it is therefore of key importance to properly assess the interlinkages between the dynamic of the forest sink, the use of biomass in other sectors of EU economy and any associated environmental impact, including indirectly on carbon stocks due to displacement of other land based activities.

#### 4.7.1.3 Land to produce substitutes to fossil carbon

*Material substitutes*

Timber products, paper, bio-chemicals, fertilizer, textiles, elastomers, bio-based plastics, all are products from biomass origins that are present in our daily life. Some have the potential to replace a significant share of fossil fuel-based materials, while simultaneously storing carbon, sometimes for decades or centuries.

The use of wood in construction of houses represents about 10% of the EU construction market but varies significantly across Europe with a market share up to 80% in Nordic countries and very low penetration in Southern Europe[432]. Moreover, the use of wood in buildings of three storeys or more is likely to be lower than 1%. In some of the major economies outside the European Union, such as the United States or Japan, wood-frames represent about 40% of new constructions[433]. The ClimWood[433] study concluded that material use of harvest wood product leads to lower GHG emissions over the whole life cycle than the use of functionally equivalent alternatives by 1.5 to 3.5 t $CO_2$ saved per ton of wood product used.

The chemical industry is also interested in the use of biomass as alternative to fossil feedstock (see section industry). A large palette of oleo-chemical products produced from biomass are already credible alternatives to fossil feedstock based products, e.g. fertilizers, detergents, glycerine, cosmetics, pesticides, coating and colours, lubricants or plastics. Nevertheless, the global bioplastic production today (bio-based and biodegradable plastics together) represents less than 1% of the 300 Mt of plastics globally produced every year. However, this is a fast growing industry and bio-plastics are used for an increasing number of applications such as packaging (which account for 40% of bioplastics today), catering products, consumer electronics, automotive parts, agriculture, toys, or textiles. Some studies claim that they could replace in the long term almost all fossil fuel based plastics[434].

Growing demand for bio-based plastics will further increase the demand for feedstock, i.e. carbohydrate-rich crops such as corn or sugar cane today and potentially lignocellulosic crops in the future. While the environmental impact of this growing demand should be carefully and systematically looked at from a lifecycle assessment perspective, the land impact itself is expected to be rather limited. It has been estimated that replacing the global production of fossil plastic with bioplastic would require about 5% of the total amount of biomass globally produced and harvested each year[435].

*Energy substitutes*

In 2014, bioenergy represented 60% of the final renewable energy consumed in the EU[12] and about 10% of the gross final energy consumed. Bioenergy is used mostly for heat, followed by electricity generation, and transport. It provided in 2014 88% of renewable energy in heating, and 19% of renewable electricity. Most of the bioenergy is used in solid form; biogas and liquid biofuels represent smaller shares[436].

Currently, the main sources of solid biomass used in electricity, heating and cooling are EU produced forestry-based feedstocks such as fuelwood, industrial residues (e.g. residues from sawmills or from the paper industry), and forest harvesting residues (such as branches or tree tops). Biofuels are mostly produced from agricultural food crops. In 2015, an amount equivalent to 61% of domestic oilseed production, 13% of sugar beet production and 3.7% of cereal production were used for the production of biofuels. While biogas is produced mainly from annual energy crops (e.g. maize), there is a large potential in producing biogas from agricultural

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[432] Hurmekoski (2016), Long-term outlook for wood construction in Europe. Dissertationes Forestales 211. 57 p. http://dx.doi.org/10.14214/df.211

[433] Climwood2030 (2016) Climate benefits of material substitution by forest biomass and harvested wood products: Perspective 2030. Thünen Report 42. https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_42.pdf?

[434] European Bioplastics (2017), Bioplastics - facts and figures http://docs.european-bioplastics.org/2016/publications/EUBP_Facts_and_Figures_2017.pdf

[435] Martien van den Oever, Karin Molenveld, Maarten van der Zee, Harriëtte Bos (2017) - Bio-based and biodegradable plastics – Facts and Figures. Focus on food packaging in the Netherlands http://library.wur.nl/WebQuery/wurpubs/519929

[436] SWD(2016) 418- Sustainability of Bioenergy - Commission Staff Working Document accompanying the document Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast)

waste, residues, by-products (e.g. manure), sewage sludge, separated household waste, as well as industrial household waste.

In the future, a more important role for fast growing energy crops, i.e. lignocellulosic grass (e.g. switchgrass, miscanthus) and short rotation coppices (e.g. poplar, willow), is expected if not hampered by upfront investment costs or land availability. When cultivated in a sustainable manner, these crops could become the main input to gasification and pyrolysis processes for the production of biogas and biofuels. These fuels would allow for instance the deep decarbonisation of air transport, road freight and maritime sectors where only few alternatives exist and would also be used to replace fossil fuel methane in the gas grid, for applications where no alternatives exist.

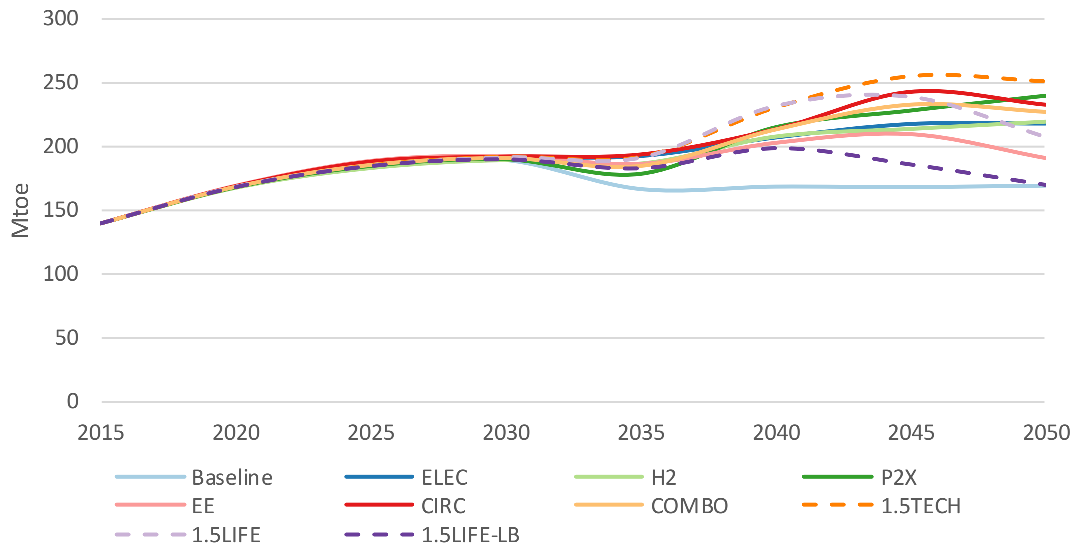
### *4.7.2 Biomass demand, supply and land use projections in the scenarios*

All the scenarios analysed in the PRIMES-GAINS-GLOBIOM set-up (see section 4.1 and annex 7.2.2 for scenario description) rely on a substantial use of biomass for energy. The 2050 gross inland consumption of biomass and waste of these scenarios is ranging from 190 Mtoe in the EE scenario to just over 250 Mtoe in 1.5TECH scenario (in 2016 the energy sector consumed 140 Mtoe of biomass[437]). The demand for biomass is similar for all scenarios until 2030 but diverges afterwards with more demand in the net zero GHG scenarios than in the scenarios achieving 80% GHG reduction until a peak in 2045 (dash line in Figure 82). Post 2045 the biomass demand is decreasing in net zero GHG scenarios, partly due to the deployment of other energy carriers (including the introduction of e-fuels). The scenarios achieving 80% GHG reduction continue to increase their biomass consumption after 2045.

In addition to the standard scenarios, a low biomass variant of the 1.5LIFE scenario has been introduced (1.5LIFE-LB) to better analyse the implications of achieving net zero GHG emissions with less increases in biomass use. Most of the characteristics of the 1.5LIFE scenario apply to this variant (circular economy, changing consumer preference and a high incentive to enhance the natural land use sink). However, compared to the standard 1.5LIFE, the 1.5LIFE-LB variant combines this with much more use of technology options available in 1.5TECH scenario that require less biomass. This results in considerably less use of biomass, with particular implication on its use in industry, residential and transport sectors.

[437] Eurostat Energy Balances 2018 edition

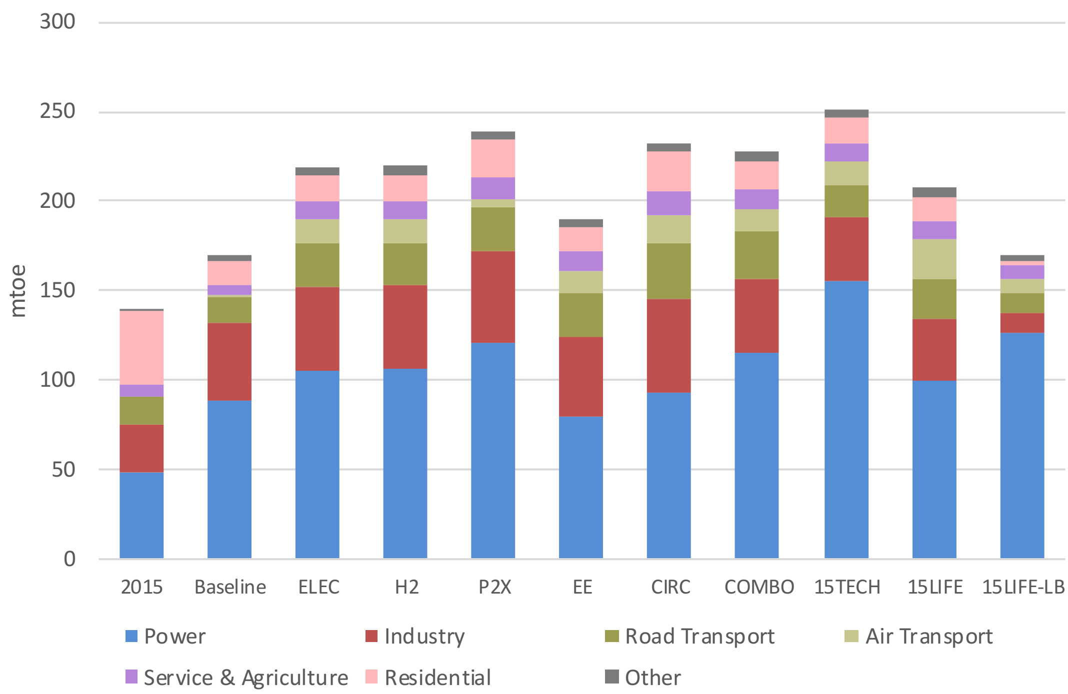
**Figure 82: Gross inland consumption of biomass and waste**




*Source: PRIMES.*

Power generation and residential heating are consuming today most of the biomass demand. Towards 2050 the use of biomass in the residential sector is expected to significantly decrease in all scenarios whereas the power and industrial sectors would absorb most of the additional demand in bioenergy. About 40% of the total biomass would be used to produce electricity in a demand-side scenarios (EE, CIRC) and up to 75% in the 1.5LIFE-LB. The 1.5LIFE-LB scenario stands out by its low requirement in biomass for industry through the high penetration of hydrogen and electricity for industrial heating as well as a very strong reduction of biomass used for residential heating and less use in transport. The decarbonisation of road and air transport requires advanced biofuels that could be produced at scale after 2030, nevertheless it would not represent more than 20% of the total use of biomass in any of the scenarios (Figure 83).

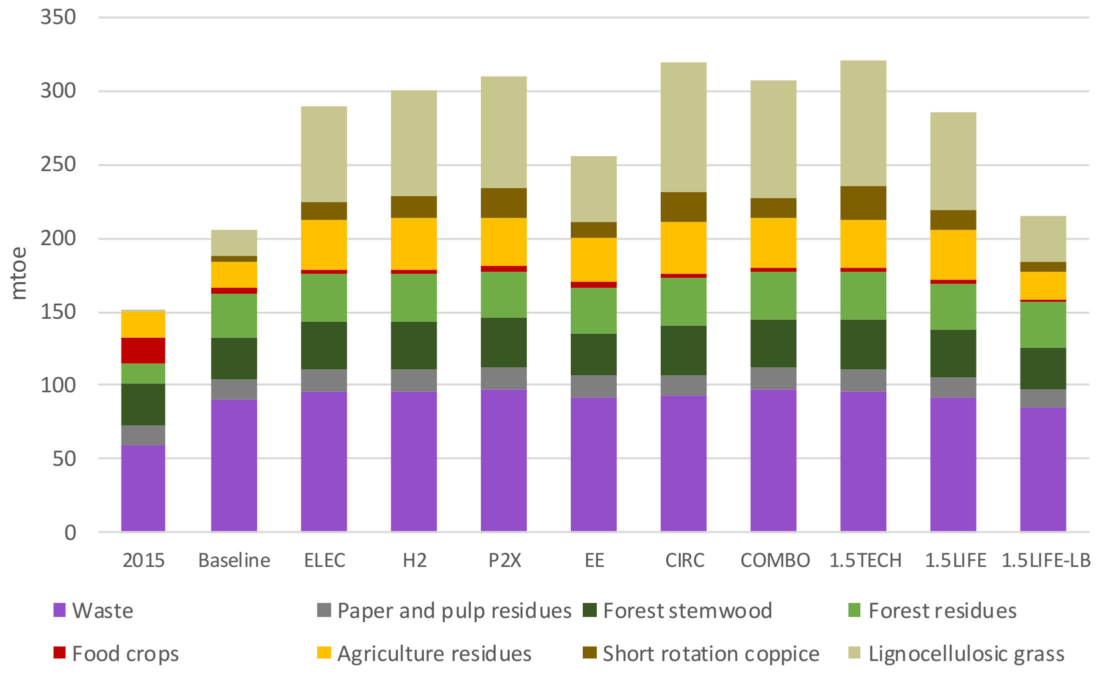
**Figure 83: Use of bioenergy by sectors and by scenario in 2050**



*Source: PRIMES.*

All the scenarios assume that most of the biomass used in the 2050 EU economy is produced domestically (only 4 to 6% of the solid biomass is imported by 2050, no assessment has been made on the overall climate impacts if biomass were to be imported instead). The domestic production of feedstock to fulfil the EU demand for bioenergy is ranging from 214 Mtoe in the 1.5LIFE-LB scenario to more than 320 Mtoe in 1.5TECH scenarios (Figure 84).

**Figure 84: Break down of bioenergy feedstock in 2050**



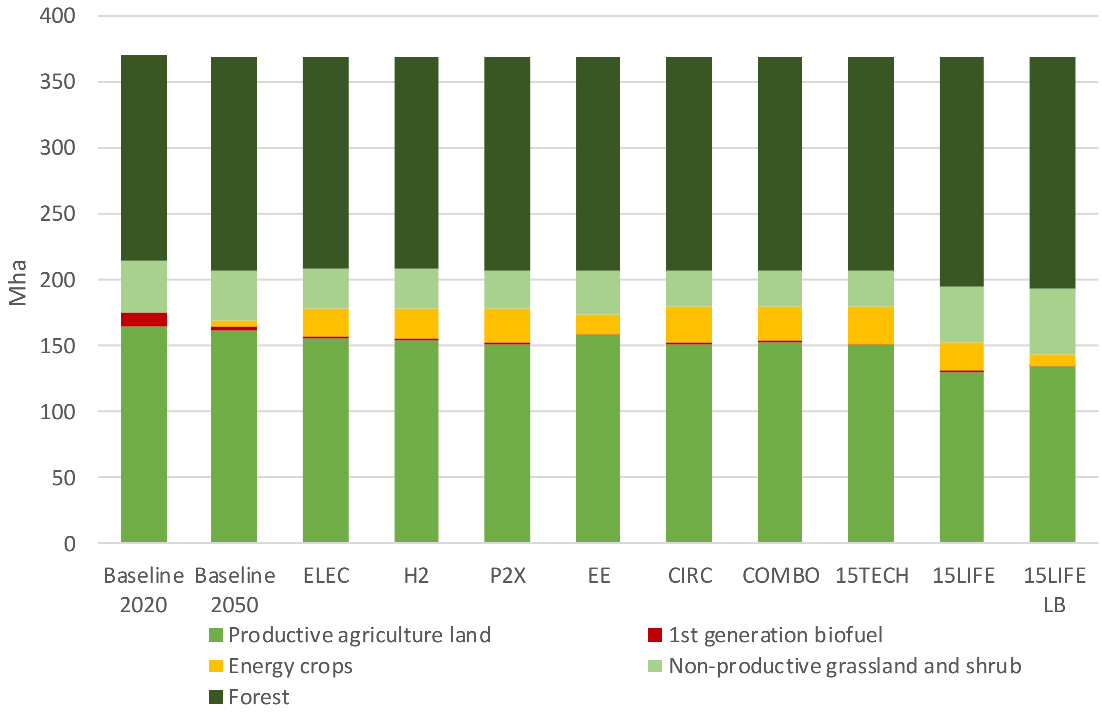

*Source: PRIMES, GLOBIOM.*

A significant share of the feedstock used to produce this bioenergy is coming from the waste sector with an improvement in the industrial and municipal waste collection that could supply about 100 Mtoe of feedstock to the energy sector. The use of harvested stemwood stays at 2015 level in all scenarios while the sustainable extraction of forest residues increases, in total the forest sector provides 60 to 65 Mtoe of wood for energy. Biogas or biofuels produced from food crops will be very marginal in EU by 2050 but more agriculture residues are used for the production of biogas or solid biomass. The optimisation of the sustainable exploitation of all these classical sources of biomass could supply just over 200 Mtoe of feedstock for bioenergy production to the EU economy.

Fast growing energy crops will provide for the rest of needs in biomass. Scenarios vary substantially in their demand for these new energy crops. The 1.5LIFE-LB scenario requires 38 Mtoe of bioenergy whereas the demand in CIRC and 1.5TECH reach 108 Mtoe. Most of the demand is supplied via lignocellulosic grass such as switchgrass and miscanthus while short rotation coppices, poplar and willow, provide only 20 to 25% of the demand in energy crops.

This substantial demand on bioenergy to help to decarbonise the EU economy can have significant impacts on land use and land use changes (Figure 85) with all scenarios having an increased amount of land dedicated to the production of energy crops. The scenarios with highest energy crop requirements (scenarios 1.5TECH and CIRC) see about 29 Mha of land being used for new energy crops. Overall this would represent a diversification of agriculture land producing energy crops, on top of the area currently used for first generation biofuels, equivalent to 10% of current productive agricultural land. The scenario with lowest energy crop requirements (scenario 1.5LIFE-LB) see about 9 Mha of land being used for new energy crops. Most of the changes happen through a large switch towards lignocellulosic grass (mainly switchgrass), notably from unused grassland and through the availability of cropland currently used for the production of first generation biofuel.[438] New demand for woody biomass could further diversify today's farming business on around 10% of EU agriculture land. Some afforestation also occurs, in particular on abandoned agricultural land. In 1.5LIFE scenarios that assume consumption patterns with lower climate impacts, including changes in food consumption preferences as discussed in 4.6.2.3 (Diet 4), the shift and reduction in meat consumption frees additional land (production of meat has one of the largest land requirement per calorie) and allows for increased afforestation.

**Figure 85: Use of natural land by 2050**




*Source: GLOBIOM.*

In terms of LULUCF emissions, the substantial use of woody energy crops instead of stem forest feedstock wood limits the negative impact on the forest sink and therefore helps to maintain the overall LULUCF sink in all scenarios. Moreover, the models shows that the LULUCF sink could be enhanced further through economic incentives targeting various mitigation options such as the

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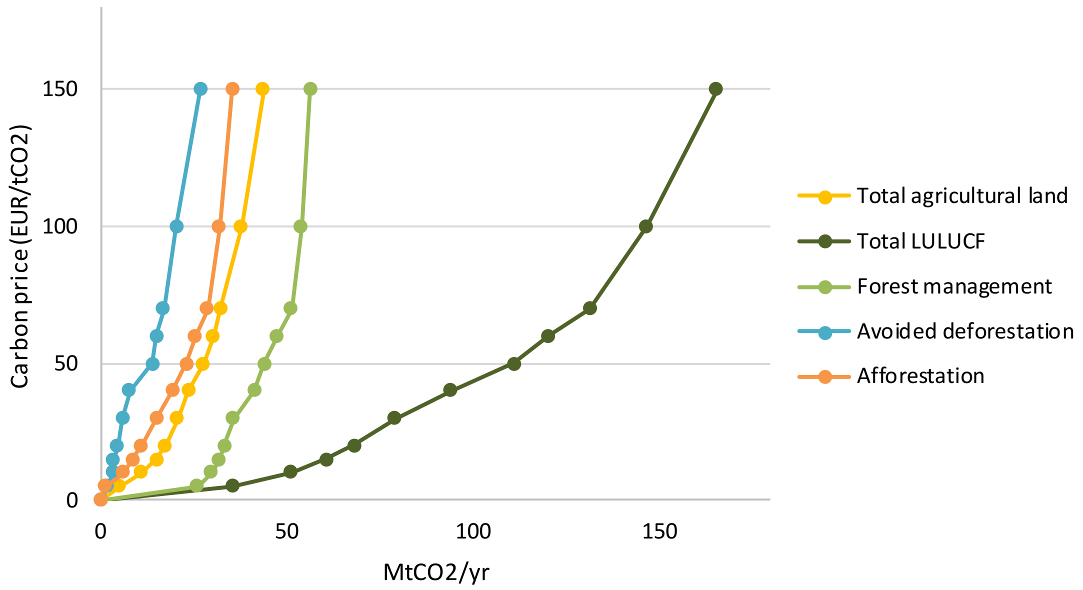
438 Effects such as foregone carbon sequestration from biofuels grown on productive and non-productive agriculture land and shrub land are captured by the models. The models also replace the protein by-products lost when replacing 1st generation biofuel with energy crops by another source of protein to ensure the feeding of animals and the land use effect of this replacement is also captured. Finally, the imports of agricultural products are limited to Baseline level to assess the impact of mitigation scenarios without displacement of agricultural production outside EU. The impacts on overall GHG emissions, direct and indirect, if changes in imports would occur is not assessed.

reduction of deforestation, increase of afforestation, better forest management and better agriculture practices storing soil carbon.

Figure 86 shows the potential for enhancing the LULUCF sink at different carbon prices. A carbon price of 150 euro in 2050 could increase the forest sink by almost 120 $MtCO_2$ and the total LULUCF sink by more than 160 $MtCO_2$ compared to a situation without carbon price applied to the LULUCF sector. At a carbon price of 70 euro the total LULUCF sink could already be above 130 $MtCO_2$. These amounts are in relative terms large compared to emissions by 2050 but small compared to emissions in 1990, this is less than 3% of emissions, underlining the priority to reduce emissions first.

The largest potential is in the optimization of forest management practices (changes of stand rotation length, ratio of thinning versus final fellings, harvest intensity or harvest locations) and could increase the forest sink by 56 $MtCO_2$. Improvement in agriculture practices aiming at sequestering more carbon into the soil would enhance the LULUCF sink by an additional 47 $MtCO_2$. Incentivised additional afforestation could remove annually 36 $MtCO_2$ from the atmosphere, requiring the conversion of roughly 5 Mha of land into new forests by 2050.

**Figure 86: Potential for carbon sequestration and LULUCF sink enhancement at different carbon prices in 2050**




*Source: GLOBIOM/G4M.*

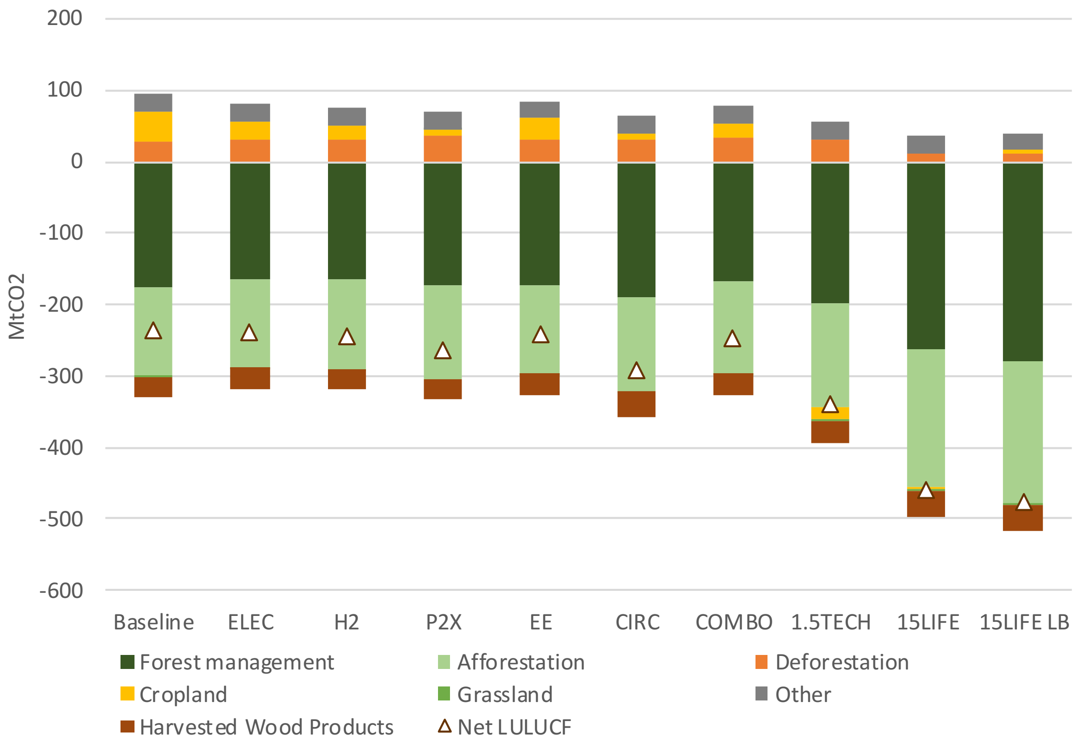
Only the net zero GHG scenarios include a specific incentive to enhance the LULUCF sink, strongest for 1.5LIFE (80€/$tCO_2$) and 1.5LIFE-LB (70€/$tCO_2$) and relatively limited for 1.5TECH (30€/$tCO_2$).

The strong penetration of energy crops in 1.5TECH coupled with the implementation of agricultural practices aiming at improving the soil carbon sequestration makes possible for EU cropland to turn, in this scenario, from net carbon source to net carbon sink by 2050, with a LULUCF sink in EU increasing to close to 400 $MtCO_2$.

In the 1.5LIFE scenarios, more land becomes available for afforestation, and this combined with the incentive to enhance the sink allows it to increase to 500 $MtCO_2$. This allow to reduce the reliance on BECCS and other carbon dioxide removal technologies to achieve net zero GHG (Figure 87).

Scenarios without incentives to enhance the LULUCF sink present variations but show that even if some scenario see a decline in the LULUCF sink compared to current level (circa 300 $MtCO_2$), all scenarios could maintain by 2050 a net LULUCF sink above 230 $MtCO_2$.

**Figure 87: LULUCF emissions across the scenarios**




*Source: GLOBIOM.*

### *4.7.3 Transition enablers, opportunities and challenges*

Most of the scenario analysed see an important increase in the use of biomass by 2050 with a doubling of the current demand in biomass feedstock for energy in some scenarios (see section 4.7.2). This energy should be firstly supplied by the efficient use of feedstock such as industrial and municipal waste or agriculture and forest residues that have less environmental impacts and affect less other economic activities.

The full mobilisation of waste streams would not be sufficient to satisfy the EU demand in bioenergy. The two main options to supply the additional biomass required that are assessed are the increased mobilization of wood from forest and the development of fast growing lignocellulosic crops. Both options have different impacts on land use, carbon sink or biodiversity that need to be considered. This assessment did not look into the consequences of increasing biomass imports.

As discussed in section 4.7.1.2, a sustainable intensification of forest biomass mobilization is constrained by the net annual increment of the forest and could potentially conflict with the production of wood material for other sectors and with other eco-services provided by the forest such as climate regulation (through carbon sequestration), pollution control, soil protection, nutriment cycle, biodiversity protection, water regulation or recreation.[439] However active sustainable management of forests is key to ensure that forests continue to sequester carbon, and provide biomass, and enhancement are possible.

Expansion of the forest area through afforestation and reforestation would limit the trade-off between the different uses of forests and develop their synergies in EU. However, it could then affect the availability of land for other sectors, in particular the agriculture sector. Finally, afforestation is a slow process and its benefits for providing biomass and $CO_2$ removal could take several decades to materialize.

Fast growing energy crops includes lignocellulosic grass and short rotation coppices characterized by faster growing rates and therefore higher productivity potential than forest biomass production. These energy crops can maintain, to some extent, economically viable yields on marginal lands and better preserve the soil content in organic carbon compared to arable land.

Energy crops are cultivated on agriculture land and can compete with the production of other agriculture commodities. Taking into account the volumes needed, energy crops could strongly contribute to farm income. But in order to not result in the displacement of food and feed production outside EU (with potentially indirect effects) further efficiency improvements and more efficient use of land are required according to the type of product grown. Such changes will have elements of intensification of agriculture production and care will need to be taken with consequences in terms of biodiversity or other environmental sustainability. But if well managed, this transition could help to reverse the trend in farmland abandonment and offer to farmers new economic perspectives.

## 4.8 Towards negative emissions

### *4.8.1 Why negative emissions and what are the options?*

In order to achieve the objectives of the 80% GHG reduction scenario, and even more so for the net zero GHG scenarios, the absolute priority is to reduce emissions. But emissions can never be reduced to zero. For instance, certain agriculture based non-$CO_2$ emissions cannot be eliminated. Reaching the global objectives of the Paris Agreement without measures aiming at removing $CO_2$ from the atmosphere is extremely challenging. It could even become quickly impossible if no immediate and very ambitious global action is undertaken.

Therefore removing the $CO_2$ from the atmosphere has to be considered as an option for a long term GHG reduction strategy. Assessing what its associated challenges are can also inform to what extent the focus has to be on achieving emissions reduction as soon as possible, which lowers the reliance on negative emissions subsequently.

Removing $CO_2$ from the atmosphere can be achieved by enhancing the natural carbon sink, by using engineering technologies or through a combination of both. Increasing the natural sink through ecosystems restoration, afforestation, reforestation, improved forest management and enhancing soil carbon sequestration has already been addressed in section 4.7.1.2.

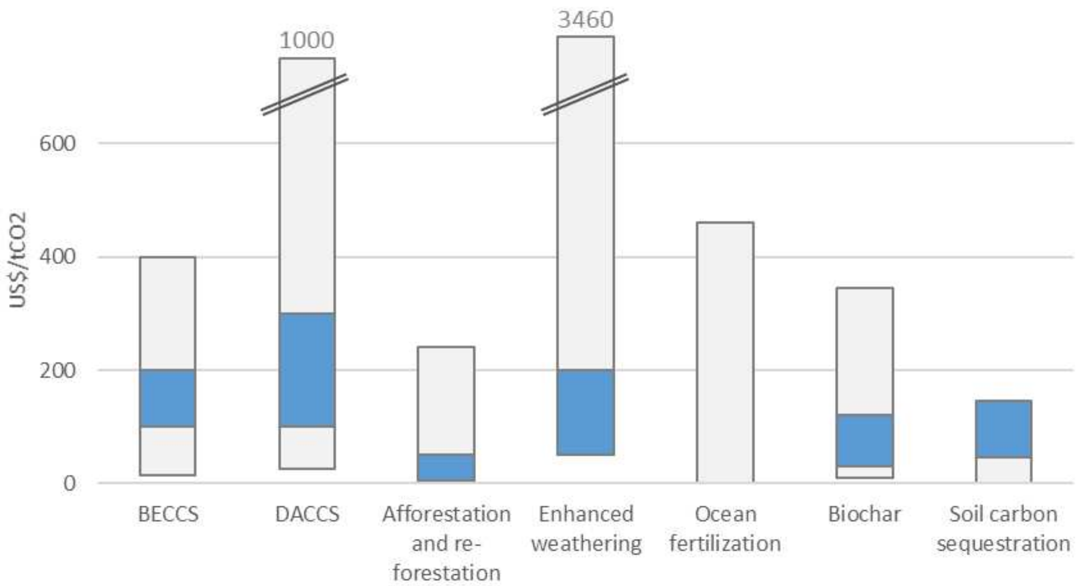
Other carbon dioxide removal (CDR) options include the use of biomass for energy coupled with carbon capture and underground storage technologies (BECCS), direct air $CO_2$ capture and subsequent underground storage (DACCS), biochar, enhanced weathering, ocean alkalinisation

[439] http://forest.jrc.ec.europa.eu/activities/forest-ecosystem-services/

and ocean fertilisation. We do not consider in this section the removal of other GHG than $CO_2$ even if some technologies exist[440]

Providing cost estimates of various options for removing carbon from the atmosphere is challenging. Costs from the literature vary significantly, reflecting the heterogeneity in the methodologies used for their estimates. These large ranges of possible costs and uncertainties are unavoidable since most of the options for carbon removals are only at an exploratory stage and none of them are sufficiently mature for large deployment (except afforestation, reforestation and ecosystem restoration). The cost estimates reported in a recent and comprehensive review[441] of the current knowledge regarding CDR technologies is summarised in Figure 88. According to this review, most of the CDR options could remove $CO_2$ from atmosphere at a cost below 200 euro/t$CO_2$, in the long term and assuming a removal of the uncertainties surrounding the development and implementation of the technologies involved. The authors of the study do not consider any real potential for ocean fertilisation.

**Figure 88: Cost of carbon dioxide removal technologies**




*Note: The full range of costs reported in the literature, the blue colour reflect the part of the ranges the authors of the study consider as the most likely.*

*Source: Adapted from Fuss et al., 2018*[441].

#### 4.8.1.1 BECCS and DACCS

*Biomass for Energy with Carbon Capture and Storage*

The concept of BECCS lies in the utilisation of biomass as feedstock to generate bioenergy in association with carbon capture and storage technologies (CCS). Together with massive afforestation, BECCS is often seen in the integrated assessment models as one of the main two options for removing permanently from the atmosphere the carbon in exceedance of an emissions budget compatible with the Paris Agreement.

[440] Ming T, de_Richter R, Shen S and Caillol S (2016), Fighting global warming by greenhouse gas removal: destroying atmospheric nitrous oxide thanks to synergies between two breakthrough technologies Environ. Sci. Pollut. Res. 23 6119–38

[441] Sabine Fuss et al (2018), Environ. Res. Lett. 13 063002, https://doi.org/10.1088/1748-9326/aabf9f

The role of BECCS in the long term will depend on the ability to supply large amounts of biomass in a sustainable way, and on the development of CCS technologies.

Large deployment of bioenergy raises the question of the quantity of land required for the production of the biomass feedstocks and the competition with other possible use of the land, including the necessity to cover demand for food, feed and fibre while preserving ecosystem services and biodiversity. This issue has been addressed in the section 4.7 dedicated to land resources.

Carbon capture and geological storage (CCS) is a technique for capturing carbon dioxide emitted from large point sources such as power plants and industrial installations, compressing it, transporting it and injecting it in suitable storage sites underground. The $CO_2$ emitted from the combustion of the biomass can be stored in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs that have the largest storage potential.

Not all bioenergy applications can be linked to CCS. Capital cost of $CO_2$ capture may prohibit the capture of $CO_2$ on small bioenergy installations. On the other hand, the $CO_2$ concentration in the flue gases of some bioenergy installations such as those for production of bioethanol and biogas is very high and thus appropriate for $CO_2$ capture.

There are a few large CCS projects under development currently in Europe[442]. The Port of Rotterdam PORTHOS project has the ambition to store 2Mt/$CO_2$ per year from 2020 on going up to 5Mt$CO_2$ per year by 2030, which would be about 15% of the Rotterdam's industrial sector emissions. Norway is putting in place a relatively large industrial CCS project: capture from the Oslo waste incinerator and a cement plant, shipping of the $CO_2$ and storing deep under the Norwegian North Sea. There is a small number of other CCS projects and clusters in preparation mostly in the countries around the North Sea but all of them are in rather early stages.

*Direct air* $CO_2$ *capture and storage (DACCS)*

Directly filtering $CO_2$ from ambient air, without relying on photosynthesis, and subsequent underground storage is an alternative to BECCS that has receive increasing attention in recent years, including from the energy and climate modelling community. DACCS comprises several distinct technologies to remove $CO_2$ from the atmosphere making use of different materials. Contrary to the flue gases of power plants and industrial installations, the concentration of $CO_2$ in the atmosphere is very low (0,04%). It is therefore key to use agents capable of binding efficiently with the few $CO_2$ molecules of the ambient air. Most attempts have focused on hydroxide sorbents, such as calcium hydroxide but today other processes and materials are under investigation, mostly involving amines. Engineering problems involve enlarging the contact surface to increase $CO_2$ withdrawal and dealing with moisture.

The main advantage of DACCS over BECCS is in terms of land impact since it does not require biomass and can be deployed on non-productive land in combination with renewable energy technologies such a solar, in the proximity of storage sites. Capturing 100 Mt$CO_2$ annually with direct air capture requires between 4 kha and 15 kha, versus 3 to 6 Mha for BECCS and 14 to 33 Mha with afforestation[443].

However, while BECCS delivers energy together with carbon removals, capturing $CO_2$ directly from the ambient air requires on the contrary a significant amount of energy. Estimates refer to

[442] COM(2016) 743

[443] This estimation assume estimates from Smith at al 2016 for BECCS and Smith at al 2016 and information available on Climworks website for DACCS (http://www.climeworks.com/our-products/) and the implied emission factor from UNFCCC for afforestation (cf section 4.7.1.2)

0.5 MJ per $kgCO_2$[444]. Depending of the type of energy used, preferably renewable, the production of this energy could also have a land impact. The release of $CO_2$ from the sorbent and the regeneration of the sorbent is particularly energy intensive.

Research and development on Direct Air Capture technologies is rather dynamic nowadays, progress can reasonably be expected in a mid-term future. Two direct air capture pilot plants are running in Canada and a third in Switzerland, providing $CO_2$ for re-use application (greenhouses, carbonated beverages, but also targeting sectors such as Enhanced Oil recovery or synthetic fuel production) with capacities of 300 to 900 $tCO_2$ per year.

A Direct Air Carbon Capture and Storage pilot plant has been launched in Iceland in 2017 with the objective to extract 50 $tCO_2$ and combine it with a specific CCS technology where the CO2 is stored underground in basaltic rocks where it is mineralised relatively rapidly into stable carbonate minerals[445]. In the long run, DACCS has a real potential for technological development and could become the predominant technological option to remove $CO_2$ from the atmosphere in an energy system dominated by cheap renewable energy and batteries.

#### 4.8.1.2 Other Options not considered further in this assessment

Biochar, Ocean fertilisation, Enhanced Weathering and ocean alkalinisation all still have uncertainties regarding the effectiveness and scalability of their $CO_2$ absorption and storage potential. Further research and large-scale field testing is needed to increase the understanding of the overall effects on $CO_2$ storage, the associated costs and other environmental impacts

*Biochar*

Biochar is produced from biomass by pyrolysis, i.e. thermal degradation of biomass in absence of oxygen. Added to soil, it can increase the amount of carbon stored with the potential co-benefit of increasing the fertility of the soil and therefore crop yields. Different processes take place when biochar is added to the soil and some uncertainties remain in the understanding of the overall effects on carbon sequestration and environment. The residence time of biochar into soils is likely to be variable and not well known. Presence of biochar in soils may influence the breakdown of other soil organic carbon which could counteract sequestration of carbon. The interactions between biochar and soils are mostly analysed in laboratories but it is not clear how applicable they are under field conditions[446]. In addition, producing the biomass feedstock for biochar requires land and water. Contrary to bioenergy, biochar does not supply by itself energy for the rest of the economy, with the pyrolysis that produces biochar being itself energy consuming. However, the gasification of biomass for the production of clean fuels can also produce biochar as by-product.

*Enhanced Weathering and ocean alkalinisation*

Weathering is the process of rock decomposition via chemical and physical processes. Rainwater is slightly acidic due to the absorption of $CO_2$ from the atmosphere that occurs in the clouds. When the drops reach the ground they chemically react with rocks and soils and the $CO_2$ content of the rainwater is transformed into bicarbonate and part of it eventually ends up in carbonate minerals in soils or on the ocean seafloor. The efficiency of this natural process depends very

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[444] American Physical Society(2011), Direct Air Capture of $CO_2$ with Chemicals A Technology Assessment for the APS Panel on Public Affairs June 1, 2011

[445] https://www.or.is/english/carbfix/carbfix-project

[446] RICARDO-AEA (2016), Effective performance of tools for climate action policy – meta-review of Common Agricultural Policy (CAP) mainstreaming (Ricardo-AEA/R/ED60006/Mitigation potential, 08/01/2016), report for European Commission – DG Climate Action.

much on temperature and climate, characteristics of the rocks, water solution, interaction with the environment and reactive surface area. Enhanced weathering aims at controlling one or several of these drivers in order to speed up the transfer of the $CO_2$ from the atmosphere to carbonate minerals through this process.

One of the most mentioned approaches is to pulverise the rocks in small grains to maximise the reactive surface area. The powder made out of this pulverisation is eventually spread over agricultural land where microorganisms help to further accelerate the mineralisation process with, as co-benefit, an increase in the soil fertility. The powder can also be spread directly on the surface of the oceans, contributing to a further alkalinisation of the oceans (reducing acidification) and therefore increasing their potential to directly absorb $CO_2$ from the atmosphere.

The main barrier with this option is the slowness of the mineralisation process and the energetic and economical costs associated to the mining and pulverisation of the enormous quantity of rocks needed to counterbalance this slowness and remove the $CO_2$ from the atmosphere at a significant rate.

*Ocean fertilisation*

Increasing the production of phytoplankton in the oceans is another possibility to remove carbon from the atmosphere. Oceans are limited in nutrients and in particular in micronutrients such as iron. About one third of the oceans could see their phytoplankton production significantly enhanced by injecting relatively small quantities of iron[447]. This can trigger a bloom of algae, of which part ultimately sink towards the ocean floor with part of the carbon sequestered in ocean floor sediments.

Part of the carbon stays in the water column on shorter time scales, limiting the quantity of carbon permanently stored. The acidity of oceans also increases after dissolution of the $CO_2$ due to the high recycling rate of organic carbon. Ocean fertilisation is expected to alter local to regional food cycles stimulating phytoplankton production, which is the food cycle’s basis. The unknown magnitude of impacts on ecosystems implies strong risks for biodiversity and the sustainability of ecosystems.

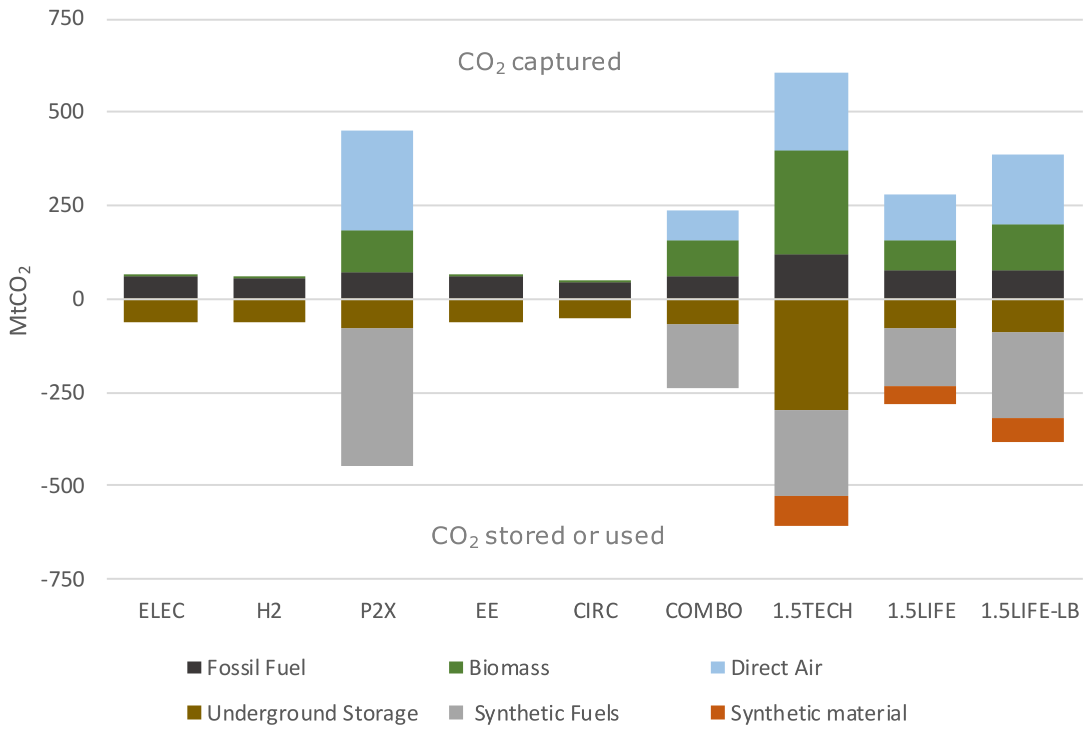
### *4.8.2 Negative emissions in the scenarios*

The only technological options envisaged to capture $CO_2$ in the scenarios analysed are the capture of carbon from the combustion of biomass or fossil fuel and direct air capture. The carbon captured is then either directly stored underground or reused for the production of synthetic fuels and synthetic material (mainly plastics). Figure 89 shows that 1.5TECH, P2X but also COMBO, 1.5LIFE and its low biomass variant 1.5LIFE-LB are scenarios that require a substantial amount of $CO_2$ captured by 2050. All these scenarios favour the reuse of the $CO_2$ rather than long-term geological storage with the exception of 1.5TECH. Only non-fossil fuel carbon from biomass or direct air capture is reused to produce e-fuels or synthetic plastics, insuring a truly carbon neutral process and not a simple delay of fossil fuel $CO_2$ emissions

Direct air and biomass $CO_2$ capture are very limited in scenarios achieving 80% GHG reduction other than P2X and COMBO. The deployment of fossil fuel CCS capacity is also rather limited in these scenarios.

[447] Sabine Fuss et al (2018), Environ. Res. Lett. 13 063002, https://doi.org/10.1088/1748-9326/aabf9f

**Figure 89: $CO_2$ capture and storage or reuse (2050)**




*Source: PRIMES.*

In all scenarios achieving 80% GHG reduction, as well as in the 1.5LIFE scenarios, most of the $CO_2$ stored underground is from fossil fuel origin and mainly captured in the industry sector (Table 8). Only the 1.5TECH scenario differs with biogenic carbon supplying the largest share of $CO_2$ stored in geological storage sites. The 1.5TECH scenario requires a substantial amount of technological carbon removal to generate negative emissions (BECCS) to offset the residual emissions (in particular non-$CO_2$ emissions from agriculture) and reach GHG neutrality by 2050. This is contrary to the 1.5LIFE and 1.5LIFE-LB scenarios that reduce further non-$CO_2$ emissions and relies on a larger LULUCF sink. The 1.5LIFE-LB scenario has a relatively high reliance on synthetic fuels as an alternative to advanced biofuels (due to lower level of biomass availability).

The CCS capacity in industry sector range from 44 $MtCO_2$ in P2X to 71-81 $MtCO_2$ in the net zero GHG scenarios.

**Table 8: Carbon Captured and stored underground ($MtCO_2$)**

| CCS | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5TECH | 1.5LIFE | 1.5LIFE-LB |
|---|---|---|---|---|---|---|---|---|---|---|
| Power | 5 | 6 | 7 | 16 | 4 | 7 | 7 | 218 | 9 | 20 |
| Industry | 0 | 59 | 57 | 61 | 60 | 44 | 60 | 81 | 71 | 71 |
| **Total** | 5 | 65 | 63 | 77 | 65 | 52 | 67 | 298 | 80 | 92 |
| *from Biomass** | 0 | 5 | 6 | 6 | 4 | 5 | 6 | 178 | 6 | 14 |

**Note: CCS with biomass is predominantly used in the power sector in the PRIMES scenarios*

*Source: PRIMES.*

### *4.8.3 Transition enablers, opportunities and challenges*

The priority is clearly at reducing GHG emissions, with negative emissions needed to offset the remaining emissions that are most difficult to abate in transport, in industry and certainly the non-CO2 residual emissions from the agriculture sector. Maintaining or even increasing the LULUCF sink is essential but might not be sufficient and will in itself depend on other developments, for instance related to changing dietary consumer preferences. In this respect, the carbon dioxide removal technologies are also part of the solution and should not be disregarded. As the IPCC 1.5°C Special Report indicated they will certainly have an important role to play at global level. Developing and testing them as such in the EU would also therefore serve a global role.

The most relevant source of negative emissions for the respondents of the open public consultation (see section 7.1) is intensive afforestation, a view shared by individuals as well as many professionals, and the potential of direct air capture raises scepticism. The replies also indicate a preference for carbon capture and long-term utilization rather than carbon capture and underground storage. BECCS was an important point of discussion among the responses of the open public consultation, with significant concerns expressed over the actual emissions savings achievable, the energy inputs needed and the diversion of resources from other technologies.

On the other hand industrial and other professional organisations often concluded that development of CCS and CCU is a needed option to reduce GHG emissions in industrial and energy sectors, requiring more investment in research and development and underlining that an enabling policy framework is needed.

Although all components of CCS are known and deployed at commercial scale, barriers to the uptake of integrated systems exist. The cost of the capture and storage remains important, the capture component being particularly costly for processes emitting flue gas with a low concentration of $CO_2$. The second barrier is the social acceptance for onshore storage in Europe, with the integrity of CCS, and the perceived risk of $CO_2$ leakage, being a concern[448]. Therefore, CCS projects under development at the moment plan to store $CO_2$ offshore, where the public acceptance issue is unlikely to arise, such as below seabed storage. Correct application of the provisions in the CCS Directive[449] is meant to ensure that the $CO_2$ captured and stored remains isolated from the atmosphere in the long term. Studies estimate that appropriately selected and

[448] ECN, Global CCS Institute. What happened in Barendrecht? Case study on the planned onshore carbon dioxide storage in Barendrecht, the Netherlands, http://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/8172/barendrecht-ccs-project-case-study.pdf

[449] Directive 2009/31/EC

managed geological reservoirs are very likely to retain over 99% of the sequestered $CO_2$ for longer than 100 years and likely to retain 99% of it for longer than 1000 years[450].

The capture of $CO_2$ and its storage can take place on different sites and possibly different countries. A typical example would be a power station with capture of the $CO_2$ emitted but then transfer this $CO_2$ to another Member State with offshore storage capacities. In this context, it would be important to ensure the deployment at scale of the necessary infrastructure to transport $CO_2$ but also the set-up of a consistent framework to account correctly for emission removals.

## 4.9 Economy wide greenhouse gas emission pathways

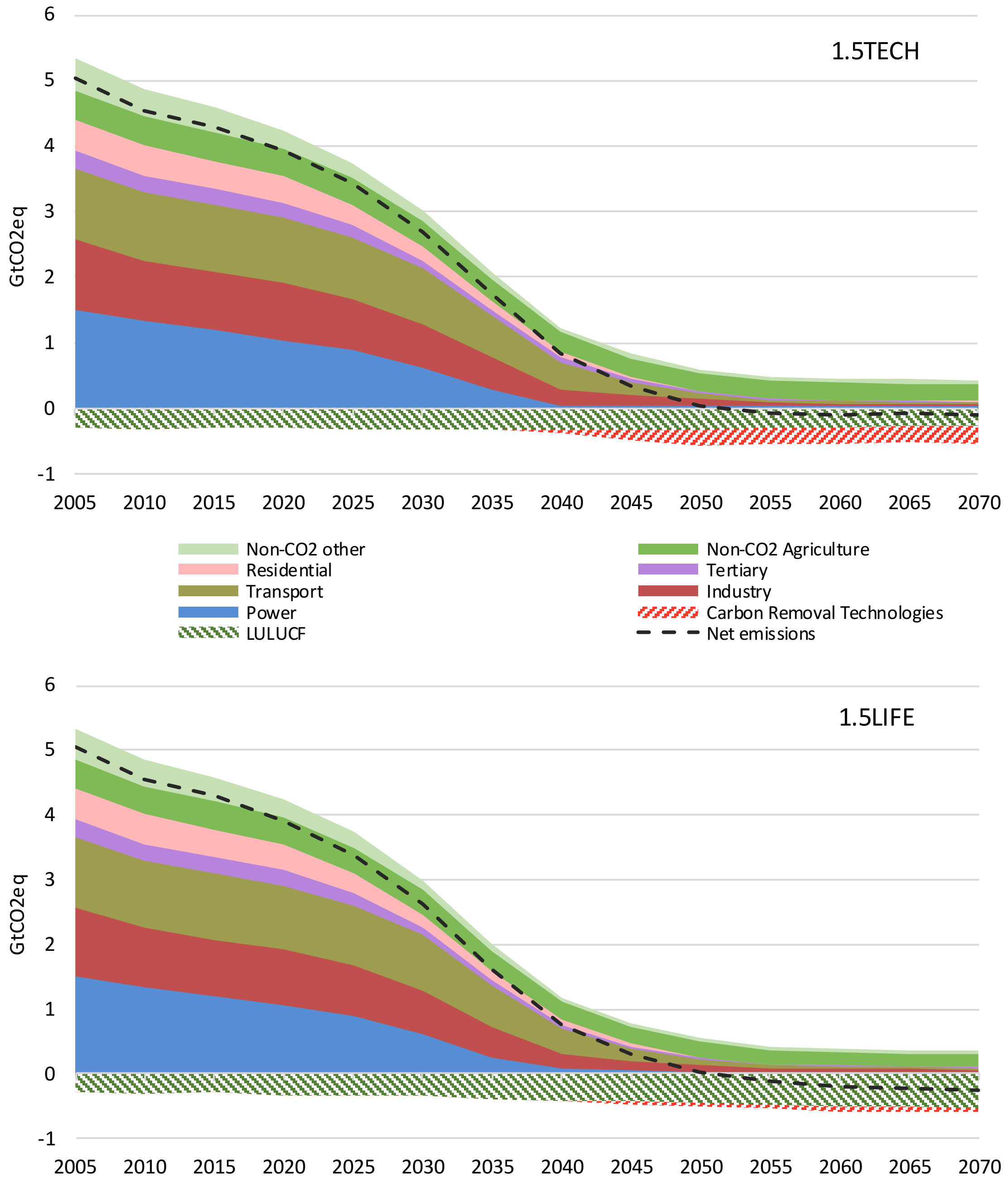
All pathways towards decarbonisation show that major progress will be required early on, and in all sectors. Under the baseline, total net GHG emissions (including the LULUCF sink) are reduced by around 64% in 2050 (relative to 1990). No sector would achieve full decarbonisation and most progress would be achieved in power generation and district heating because of the falling cost of renewable electricity sources. Also industry sectors included in the ETS see significant reductions, though no full decarbonisation by 2050.

Instead, in the net zero GHG pathways all energy and $CO_2$ related emissions strongly decrease towards full decarbonisation. Non-$CO_2$ emissions will be the most difficult ones to reduce and become a critical factor in the achievement of zero GHG emissions and the corresponding need to materialise negative emissions. Even with consumer choices evolving towards more climate friendly options, non-$CO_2$ emissions would remain by far the most important source of GHG emissions.

As a result, the size of the carbon sink and the deployment of carbon dioxide removal technologies will be a determining factor in achieving GHG neutrality and net negative emissions (see Figure 90).

[450] IPCC (2005) Carbon Dioxide Capture and Storage (SRCCS) https://www.ipcc.ch/report/srccs/

**Figure 90: Two ways to reach net zero GHG emissions - reduction pathways for 1.5TECH (above) and 1.5LIFE scenario (below) with enhanced LULUCF sink[451]**




*Source: PRIMES, GAINS, GLOBIOM.*

Under the various decarbonisation pathways, the fastest sector to decarbonise is the power sector. This is the first sector to reach zero emissions in all scenarios and even net negative emissions in the most ambitious scenarios with the use of bioenergy associated to CCS. The residential and tertiary sectors are also decarbonising faster than average thanks to the advances in energy efficiency and increased renovation rates. Instead, in industry (including process $CO_2$ emissions) and transport, reductions are somewhat lower. This is most notable for transport, with emissions remaining above 1995 levels until 2025 and only reducing by 2050 to around -60% of 1990

[451] See Annex 7.7 for GHG emissions reduction pathways of other scenarios

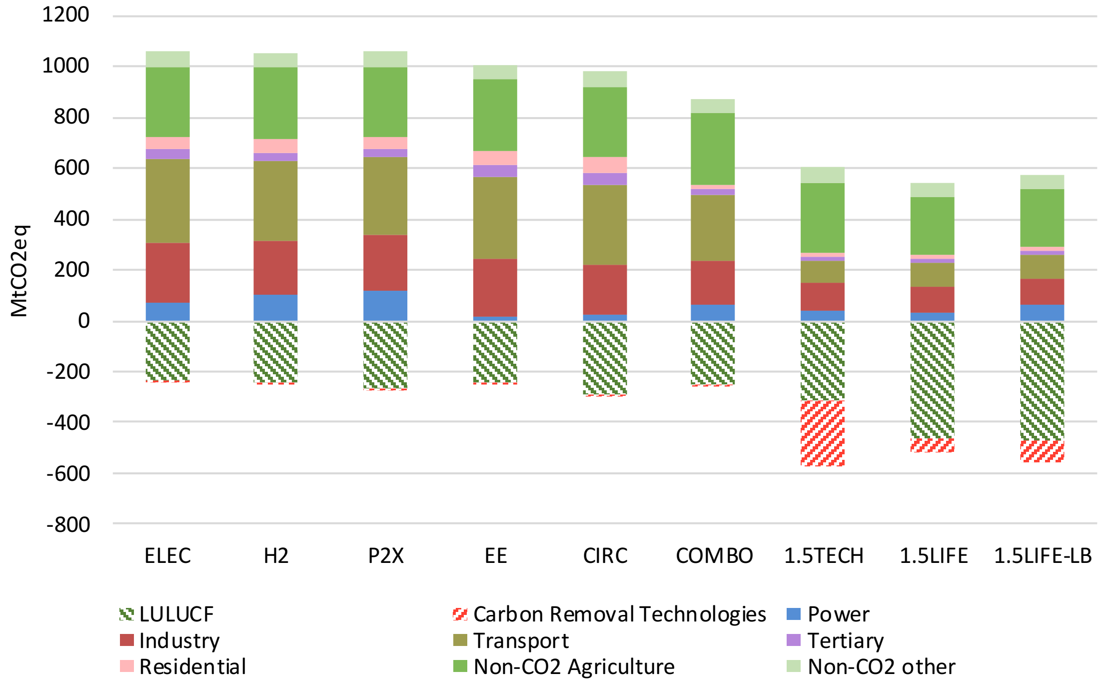
emissions for scenarios achieving economy wide 80% GHG reductions. Nevertheless, under deep decarbonisation pathways achieving net zero GHG by 2050, also these sectors will have to achieve sharp emissions of more than 80%.

Sectors encompassed in the EU ETS have so far seen greater reduction compared to historic emission levels. This is set to continue in the long term under all pathways with the ETS reducing emissions more than non-ETS sectors. Regarding non-$CO_2$ emissions, these are lowest in the two1.5LIFE scenarios because of assumed food consumer preferences changes.

The pathways envisaged vary significantly in terms of the deployment of carbon capture, storage and use technologies (see also section 4.8.2). Capture of $CO_2$ for use or for storage though is large under any net zero GHG scenarios and in particular under 1.5TECH (600 $MtCO_2$ captured). Carbon capture, storage and use technologies are likely to pick up slowly before 2040 and accelerate only subsequently, given the current technology readiness levels of such options. For the scenarios achieving 80% GHG reduction, the P2X scenario requires highest capture rates, well above 400 $MtCO_2$ by 2050, given the substantial use of e-gas. Underground storage (CCS) is envisaged under all pathways, with the deployment in scenario achieving 80% GHG reduction seeing levels at around 50-70 $MtCO_2$. These levels are much lower than projected for the 2050 Low Carbon Economy and Energy Roadmaps[452], notably because increased penetration of renewable energy and additional mitigation options in industry.

Overall, GHG emissions are projected to fall by around 62% compared to 1990 under the baseline in 2050 when LULUCF is excluded. The EE, H2, P2X, EE and CIRC scenarios all achieve between 80% and 83% GHG reductions (Figure 91). Including LULUCF, these scenarios perform a bit better with reductions between 85% and 88% or on average an extra 4% reduction compared to the reduction without LULUCF.

**Figure 91: Sectoral emissions by 2050**




[452] COM (2011) 112

*Source: PRIMES-GAINS-GLOBIOM.*

The scenarios in-line with the net zero GHG objective reduce emissions by 91% to 94%. Thus optimising the natural sink and deploying carbon dioxide removal options are necessary to reach net zero emissions and possibly generate net negative emissions thereafter.

The different pathways indicate some variability in the evolution of the natural sink, which is estimated to vary between 230 Mt$CO_2$ and 480 Mt$CO_2$ in 2050. Important in this context will be how different increasing levels of biomass are produced, with pathways using energy crops having least impact on the size of the natural sink, though at the cost of substantial land use changes.

Pathway such as the 1.5LIFE or 1.5LIFE-LB, which include changes in consumer choice and circular economy, the combination of reduced energy consumption and increased availability of land allows for a potential larger role for afforestation and land restoration, reducing significantly the need for the deployment of biomass with CCS to achieve net zero GHG emissions (see Figure 91 and Table 9).

In the scenarios achieving net zero GHG by 2050, the emitted $CO_2$ budget for the period 2020-2050 is just below 0 Gt$CO_2$. This represents the peak of the cumulative $CO_2$ emissions since after this period they decrease due to negative emissions post 2050. They reduce as low as 28 Mt$CO_2$ in the 1.5TECH scenario and only 23 Mt$CO_2$ in 1.5LIFE-LB (with continuing reduction after 2050 and assuming a stabilization of the annual $CO_2$ removals to 2070 level for the period 2070-2100). Depending on assumptions of negative emissions post 2070 this budget could actually further vary.

**Table 9: Sectoral emissions levels and percentage change in total emissions**

| | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5TECH | 1.5LIFE | 1.5LIFE-LB |
|---|---|---|---|---|---|---|---|---|---|---|
| **2030 ($MtCO_2eq$)** | | | | | | | | | | |
| **Total GHG excl. LULUCF** | 3108 | 3101 | 3096 | 3105 | 3115 | 3105 | 3109 | 3091 | 3067 | 3060 |
| *Reduction vs 1990* | -46% | -46% | -46% | -46% | -46% | -46% | -46% | -46% | -47% | -47% |
| **Total GHG incl. LULUCF** | 2856 | 2849 | 2834 | 2842 | 2865 | 2862 | 2846 | 2780 | 2716 | 2710 |
| *Reduction vs 1990* | -48% | -48% | -48% | -48% | -48% | -48% | -48% | -49% | -51% | -51% |
| **2050 ($MtCO_2eq$)** | | | | | | | | | | |
| **Total GHG excl. LULUCF** | 2214 | 1054 | 1050 | 1051 | 1004 | 976 | 868 | 343 | 489 | 494 |
| *Reduction vs 1990* | -62% | -82% | -82% | -82% | -83% | -83% | -85% | -94% | -92% | -91% |
| **Total GHG incl. LULUCF** | 1978 | 816 | 806 | 788 | 763 | 684 | 620 | 26 | 25 | 23 |
| *Reduction vs 1990* | -64% | -85% | -85% | -86% | -86% | -88% | -89% | -100% | -100% | -100% |
| | | | | | | | | | | |
| **ETS GHGs emissions** | 772 | 348 | 362 | 385 | 301 | 275 | 297 | -50 | 123 | 137 |
| *Reduction vs 2005* | -69% | -86% | -86% | -85% | -88% | -89% | -88% | -102% | -95% | -95% |
| **Non-ETS GHG emissions** | 1442 | 706 | 687 | 665 | 702 | 700 | 571 | 393 | 366 | 358 |
| *Reduction vs 2005* | -49% | -75% | -76% | -77% | -75% | -75% | -80% | -86% | -87% | -87% |
| | | | | | | | | | | |
| **CO2 emissions** | 1604 | 717 | 712 | 713 | 666 | 638 | 531 | 5 | 203 | 208 |
| *Residential* | 130 | 49 | 56 | 45 | 60 | 66 | 19 | 12 | 11 | 13 |
| *Transport* | 667 | 328 | 317 | 309 | 325 | 317 | 257 | 86 | 95 | 90 |
| *Tertiary* | 78 | 40 | 34 | 30 | 44 | 43 | 23 | 19 | 19 | 19 |
| *Industry* | 484 | 231 | 205 | 217 | 225 | 192 | 176 | 29 | 53 | 39 |
| *Power* | 246 | 69 | 99 | 113 | 13 | 20 | 56 | -141 | 24 | 47 |
| | | | | | | | | | | |
| **Non CO2** | 610 | 337 | 337 | 337 | 337 | 337 | 337 | 337 | 286 | 286 |
| *Agriculture* | 404 | 277 | 277 | 277 | 277 | 277 | 277 | 277 | 230 | 230 |
| *Waste* | 90 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 29 | 29 |
| | | | | | | | | | | |
| **Carbon captured** | 5 | 65 | 63 | 449 | 65 | 52 | 239 | 606 | 281 | 385 |
| *From Biomass* | 0 | 5 | 6 | 114 | 4 | 5 | 95 | 276 | 84 | 122 |
| *From Direct Air Capture* | 0 | 0 | 0 | 264 | 0 | 0 | 83 | 210 | 123 | 186 |
| | | | | | | | | | | |
| **Carbon used** | 5 | 65 | 63 | 449 | 65 | 52 | 239 | 606 | 281 | 385 |
| *Geological Storage* | 5 | 65 | 63 | 77 | 65 | 52 | 67 | 298 | 80 | 92 |
| *Synthetic fuels* | 0 | 0 | 0 | 372 | 0 | 0 | 172 | 227 | 154 | 226 |
| *Synthetic Materials* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 80 | 47 | 67 |
| | | | | | | | | | | |
| **LULUCF** | -236 | -238 | -244 | -263 | -241 | -292 | -248 | -317 | -464 | -472 |
| *Sink without carbon price* | -236 | -238 | -244 | -263 | -241 | -292 | -248 | -247 | -329 | -340 |
| *Enhancement with carbon price* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -70 | -135 | -132 |
| **Cumulative $CO_2$ emissions ($GtCO_2$)** | | | | | | | | | | |
| 2018 - 2050 | 71 | 60 | 60 | 61 | 59 | 58 | 58 | 49 | 48 | 48 |
| 2018 - 2070 | 98 | 61 | 61 | 62 | 61 | 58 | 57 | 41 | 39 | 39 |
| 2018 - 2100 | 136 | 57 | 56 | 57 | 57 | 53 | 49 | 28 | 24 | 23 |

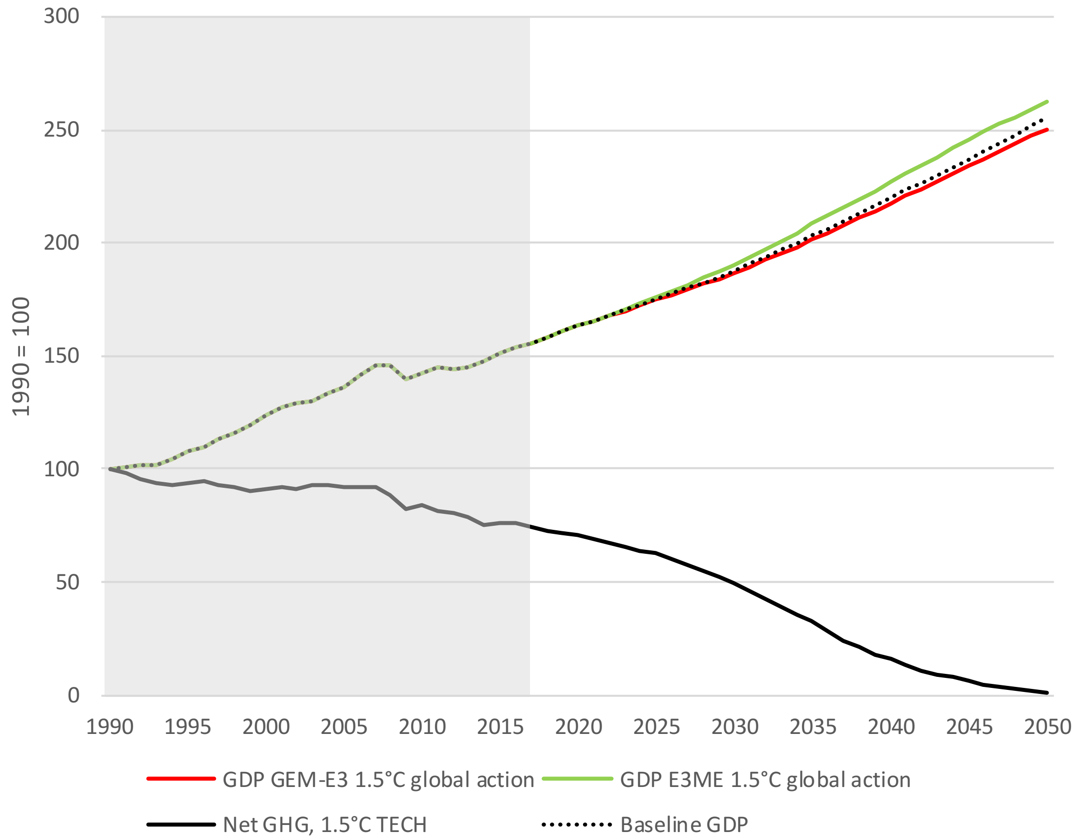
*Note: The cumulative emissions 2018-2100 listed as total cumulative CO2 budgets assume the stabilisation of net emissions at the 2070 level from 2070 onwards.*

*Source: PRIMES, GLOBIOM, GAINS.*

## 4.10 Economic aspects of energy transformation and decarbonisation pathways

The decarbonisation of the EU economy is expected to generate significant transformations across the board. Other factors will nevertheless also influence expected macro-economic developments to a significant extent, including for example further technological progress (e.g. innovation in automation, IT and artificial intelligence) and the rise of a global middle class. Such trends are expected to underpin constant though moderate increases in total factor productivity growth, which would drive continued real GDP growth, both in absolute terms and on a per capital basis. The baseline macro-economic growth projections underpinning the modelling for this strategy indicate that real GDP could be about 2.5 times as large by 2050 than in 1990. Macro-economic modelling indicates that the impact of decarbonisation and the energy transition on this headline GDP figure would be moderate (section 4.10.5). Evidence from the period 1990 to date demonstrates that the decoupling of GDP and greenhouse gas emissions has already started. Modelling results indicate that this trend can be accelerated and reinforced to the point of achieve a full decoupling, i.e. net zero GHG emissions and continued economic growth (Figure 92).

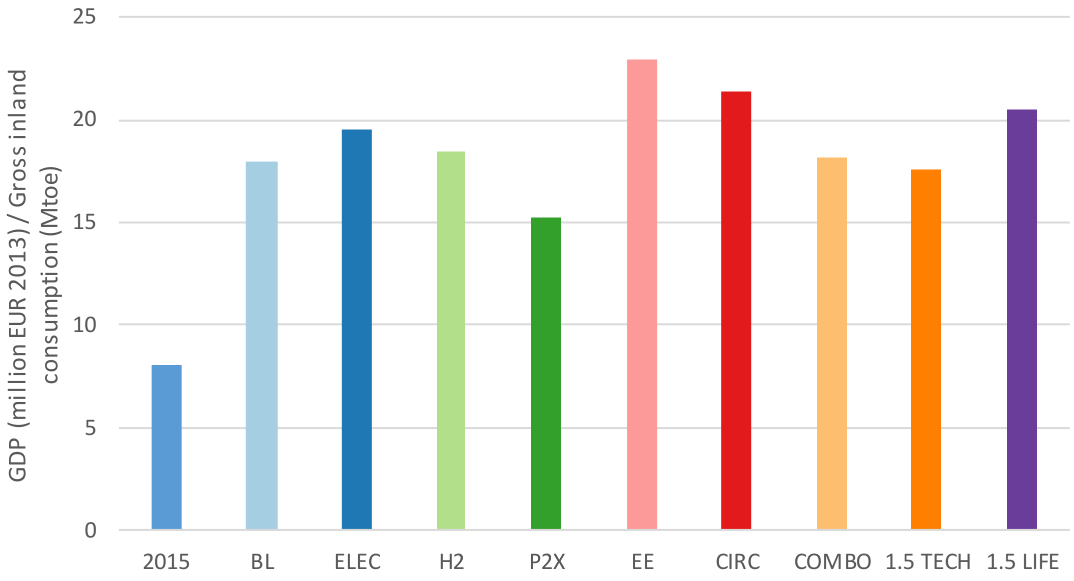
**Figure 92: Real GDP and net GHG emissions 1.5 TECH (1990 = 100)**




*Sources: PRIMES, ESTAT, JRC-GEM-E3 and E3ME.*

The decoupling of economic growth and GHG emissions would be associated with an increase in output per energy consumed, as energy efficiency would increase across all scenarios. The degree to which the "productivity" of energy consumption would increase varies across scenarios, with the highest gains expected in the energy efficiency and 1.5 LIFE scenarios. By 2050, output per unit of gross inland consumption could increase by about a factor of two to three depending on the scenarios (Figure 93).

**Figure 93: Real GDP (million EUR 2013) per energy consumption (Mtoe of GIC), 2015 and 2050**




*Source: PRIMES.*

### *4.10.1 Investment requirements*

The investments required for achieving the 2030 climate and energy targets have been estimated in the context of previous policy initiatives using the PRIMES model and a comparable methodology[453].

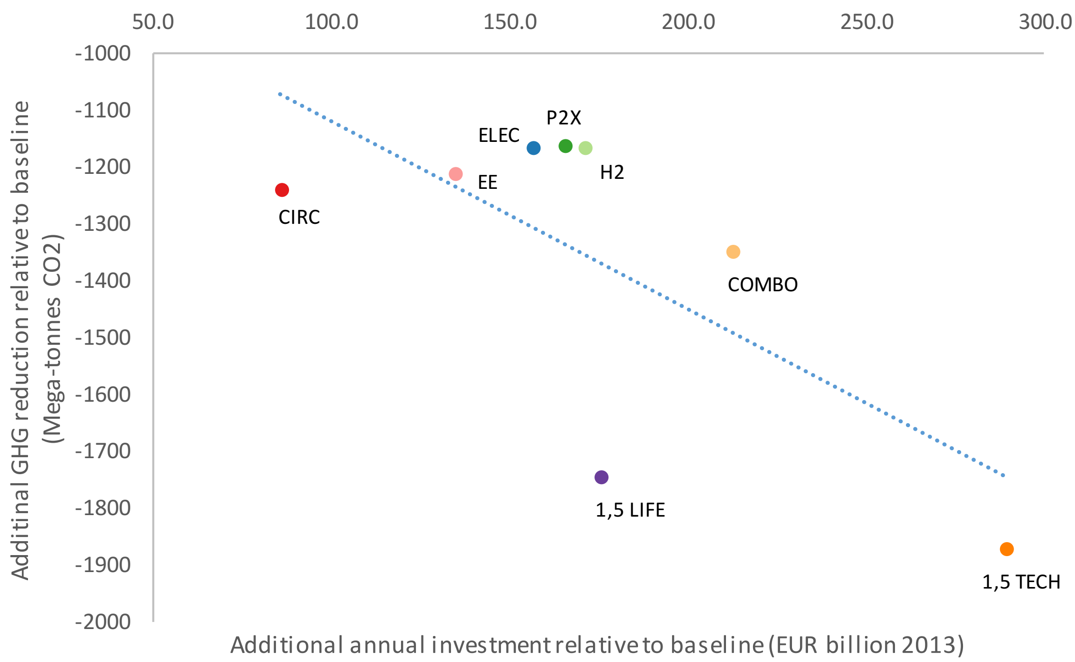
The pathways envisaged in this strategy (including the Baseline) all reach the 2030 climate and energy targets along the same trajectory and are therefore very close in terms of costs and investment up to 2030. Beyond 2030, however, investment and costs diverge significantly across pathways, reflecting both the level of ambition for decarbonisation and the estimated economic implication of the options pursued. A higher level of ambition would lead to significantly higher investment. At the same time, some decarbonisation pathways are more capital intensive than others and the 80% emissions reduction target by 2050 can be achieved with significantly different additional investment, depending on the pathway.

This analysis shows that, on average, net zero GHG pathways would require 6.7% more investment compared to 80% reduction scenarios (see Table 10). Excluding transport, in which most of the investment represents the replacement of the vehicles as a whole, the increase would amount to 17%. At global level, the IPCC 1.5°C Special Report estimates that a similar increase in ambition would require a 12% (ranging between 3% and 23%) increase in global investment compared to 2°C pathways[454].

[453] The impact assessment accompanying the revision of the Energy Efficiency Directive estimated that an additional EUR 177 billion in annual investment would be needed to reach the 2030 climate and energy targets. However, this figure does not take into account the increased ambition of the 2030 targets as finally adopted following negotiating with the European Parliament and the Council nor the recent cost reduction of renewable energy technologies. The net results of these two opposing trends is a reduction of approximately 15% of the estimated investments required to reach the 2030 targets.

[454] See Section C2.6 of the IPCC Special Report Summary for Policymakers

**Figure 94: Additional annual investment (2031-2050) and total GHG reductions (2050) relative to Baseline**




*Source: PRIMES.*

In terms of overall investment levels, the 80% reduction scenarios would require an average annual investment of EUR 1.33 trillion in 2031-2050, compared to EUR 1.19 trillion for the baseline and EUR 1.42 trillion for the more ambitious pathway (Table 10). Excluding transport vehicles, average annual investment under the 80% reduction scenarios would amount to EUR 468 billion (2.4% of GDP) in 2031-2050 compared to EUR 377 billion (1.9% of GDP) for the baseline and EUR 547 billion (2.8% of GDP) on average for the net zero GHG pathways. This compares to today (period 2016-2020), when around 2% of GDP is to be invested in the energy system and related infrastructure (excluding transport). This is in line with the IPCC 1.5°C Special Report that estimates that 1.5°C pathways involve investment in the energy system of around USD 2.4 trillion per year between 2016 and 2035 (equivalent to around 2.5% of the world GDP). The Special Report also projects substantial investment needs even under a baseline scenario (around USD 2 trillion).

**Table 10: Average annual investment by scenario (billion EUR 2013 over the 2031-2050 period; baseline for 2021-2030 is also shown).**

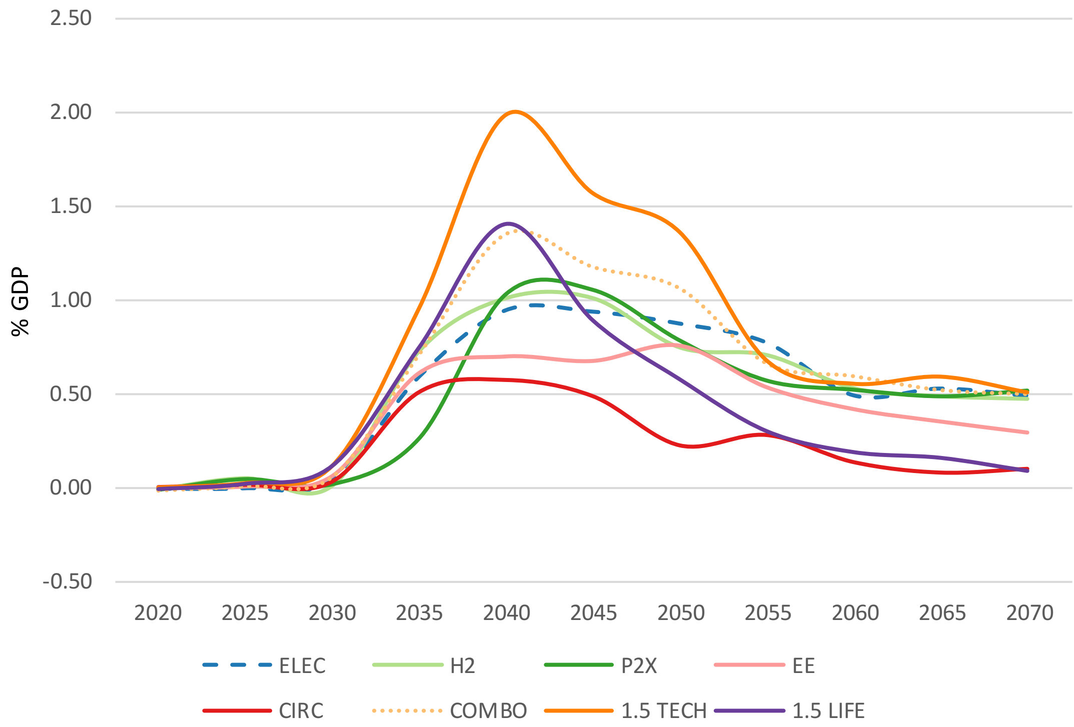
| | **Baseline 2021-2030** | **Baseline** | **EE** | **CIRC** | **ELEC** | **H2** | **P2X** | **COMBO** | **1.5 TECH** | **1.5 LIFE** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Supply** | **115** | **113** | **133** | **154** | **190** | **184** | **233** | **210** | **246** | **201** |
| Power grid | 59.2 | 71.3 | 80.7 | 91.0 | 110.3 | 91.1 | 95.3 | 99.4 | 102.8 | 90.3 |
| Power plants | 53.9 | 40.2 | 50.5 | 60.3 | 76.8 | 86.6 | 107.9 | 93.6 | 120.3 | 93.9 |
| Boilers | 1.7 | 1.3 | 1.1 | 1.8 | 1.9 | 1.0 | 0.6 | 0.7 | 0.8 | 0.6 |
| New carriers | 0.1 | 0.3 | 0.9 | 0.9 | 1.0 | 5.5 | 28.9 | 16.2 | 21.9 | 16.5 |
| **Demand exc. trans.** | **281** | **264** | **335** | **285** | **285** | **270** | **271** | **312** | **330** | **318** |
| Industry | 18.1 | 11.1 | 35.6 | 13.2 | 13.6 | 13.2 | 13.8 | 26.3 | 28.1 | 22.3 |
| Residential | 198.9 | 199.4 | 235.1 | 211.6 | 214.4 | 198.9 | 198.1 | 218.3 | 225.9 | 227.7 |
| Tertiary | 64.3 | 53.7 | 63.8 | 60.3 | 57.0 | 58.0 | 59.5 | 67.1 | 76.0 | 67.8 |
| **Transport** | **685** | **813** | **857** | **837** | **881** | **907** | **843** | **881** | **904** | **847** |
| ***TOTAL*** | ***1081*** | ***1190*** | ***1325*** | ***1276*** | ***1356*** | ***1361*** | ***1347*** | ***1402*** | ***1480*** | ***1366*** |
| *(TOTAL exc. trans.)* | (396) | (377) | (468) | (439) | (475) | (454) | (504) | (522) | (576) | (519) |

*Source: PRIMES.*

Much of these investments[455] are needed to replace assets at the end of their economic lifetime and additional investment requirements are not constant over time. The additional investment need compared to Baseline is highest between 2040 and 2050 for most scenario. Investment would be on average around 0.7 percentage point of GDP above baseline in the 80% reduction scenarios achieving 80% GHG reduction and on average up by 1.2 percentage points in the net zero GHG scenarios, with a peak of 2 percentage points in some years (see Figure 95). Moreover, total investment as a share of GDP is around 1 percentage point of GDP higher in 2030 than the 2020 level. The difference relative to 2020 levels gradually declines subsequently before turning negative between 2050 and 2055. Such increases in investment are large from a macro-economic perspective, as gross fixed capital formation is currently close to 20% of GDP in the EU. An increase in total investment of 1-2 percentage points of GDP, for example, would represent a considerable shift from consumption to capital investments (see section 4.10.5. for a discussion of macro-economic impacts).

[455] See section 7.2.3 for a discussion of investment expenditures reported in PRIMES.

**Figure 95: additional investments (including transport) compared to Baseline in % of GDP**




*Source: PRIMES.*

On average across scenarios, an additional level of annual investment of EUR 143 billion (equivalent to a 12% increase in total investment) compared to Baseline is needed to reach an 80% emissions reduction in 2050, which is lower than the incremental investment needed to achieve the 2030 targets. This nevertheless hides significant differences across pathways, with values ranging from a minimum of EUR 86 billion (for the circular economy pathway) to EUR 171 billion (for the H2 pathway) (Table 11). Additional annual investment under the higher ambition pathways range from EUR 176 billion (1.5LIFE scenario) to EUR 290 billion (1.5 TECH).

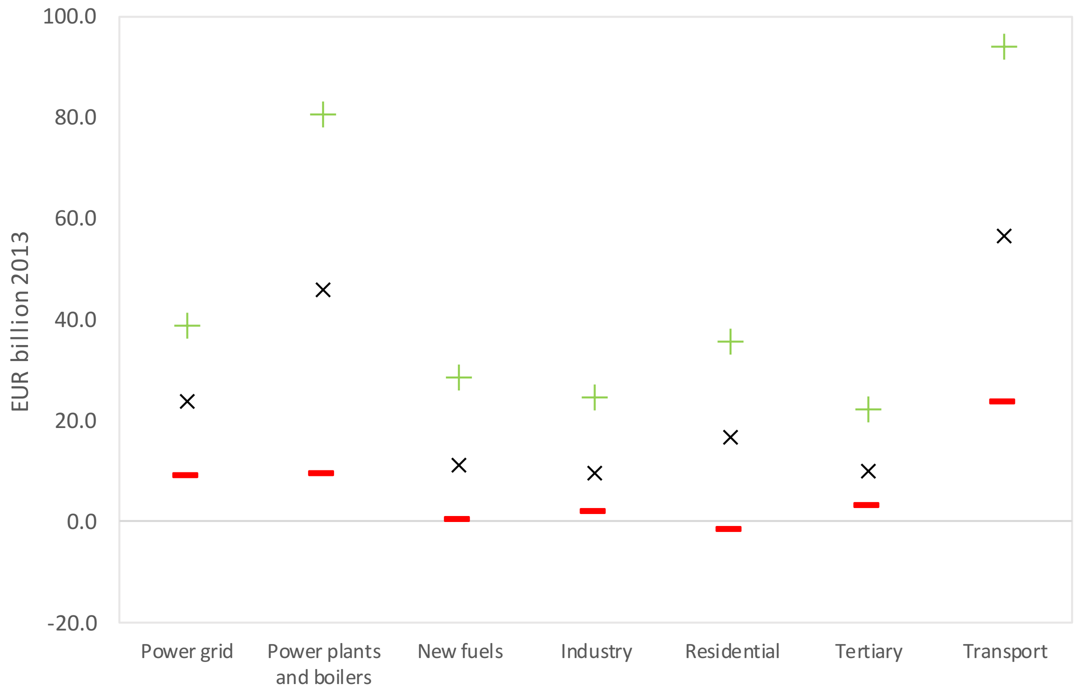
**Table 11: Additional average annual investment compared to baseline (2031-2050, billion EUR 2013).**

| | EE | *CIRC* | ELEC | H2 | P2X | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|
| **Supply** | **20.1** | **41.0** | **76.9** | **71.0** | **119.5** | **96.8** | **132.7** | **88.2** |
| Power grid | 9.3 | 19.7 | 39.0 | 19.7 | 24.0 | 28.1 | 31.4 | 18.9 |
| Power plants | 10.3 | 20.1 | 36.6 | 46.5 | 67.7 | 53.4 | 80.2 | 53.7 |
| Boilers | -0.2 | 0.5 | 0.6 | -0.4 | -0.8 | -0.7 | -0.5 | -0.7 |
| New fuels | 0.6 | 0.6 | 0.7 | 5.2 | 28.6 | 16.0 | 21.6 | 16.2 |
| **Demand exc. trans.** | **70.4** | **20.9** | **20.8** | **5.9** | **7.2** | **47.5** | **65.9** | **53.6** |
| Industry | 24.5 | 2.1 | 2.5 | 2.1 | 2.7 | 15.2 | 17.0 | 11.2 |
| Residential | 35.8 | 12.2 | 15.0 | -0.5 | -1.3 | 18.9 | 26.6 | 28.3 |
| Tertiary | 10.1 | 6.6 | 3.3 | 4.3 | 5.8 | 13.4 | 22.3 | 14.1 |
| **Transport** | **44.2** | **23.9** | **67.9** | **94.0** | **29.8** | **68.1** | **90.9** | **33.9** |
| **TOTAL** | **134.7** | **85.8** | **165.6** | **170.9** | **156.5** | **212.4** | **289.5** | **175.7** |
| *(TOTAL exc. trans.)* | *(90.5)* | *(61.8)* | *(97.7)* | *(76.9)* | *(126.7)* | *(144.3)* | *(198.6)* | *(141.8)* |

*Source: PRIMES.*

While the modelling highlights the large scale of the additional investment needs, it also shows the significantly different implications of the various pathways, both in terms of total additional investment and in terms of the composition of the additional investment (Figure 96). This highlights the partial substitutability that exists between, for example, investments in energy efficiency and additional supply-side investments in power generation, or between electrifying road transport and increasing the use of synthetic fuels. The modelling also shows the potential of the circular economy and lifestyle changes to reduce additional investments overall. These pathways indeed require a total level of annual investment around 5% and 8% lower, respectively, than that of the other pathways with a similar level of ambition. However, energy models are not in a position to capture fully the related investment needs and costs of the circular economy or lifestyle changes (see section 7.2). Yet, whenever easy to implement, this type of measures can be considered as no-regret options to limit investment needs.

**Figure 96: Minimum (-), maximum (+) and average (x) additional annual investment per sector (billion EUR 2013 compared to baseline)**




*Source: PRIMES.*

Supply side investments represent approximately 14% of total annual investment levels (average for all scenarios) in 2031-2050. All pathways show that major additional investments will be required in power generation and in the grid alike. On average, annual investment in supply is 58% higher under the scenarios achieving 80% GHG reduction than under baseline, with a minimum of 18% for the energy efficiency pathway and a maximum of 106% for the Power-to-X pathway. This implies large increases in investment not only in power generation, but also in the transmission and distribution network. Because of the reduced energy demand, the high energy-efficiency and the circular economy scenarios have the lowest supply-side investment among the scenarios reaching -80% emissions reduction in 2050.

In monetary terms, investments in power plants increase in the period up to 2040-2045 and fall subsequently. The anticipation of the emissions cuts in 2050 and beyond, the need of replacing the obsolete fleet, the increase of electricity demand due to transport, heating and the production of new fuels, where applicable, explain why the restructuring of the power generation fleet takes place well before 2050.

In addition, investment needs in power generation and the grid rise markedly with the increased ambition level of the 1.5°C pathways. At EUR 224 billion per year in 2031-2050, supply side investments in the 1.5°C scenarios are 98% higher than under the Baseline and 18% to 68% higher than in 80% reduction pathways, with the exception of the Power-to-X scenario. The latter requires a similar level of investment in power supply, reflecting the high costs of producing hydrocarbons from $CO_2$ and the electricity needs of these technologies.

Because of the reduced energy demand, the high energy-efficiency and the circular economy scenarios require the lowest additional supply-side investment among the scenarios reaching an 80% emissions reduction in 2050. However, for the high energy-efficiency scenario this is compensated by higher investments on the demand-side.

Demand side investment, excluding transport, represent approximately 22% of total annual investment levels (average for all scenarios) in 2031-2050. Within this, the residential sector represents by far the largest component (71.9%) followed by the tertiary sector (21.2%) and industry (6.9%).

As for the supply side, there are also significant differences between technology pathways. Among the scenarios with similar ambition, the high energy-efficiency scenarios requires by far the highest increment in investment in the residential, tertiary and industrial sectors, with an increase of 27% relative to Baseline. This compares with an increase of 2-3% for the hydrogen and power-to-X scenarios and 8% for the electrification pathway. This is counterbalanced, however, by lower investment on the supply side compared to other pathways. This underscores the extent to which investment in energy efficiency and clean energy production/consumption can be substitutes, though at varying costs.

Additional investment needs again increase with the level of ambition, but not as markedly as for the supply side. At an average of EUR 324 billion per year in 2031-2050, demand side investment in the 1.5°C scenarios is 23% higher than under the Baseline and 14% to 20% higher than in the 80% reduction pathways, with the exception of the high energy-efficiency scenario which is 3% higher than the 1.5°C scenarios on this account.

It is notable also that additional investment needs are expected to be very large in industry in some pathways, not in terms of total amounts compared to other sectors, but as increases relative to Baseline. The high-electrification, hydrogen, power-to-X and circular economy pathways enable a limited increase relative to Baseline of 19% to 24%. However, the energy efficiency and the 1.5°C scenarios would imply doubling or more than tripling (energy efficiency scenario) Baseline investment levels in this sector. The reason for this increase is that the model PRIMES assumes rapidly increasing costs as energy efficiency options in industry saturate in the long-term. Despite using somewhat different assumptions, the investment requirements estimated for industry by the FORECAST model (see section 4.5.2) are comparable to those estimated by PRIMES. Depending on the scenario, the FORECAST model estimates that decarbonising the European industry will require additional investment of EUR 4 to 9 billion per year between 2015 and 2050.

In transport the additional investment needs[456] relative to the Baseline range between EUR 24 billion and EUR 94 billion annually during 2031-2050 (39% to 94% of total additional demand-side investments). Among the scenarios achieving 80% GHG reduction, the highest level of investment is projected in the hydrogen scenario, due to the higher costs of fuel cell vehicles. In the power-to-X scenario, investment needs are low as e-fuels can work with conventional power trains and the uptake of plug-in hybrid and battery electric vehicles is more limited than in other scenarios. As explained above, investment needs increase with the level of ambition in the Combined and 1.5 TECH scenarios. However, the 1.5 LIFE scenario shows low additional investment needs driven by shared mobility and the assumed increase in the occupancy rates. This results in a decrease of the total passenger cars fleet relative to the Baseline, and lower investment in air transport[457]. In the CIRC scenario, similar considerations apply regarding the passenger cars fleet.

[456] This includes investments in transport equipment for mobility purposes (e.g. rolling stock) and energy efficiency. They exclude investments in road infrastructure and recharging infrastructure.

[457] The strong shift from air transport to rail in this scenario implies lower investments in aircraft. However, for rail only the investments in the rolling stock are reflected; the investments required for additional infrastructure are not covered.

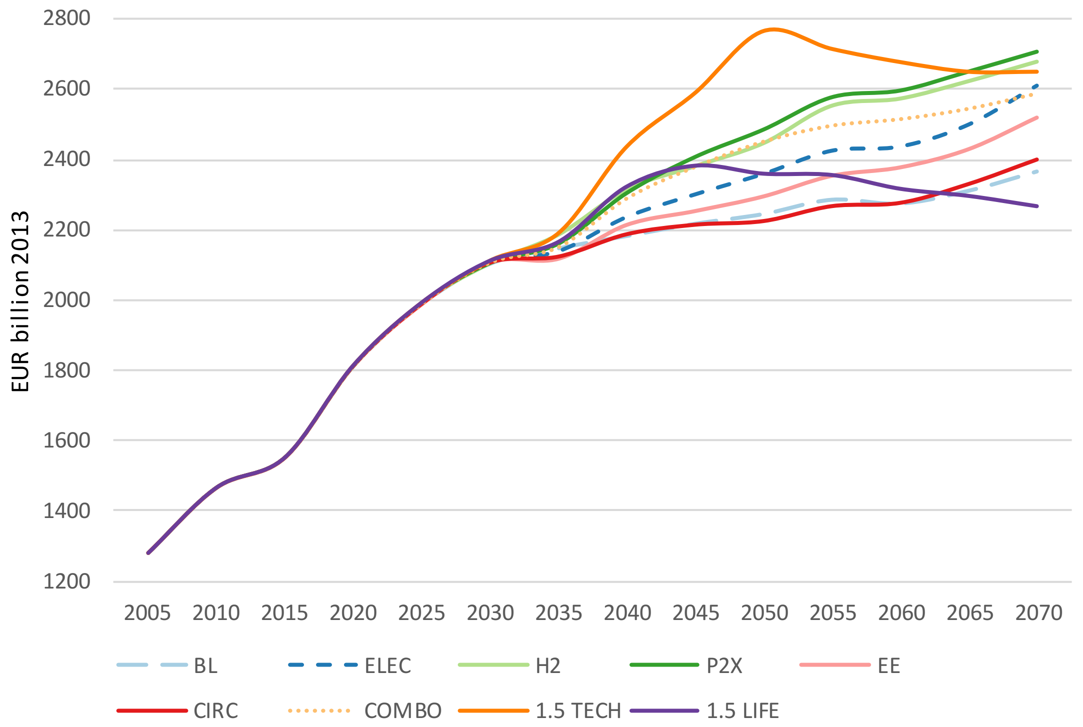
The additional investment for decarbonisation will be reflected in total system costs, and accounted for as equivalent annuity payments for capital. However, decarbonisation will also affect system costs as a result of the substitution of fossil fuels with renewable energy sources. Total system costs reflect the total impact of the scenarios on energy costs as borne by end-consumers.

### *4.10.2 Energy system costs and prices*

Total energy system costs[458] increase over the entire modelling horizon and progressively diverge across scenarios to differ significantly by 2050 (Figure 97). The level of cost is strongly correlated with the level of ambition, though not perfectly. Total system costs are lowest under the Baseline and highest under the 1.5 TECH scenario. The power-to-X and H2 pathways generate total system costs that approach higher ambition scenario, although they achieve a lower level of reduction in emissions. As indicated above, the high energy-efficiency generates the largest additional investment need among all the 80% scenarios, but the impact on total system costs is mitigated by the lower energy consumption that results from efficiency gains.

[458] Energy system costs for the entire energy system include capital costs (for energy installations such as power plants and energy infrastructure, energy using equipment, appliances and vehicles), energy purchase costs (fuels + electricity + steam) and direct efficiency investment costs, the latter being also expenditures of capital nature. Capital costs are expressed in annuity payments, calculated on the basis of sector-specific discount rates. For transport, only the additional capital costs for energy purposes (additional capital costs for improving energy efficiency or for using alternative fuels) are covered. Direct efficiency investment costs include additional costs for house insulation, double/triple glazing, control systems, energy management and for efficiency enhancing changes in production processes not accounted for under energy capital and fuel/electricity purchase costs. They do not include any disutility costs associated with changed behaviour, nor the cost related to auctioning of allowances which lead to corresponding revenues which can be used. Energy system costs are calculated ex post after the model is solved. The calculated cost is influenced by the discount rate used; capital expenditures and energy efficiency investment costs have been discounted with a financial discount rate of 10%.

**Figure 97: Total energy system costs, 2005-2070**



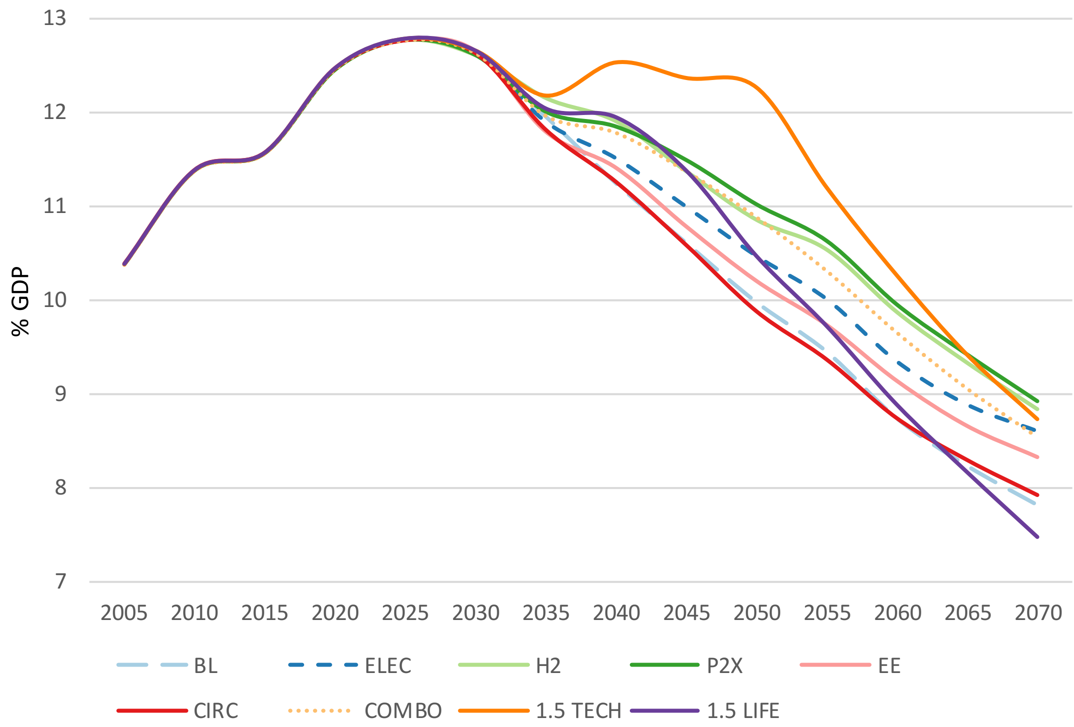

*Source: PRIMES.*

As a percentage of GDP, energy system costs are expected to increase from 12.5% in 2020 to 12.6% in 2030. These costs are lower than previously estimated[459] due to cost reduction for key technologies (e.g., renewable energy and electric batteries). In addition, after 2030, GDP growth offsets the increase in system costs and the rising trend in the ratio to GDP is reversed (Figure 98).

The energy purchases part of total system costs (i.e. the bulk of non-capital costs) falls below Baseline for most scenarios and most sectors, with the exception of industry. Due to fuel switching to electricity and other carbon-free fuels, energy purchases in industry are higher than under the Baseline in all scenarios except the high energy-efficiency and the circular economy pathways. As a consequence of their additional investment, households and the tertiary sector face lower energy purchases for virtually the entire 2030-2050 period than under the Baseline. Savings on energy purchases are significant in all scenarios except the Power-to-X pathway. In this case, the lower level of additional investment is counter-acted by higher fuel costs.

[459] Impact Assessment of the 2050 Energy Strategy: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy

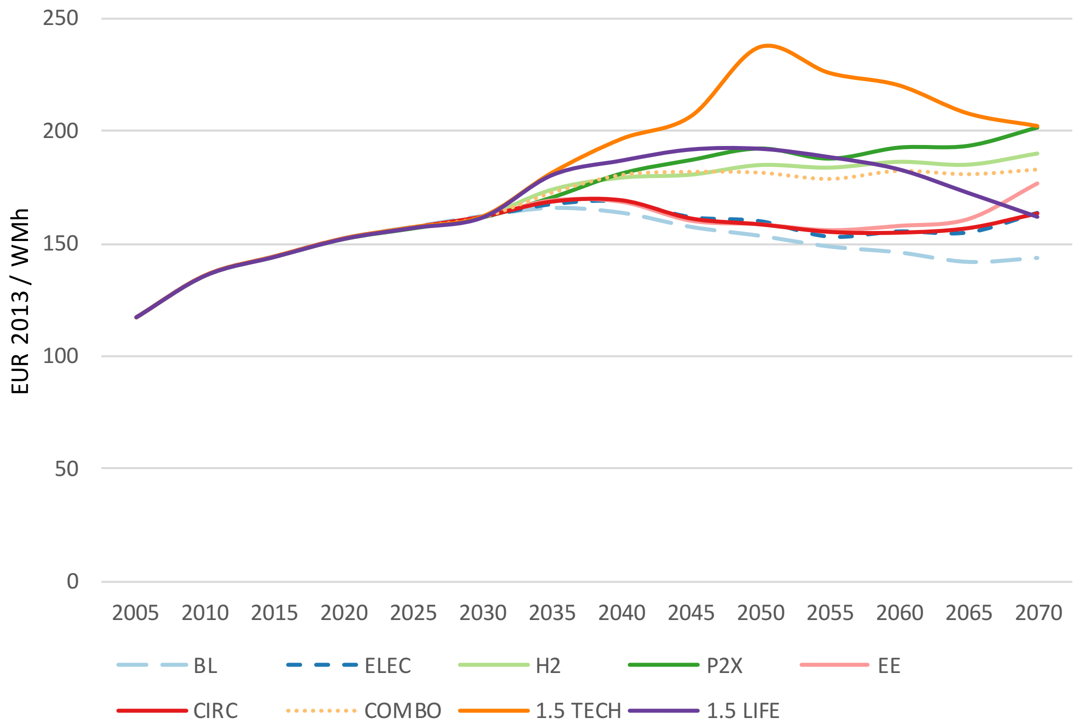
**Figure 98: Total energy system costs as a percentage of GDP, 2005-2070**




*Source: PRIMES.*

The modelling used considers that the average electricity prices ensure a full recovery of the power system costs. Fuel costs and annualised capital costs are divided by the total electricity generation deriving an estimate of the average electricity generation price. Transmission and distribution costs are allocated according to user characteristics (e.g. connection voltage) and consumption profiles (e.g. mainly off-peak or on-peak consumption). This results in different average prices for different final users. Figure 99 shows the weighted average of final end-users electricity prices as projected by PRIMES for both the Baseline and decarbonisation scenarios. Electricity prices increase until 2030, reflecting the costs of decarbonising the power system. After 2030, the electricity price stabilises at a level similar to the Baseline for the Electrification (ELEC) Energy Efficiency (EE) and Circular Economy scenarios. However, average electricity costs after 2030 are higher for the H2 and Power-to-X scenario and also increase with increasing climate ambitions (COMBO, 1.5 TECH and 1.5 LIFE scenarios). In the scenarios in which the power system produces hydrogen and e-fuels sold to final consumers, the storage of these fuels in fuel distribution facilities help the power system to further maximise the use of renewables and manage the system. These indirect contributions of final consumption e-fuels to the power system costs are not included in electricity costs, as the e-fuel producers do not receive payment for the indirect services provided to the power system.

**Figure 99: Projected average electricity prices for final users**

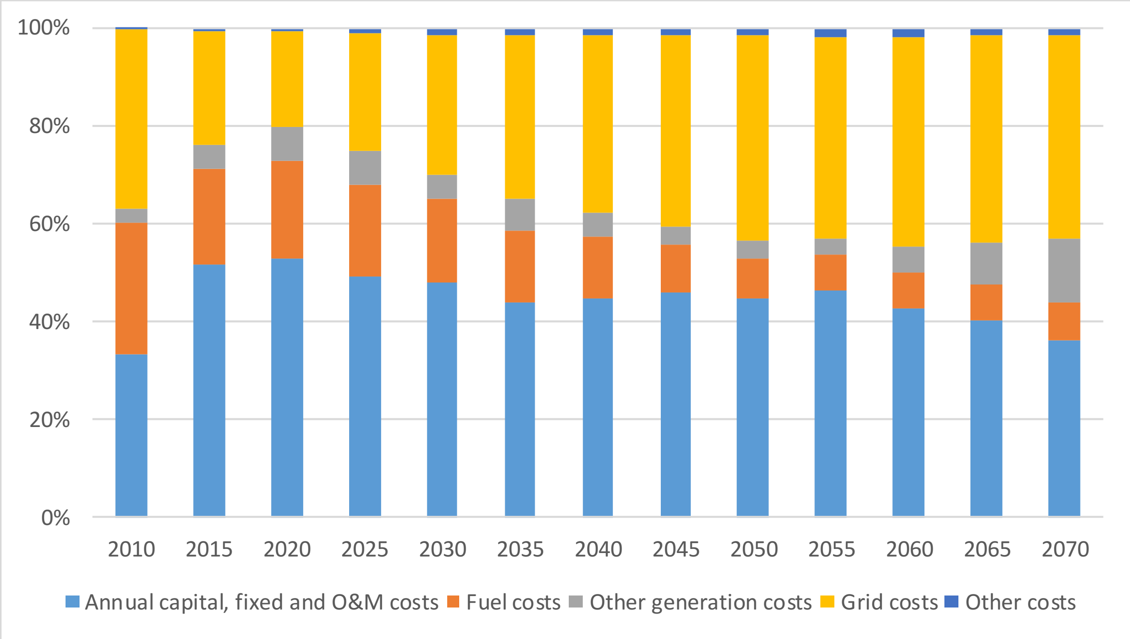



*Source: PRIMES.*

The modelling applies a stylised carbon price in the ETS sectors, which increases significantly under all scenarios, with carbon prices at 250 EUR/t$CO_2$ in 2050 under the 80% reduction scenarios and 350 EUR/t$CO_2$ under the scenarios that achieve net zero GHG emissions by 2050 (see also 7.2.2.2 on the modelling methodology of the carbon price signal). Such carbon prices of course apply only to a residual volume of remaining emissions. For the power sector (including CHP installations) auctioning is assumed, and thus any costs related to the carbon price are incorporated in the electricity price. For the 1.5 TECH scenario, emissions from the power sector (and ETS sectors as a whole) are actually negative by 2050.

Generation costs depend mainly on the cost of carbon-free technologies. As a result, generation costs are very similar in all scenarios and projected to decrease from 2020 onwards. However, transmission and distribution costs are projected to increase and offset the decrease of generation cost. As an example, Figure 100 shows the composition of electricity costs in the high electrification scenario (ELEC).

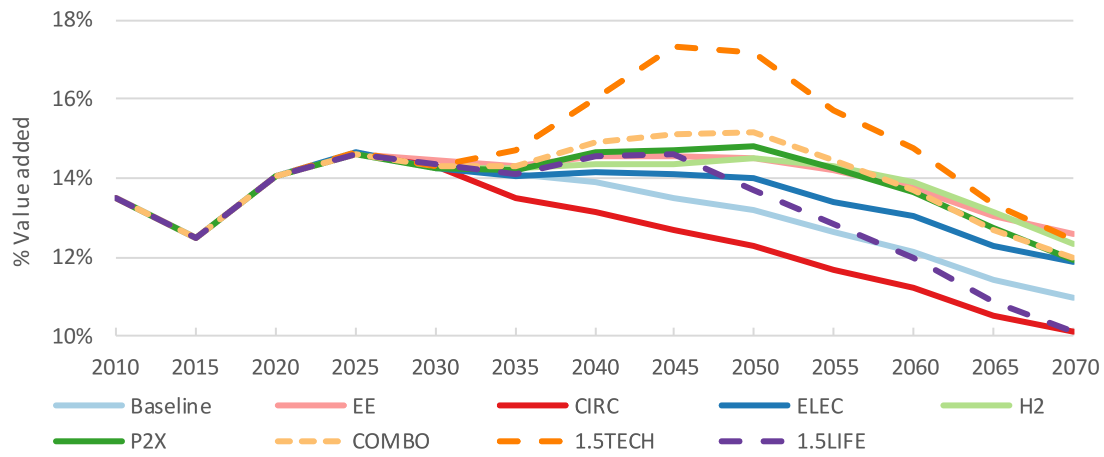
**Figure 100: Composition of electricity costs in the high electrification scenario (ELEC)**




*Source: PRIMES.*

For industry, energy related costs are projected to increase throughout the modelling horizon. In most of the 80% reduction scenarios, the rate of increase is slightly higher between 2020 and 2030 than from 2030 onwards. The cost is noticeable higher in the 1.5 TECH scenario though. Figure 101 shows the energy related expenses per unit of value added. It reaches in 2050 from 12% to 14%, to the exception of 17% for 1.5 TECH, compared to about 12%-14% in 2010-2015.

**Figure 101: Energy related expenses in % of sectoral value added in industry**




*Source: PRIMES.*

While the scale of the investment challenge in transport is significant in all scenarios it leads to lower *operational costs* (energy expenditures). Average annual energy purchases in transport during 2031-2050 are reduced between EUR 52 to 78 billion relative to the Baseline. Only the P2X scenario shows higher energy expenditures relative to the Baseline (EUR 4 billion) due to the higher costs of e-fuels. The other 80% reductions scenarios, show very similar energy cost savings.

Overall, *total average annual costs* in transport[460] during 2031-2050 are EUR 15 to 60 billion higher relative to the Baseline. The highest costs are shown in the H2 and P2X scenarios, driven by the costs of powertrains and e-fuels, respectively. At the opposite end, the lowest costs relative to the Baseline are projected in the CIRC scenario and 1.5 LIFE scenario; however, the disutility associated to lower transport activity and the possible loss of comfort are not monetised.

### *4.10.3 Social aspects related to the fuel expenses*

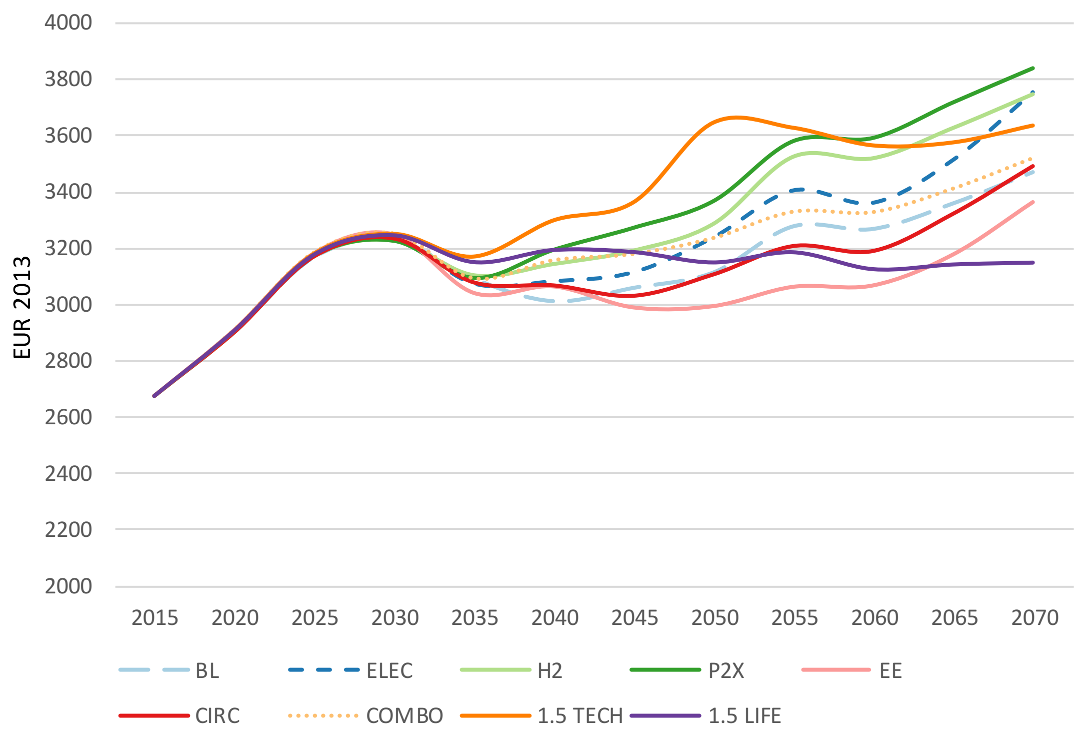
The energy transition will impact consumers in contrasting ways in the medium and long term. Up to 2030, energy-related expenses (including fuel costs and energy equipment expenditure) per household are expected to increase significantly in absolute terms under the baseline and all scenarios (Figure 102). In 2030, on average, every household is expected to spend for energy services EUR 570 per year more than in 2015 (at EUR 2013 prices). This corresponds to a 21% increase and comes on the back of a 67% increase over the 2000 – 2015 period. Rising real GDP and household income means that energy-related expenses in 2030 amount to the same share of household income (7.3%) as in 2015. Much of the impact on households was absorbed between 2000 and 2015, when energy-related expenses as a share of income rose from 4.7% to 7.3%.

After 2030, the results vary significantly across scenarios, with the energy efficiency scenario yielding a pay off in terms of lower fuel expenditure. In contrast, the high-ambition 1.5 TECH scenario and the scenarios relying on costly power-to-X and hydrogen yield higher energy-related expenses for households.

There are several reasons for these trends. The decarbonisation effort is already strong in the first part of the transition. Moreover, a large share of the emissions reduction will be achieved with technologies that are projected to become cheaper in the coming decade. Deploying such technologies will be cheaper after 2030 than it is now. Finally, energy efficiency gains are expected to continue in the long term, thereby reducing energy consumption and expenditures over several decades.

[460] These costs mainly cover the additional capital costs for energy purposes (additional capital costs for improving energy efficiency or for using alternative fuels) and the energy expenditures.

**Figure 102: Energy related expenses per households in different scenarios (EUR 2013)**



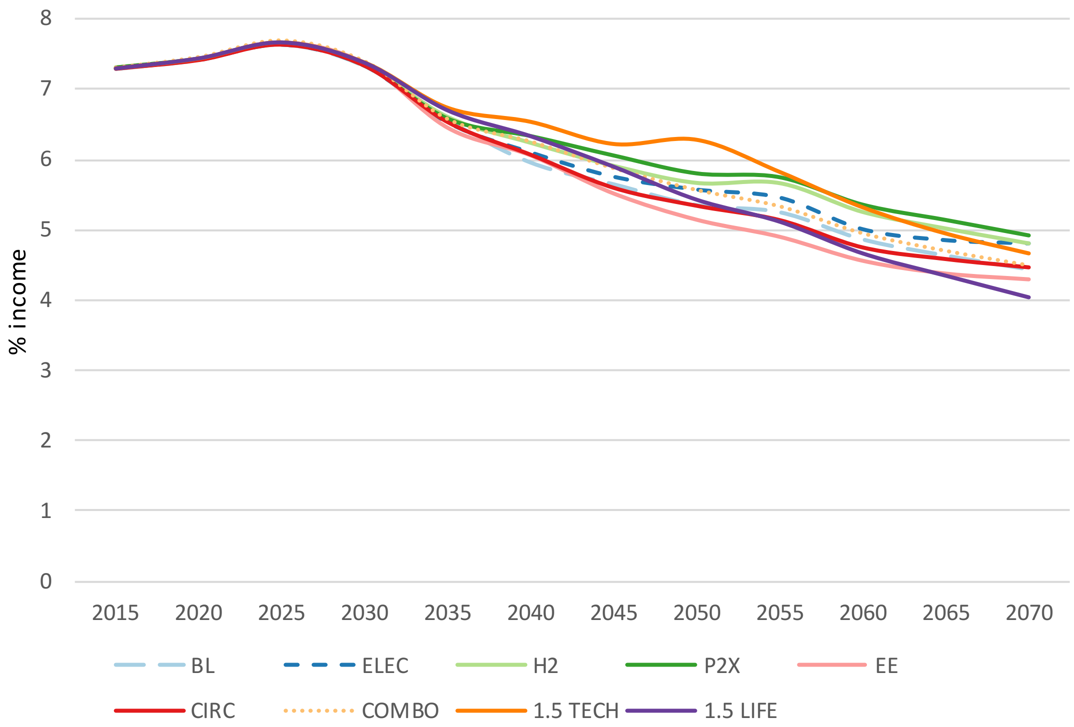

*Source: PRIMES.*

The rising trend in energy-related expenses as a share of income is expected to peak at about 7.5% around 2025-2030 before declining thereafter under all scenarios as the benefits of the energy transition materialise in full (Figure 103). By 2050, households would spend 5.6% of income on energy-related expenses, i.e. nearly 2 percentage points lower than in 2015 and lower than the share in 2005.

These figures should be understood in the context of significant variability across Member States and across income classes. For example, recent analysis shows that the poorest ten percent of the European population currently spends on average 10.4% of its income to satisfy its energy needs (i.e. higher than the average 7.3% quoted above). Currently, the poorest households in Sweden spend only 3% of their total expenditure on energy, whereas in Slovakia this share is higher than 23%.

Increases in energy-related expenses in the recent past highlight that the European Union needs to step up its effort to mitigate the social costs of the transition. Households with financial means and available options will be in the position to offset higher energy costs investing in energy efficiency and renewable energy. Other households might not have this opportunity and this category includes low-income households that are more exposed to energy poverty. Guaranteeing continued and inclusive economic growth and rising living standard is the most important measure to offset the sustained high-levels of energy-related expenses a share of income through the 2030 horizon. In this context, it will be particularly important to protect vulnerable consumers with the effort should focused on the next decade.

**Figure 103: Energy related expenses per households in different scenarios (% of income)**




*Source: PRIMES.*

## *4.10.4 Impact on energy import expenditure*

In 2016, the EU produced 45% of the energy it consumed and imported 55%[461], almost entirely as fossil fuels. Oil imports represent the bulk of these imports (60% of the total and more than 90% of oil consumed in the EU), followed by natural gas (30% the total and more than 70% of gas consumed in the EU) and coal. Because of higher volume and higher unit price, oil represents the most expensive energy import cost[462] for the EU, which since 2005 has oscillated between 1% and 2.5% of GDP[463] (1.7% on average over 2005-2015). The cost for the EU of fossil fuel imports (thus also including gas and coal) has been close to 2.5% of GDP on average over 2005-2015.

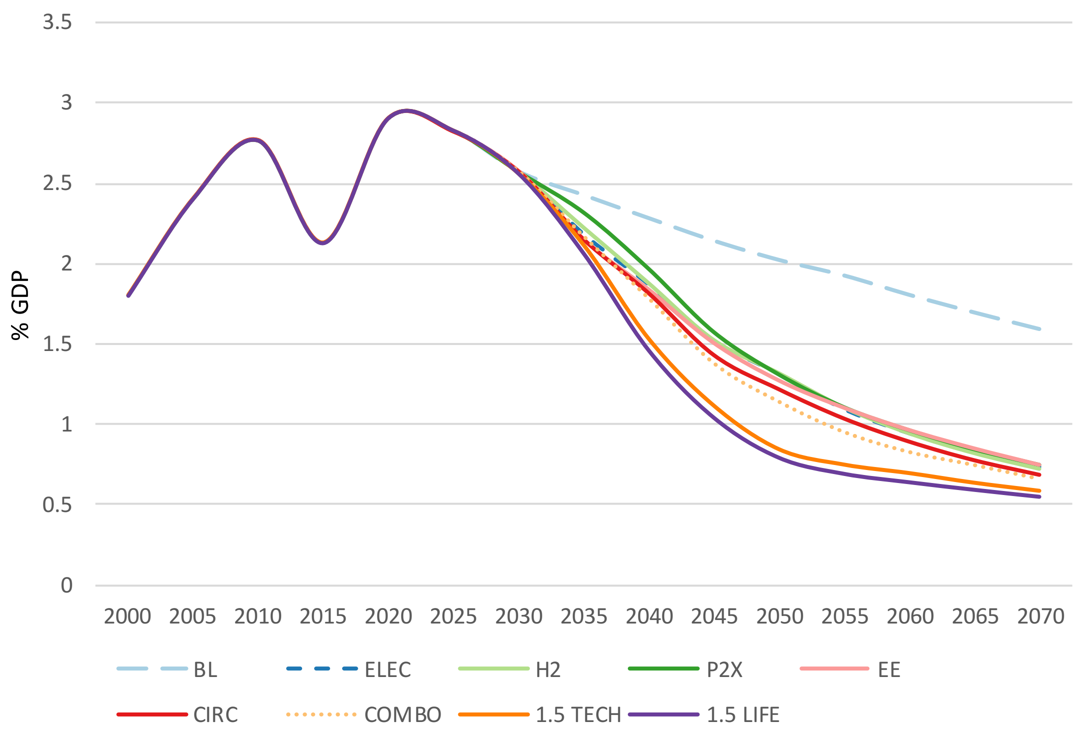
In decarbonisation scenarios, energy imports in the EU remain close to current levels until 2030, mostly because of the expected reduction of domestic oil and gas production, which could be halved by 2030 compared to 2010. However, import dependency fall strongly afterwards from more than 50% in 2030 to 27-38% by 2050 in the scenarios reaching 80% reductions and to 20% in the net zero emissions scenarios – see more detail in section 4.2.2.5.

The value of net fossil fuel imports decreases in all decarbonisation scenarios[464]. In the period 2021-30 the value of fossil fuels import bill is projected to reach EUR 421 billion per annum on average and it would continue to grow without strong decarbonisation throughout because of rising fossil fuel prices (volume of imports decreases as described in section 4.1.2). As a share of

[461] Eurostat (2018): https://ec.europa.eu/energy/en/data-analysis/energy-statistical-pocketbook
[462] EC, EU Crude Oil Imports and supply cost (retrieved 02/08/2018)
[463] WB, GDP (retrieved 02/08/2018)
[464] Fossil fuel prices are assumed to be the same in all scenarios.

GDP, net fossil fuel imports are expected to decrease after 2025, and even to go below current levels after 2030 in all decarbonisation cases (Figure 109).

**Figure 104: Net fossil fuel imports as % of GDP**

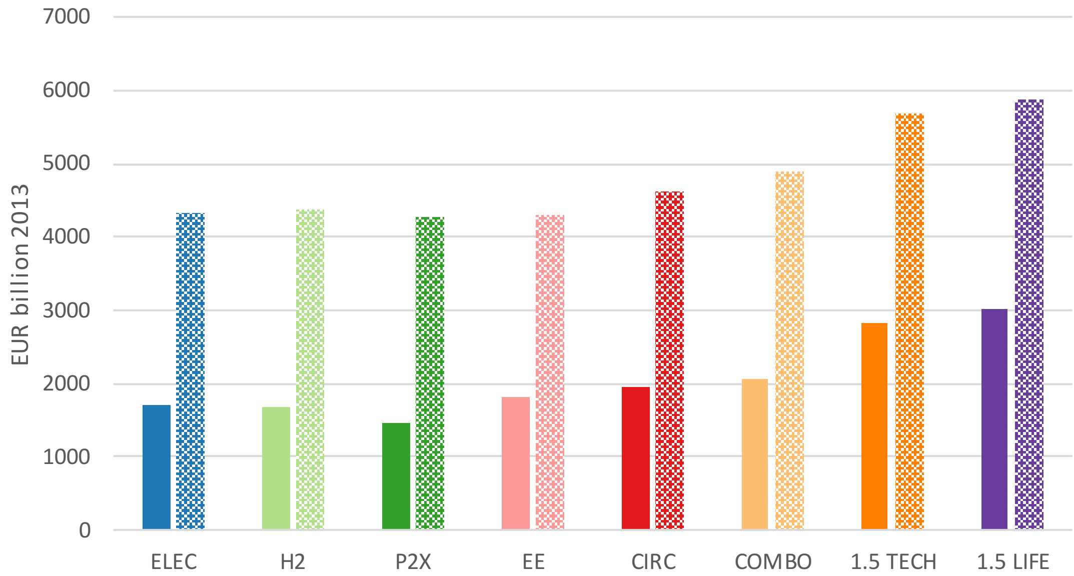



*Source: PRIMES.*

Net fossil fuel imports in the Baseline amount to 2.2% of GDP per annum over 2031-2050, and 1.7% over 2051-2070. In the decarbonisation scenarios, average yearly imports are reduced to between EUR 286 billion/year and EUR 362 billion/year over the period 2031-50, i.e. 1.4% to 1.8% of GDP. In 2050, energy imports represent 1.2% to 1.3% of GDP in the 80% reduction cases, and 0.8% in the net zero emissions scenarios. Over 2051-2070, annual net fossil fuel imports are expected to be further reduced to between EUR 164 billion/year and EUR 245 billion/year.

Based on these figures, it is estimated that in the period 2031-50 the decarbonisation scenarios would bring cumulative savings (over 20 year) in the fossil fuels import bill ranging from EUR 1.4 trillion to EUR 3 trillion.

**Figure 105: Cumulative savings on net imports of fossil fuels, difference from baseline in 2031-2050 (full bars) and 2051-2070 (patterned bars)**




*Source: PRIMES.*

In addition, the import prices of oil, gas and coal are actually likely to decrease in a global decarbonisation context whereby all regions would move away progressively from fossil fuels[465]. As a consequence, it is expected that the cost for the economy of fossil fuel imports would be even lower if this impact of global action would have been taken into account.

By 2030 natural gas imports will still remain an important energy source. However, with natural gas imports expected to reduce by 60-92% by mid-century in a decarbonisation context, the long-term use of existing import capacities is an open question. Answering this question requires an accurate estimate of gas demand in the short and medium term, its interaction with Member States policies (such us the coal phase outs announced by several Member States) and its timing compared with the projected rise of electricity demand. The long-term analysis performed in the context of the Long Term Strategy is not best suited to address this issue. Imports of carbon-free fuels, like biomass (in a solid or liquid form), hydrogen or e-fuels could benefit from existing energy import facilities.

At global level, shifting away from fossil fuels will trigger considerable shifts in the energy trade patterns. For exporting regions diversification of their economy, including probably developing other energy sources, would help producers adapt.

The challenges to security of supply will evolve over time and existing security challenges are likely to lose importance and new challenges are likely to emerge. Although the energy transition will improve the energy trade balance of the EU, it might increase import dependency on other raw materials used in low-carbon technologies. Current production of resources such as lithium, cobalt or graphite are located in few countries or regions in the world, which may require a re-assessment of the EU diplomacy priorities to secure access to scarce and valuable raw materials[466].

[465] See WEO 2017, figure 1.5 (IEA, 2017), or GECO 2017, figure 28 (JRC, 2017, doi:10.2760/474356)

[466] Andrews-Speed, P. et al. (2014). Conflict and cooperation over access to energy: Implications for a low-carbon future. https://doi.org/10.1016/j.futures.2013.12.007

### *4.10.5 Macroeconomic impacts of the climate and energy transition*

The EU's deep decarbonisation and the energy transition will affect all sectors of our economies, as well as our trade relations with the rest of the world. Deep decarbonisation will not only determine *what* we produce and *how* we produce it, but also *what* we consume and *how* we consume it. At the core of the transition, the structure of our energy system will evolve in fundamental ways, thereby reducing our dependency on energy imports. Deep decarbonisation will not be the only transformative trend that will affect the EU and global economy over the coming decades. For example, the transformation will take place in a context of an ageing EU population and evolving globalisation as well as some effects of climate change (much more moderate though if decarbonisation objectives are achieved).

Macro-economic modelling enables an assessment of the impact of decarbonisation on broad economic aggregates as well as the composition of output, employment, international trade and sectoral competitiveness. It faces limitations, however, when it comes to providing deeper insights on the precise nature of the transformation of individual sectors (see section 7.2).

In addition, modelling over very long-term horizons (e.g. 2050 and beyond) should not be seen as forecasts in the sense of short-term economic forecast, which seek to make relatively firm predictions of detailed economic indicators. Instead, long-term modelling is constructed to assess the impact of key factors and assumptions relative to a "baseline" of likely long-term developments. It therefore abstracts from short- or medium-term economic factors that may affect the trajectory of our economies in significant ways, e.g. financial crises, disruptive technological innovation, etc.

All modelling results used in this section operate on this principle and seek to isolate the impact of decarbonisation by focusing on deviations from the Baseline. Projections of long-term GDP growth under the Baseline rely on the growth accounting methodology used in the European Commission's Ageing Report[467]. The Baseline is constructed based on the report's assumptions regarding population and labour force projections, as well as expectations about the growth of total factor productivity. It uses the report's central assumptions and the modelling in this context does not seek to mirror the sensitivity analyses conducted for the Ageing Report[468] as scenarios focus on the impact of decarbonisation.

The Joint Research Centre's GEM-E3 (computable general equilibrium) model was used to assess a range macro-economic issues stemming from the analysis of the energy transition. The macro-economic baseline was constructed using the results of the PRIMES energy system model for the baseline energy scenario[469]. For the rest of the world, the macro-economic baseline assumes implementation of the Intended Nationally Determined Contributions (INDCs) as reported to the UNFCCC and as modelled by POLES-JRC. Two levels of ambition for the EU were modelled: (1) a reduction in GHG emissions of 81% by 2050 relative to 1990, consistent with the EU's contribution to a 2°C objective, using the results from the PRIMES ELEC scenario (the 80% reduction scenarios); and (2) a reduction in GHG emissions of around 94% consistent with emissions reduction achieved in the 1.5TECH scenario (1.5°C scenarios). Including the

[467] European Commission (DG ECFIN), "The 2018 Ageing Report. Underlying Assumptions & Projection Methodologies", European Economy Institutional Paper 065; and European Commission (DG ECFIN), "The 2018 Ageing Report Economic & Budgetary Projections for the 28 EU Member States (2016-2070)", European Economy Institutional Paper 079.

[468] The Ageing Report conducts sensitivity analyses based on different assumptions regarding life expectancy, fertility, migration, total factor productivity growth or retirement age. None of these sensitivities are assessed here as they are not directly related to the decarbonisation pathways.

[469] The macro-economic baseline therefore integrates the measures as adopted under the 2030 climate and energy framework, e.g. on the EU ETS, the Effort Sharing Regulation or energy efficiency.

LULUCF sink, the 1.5°C scenarios achieve GHG neutrality by 2050, but JRC-GEM-E3 does not model LULUCF absorptions and emissions.

Further, two possible configurations for the EU and the rest of the world were modelled in each case: (1) fragmented action scenarios where the EU achieves the 81% reduction in 2050 relative to 1990 levels or net GHG neutrality while the rest of the world adheres only to nationally determined contributions as submitted to the UNFCCC, (in-line with projections by the POLES-JRC model); and (2) global action scenarios where the EU achieves the 81% reduction or net GHG neutrality by 2050 while the rest of the world achieves reductions of 46% or 72%, respectively, in-line with projections by the POLES-JRC model.

In addition, several variants to the scenarios were modelled to assess the impact of varying assumptions on the labour market, carbon pricing in the ETS and non-ETS sectors, the behaviour of firms in ETS sectors and the use of carbon-based revenues.

The E3ME (Cambridge Econometrics) macro-econometric model was used in parallel to provide as comprehensive a picture as possible. The model was similarly made consistent with the PRIMES Baseline. As for the JRC-GEM-E3, fragmented and global action scenarios were modelled for two given levels of efforts for the EU: an 81% reduction in GHG by 2050 (ELEC scenario) and net GHG neutrality by 2050 (1.5°C TECH scenario). Finally, the QUEST model from the Directorate General Economic and Financial Affairs was also used to simulate results for the Baseline, an 80% reduction scenario and a 1.5°C scenario (net GHG neutrality by 2050), with a sensitivity analysis on the use of revenues from the auctioning of ETS allowances.

Modelling results vary to a limited extent only, regardless of scenario, and convey a consistent message: the impact of decarbonisation on GDP will be limited[470]. While JRC-GEM-E3 indicates that decarbonisation will typically entail a small negative effect on GDP by 2050, E3ME and QUEST suggest that the impact of decarbonisation efforts on GDP could actually be moderately positive, including in the context of achieving net GHG neutrality. The distinct assumptions regarding market imperfections and whether the economy operates at full capacity are at the heart of these differences. E3ME assumes that the economy has some unused resources to begin with, which means that additional investment in decarbonisation operates as a demand stimulus and spurs additional growth. Additional investments need to be financed through borrowing, however, and the cost of repaying loans generates a negative stimulus at a later stage. QUEST also assumes that decarbonisation efforts generate a positive expenditure shock (additional investment). Instead, JRC-GEM-E3 assumes that the economy is at an equilibrium, without any unused resources. It therefore projects small negative impacts due to changes in the allocation of production factors between sectors, with resulting impacts on productivity. It must be noted, however, that the differences in results between the three approaches are small.

The negative impact implies at worst that real GDP would be 1.30% lower in 2050 than under the baseline (JRC-GEM-E3, 1.5°C global action scenario). At best, the positive impact could imply that real GDP would be 2.19% higher than baseline in 2050 (E3ME, 1.5°C global action scenario). The QUEST modelling results lie between these two (Table 12). Considering the GDP impact over the entire period, JRC-GEM-E3 indicates that the deviation from baseline gradually increases through to 2050 where it is highest. In turn, the impact on GDP under the E3ME model gradually increases over time as the stimulus operates in full by around 2045, after which the repayment of loans moderates the positive impact on GDP. Under the 1.5°C global action scenario, the positive impact peaks at 3.0% in 2045 before falling to 2.2% in 2050.

[470] These estimates exclude the co-benefits of the energy transition (e.g. the benefits of reduced air pollution, see also 5.7), the costs of adapting to climate change and avoided climate impacts.

**Table 12: GDP impacts of 80% reduction and 1.5°C scenarios (deviation from Baseline, percent).**

| GDP vs. Baseline, 2050 | Fragmented action | | Global action | |
|---|---|---|---|---|
| Temperature target | **2°C** | **1.5°C** | **2°C** | **1.5°C** |
| EU action[1] | -80% | Net GHG neutrality | -80% | Net GHG neutrality |
| Global[1] action | NDC | NDC | -46% | -72% |
| **JRC-GEM-E3[2]** | -0.13% | -0.63% | -0.28% | -1.30% |
| **E3ME** | 1.26% | 1.48% | 1.57% | 2.19% |
| **QUEST** | 0.31% | 0.68% | -- | -- |

[1] GHG emissions or policy implemented.

[2] Deviation from Baseline in % of GDP for the model variant that assumes maximisation of profit in ETS sectors, flexible wages in the long run and lump-sum transfer of carbon revenue to households.

*Sources: JRC-GEM-E3 and E3ME.*

As expected, the 1.5°C scenarios yield the biggest difference between modelling approaches, but all modelling results (including the 80% reduction scenarios) fall within this narrow 3.5 percentage points range. The three approaches therefore indicate that net GHG neutrality can be achieved with only limited impacts on GDP, either positive or negative. Results from the JRC-GEM-E3 model also indicate that unilateral action by the EU to achieve net GHG neutrality by 2050 would entail only limited costs in terms of GDP. In turn, the OECD estimated that mitigation policies could have a positive impact of 2.2% by 2050 for advanced fuel-importing G20 countries under a coordinated 2°C scenario, if accompanied by structural reforms and green innovation[471].

These GDP impacts must also be put in the context of economies that are set to continue growing under all circumstances, mainly because of increases in total factor productivity (technological progress and innovation). They should therefore be understood as decarbonisation leading the EU economy to grow at worst by 66.0% between 2015 and 2050 instead of 68.1% under the Baseline (JRC-GEM-E3, 1.5°C global action scenario), or growing at best by 73.7% instead of 70.7% (E3ME, 1.5°C global action scenario) and growing by 69.3% instead of 68.4% (QUEST, 1.5°C scenario). If 1990 is used as a point of comparison, net GHG neutrality could be achieved by 2050 while growing the economy by 152% to 163%. This would translate into increases in GDP per capita of 126% to 136%.

While GDP impacts differ relatively little between modelling approaches, the implications of fragmented vs. global action are more contrasted[472]. Under JRC-GEM-E3, fragmented action generates somewhat less negative impacts on GDP than global action. A unilateral effort to

[471] OECD (2017), "*Investing in Climate, Investing in Growth*", OECD Publishing.

[472] Without taking into account the economic cost of climate change affecting economy or, in case of global action, avoiding large part of such costs.

reduce emissions by 80% or achieve net GHG neutrality by 2050 means that producers of internationally traded goods face higher costs and potentially negative impacts on competitiveness. However, global action also means that world GDP, and hence export markets, are negatively affected by the cost of decarbonisation[473]. Overall, the market size effect predominates the competitiveness effect, which means that leading the way on decarbonisation actually entails some gains for the EU in terms of GDP rather than costs. Further, the competitiveness effect is mitigated by the effort already present in the baseline for the EU. The difference between fragmented and global action is nevertheless small and does not exceed 0.2 percentage point of GDP under the 80% reduction scenarios and 0.8 percentage points under the 1.5°C scenarios.

Individual sectors are nevertheless affected in ways that differ from the impact on GDP. In particular, the impact on key internationally traded goods sectors (ferrous metals, non-ferrous metals, chemicals, paper products and non-metallic minerals) is more favourable (bigger positive or smaller negative) under the global action scenario than under fragmented action (Table 13). For these sectors, the competitiveness effect appears to be more important than the market size effects and the contrast is larger for the more energy-intensive and trade-oriented sectors. This entails that under a global action scenario, EU industry could benefit from first-mover advantages, even though they would likely decrease over time[474]. Overall, it is important to note that the impacts on output remain relatively small under both the fragmented and global action scenarios.

[473] As for the EU, JRC-GEM-E3 assumes that the economies of other countries or blocks operate at full capacity and that decarbonisation entails a moderate cost in terms of GDP.

[474] European Commission (2017), "A technical case study on R&D and technology spillovers of clean energy technologies", https://ec.europa.eu/energy/sites/ener/files/documents/case_study_3_technical_analysis_spillovers.pdf

**Table 13: Sectoral output impacts, (deviation from Baseline, percent)[475].**

| 2050 | Fragmented action | | Global action | |
|---|---|---|---|---|
| | 80% reduction | 1.5°C | 80% reduction | 1.5°C |
| Fossil-fuels industries[1] | -32.6 | -54.5 | -33.0 | -40.6 |
| Electricity supply[2] | 10.1 | 23.8 | 9.2 | 29.7 |
| Ferrous metals | -4.4 | -10.1 | 2.3 | 5.5 |
| Non-ferrous metals | -1.0 | -1.2 | 0.6 | 6.1 |
| Chemical Products | -1.9 | -2.7 | -1.8 | -1.1 |
| Paper products | 0.2 | 1.1 | 1.3 | 6.8 |
| Non-metallic minerals | -1.3 | -3.5 | 0.3 | 1.7 |
| Electric Goods | 0.6 | -2.7 | 0.1 | -3.4 |
| Transport equipment | -2.3 | 0.0 | -2.9 | -3.9 |
| Construction | 1.4 | 3.3 | 1.0 | 2.5 |
| Transport | -2.5 | -5.6 | -2.5 | -8.7 |
| Market Services | -0.4 | -0.7 | -1.1 | -2.9 |

[1] *Coal and crude oil, oil and gas industries.*
[2] *Power generation, transmission and distribution as well as electricity sales and trade.*

*Source: JRC-GEM-E3.*

E3ME offers a contrasting perspective on the effect of fragmented vs. global action. Since decarbonisation investments act as an economic stimulus in economies with spare capacity, global action generates higher output in the rest of the world than fragmented action. Increased market size therefore cumulates with the positive impacts of global action on the competitiveness of EU industries so that global action generates a higher stimulus than fragmented action. Under the 80% reduction scenario, the positive impact on GDP by 2050 amounts to 1.26% under fragmented action and 1.57% under global action.

While aggregate output is unlikely to be affected significantly by decarbonisation, this is not so for the sectoral composition of output, i.e. what we produce. The output of sectors related to

[475] Variant of the model with profit maximisation in ETS sectors, perfect labour markets and lump-sum transfers of carbon revenue to households.

fossil fuels is expected to contract sharply relative to baseline by 2050, with the baseline itself already factoring-in significant declines in output (Table 13). In turn, output in industrial sectors is expected to remain slightly above or below baseline, depending on the scenario (fragmented or global action). This reflects both continued demand for industrial products and the preserved competitive position of EU industries globally. The modelling indicates that transport will be negatively affected, as the sector starts from a high initial reliance on fossil fuels and in certain cases has more limited decarbonisation options.

In addition to assessing the impact of fragmented vs. global action, a sensitivity analysis was run under the JRC-GEM-E3 scenarios in order to assess the impact of firms in ETS sectors fully reflecting the opportunity costs of free allowances in their behaviour (profit maximisation) vs. not reflecting such opportunity costs (maximisation of volumes or market shares). This sensitivity analysis was run as industrial firms, particularly those exposed to international competition, often claim that they are not able to include the opportunity cost of free allowances in their price setting. The impact of labour market imperfections and the recycling of carbon revenue to reduce labour market taxation was also considered as part of this analysis (see also below).

Market share maximisation generates a minimally smaller loss in GDP than profit maximisation under the model set-up with perfect labour markets and lump-sum transfers of carbon revenue[476] to households as higher output in ETS sectors is offset by somewhat lower output in non-ETS sectors due to higher carbon prices (Table 14). If labour market imperfections are also factored in, recycling carbon revenues to lower labour taxation generates a small positive effect on GDP as carbon revenues enable a tax shift that reduces distortions linked to labour market taxation. The larger the carbon revenues (as occurs under market share maximisation vs. profit maximisation), the more positive the effect. Overall, the recycling of carbon revenues to reduce labour taxation improves economic output and reduces production costs in industry, which has a positive impact on the competitiveness (and output) of industrial sectors. Recycling of carbon revenues to reduce labour taxation is therefore and additional policy measure that can be used to facilitate the transition of the industrial sector.

[476] Under this assumption, all carbon revenues are redistributed to households in the form of a lump sum. Under the recycling assumption, carbon revenues are instead used to lower taxes on labour. In both cases, the impact on the government is assumed to be neutral, which means that the scale of the labour taxation shift (and hence is distortionary impact) is commensurate to the level of carbon revenues raised. Carbon revenue in the JRC-GEM-E3 model arise both from ETS and non-ETS sectors.

**Table 14: Impact on GDP, profit maximisation, market share maximisation and carbon revenue recycling.**

| GDP vs. Baseline, 2050 JRC-GEM-E3 | Fragmented action | | Global action | |
|---|---|---|---|---|
| | 80% reduction | 1.5°C | 80% reduction | 1.5°C |
| Profit maximisation<br>Perfect labour market<br>Lump-sum transfers | -0.13% | -0.63% | -0.28% | -1.30% |
| Market share maximisation<br>Perfect labour market<br>Lump-sum transfers | -0.10% | -0.59% | -0.25% | -1.26% |
| Market share maximisation<br>Imperfect labour market<br>Revenue recycling | 0.05% | -0.29% | -0.18% | -1.09% |

*Source: JRC-GEM-E3.*

The intensity of the positive impact on the output of ETS sectors of shifting from profit maximisation to market share maximisation varies depending on exposure to international trade and carbon intensity. Sectors that are both carbon intensive and highly exposed to international trade (ferrous metals, non-metallic minerals) register a larger positive effect on output when shifting to market share maximisation than sectors that are less carbon intensive and more focused on domestic markets (chemicals, paper products, non-ferrous metals). The positive effect on output is also larger when carbon revenues are used to lower labour taxation (Table 15).

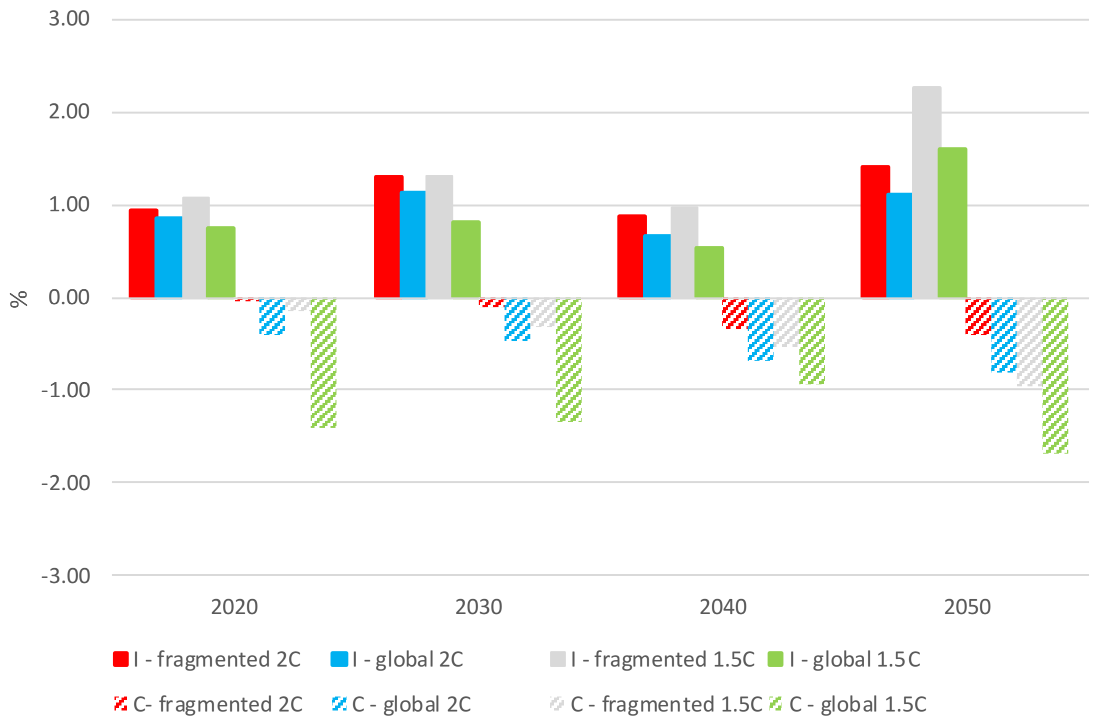
**Table 15: Impacts on ETS sectors, (deviation in output from baseline, percent).**

| Deviation in output vs. baseline maximisation, 2050 JRC-GEM-E3 | Fragmented action 80% reduction | | |
|---|---|---|---|
| | Ferrous metals | Non-metallic minerals | Chemicals |
| Profit maximisation<br>Perfect labour market<br>Lump-sum transfers | -4.4 | -1.3 | -1.9 |
| Market share maximisation<br>Perfect labour market<br>Lump-sum transfers | 2.4 | 0.8 | -1.2 |
| Market share maximisation<br>Imperfect labour market<br>Revenue recycling | 2.9 | 1.1 | -0.8 |

*Source: JRC-GEM-E3.*

The impact of decarbonisation on private consumption could be somewhat more significant, though still not very large. Differences between modelling approaches are also more noticeable. The negative impact under JRC-GEM-E3 is at most 1.0% under the 80% reduction scenarios and 3.4% under the 1.5°C scenarios. However, this mostly reflects a sharp drop in the consumption of non-durables linked to durables, i.e. mainly a drop in energy consumption for heating and cooling as well as for transport, falling by more than 30% relative to Baseline in 2050 under the 80% reduction scenarios and by close to 50% under the 1.5°C scenarios. In contrast, consumption of durables could rise by up to 12% by 2050 under the 80% reduction scenarios and by more than 20% under the 1.5°C scenarios. In turn, the consumption of non-durables other than energy would increase by up to 1.8%. Given that the model assumes that the economy operates at full capacity, any increase in investment in one sector must be met by a decrease in investment in other sectors, or a decrease in private consumption through a reallocation of resources (full crowding out). It does indeed appear that decarbonisation entails a shift from consumption to investment throughout the transition period (Figure 106). This shift is generally more significant under the 1.5°C scenarios than under the 80% reduction scenarios.

**Figure 106: investment (full bars) and private consumption (patterned bars), deviation from baseline (%)[1]**




[1] *Model variant that assumes maximisation of profit in ETS sectors, flexible wages in the long run and lump-sum transfer of carbon revenue to households.*

*Source: JRC-GEM-E3.*

Significant investments will be required to decarbonise the energy system and industry and to foster research and innovation. To some extent, this will mean *other types* of investment than under the Baseline rather than *additional* investments. At the aggregate level, it nevertheless remains that additional resources will need to be mobilised for investment, as reflected in the modelling. The assumed crowding out effect dampens the impact of the decarbonisation scenarios on aggregate investment, even though a small shift in aggregate resources from consumption to investment takes place under almost all scenario variants. This shift is persistent during 2020-2050 in most cases, with investment between 0.5% and 1.2% above Baseline throughout the period for most scenario variants, which reflects the sustained nature of the investment needs.

The most significant impacts, however, concern the types of investment that take place, with impacts of a similar nature regardless of the scenarios envisaged. As expected, investment in fossil fuels are expected to drop below Baseline throughout the period, reflecting the need to accelerate the phasing out of such fuels from the energy system early on (Table 16). Industrial sectors instead are projected to require additional investment to decarbonise for a sustained period of time, while higher reliance on electricity will necessitate a significant shift of resources to supply and power technologies.

**Table 16: Sectoral investment impacts in the EU, (deviation from Baseline, percent)[477].**

| 2050 | Fragmented action | | Global action | |
|---|---|---|---|---|
| | 80% reduction | 1.5°C | 80% reduction | 1.5°C |
| **Fossil-fuels industries** | -40.6 | -58.2 | -40.4 | -40.9 |
| **Electricity supply** | 8.5 | 21.9 | 7.4 | 26.3 |
| **Ferrous metals** | -3.7 | -9.4 | 3.3 | 6.7 |
| **Non-ferrous metals** | -0.4 | -1.1 | 1.0 | 5.2 |
| **Chemical Products** | -1.1 | -2.3 | -0.9 | -0.1 |
| **Paper products** | 0.8 | 1.2 | 1.8 | 6.5 |
| **Non-metallic minerals** | -0.7 | -2.4 | 0.9 | 2.7 |
| **Electric Goods** | 1.6 | 3.1 | 0.9 | -3.9 |
| **Transport equipment** | -1.3 | 0.8 | -2.1 | -3.4 |
| **Construction** | 2.0 | 3.6 | 1.7 | 3.0 |
| **Transport** | -0.8 | -3.1 | -0.9 | -6.1 |
| **Market Services** | 0.0 | -0.4 | -0.7 | -2.7 |

*Source: JRC-GEM-E3.*

In contrast, the assumption that the economy typically operates below capacity enables an increase in investment for decarbonisation in E3ME without full crowding of other investments or consumption. Under this model, private consumption could increase by up to about 1.5% in 2050 relative to Baseline (global action, 80% reduction scenario).

Overall, macro-economic modelling indicates that: (1) the impact of decarbonisation on broad economic aggregates like GDP, consumption or total employment (see section 4.10.6 on employment impacts) is likely to be relatively limited under all scenarios, including those achieving net GHG neutrality; and (2) modelling approaches that differ significantly structurally as well as in their underlying views on the working of the economy and the scale of market imperfections concur on conclusion.

As far as capital is concerned, decarbonisation will indeed require not only additional investment, but also different kinds of investments than under the Baseline. The transition will therefore generate risks of capital misallocations in view of long-term objectives. One of the goals of the long-term strategy is to provide a clear sense of direction upon which investors can reliably base

477 Variant of the model with profit maximisation in ETS sectors, perfect labour markets and lump-sum transfers of carbon revenue to households.

their investment decisions. Finally, the architecture of the financial system will have to be fit for purpose in order to be in a position to fund the right kind of investments (see also section 5.1).

### *4.10.6 Employment impacts of the climate and energy transition*

The macro economic modelling can also be used to assess the employment impacts. Under the JRC-GEM-E3 model, when assuming that wages are fully flexible and that the labour market always clears, aggregate employment is not affected. However, sectoral composition is significantly impacted (see discussion below).

The variant of the model that assumes labour market imperfections and involuntary unemployment does show an impact on aggregate employment. Under such a setting (with market share maximisation in ETS sectors) for the 80% reduction scenario, using carbon revenues to reduce labour taxation generates a positive impact on aggregate employment of the low carbon transition, both under the fragmented and global actions scenarios. Employment in 2050 could increase by 0.3% compared to Baseline. This would mean an additional 492 000 (global action) or 616 000 (fragmented action) jobs in 2050 relative to Baseline. Under the same variant of the 1.5°C scenarios, employment in 2050 could increase by around 0.6%. This highlights the potential benefits that a shift in taxation away from labour may have, as this modelling variant also implies that GDP could be 0.05% higher than under Baseline by 2050 and 0.13% higher on average during each year of the 2020-2050 period (fragmented action 80% reduction scenario). QUEST estimates that an 80% reduction scenario would have a small positive impact (+0.3%) on total employment by 2050.

In turn, E3ME estimates a positive impact on employment of about 0.6% by 2050, equivalent to 1 316 000 additional jobs, under the 80% reduction scenarios (fragmented and global action) and up to 0.9% (2 100 000 additional jobs) under the 1.5°C scenario (global action). Similarly, the OECD's *Investing in Climate*, *Investing in Growth* report estimates a positive impact on employment of about 0.2% by 2050 for G20 countries, based on the assumption that additional investment and structural reforms to labour and product markets would take place. Overall, this indicates that the aggregate impact on employment is likely to hinge upon factors that relate more to the structure of the labour market than to decarbonisation *per se*.

However, the composition of employment across sectors and within sub-sectors is likely to be affected in significant ways. The low carbon transition will see significant increases in turnover for sectors involved in renewable energy and energy efficiency, with associated job increases. Previous research concluded that the shift from fossil fuel based energy towards renewable energy deployment increases employment in the EU[478]. The reason for the positive impact of renewable energy deployment is a higher labour intensity in this sector compared to for instance power generation from fossil fuels[479]. However, the mining and extraction and power generation sectors account at the EU level for only a small share of total employment and the impact of a low-carbon transition on total employment is less substantial. Research also showed that the expansion of the workforce in the green energy sector outweighs the compression in the declining fossil fuel sectors[480]. Furthermore, the EU is likely to observe employment gains from a switch to

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[478] Fraunhofer ISI (2014) Employment and growth effects of sustainable energies in the EU: https://ec.europa.eu/energy/sites/ener/files/documents/EmployRES-II%20final%20report_0.pdf

[479] Wei (2010) Putting Renewables and Energy Efficiency To Work: https://doi.org/10.1016/j.enpol.2009.10.044

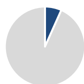
[480] UNIDO (2015) Global green growth: http://www.greengrowthknowledge.org/sites/default/files/downloads/resource/Clean_energy_industrial_investment_vol1_GGGI_UNIDO.pdf

renewable energy since the region is currently a net fossil fuel importer[481]. Positive employment effects were found for energy efficiency measures[482 483]. A particular characteristic is that energy efficiency investment is comparatively favourable for local job creation, often associated with activities in the building sector[484]. For the deployment of renewables, the impact on employment is positive particularly in the sectors related to installation, management, and maintenance).

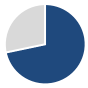
The 80% reduction and 1.5°C scenarios by the JRC-GEM-E3 and E3ME as presented in section 4.10.5 were used to assess sectoral employment effects, in addition to aggregate employment impacts[485]. The results indicate that the low-carbon transition does not significantly impact most sectors. Table 17 shows that the sector that might experience largest relative change in employment (mining & extraction) accounts for small shares of total employment. The transition triggers more investments and activities in construction, and agriculture (bioenergy), and power generation leading to higher employment. Instead, the mining and extraction sectors are expected to contract, as the demand will shift away from fossil fuels. This is in line with a recent study by IRENA[486], according to which the energy transition would lead to a loss of 7.4 million jobs in fossil fuels and other extraction sectors on a global level by 2050, but a simultaneous gain of 19.0 million jobs in renewable energy, energy efficiency, and grid enhancement.

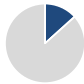
Results are more mixed in the manufacturing industries. These sectors, particularly the energy-intensive sectors, will face significant changes in their production processes in the future due to the transition towards a low-carbon economy (see section 4.5). If successful, this should not be negative for employment. Particularly the circular economy is often associated with job increases in the value chain supplying the energy-intensive industries. The situation in the manufacturing sector is also ambiguous. For instance, the European automotive manufacturing sector has to switch from internal combustion engines to electric drive trains. This development is expected to accelerate if there will be a reduction in battery prices.

**Table 17: Impacts of a low-carbon transition on different sectors.**

| Sector | Qualitative assessment of impacts of a low-carbon transition | Share of total jobs in 2015 | Range of change in jobs by 2050 compared to baseline |
|---|---|---|---|
| Construction | • Direct benefits from investments related to the low-carbon and climate-resilient transition (e.g. renewable energy technologies, energy |  |  |

[481] Fragos (2017) Job creation related to Renewables: http://www.asset-ec.eu/downloads/ASSET_1_RES_Job_Creation.pdf
[482] Cambridge Econometrics (2015) Assessing the Employment and Social Impact of Energy Efficiency: https://ec.europa.eu/energy/sites/ener/files/documents/CE_EE_Jobs_main%2018Nov2015.pdf
[483] EC (2016a) The macro-level and sectoral impacts of Energy Efficiency policies: https://ec.europa.eu/energy/sites/ener/files/documents/the_macro-level_and_sectoral_impacts_of_energy_efficiency_policies.pdf
[484] RAP (2016) Costs and benefits of EE: http://www.raponline.org/wp-content/uploads/2016/11/rap-rosenow-bayer-costs-benefits-energy-efficiency-obligation-schemes-2016.pdf
[485] This represents the range of employment impacts of all the scenarios by JRC GEM-E3 and E3ME. For agriculture employment represented by the JRC GEM-E3 model only results from fragmented action scenarios are included.
[486] IRENA (2018), Global energy Transition – A Roadmap to 2050, http://www.irena.org/publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050

| Sector | Qualitative assessment of impacts of a low-carbon transition | Share of total jobs in 2015 | Range of change in jobs by 2050 compared to baseline |
|---|---|---|---|
| | efficiency, and adaptation measures)<br>• Job-impact strongly dependent on investments in the sector<br>• Workers need to up-skill to handle innovative building materials | **6.7%** | **+0.3% to +2.8%** |
| Services | • The business services and distribution & retail sectors are indirectly influenced as they depend on corporate and household demand<br>• Digitalisation will grow in importance in the long-term due to the low-carbon transition<br>• The transport sector is expected to undergo a substantial transformation that might lead to a change in skills requirements<br>• In the non-business services sector, the skills profile of procurement-related jobs might change due to a shift towards green procurement | <br>**71.7%** | ⇨<br>**-2.0% to +0.9%** |
| Agriculture | • Bioenergy production has a positive effect<br>• In the long-term, decarbonisation policies help to protect jobs that depend on eco-system services | <br>**4.5%** | ⇗<br>**-0.7% to +7.9%** |
| Mining & extraction | • Automation and global competition have led to a continuous contraction of the workforce in the mining sector<br>• A low carbon transition will continue the shift away from fossil fuels with significant impact on employment in the mining and extraction of fossil fuels | <br>**0.5%** | ⇩<br>**-62.6% to -2.9%** |
| Power generation | • Energy efficiency measures lead to a reduced demand in energy in the mid-term but electrification will increase the demand again<br>• The higher labour intensity of renewable energy technologies has a positive impact on employment | <br>**0.7%** | ⇗<br>**+3.6% to +22.3%** |
| Manufacturing (energy-intensive industries) | • Risk of carbon leakage depends on measures that allow EU industries to remain competitive and if there is a unified global decarbonisation ambition<br>• Existing production processes face structural changes due to decarbonisation needs, opportunities related to the circular economy<br>• An increase in investments in renewable technologies or energy efficiency measures would lead to an increase in demand in upstream sectors to the construction sector, | <br>**2.0%** | ⇨<br>**-2.6% to +1.8%** |

| Sector | Qualitative assessment of impacts of a low-carbon transition | Share of total jobs in 2015 | Range of change in jobs by 2050 compared to baseline |
|---|---|---|---|
| | such as the manufacture of iron, steel or cement | | |
| Other manufacturing | • Direct benefits from higher investments triggered by climate policy (increase in demand for clean energy products produced by some sub-sectors)<br>• Indirect benefits in upstream sectors to other growing sectors, for example construction<br>• Automotive manufacturing will face structural changes due to electrification |  **13.3%** | ⇨ **-1.4% to +1.1%** |

*Source: E3ME, JRC-GEM-E3 scenarios as included in section 4.10.5.*

In the public consultation, social partners stressed the importance of considering the impact of a low-carbon transition on jobs in the different economic sectors. To evaluate the sectoral magnitude of the employment impact, it is of interest to compare this to general employment developments. Table 18 shows the current number of employees in these sectors, the development of employment up to 2030 and the number of employees that are at least 50 years old and will most likely retire by 2030. For each sector, the decarbonisation scenario with the least favourable employment development from Table 17 was selected.

Most of the change already occurs in baseline due to structural change. For example, efficiency improvements cause continued employment reductions in the agriculture sector. Only in some sectors, limited impacts are due to decarbonisation (both positive and negative impacts compared to baseline, see table above). The table shows that even in the least favourable scenario, any decline in jobs can be absorbed by retirements in all sectors but one. Only the mining and extraction sector is expected to contract in a way that the decrease in jobs cannot fully be compensated by retirements.

**Table 18: Potential to absorb work force changes**

| Million | 2015 total employment | **2015-2030 change** (accumulated effect from baseline development and decarbonisation) | **Number of people expected to retire between 2015 and 2030** (proxy used is labour in the 50+ years age bracket in 2015) |
|---|---|---|---|
| Construction | 14.8 | 0.4 | -4.3 |
| Services | 158.5 | 5.0 | -48.2 |
| Agriculture | 9.9 | -1.3 | -4.3 |
| Mining & extraction | 1.0 | -0.5 | -0.3 |
| Power generation | 1.6 | -0.3 | -0.5 |
| Manufacturing: Energy-intensive industries | 4.4 | -0.5 | -1.4 |
| Other manufacturing | 29.4 | -1.2 | -8.4 |

*Source 2015 data: Eurostat LFS.*

As far as the labour market is concerned, the transition will generate significant implications both on labour demand at the sectoral and sub-sectoral level and in terms of skills in demand, with potential impacts on income distribution as well. This is likely to have repercussions at the national level as well as the level of sub-regions, depending on their current specialisation in production. For example, rural areas experience an outflow of young people. To keep the rural areas vibrant, there is the need develop the essential services (mobility, infrastructure, etc.). Such implications will need to be managed carefully in the context of a just transition and to ensure that no segments of the population are left behind in the process.

# 5 CROSS-CUTTING FACTORS

## 5.1 Regional employment aspects, education and skills

The transition to a low carbon economy is a transition towards new growth sectors and jobs and overall benign for aggregate employment (Section 4.10.6). The differentiated impacts across sectors imply that the transition could be particularly challenging for the job market in a number of limited regions with high activity rates in sectors that are affected most negatively.

Historically, the EU job market has benefitted from climate policies. A review of several studies on the effect of the EU's 20-20-20 targets on jobs concluded that the implementation of these targets leads to an increase in jobs, some estimates putting it as high as 1.0% and 1.5%.[487] Also, the International Labour Organisation estimated that by 2030 the low-carbon transition could increase EU jobs by 2 million jobs compared to a business as usual case.[488]

### *5.1.1 Implication for regions*

The transition towards green jobs is seen as a positive evolution for the job market. Green jobs are often quality jobs contributing often also to local (non-outsourceable) employment in rural or disadvantaged areas and thus to social reinsertion and territorial cohesion. The EU's green economy has proven itself to be resilient, and has maintained jobs in recent years, including in the recession years. The European environmental goods and services sectors employed 4.1m people in 2015, which is an increase of 47% compared to 2000.[489]

However, it is clear that a low-carbon transition can entail significant economic and societal challenges for regions. Particularly challenged are regions whose economies largely depend on sectors that either are expected to decline or will have to transform in the future. An assessment was made on which regions might be in this situation in the EU. Table 19 shows which sectors and sub-sectors were included in the two different categories in this assessment and the respective NACE codes.

**Table 19: Sectors shown in the heat maps**

| Sectors expected to decline | Sectors expected to transform |
|---|---|
| • Mining of coal and lignite (B05)<br>• Extraction of crude petroleum and natural gas (B06)<br>• Mining support service activities (B09) | • Manufacture of chemicals and chemical products (C20)<br>• Manufacture of other non-metallic mineral products (C23)<br>• Manufacture of basic metals (C24)<br>• Manufacture of motor vehicles, trailers and semi-trailers (C29) |

To visualise the regional impact of a low-carbon transition, the maps below (Figure 107) show the relative share of employment in sectors that are expected to decline and in sectors that will have to transform.

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487 Cambridge Econometrics (2011), Green jobs, http://ec.europa.eu/social/BlobServlet?docId=7436&langId=en

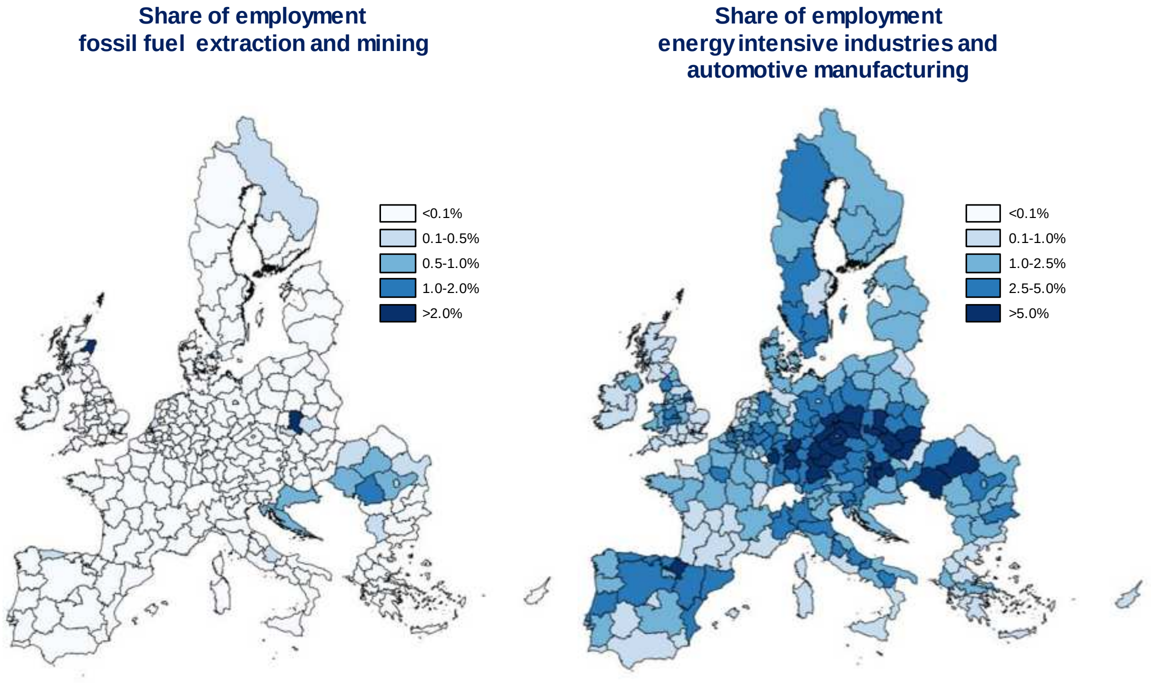
488 ILO (2018), World Employment and Social Outlook, https://www.ilo.org/weso-greening/documents/WESO_Greening_EN_web2.pdf

489 Eurostat (2018), Employment in the environmental goods and services sector, http://ec.europa.eu/eurostat/statistics-explained/index.php/Environmental_goods_and_services_sector

Three EU regions (NUTS-2 level) have employment shares of more than 1% in sectors that are expected to decline. The region with the highest share (11.3%) is North Eastern Scotland in the United Kingdom because of high employment in extraction and support service activities, focussed on oil and gas. Similarly but with a focus on coal and lignite, Silesia in Poland and Sud-Vest Oltenia in Romania have a share of 5.3% and 1.8% of overall employment in mining activities and support services.

When considering the industries that will have to transform, it becomes apparent that many more regions will be affected. Out of the EU's 28 Member States, 24 have regions where more than 1% of the work force is employed in such a sector, with higher shares in Member States with lower GDP per capita levels. The regions with the highest exposure are Strední Cechy in the Czeck Republic (10.4%), Közép-Dunántúl in Hungary (9.7%), and Vest in Romania (9.3%).

**Figure 107: Regional exposure to sectors that will decline (left) and transform (right)**




*Source: Eurostat SBS*[490].

A conclusion of the above analysis is that only a few regions highly depend on sectors that will decline. Many more regions depend on sectors that will have to undergo low-carbon transformations. This can be more challenging in low-income regions, which often suffer from low levels of technology, weak business organisation, a work force with more limited skills, and an outflow of talented people. Many middle-income regions are experiencing slow growth, have lost manufacturing jobs and also face demographic challenges as the population ages. In contrast, more dynamic regions, and also cities and urban areas, are facing increasing congestion, population pressures and challenges for more efficient energy and resource use.

[490] SBS data at the second NACE level was used to show affected sectors at sufficient detail (e.g. fossil fuel mining and extraction and not for instance mining and quarrying of other minerals). If for some countries or regions some of the employment is reported only at the first NACE level in EUROSTAT and not split into subsectors, actual employment in the represented subsectors might be higher than shown in the maps.

Many regions are likely to benefit from the transition to a green economy. This is for instance the case of regions which are or could be involved in the production of renewable energy. The potential for producing renewable energy depends on their geo-physical characteristics. For instance, coastal regions generally have a high potential for producing wind energy, especially those along the shores of the North and Baltic Seas and some Mediterranean islands. The potential for solar energy production is obviously higher where there are large amounts of sunshine, while the production of hydroelectricity also requires suitable geo-physical features. Realising whatever potential exists, however, depends on the policies implemented.

### *5.1.2 Implication for education and skills*

While overall gains more than offset losses between and within sectors, resources released by a declining sector are not perfect substitutes for those required by an expanding sector. The demographic shift will also increase the number of job openings in all sub-sectors, putting further pressure on skills supply. Already today, depending on the sub-sector, 17-32% of companies are experiencing skills gaps, and in technical occupations 9-30% are experiencing skills shortages.[491] A low-carbon transition is expected to increase the capacity constraint in the labour market, also because skills needed during a transition might be in short supply.

This issue was analysed in a study recently commissioned by the European Commission[492] using the E3ME model and GEM-E3-FIT, a version of the GEM-E3 model. The study analyses the differences between a decarbonisation scenario compatible with a 2°C trajectory and a business as usual scenario based on the Reference 2016 scenario developed by the European Commission, and looked at the impact of level of qualifications needed.

Table 20 shows results from the E3ME model of the implications of a low-carbon transition on the level of qualifications[493] of workers. Large shifts already occur in reference from low- and medium- to high-level qualifications and reflect the trends observed over the past two decades. The decarbonisation scenario increases employment by around 1.4 million compared to reference by 2050 with all levels of qualification having more jobs than in the Reference scenario. Largest increases compared to reference are in the medium and high skill categories.

**Table 20: Labour by qualification level**

491 Knowledge Centre for Renewable Energy Jobs (2016), Skills Gaps Analysis, http://www.knowres-jobs.eu/en/Jobs-and-skills/Education-and-training/Skill-gaps-analysis-and-Training-needs/

492 Cambridge Econometrics, E3 Modelling (2018), A technical analysis on decarbonisation scenarios - constraints, economic implications and policies, Tender ENER/A4/2015-436, https://ec.europa.eu/energy/sites/ener/files/documents/technical_analysis_decarbonisation_scenarios.pdf

493 Low: up to and including lower secondary education; Medium: upper secondary and post-secondary non-tertiary education; High: tertiary education.

| Scenario | Qualification level | 2020 | 2030 | 2050 | 2020-50 |
|---|---|---|---|---|---|
| REF | Low | 40,877 | 33,199 | 19,646 | -51.9% |
| | Medium | 109,346 | 104,658 | 81,898 | -25.1% |
| | High | 79,128 | 94,153 | 118255 | 49.4% |
| | Total | 229,350 | 232,011 | 219,800 | -4.2% |
| 2D EG | Low | 40,890 | 33,273 | 19,800 | -51.6% |
| | Medium | 109,380 | 104,857 | 82,450 | -24.6% |
| | High | 79,1 50 | 94,309 | 118,944 | 50.3% |
| | Total | 229,420 | 232,438 | 221,194 | -3.6% |
| Difference | Low | 13 | 73 | 154 | |
| | Medium | 35 | 198 | 552 | |
| | High | 22 | 156 | 689 | |
| | Total | 69 | 427 | 1394 | |

*Source: E3ME.*

The analysis confirms that Europe will be faced by a skills challenge[494] as its economy undergoes structural changes. Table 20 shows that decarbonisation will add to this challenge but only very moderately. The impact of the low-carbon transition will mainly take the form of new 'green' skills within existing occupations. Occupational groups for which this transition will considerably change the task profiles are construction workers, electro-engineering workers, drivers and vehicle operators, farmworkers and gardeners, machine and plant operators, other manufacturing workers, handicraft & printing workers, production and specialised services managers, researchers and engineers as well as science and engineering technicians.[495] The two latter occupation groups are already now the most wanted in the European renewable energy industry (geothermal, small hydropower, biomass, photovoltaics, offshore wind farms, solar thermal electricity[496]).

The challenge of changing job profiles through 'greening' and of shifts to new clean and energy-saving production processes will be to align education and training to meet the emerging skills needs (professional and transversal) of both emerging, and existing, occupations and industries. For example, the renovation of the existing building stock will not be possible without the right workforce, in particular if the EU wants to double the renovation rate. This is the same situation for the mobility value chain. Moving from combustion engines to electric power trains with batteries will require new skills and new types of jobs.

In many industries and countries, the most in-demand occupations or specialties did not exist ten or even five years ago, and the pace of change is set to accelerate. New occupations are also emerging, for example related to the manufacture of renewable equipment (e.g. wind power design engineer), project development (e.g. wind resource assessment specialist), and production and operation (e.g. wind service mechatronics technician, biomass production managers).

'Key competences' will be needed by all in order to cope with the upcoming technological changes in general, and this trend is amplified by the transition to a low carbon economy. These key competencies are also referred to as "21st century skills" and cover basic and digital skills as

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[494] CEDEFOP (2010), Skills for green jobs: http://www.cedefop.europa.eu/files/3057_en.pdf

[495] CEDEFOP, (2018), Skills Panorama, Skills opportunities and challenges in occupations: https://skillspanorama.cedefop.europa.eu

[496] The last four sub-sectors being good examples of 'green' activities being embedded in traditional sectors: agriculture, chemical & electronic industries, shipyards, plumbing & roofing respectively

well a mix of cognitive and socio-emotional skills such as problem solving, creativity, communication and collaboration. Furthermore, they include STEM subjects (science, technology, engineering and mathematics) which, in view of the high demand for a qualified workforce in technology- and research-intensive sectors (see above), should be a priority area for education.[497]

Therefore, education, training and lifelong learning have an important role in addressing the changing demands in skills and ensure that the workforce is equipped with up-to-date skills. Workers will need both, upskilling and reskilling. Countries' policies for reaching carbon reduction targets are the main drivers for the development of 'green' skills across economic sectors. Social partners supported this finding during the public consultation and stressed the importance of re-skilling to make the low-carbon transition a just transition. However, it should be stressed that the significant changes expected in employment profiles in Europe are the results of trends (e.g. digitalization and demographic shifts) that are already largely occurring independent from the energy transition.

## 5.2 Role of finance

The financial sector will play a critical role in enabling the decarbonisation transition and in funding the appropriate types of investments at the scale required. Fulfilling this role will require a transformation of the sector itself. The sector will have to support the long-term societal needs for innovation and infrastructure, while at the same time it will have to enable the rapid development of the technologies necessary for a low-carbon and resource-efficient economy. The necessary reorientation of capital should also help strengthening financial stability by explicitly integrating long-term physical risks and intangible value creation factors (including environmental, social and governance factors) in asset pricing. If done in a consistent manner across the real economy and the financial sector, losses for companies and financial institutions arising from stranded assets can be avoided. This will protect both financial institutions and beneficiaries, in particular where long-term returns are important, such as in the case of pensions.

In order to avoid the possible high funding costs and other financial constraints that could hamper the transition significantly and increase its cost[498], it is necessary to put in place the conditions to promote affordable funding through financial innovation together with government intervention. For example, the IEA estimated that better debt financing[499] terms have helped lower generation costs for new offshore wind in Europe by nearly 15% in the past five years[500].

The main sources and instruments available for financing some of the clean energy projects today in Europe are summarised in Figure 108 (non-exhaustive of all possible sectors to be financed).

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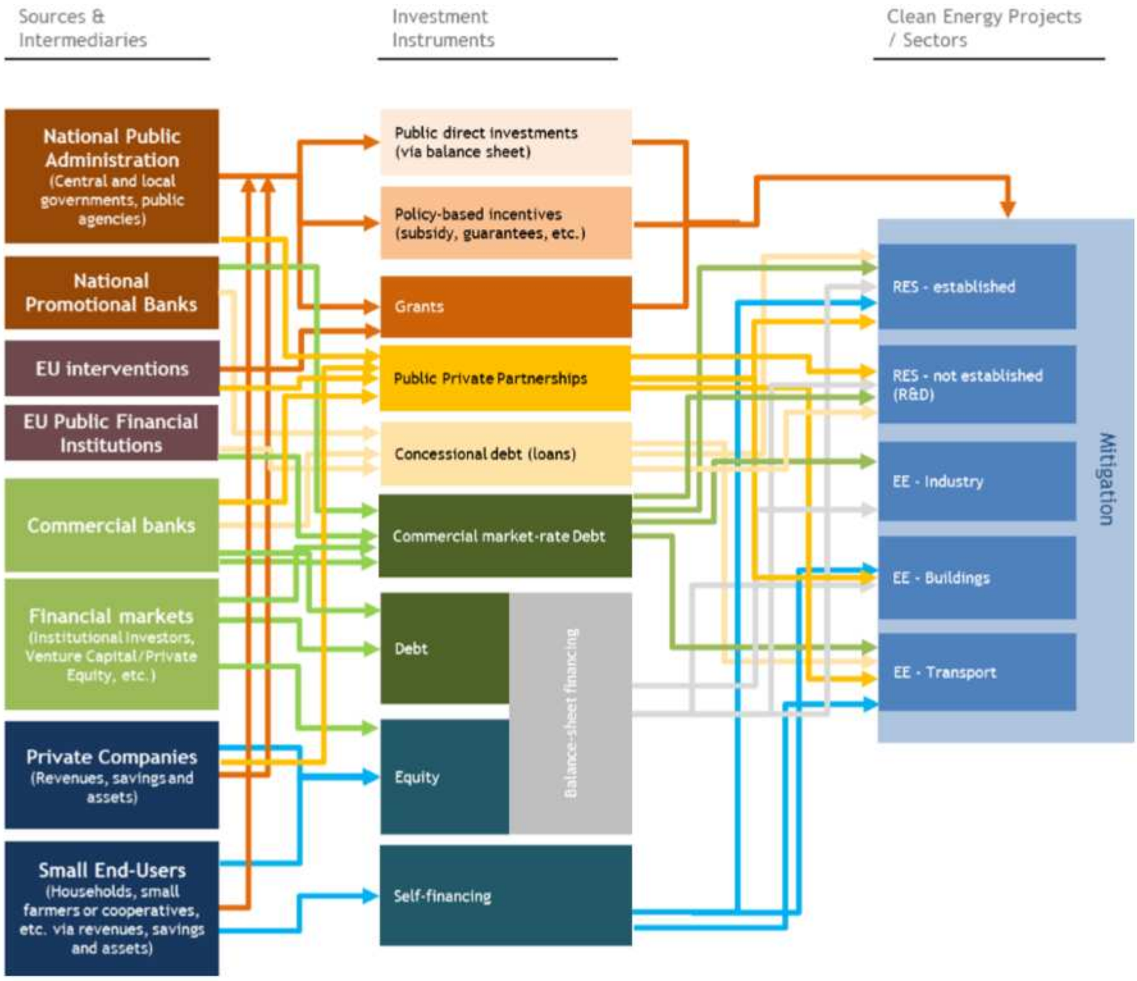
[497] Council Recommendation of 22 May 2018 on key competences for lifelong learning (2018/C 189/01)

[498] A recent study commissioned by the European Commission finds that a higher discount rate (13%) increases significantly the cost of investments in capital-intensive goods such as wind energy and solar PV compared to a scenario with slightly lower discount rate (10%). The levelised cost of electricity from wind and PV in 2050 could increase by more than 15%. Tender ENER NER/A4/2015 - 436 https://ec.europa.eu/energy/sites/ener/files/documents/technical_analysis_decarbonisation_scenarios.pdf

[499] Although variable case by case depending on the scale of project, the technology used and the financing structure, debt-to-equity ratios range between 60-80% in clean energy technologies. (see IRENA (2018) *Global landscape of renewable energy finance 2018*; RolandBerger (2011) *The structuring and financing of energy infrastructure projects […]*; and EIB EPEC PPP guide).

[500] IEA (2018), World Energy Investment 2018, https://www.iea.org/wei2018/

**Figure 108: European clean energy finance landscape**




*Source: Trinomics (2017)*[501].

Private finance will have to account for the bulk of investment needs – there is already a high share of private investments in some of the sub-sectors, such as energy efficiency and renewable electricity generation[502].

Regulatory measures and financial support at Member State and Union level will continue to be necessary to stimulate energy and transport investments and would have to be scaled up in an efficient way to direct capital to the low carbon transition. Efficient resource allocation requires that, whenever possible, investments should be driven by market signals reducing the role of state intervention. However, according to the IEA 95% of global investment is currently made in areas where revenues are fully regulated or affected by mechanisms to manage the risk associated with variable prices on competitive markets[500]. As recognised also by the IPCC 1.5°C Special Report, public sources of financial support (see for instance the EFSI program) are well-equipped to support investments with high added value but facing high risk.

[501] Trinomics (2017), Assessing the European clean energy finance landscape, with implications for improved macro-energy modelling, https://ec.europa.eu/energy/sites/ener/files/documents/macro_eu_clean_energy_finance_final.pdf

[502] Cambridge Econometrics, E3 Modelling (2018), A technical analysis on decarbonisation scenarios - constraints, economic implications and policies, https://ec.europa.eu/energy/sites/ener/files/documents/technical_analysis_decarbonisation_scenarios.pdf

In recent years, financial instruments and budgetary guarantees have been developed at the EU level to support objectives across different EU policy areas. Financial instruments may take the form of equity or quasi-equity investments, loans or guarantees, or other risk-sharing instruments, and may be combined with other forms of support, including grants[503] [504]. Budgetary guarantees are legal commitments of the EU to support a programme of actions by taking on the budget of the Union a financial obligation that can be called upon, should a specified event materialise during the implementation of the programme[505].

Leveraging private investments, financial instruments and budgetary guarantees may allow for a more efficient allocation of EU budgetary resources compared to grants.

The type of financing and public intervention depends on the risk profile and potential for revenues of targeted investments[506]. While public-funded grants should target the initiatives that do not assure sufficient financial return (such as the early stages of research and development), revenue-generating market-based instruments such as preferential loans and loan guarantees should cover the more financially viable projects. In cases of non-financially viable projects, grants or blending of grants with other sources of financing could prove useful, as long as they yield long-run added value for the EU.

Despite a significant increase in absolute terms in recent years, investment in low-carbon technologies still accounts for a very small share of institutional investors' assets. Institutional investors are one of the largest sources of private capital investments, with the insurance sector alone managing assets accounting for nearly EUR 10 trillion[507]. Although it is difficult to quantify the precise share, a recent analysis[501] found that the share of green investment in the portfolios of pension funds and insurance companies is around 1-2%. Institutional investors are often prudent, with a more risk-averse profile, opting for investment in large volumes of mature technologies already on the market associated with lower operational risk. They appear increasingly reluctant to invest in carbon-intensive electricity generation (coal-fired power plants), and rather favouring large-scale projects in mature green technologies, such as solar PV and onshore wind. Their investment objectives are well-aligned with the needs of sustainable investments. As pointed out by the High-Level Expert Group on Sustainable Finance[501], the long-term liabilities of pension funds make them ideal providers of sustainable finance, and the business model of the insurance sector is particularly well-suited to supporting sustainability[508]. The transport sector, which represents about 30% of additional annual investment needs, also offers considerable potential for financial instruments such as green bonds. According to a study by the Climate Bonds Initiative[509], over 40% of investment grade bonds come from the transport sector.

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503 Regulation 2018/1046 of the European Parliament and of the Council on the financial rules applicable to the general budget of the Union, Art. 2(29)

504 European Commission, "Note on Budgetary Guarantees, Financial Instruments and Grants: Optimizing the mix to maximise the impact of EU budget in financing EU policies.

505 Ibid, Art. 2(9).

506 European Commission, Note on Budgetary Guarantees, Financial Instruments and Grants: Optimizing the mix to maximise the impact of EU budget in financing EU policies.

507 High-Level Expert Group on Sustainable Finance (2018), Financing a Sustainable European Economy, https://ec.europa.eu/info/sites/info/files/180131-sustainable-finance-final-report_en.pdf

508 As an example of the behaviour of institutional investors, the European Central Bank has already taken concrete steps to pursue a sustainable investment policy for their pension fund portfolio. Furthermore, the ECB has started an internal investigation on how to incorporate environmental, social and corporate governance standards in the management of their own funds portfolio.

509 Bonds and Climate Change: The State of the Market 2018, CBI, 2018 https://www.climatebonds.net/track/click/7877/14299

In the long-term it will be necessary to systematically re-orient private capital towards more sustainable investments. Three conditions need to be present within financial markets in order for private investment to support the transition. Firstly, investors need to consistently be given the option of investing into zero or low carbon assets. Secondly, climate and environmental risks should be mainstreamed in economic and financial decision-making and the valuation of assets. Once markets and credit risk agencies will price climate risks properly, borrowing conditions will adjust to favour sustainable investments. Thirdly, companies and financial institutions need to think long-term and be transparent about their operations.

To this end, the Commission unveiled in March 2018 a ten-point Action Plan for financing sustainable growth[510] with the aim to mobilise private capital to fund sustainable projects and activities, by changing incentives and culture all along the investment-chain. Inspired by the work of the High-Level Expert Group on sustainable finance, this Action Plan is a big step forward, both for the fight against climate change and other forms of environmental degradation and for Europe's financial sector. Its three main objectives are:

- to redirect capital flows towards green and sustainable investments;
- to embed sustainability into risk management;
- to increase transparency and long-term thinking in financial and economic activity.

To achieve these objectives, the Action Plan lists a series of actions that should be implemented by 2019. An important building block is establishing an EU classification system for sustainable activities, often referred to as "taxonomy". The aim is to have a system that will provide clarity on which economic activities can be considered "sustainable". It has been proposed to develop the taxonomy along a gradual approach, classifying first economic activities that contribute to climate change mitigation and adaptation, and later to other environmental objectives. The classification with its coherent language will help investors allocate their capital towards activities identified as truly sustainable.

In addition, policy needs to mainstream sustainability considerations into the financial sector:

- Combining the taxonomy with relevant standard and certification measures for the retail market.
- Consistently treating opportunities and risks related to climate change and other sustainability issues along with other factors impacting the profitability of an investment. In particular, when mainstreaming the use of tools which can appropriately gage the potential scenarios that will materialise if the transition does not happen.
- Providing sufficient transparency within the market both by corporate actors and financial institutions with regards to their operations and their exposure to climate risks.
- Ensuring that both professional and private investors are aware of the risks and opportunities posed by climate change and related environmental challenges to their investments, in particular where this affects their long-term performance.
- Benchmarking the cost effectiveness of the EU financial governance compared to the ones of its main trading partners such as China or the USA.

Work has already started on these long-term priorities. In May 2018, the Commission presented a package of measures to implement several key actions announced in its Action Plan. This package includes three legislative proposals aimed at:

[510] COM(2018) 97

- Establishing a unified EU classification system of sustainable economic activities ("taxonomy");
- Improving disclosure requirements on how institutional investors integrate environmental, social and governance (ESG) factors in their investment process and – if they claim to be sustainable - how they achieve these objectives;
- Creating a new category of benchmarks which will help investors compare the carbon footprint of their investments.

In discussing the impact of the energy transition on investments, a clear distinction should be made between risks inherent to investment in a market economy, which should be borne by the economic operators, and risks that arise from regulatory uncertainty or regulatory changes. Public policy needs to minimise the risk that arise from the latter, including through transparency and policy stability. This should be based on long-term planning that defines clear and transparent objectives, firmly set and accepted by society as a whole, clearly indicating also the rate of change.

Providing clarity to investors is indeed one of the goals of the Long-Term Decarbonisation Strategy and the best way to avoid stranded assets. The European energy policy has strived to provide coherent and timely signals to the market, notably with the recent adoption of review of the ETS, the Clean Energy for All Europeans legislative package, with the Mobility Packages adopted in 2017 and 2018 (see section 2.2.3) and with the establishment of the National Energy and Climate Plans which should include investment needs foreseen by Member States for fulfilling their energy and climate goals. Public-use infrastructures with very long economic lifetime will require careful and strategic planning, since they might face cost recovery issue. A relevant example is the gas network that is likely to face lower utilisation rates by 2050 (see section 4.2.2). A strategic approach to infrastructures will also have to be considered in the context of Member States' budget and debt constraints.

## 5.3 Industrial competitiveness

The EU's industrial transition will require more than only an enabling framework for affordable finance. Reaching a net zero emissions economy will affect the full industrial value chains of goods production, the ICT sector and other service providers, from raw materials through energy intensive industries and downstream sectors to recycling and waste, large and small industrial players alike.

The Paris Agreement can be a powerful driver for EU industrial competitiveness in mid-century perspective. The main challenge will be to manage the transition of European industry while ensuring its competitiveness so as to secure jobs, growth and investment in Europe and positioning it to exploit the huge potential global market for low-emission technologies and services. Studies suggest that the global market volume of key climate technologies will grow to EUR 1-2 trillion per year by 2030[511].

Based on the results of the open public consultation carried out by the European Commission in preparation for this report, a majority of stakeholders considers that the low-carbon transition will contribute to modernise and reinforce the European competitiveness (see section 7.1). Several stakeholders identified sustainable production as an essential need for industry.

[511] BCG & Prognos, (2018), Climate paths for Germany, https://www.bcg.com/en-be/publications/2018/climate-paths-for-germany-english.aspx https://bdi.eu/publikation/news/klimapfade-fuer-deutschland/ (full study in German)

As discussed in Section 4.5 and underlined by the Commission in its Industrial Policy Strategy[512] the industrial transition will require EU industry to profoundly alter business models and supply chains. It will require an integrated and systemic approach covering:

- sustainable supply of raw materials
- optimised material flows in cross-sectoral value chains supporting circular economy and industrial symbiosis.
- energy and resource efficiency
- breakthrough decarbonisation technologies, innovative materials, digital and space technologies, servitisation[513] and social innovation
- large-scale demonstration projects.
- demand-side measures to stimulate the creation and the fast development of markets for low and zero-carbon products/solutions

In some cases breakthrough technologies will have to be developed or their technology readiness levels increased in order to ensure market uptake. Strong support through research and innovation will be needed to prove new solutions based on emerging technologies, scale up technologies to large-scale demonstration projects, industry wide roll-out and reduce cost gaps compared to existing industrial processes. A dedicated approach will be needed in Horizon Europe on GHG neutral industry to provide the broad vision and framework for action to do this, with the involvement of industry and other stakeholders (see also section 5.4 for discussion on the future role research and innovation).

Many new technologies should be ready for large-scale deployment by the end of the next decade. Well before then there also has to be a business case for investment. How to make low-carbon investments attractive in Europe for industries that operate internationally rather than in regions that enjoy higher growth and lower regulatory costs has to be addressed. The introduction of breakthrough technologies in the energy-intensive industries is a case in point. They have mature assets, typically with a 30-40 year life that will need to be replaced at high capital cost and/or with operating costs likely to be higher than those for today's products.

The analysis in Section 4 indicates that the availability of affordable low-carbon electricity, at sufficient scale, will be an important factor for industry and other sectors of the economy. Switching industrial production from fossil fuels to electricity and feedstocks such as green hydrogen or carbon will require a major development of the energy system and of the accompanying infrastructure. Without the energy transformation, the industrial transformation required will not be possible.

While several trade, business or professional associations in their replies on the public consultation indicated the prominent role of the EU ETS as a key tool to drive decarbonisation, they often also underlined the need for an complementary policy framework to achieve the industrial transformation (see section 7.1).

In this transformation industry may face competitiveness challenges. The transition will generate first deployment and cost challenges and may involve earlier depreciation of higher emission assets. The necessary shift away from fossil fuels for industrial heating and processes will make many industries become electricity intensive to a certain extent. In the absence of a true global level playing field, these industries also face a carbon leakage risk, with different industries being more exposed than other (see also section 4.10.5, Table 13).

The competitiveness of low carbon industry will require a framework that facilitates differentiation and encourages markets to recognise low carbon value. The fact that high climate ambition implies higher priced industrial goods, more clean energy infrastructure and the need for sustainable raw materials from international and EU sources has not yet penetrated public

[512] COM(2017) 479 final

[513] The servitisation of products describes the strategy of creating value by adding services to products or even replacing a product with a service.

opinion. Public acceptance in these areas will be key to ensure the competitiveness of EU industry as it transforms.

Industrial policy can deliver part of the enabling framework supporting industry's transition to competitive GHG neutrality - for example through the Single Market; a well-functioning internal market for primary and secondary raw materials; substitution of critical raw materials; strategic use of public procurement, standard-setting and product-labelling; SME policy and promotion of key enabling technologies. Other framework conditions need to be in place to turn low carbon transition challenge into an industrial competitive advantage and growth opportunity. These include a supportive trade policy, the investment environment, competition, taxation, research and innovation, regional policy, energy infrastructure and access to raw materials.

From a trade policy perspective, a truly fair and level playing field with open access to global markets and protection against unfair trade practices should guarantee the competitiveness of those companies that are able to successfully lead the transition and export low carbon technologies and services.

From a competition policy perspective, openness to cross-sectoral projects, partnerships between energy providers and industry will all be necessary to attract investment and protect against carbon leakage.

From an industrial policy perspective, the timing of the transition will be crucial. As European industrial installation age, old factories should be replaced with new, low-emissions plants. New products should be brought to the market as demand for emissions-free alternatives increases. Answering these policy questions requires a detailed industrial roadmap.

## 5.4 Role of research and innovation

As demonstrated in Section 4, the low carbon transition appears as a technological rupture vis a vis the (still largely) fossil fuel-based energy and economic system in place. As such, it is a source of challenges and opportunities for a multitude of social and economic actors within the EU and beyond. At a time of rapid change, and risks of lock-in and stranded technologies, research and innovation (R&I) will play a crucial role to accompany the transformation and maximise the "opportunities" for our society, be it through individual technology development, system deployment or even social innovation. R&I also has to address a longer time perspective. Long investment cycles, in particular for industrial installations and infrastructure, require a focus well beyond 2050 to turn science into products and ensuring market uptake.

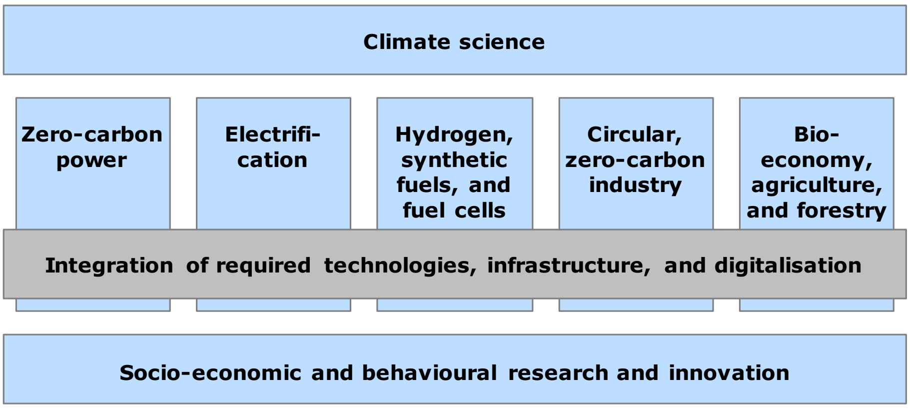
R&I will define the speed at which the decarbonisation can take place, at which costs and with which co-benefits. However, how it can materialise and how it would benefit the EU's private sector in building leadership in the upcoming global clean technologies markets, are also fundamental questions for the strategy to yield the positive economic and social impacts that will underpin the necessary political support it requires.

This section first reviews the identified needs in terms of R&I to achieve decarbonisation, and then the instruments and policies to be put in place to transform these needs into an opportunity for the EU's economy.

### *5.4.1 RDI for a decarbonised economy*

The key to success is to develop a wide portfolio of cost-effective and efficient carbon-free alternatives for each GHG-emitting activity, often in combination with enhanced sector coupling, digitalisation and system integration. At the same time, the rate at which the European R&I system succeeds in developing and commercialising such innovative solutions will steer the EU's future competitiveness of its existing and newly emerging industries. Relevant research areas include issues around climate science and the climate-earth system, technological challenges to create an environment that supports the required substitutions, socio-economic issues and lifestyle change (Figure 109).

**Figure 109: Relevant research and innovation areas**




Given the uncertainty related to the outcomes and results of research and innovation, it is not yet clear from today's perspective to which extend the five technological pathways explored in Section 4 will be part of the solution. Therefore, it is important to focus on a portfolio of solutions that could be enablers for decarbonisation and to develop competing solutions to avoid a potential technological lock-in[514].

The IPCC Special Report on 1.5°C also highlights the potentially large (though uncertain) role contribution that General Purpose Technologies could play to both mitigation and adaptation. These technologies include the Internet of Things, biotechnology, nanotechnology, artificial intelligence, robots and information & communications technology. The Special Report explores their potential applications to climate action in energy, industry, transport, buildings, agriculture and disaster risk reduction[515]. Such innovations have the potential to contribute enormously to deep decarbonisation, but may have to be accompanied by behavioural changes, in particular to combat the rebound effect

#### **5.4.1.1** Climate science

An effective implementation of the Paris Agreement has to be based on science, which requires a continuous development of our knowledge on the climate-earth system and potential mitigation and adaptations options. Relevant topics are the determination of whether the EU is on track to meet its climate targets (including earth systems feedbacks and the remaining global emission budget) as well as the functioning and future evolution of the earth-climate system (including improving climate projections).

Improved climate science will help to establish climate services for businesses, public authorities and citizens, facilitating to develop mitigation strategies and adaptation pathways and policies for vulnerable ecosystems, for critical economic sectors and infrastructure in the EU.

[514] The portfolio approach is also responds to concerns expressed by the participants of the public consultation (see section Annex 7.1) who see the opportunity to support research and development by investments but also a challenge in terms of picking 'picking winners'.

[515] See IPCC Special Report on Global Warming of 1.5°C, Table 4.9

#### 5.4.1.2 Technological innovation challenges

A portfolio of enabling technologies is necessary to facilitate the necessary substitutions for a low-carbon transition. While this section does not provide an exhaustive list of technologies, a number of key technological pathways have emerged based on modelling results. To include a diverse portfolio of technologies, the discussion below focusses on these promising options. As different technological means can be used to decarbonise certain sectors or processes, it is from today's perspective not yet clear to which extend they will be used in the future. Technologies are currently at very different levels of market readiness and often lagging behind the status required by decarbonisation pathways as can be shown by classification schemes.[516] [517] [518] [519] It is however important to assess and mitigate their risks before large-scale deployment.

*Zero-carbon power*

Renewable energy technologies are a key enabler for the decarbonisation of the power sector. There are several technological options ranging from mature technologies (e.g. onshore wind, solar photovoltaics, and established bioenergy) to proven technologies that still have optimisation potential (e.g. offshore wind) to less mature technologies (e.g. ocean power). Efforts are needed to further optimise the more mature technologies and to widen the portfolio of options, such as in the field of ocean energy (wave/tidal), alternative photovoltaic concepts (thin-film, concentrated PV), or concentrated solar power.

The transition towards a more decentralised and variable power system implies that it will need to be much more intelligent (through digitalisation) and flexible. R&I will have to focus on increasing the intelligence of the system via digitalisation and developing the smartness of its components, increase the flexibility of the system by means of more renewable dispatchable generation capacity (e.g. dispatchable renewables, hydrogen-based power), energy storage (e.g. storage capacities or power-to-gas solutions such as green hydrogen), demand-side management programmes, and by a faster reacting grid.

Moreover, completely new power generation technologies may emerge from current research efforts. For instance, a number of countries have engaged in scientific programmes developing nuclear fusion energy, a process that would not produce greenhouse gases or long-lasting radioactive waste and uses fuels available in abundance. One of the major global initiatives is the International Thermonuclear Experimental Reactor (ITER)[520], which includes all major economies (EU, USA, China, Japan Russia, South Korea) and is the European Union's main contribution to fusion research.

*Electrification*

Electrification offers great opportunities to contribute to the decarbonisation of demand side sectors such as transport, heating and industry, which largely still use fossil fuels. In a world that

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[516] IEA (2018), Tracking Clean Energy Progress, https://www.iea.org/tcep/. This traffic light indicator is based on technology penetration, market creation and technology development. The IEA Energy Technology Perspectives 2017[204], applies the traffic light system and sees only 3 of 26 technologies on track.

[517] VUB-IES (2018), Industrial Value Chain. A bridge towards a carbon neutral Europe, https://www.ies.be/files/Industrial_Value_Chain_25sept_0.pdf. This report addresses the readiness of more than 80 different industrial decarbonisation technologies according to their Technology Readiness Level.

[518] IRENA (2017), Accelerating the Energy Transition through Innovation, http://www.irena.org/publications/2017/Jun/Accelerating-the-Energy-Transition-through-Innovation

[519] WIPO (2018), GLOBAL INNOVATION INDEX 2018, http://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2018.pdf

[520] https://www.iter.org

is increasingly electrified, batteries will become one of the key technological components of a low-carbon economy. A fast growing global value chain is emerging. The current generation of Li-ion batteries is already well developed but still has significant potential for optimisation, and new emerging technologies are appearing on the horizon (solid-state, Li-air etc.…). Furthermore, Redox flow batteries are a promising technology option for stationary applications. Despite their strategic importance, the EU is lagging behind in the manufacturing of Li-ion batteries.[521] To build up a strong battery production value chain in the EU, research and innovation should focus on the entire value chain: active materials, cells, modules, battery management systems and re-use and recycling. It should spur the emergence of new promising technological solutions, improve performance and cost, and investigate different possible applications in energy and in transport sectors.

Several of the trends affecting infrastructure/systems, notable the accelerated electrification of all sectors, can only optimise their contribution to the decarbonisation when integrated. This sector-coupling requires additional research, innovation and demonstration on energy systems themselves. The interconnection and integration of energy supply and demand sectors, and their joint adaptation to the energy production patterns, are the basis for the best possible use of the available resources, the avoidance of stranded assets, and the best information base for decisions on investments. Digitisation will be a main enabler of managing a decentralised energy system.

*Hydrogen, synthetic fuels, and fuel cells*

Hydrogen, in combination with demand side technologies such as fuel cells, may provide an alternative for applications in transport, heating and industry where electrification (and batteries in particular) cannot or struggle to reach the required level of cost and performance. While large quantities of hydrogen are produced today using natural gas, hydrogen can also be produced from zero-carbon power sources, such as renewable or nuclear power through electrolysis or through methane steam reforming in combination with carbon capture and storage. Furthermore, hydrogen can be produced during periods of excess renewable power supply and reconverted to dispatchable zero-carbon power during periods of undersupply. This could ensure low carbon security of electricity supply without the need to use fossil fuels.

A much larger research and innovation effort will be needed along the hydrogen supply chain to improve performance and reduce cost (e.g. for electrolysers, methane steam reforming in combination with carbon capture and storage, storage technologies, and stationary and mobile fuel cell applications). This effort should be combined with support to facilitate early deployment of technologies and related infrastructure.

*Circular zero-carbon industry*

Energy- and material-intensive industries can reduce their environmental footprint by decreasing the required amount of energy and raw materials. Therefore, efficiency and a more circular economy are first obvious win-win measures. This development would require a conversion of most material fluxes into closed loops. A circular economy would increase the availability of raw materials for these sectors that will manufacture key technologies for decarbonisation, such as cobalt and li-ion for batteries or rare earths for wind turbines. Furthermore, a circular economy is a possible path for some industrial sectors to decarbonise by re-using waste from other sectors as raw material input, in a so-called industrial symbiosis.

[521] JRC (2017), EU Competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC108043/kjna28837enn.pdf

Some of the current production processes have high process-related greenhouse gas emissions (for example blast furnace/basic oxygen furnace-based steel production). Carbon capture and storage is a possibility to reduce process-related emissions without fully substituting existing processes and R&I should focus on the efficiency and cost-optimisation of capture technologies. Furthermore, R&I should develop alternative processes for the energy-intensive industries, for example the direct reduction of iron with hydrogen as an alternative steel production process, or investigate new processes in the cement and chemicals industries. Another option is to reduce the use of carbon-intensive products. For example, the usage of carbon-intensive cement could be reduced through substitution by hybrid construction materials such as wood-concrete. Research and innovation should look into the development of such products and the extent to which they can reduce greenhouse gas emissions in industry.

*The bioeconomy, agriculture, and forestry*

The bioeconomy comprises the use of renewable biological resources from land and sea (e.g. crops, forests, fish, animals, and microorganisms) to produce food, materials and energy. The bioeconomy can be a catalyst for decarbonisation in many different ways. Research and innovation should focus on sustainable forestry and agricultural practices, in particular those that increase production while reducing non-$CO_2$ emissions and with the objective of enriching and conserving carbon in soils that can play a role as a potential source of negative emissions. Furthermore, there remains significant potential for alternatives for industrial production of fertilisers, bio-waste management, ruminant livestock management, and a reduction in burning of agricultural residues.

Consumption-based measures can also contribute to a reduction of greenhouse gas emissions. Changes in consumer behaviour can lead to a reduction in food-related land use and food waste. However, social acceptance for such changes might be difficult to achieve because of existing habits and cultural aspects. Therefore, research should address behavioural changes such as changes in food habits and diets.

Most, but not all, of the potential bio-solutions require land use. The analysis in preceding sections has demonstrated that the production of advanced biofuels and bio-energy (potentially coupled with CCS and CCU to produce negative emissions), biomaterials (to replace more carbon intensive products) and the carbon sink (the amount of carbon stored on land and in soils) will all have to contribute towards net zero greenhouse gas emissions. This raises important system-wide research issues regarding how to use the available land in the best way, how to increase the carbon uptake by the land (carbon productivity), and how to use the available biomass[522] in the most resource efficient way without damaging biodiversity and environmental quality.

*Socio-economic and behavioural research and innovation*

The transition to the low-carbon society also requires socio-economic research into many areas: The large-scale deployment of current and future low-carbon technologies and practices will require the development and implementation of new business models that make them economically and socially attractive, and on the role of possible enablers such as trade, consumers' habits, digitalisation, big data[523], block-chain[524] or artificial intelligence[525]. Knowledge is needed on what price-signals and other measures maximise the demand-response

[522] Also taking into account future impacts of climate change on availability of biomass.
[523] https://ec.europa.eu/digital-single-market/en/big-data
[524] https://ec.europa.eu/digital-single-market/en/blockchain-technologies
[525] https://ec.europa.eu/digital-single-market/en/news/communication-artificial-intelligence-europe

potential of consumers, on understanding barriers to implementing economically beneficial low-carbon measures.

Next to technological solutions, consumer choice and human behaviour, including the impact of technology on human behaviour, are important determinants for future GHG emissions. Advancing social sciences can therefore give new insights and solutions that make an essential contribution in areas such as food diet, mobility services and the consumption of energy. "Social innovation" will be essential, in particular how to engage citizens in the decarbonisation challenge as convinced actors in this transition, and to promote living-lab experiments on ways to boost the zero-carbon economy through lifestyle changes, for instance through the sharing economy.

### *5.4.2 Advancing the European R&I system*

#### 5.4.2.1 Role of RDI

Research, innovation and education can be understood as a 'knowledge triangle', connecting universities, research institutions and business[526]. Learning, discovering and innovating all go together, as parts of a system that can create wealth, jobs, growth and social progress[527]. Public budgets largely finance education and fundamental research while the private sector is driving applied research and is responsible for product and process level innovation.

#### 5.4.2.2 Where the EU is today

The EU shows both strengths and weaknesses in this race to new low-carbon technologies markets.

First of all, Europe is still a very active actor of the global research landscape, accounting for 30% of all scientific publications and one fifth of global research expenditure[528]. European enterprises are responsible for an important share of technological innovation and are responsible for almost two thirds of the EU's R&D investments[529]. More than half regularly innovate in terms of product, process, organisational and marketing[530] [531] (varying across Member States from 13% to 67%). More than half of the innovative companies reported to have made improvements with respect to the environment[531].

The public investment is split between Member States (roughly three quarters) and the EU.

However, the EU is progressively falling behind, spending comparatively less on research than other regions. The ratio of expenditures to GDP, also known as R&D intensity, remains at 2%

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526 European Commission (2017), LAB-FAB-APP – investing in the European future we want, http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/hlg_2017_report.pdf

527 The expectation, that R&I creates jobs and secures wealth was shared by a number of respondents to the public consultation (see section 7.1).

528 European Commission (2016), Open innovation, Open Science, Open to the World – a vision for Europe, https://ec.europa.eu/digital-single-market/en/news/open-innovation-open-science-open-world-vision-europe

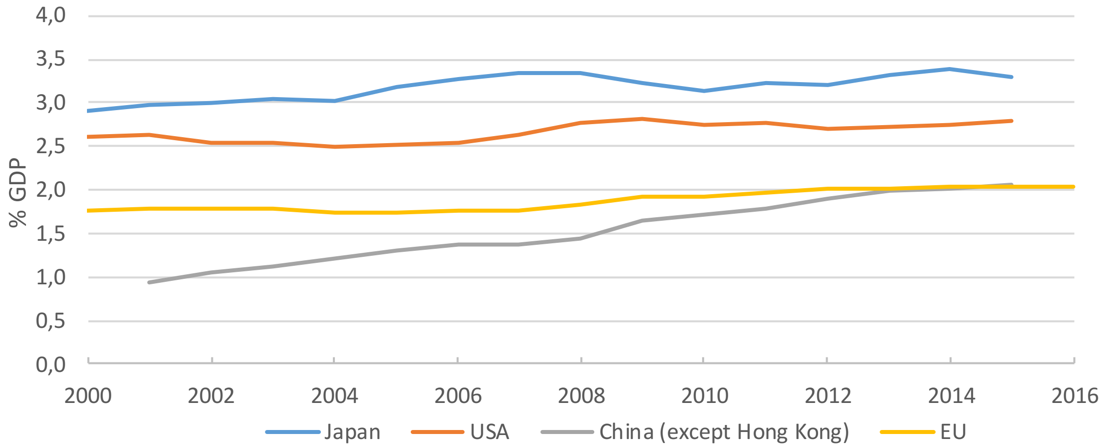
529 European commission (2018), Smarter, greener, more inclusive? — Indicators to support the Europe 2020 strategy - 2018 edition, http://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-02-18-728

530 As set in COMMISSION REGULATION (EC) No 1450/2004

531 Eurostat (2017), Eurostat Innovation statistics, http://ec.europa.eu/eurostat/statistics-explained/index.php/Innovation_statistics

(see Figure 110), hence below the targeted 3% envisaged in the Europe 2020 Strategy[532] and well below levels in Japan (3.3% in 2015) and the USA (2.8% in 2015). China is also progressing and, with almost 2.1% in 2015, is now spending more on R&D per share of GDP than the EU. This is due to lower private investment in research and innovation in Europe.

**Figure 110: Gross domestic expenditure on R&D compared to GDP**




*Source: Eurostat*[533].

In 2015, the EU spent 0.02% of GDP on energy-related research[534], about a tenth of total R&D. Patenting in clean energy technologies has been increasing over the last decade, with European companies targeting "high value" inventions with international protection, which displays a growing confidence of their competitiveness in the global energy technology market. However, in sheer number of patents, Europe is being outnumbered by Japan, China and, more recently, by South Korea.

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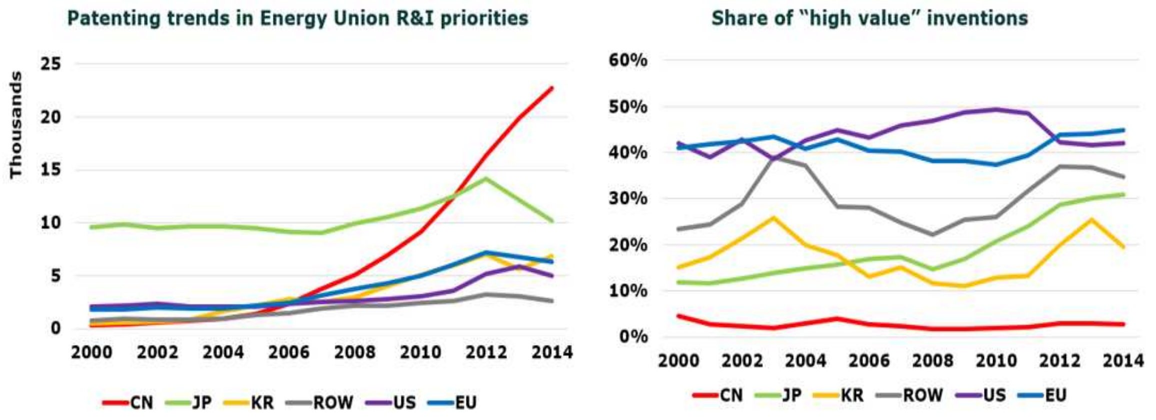
532 European Commission (2018), Europe 2020 strategy, https://ec.europa.eu/info/business-economy-euro/economic-and-fiscal-policy-coordination/eu-economic-governance-monitoring-prevention-correction/european-semester/framework/europe-2020-strategy_en

533 Eurostat (2018), Statistics explained, R&D expenditure, http://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure#Main_statistical_findings

534 European commission (2018), Indicators for monitoring progress towards Energy Union objectives, https://ec.europa.eu/energy/en/atico_countrysheets/scoreboard?dimension=Research%2C+innovation+and+competitiveness

**Figure 111: Trends in energy patenting**




*Source: JRC[535] based on EPO (Patstat)*

These general trends also reflect the situation of EU companies, which are very active in the global clean energy market (sized at USD 1.4 trillion in 2016[536]). Indeed, in 2017 Europe was hosting 41 of the top 100 global energy companies, and the EU 6 of the 25 largest renewables companies[537]. European renewable energy businesses employed almost 1.5 million people (out of 10 million globally[538]). They are accelerating R&I investments with an increasing number of patents filed (+50% between 2010 and 2016[539]), clearly contributing to the global shift towards renewables developments (global patents in the field have doubled over 2010-2016). However, international competition is increasing, with Asian and North American companies getting an increasing weight in the market[533] [540].

Over the years, the EU has put in place a number of instruments to deliver on research and innovation for the EU economy as a whole, and on clean energy and climate mitigation activities in particular:

- The EU R&D programmes Horizon 2020[541] (by 2020) and Horizon Europe[542] (2021-2027), which should benefit from a budget increase to EUR 100 billion, of which 35% is intended to be allocated to tackling climate change. The Strategic Energy Technologies (SET) Plan[543] [544]

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[535] JRC (2017), Monitoring R&I in Low-Carbon Energy Technologies, http://publications.jrc.ec.europa.eu/repository/handle/JRC105642

[536] Advanced Energy Economy (2017), 2017 Market Report, https://info.aee.net/aen-2017-market-report

[537] Thomson Reuters (2017), Top 100 Global Energy Leaders. https://www.thomsonreuters.com/en/products-services/energy/top-100.html

[538] IRENA (2018). Renewables and Jobs – Annual Review 2018, https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/May/IRENA_RE_Jobs_Annual_Review_2018.pdf

[539] IRENA (2018), Database on patents evolution, http://resourceirena.irena.org/gateway/dashboard/

[540] Stash Investments, Top 10 Largest Clean Energy Companies by Revenue, https://learn.stashinvest.com/largest-clean-energy-companies-revenue

[541] https://ec.europa.eu/programmes/horizon2020/en/

[542] European commission (2018), Horizon Europe - the next research and innovation framework programme, https://ec.europa.eu/info/designing-next-research-and-innovation-framework-programme/what-shapes-next-framework-programme_en

[543] COM (2015) 6317

linking EU, Member State and industry action which has put in place 10 platforms promoting market uptake by technologies, or the European Energy Research Alliance[545] that brings together 175 research organisation across the EU.

- The SET Plan is complemented by the Knowledge Innovation Community scheme (KIC), which aims at spurring public-private partnerships on different societal challenges, including on energy[546].
- Energy related innovation is among the most frequently identified priorities in the current 120 Smart Specialisation Strategies that chart out the investment of over EUR 41 billion from European Regional Development Fund (ERDF) programmes. The current Smart Specialisation Platforms[547] (on agriculture, energy, industrial modernisation, all relevant topics for the decarbonisation) help coordinating the efforts and use of regional funds to strengthen the regional innovation capacities. As of 2021, a new interregional innovation investment scheme under the Interreg part of the ERDF will further strengthen the cooperation of regions around shared smart specialisation priorities.
- The Innovation Fund under the Emissions Trading System[355].
- R&I is a key dimension of the National Energy and Climate Plans (NECPs[548] [549]). The inclusion of specific and measurable R&I objectives in the NECPs will help integrating national strategies and priorities at EU level in a 2030-2050 perspective.
- The EU is participating in international fora on innovation related to decarbonisation, in particular as a member of the Clean Energy Ministerial[550] and of the Mission Innovation[551], the global initiatives launched in the context of COP15 and COP21, to accelerate clean energy innovation. Members of the Mission Innovation[552] have committed to double governments' clean energy research and development investments, and to cooperate on different Innovation Challenges[553]. Furthermore, the EU supports the IPCC which makes a major contribution to the advancement of climate science.

#### 5.4.2.3 Future R&I for EU decarbonisation and industrial growth

As innovation is happening within business environments or at the interface between enterprise and research, it will be crucial to create innovation ecosystems. Economic incentives for embracing innovation are required on the firm level. New entrants, often small and medium enterprises, need to be able to compete and develop: for instance, financial instruments for SMEs could be systematically adapted to the challenges of a low carbon economy. It will also require markets free of discrimination, access to capital and a favourable regulatory environment[528].

It is crucial that European enterprises are incentivised to innovate, since they would improve their global market positons and open up export opportunities only by being frontrunners of the upcoming transition. An innovation policy that is "open to the world" would help extending

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544 https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan
545 https://www.eera-set.eu/
546 http://www.innoenergy.com
547 http://s3platform.jrc.ec.europa.eu
548 COM(2016) 759 final/2
549 https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union
550 http://www.cleanenergyministerial.org/about-clean-energy-ministerial
551 http://mission-innovation.net/
552 As of September 2018: the EU, 9 EU Member States and 14 non-EU large countries
553 The European Commission is co-leading on 3 of them: "Affordable heating and cooling of buildings", "Converting Sunlight" and "Hydrogen"

innovation ecosystems beyond their current geographic limitations[528], thus allowing to test new concepts and products on global markets, international collaboration and the development of common standards. In addition, showing leadership also implies to work with others, and the global dimension of the low carbon transition has indeed already led to a number of international initiatives through which Europe can leverage investments in R&I. Climate finance and the implementation of national commitments are stimuli for global technology cooperation and to create market opportunities for European businesses.

As the world outside of Europe increases its scientific output, the EU will need to ensure access to this knowledge, in particular in the global research field of energy and climate[528]. In addition, the development of global supply and value chains around new zero-carbon technologies provide a better sharing of the risks that exist in running alone. International cooperation should also help less developed countries to jump over the technological divide and to base their future growth on sustainable solutions. It will be a critical component of future development policies, with multiple and reciprocal spill over effects on growth, stability and security.

Therefore, the future EU R&I strategy for supporting its greenhouse gas emissions reduction efforts should be inspired by the following guiding principles:

- To keep Europe's fundamental research's excellence and be active on global research cooperation;
- To develop an innovation agenda motivated by a race to the top, catching up in strategic technologies and avoiding running behind if the distance is excessive;
- To explore and develop portfolios of technologies considering users’ needs and avoiding technological lock-in;
- To link R&I strategies with European industrial capacity and strengths;
- To give priority to zero-carbon and GHG-neutral solutions;
- To address system-level innovation and sector-coupling;
- To review regulations in order to make them more innovation friendly, allowing faster market take-up of innovative solutions, while providing disincentives for continued use of carbon intensive technologies.

### *5.4.3 Possible route for R&I to a EU decarbonised economy*

Successful uptake of novel decarbonisation solutions will require a specific support throughout the innovation chain. This involves the coordinated efforts of the different EU funds to achieve greater impact and efficiency throughout the basic research, demonstration, first-of-a-kind and market upscaling phases up to the creation of market-pull instruments in order to bridge the 'valley of death' which is particularly pronounced in the energy and the manufacturing sectors[554].

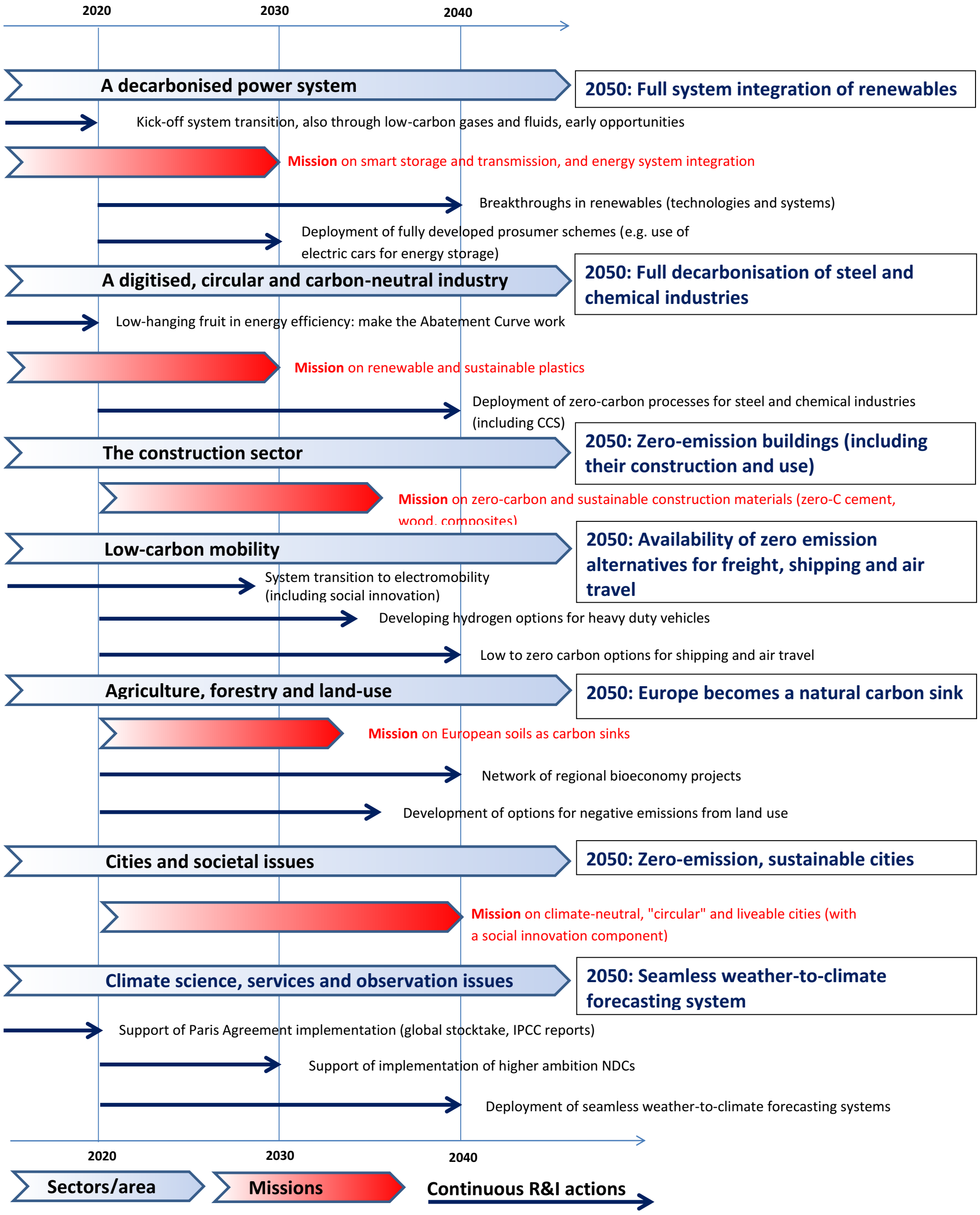
In addition to the current strategic framework for R&I in place[555], the EU medium-term budget aims at incentivising and catalysing the participation from the private sector. Hence, complementarity and synergies are sought between energy, transport and digital through the various funding R&I programmes, in particular through Horizon Europe, the Innovation Fund, the Connecting Europe Facility and the European Regional Development Fund.

[554] Due to the long lifetime of assets, the size of the investments, the need for infrastructure or the variety of actors.

[555] SET Plan for energy, STRIA for transport.

In terms of presenting areas for further work, the High-Level Panel of the European Decarbonisation Pathways Initiative proposed priority actions towards a low carbon economy (see Figure 112).

**Figure 112: Proposed R&I actions for decarbonisation**




Proposed priority research and innovation actions for supporting the decarbonisation process in different sectors/areas along the time frame 2017-2040, in order to get the 2050 goals indicated in the boxes. Red arrows represent mission-oriented actions; all arrows have to be intended as roadmaps that produce various outputs throughout their time frame until their end-date, when the activity should be completed and deployed in society.

*Source: High level Panel of the European Decarbonisation Pathways Initiative*[556].

[556] High-Level Panel of the European Decarbonisation Pathways Initiative (2018), Interim Recommendations, http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=36435&no=1

As also identified by the High-Level Panel of the European Decarbonisation Pathways Initiative, tools and instruments on delivering on low carbon technological solutions full-scale deployment will include and build on:

- New policy instruments to achieve a better pan-European R&I coordination of efforts, in particular through a broader efficacy and effectiveness of the financial instruments to support moving high-TRL[557] solutions to the market.
- Public-Private Partnerships of a relevant size, and Mission-oriented R&I actions should be used to focus resources on critical topics.
- Levelling the playing field - removing fossil fuel subsidies and internalising the climate change externalities of GHG-emitting technologies is necessary in order to allow zero-carbon technologies to compete.
- EU competitiveness - better monitoring of EU competitiveness along the new value chains, in particular for the most strategic parts in terms of dependency and added value.
- Conflicting policy objectives - innovative approaches to deal with conflicting policy objectives and support the decision making process to optimise the trade-offs along the life cycle and the value chains.
- Voluntary Instruments / labelling – more focus could be given to creating right framework conditions.
- Economic Incentives – new instruments should be established to introduce economic incentives for enhanced life-cycle performance, durability, upgradeability and ease of repair and recyclability. Fiscal policies should focus more on taxing capital and consumption than labour. More reliance on polluter pays principles.
- Corporate Social Responsibility - essential to ensure that carbon-neutral technologies are developed in an ethical way.
- Stronger focus on Circular Materials rather than waste e.g. 'Circular Materials Framework Directive' consolidating and simplifying waste legislation.
- Support and empower cities to innovate by enhancing capacity-building and experimentation, and in doing so, develop transferable and scalable solutions to climate and energy change challenge, and spatial development approaches to facilitate circular economy and bioeconomy business models and resource efficient life-styles.
- Large-scale demonstrators - competition policies may be adapted in order to allow subsidised large-scale demonstration of systemic solutions at reasonable scale.
- Modelling - Innovative approaches to better integrate the multi-sectoral and global dimension in current quantitative assessments while adequately addressing also behavioural aspects.

## 5.5 Lifestyle and consumer choices

Reducing greenhouse gas emissions by adopting more climate conscious lifestyles, and consumer choice for products/services with lower carbon footprint help to diversify decarbonisation pathways. More technology solutions would be required in situations where consumer

[557] TRL: technology readiness level

lifestyle/choice would not evolve in a manner that would see a lower carbon footprint. In the context of achieving a zero greenhouse gas economy this would mean also larger use of not yet mature technologies such as biomass and CCS (which might face several additional difficulties such as competition for land use and loss of biodiversity), or direct air capture and CCS (which has not yet been demonstrated at a large scale and which also encounters some public acceptance problems).

Demand-side solutions related to consumer choices are powerful tools to reduce the carbon footprint of our economy[558] with a clear potential for co-benefits to citizens themselves and society as a whole - as already clearly demonstrated for example in case of urban mobility.

Awareness raising should continue to be a vital element of guiding consumers towards the right habits and attitudes of energy use by educating consumers from an early age through daily practices and choices.

Multiple examples can be found in section 4 where consumer choices impact the emission profile. There is a visible trend towards greater use of walking, cycling and public transport as well as sharing vehicles (rather than vehicle ownership) among younger people, particularly in urban areas. Over the last decades shifts in diets already took place. On the other hand, demand for long distance travelling, notably aviation, has strongly increased and, with increasing welfare, will likely continue to increase.

To achieve the transformation, it is important to move consumer needs and rights into the centre of policy discussions, as happened with the Energy Union process. The question is how to reduce barriers that can hamper the market uptake of the low-carbon solutions that can have multiple other benefits, be it in transport, the building or food sector, and how to spur social innovation that can alter lifestyles towards reducing our carbon footprint.

Often there is a lack of information[559]. "Soft" measures like information campaigns and labelling programs[560] can play a significant role across a wider set of products and services, so as to allow the consumer to be able to identify and rank options according to a product's efficiency and expected economic benefits (as well as their own preferences). There are many schemes that have already a very good track record in this respect (e.g. eco-labelling)

Labelling can include consumption performance, but also the nature of the good or service provided.

Moving a step further, standards and norms are "hard" measures that allow removing inefficient technologies from the market that often would be to the detriment of consumer welfare in the longer term.

In the future, policy making will have to look at how to engage citizens with appropriate economic and fiscal instruments, creating a positive environment that not only better informs about the different options and benefits, but also addresses externalities, encourages purchasing decisions towards lower carbon content products, as well as designing standards and norms that will benefit the society as a whole.

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[558] As concluded in the 2018 Special Report on Global Warming of 1.5°C. For example Section D4.2 of the Summary for Policymakers

[559] Consumers' preference for the present (the "discount rate") tend indeed to be fairly high, placing great value on immediate cost savings while having a low degree of confidence in expected paybacks that would be generated by lower consumption over the lifetime of the equipment.

[560] Regulation (EU) 2017/1369 setting a framework for energy labelling: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.198.01.0001.01.ENG&toc=OJ:L:2017:198:TOC

By the middle of the century, consumers should be better informed and benefitting from the economic stimulus when making buying decisions directly contributing to reducing the carbon footprint of the economy, while improving welfare for all.

## 5.6 The international dimension, implications for the EU Long Term Strategy

This section will reflect on how the EU long term strategy interacts with a number of international dimensions, notably:

- Addressing the global economic and security consequences of the transition.
- How trade can support global competitiveness of the EU economy and secure access to the critical raw materials.
- Supporting the development of an international regulatory framework towards lower emissions, and supporting others in reaching their goals.

### *5.6.1 Security*

#### 5.6.1.1 Geopolitical stability and energy security of supply

The causes of insecurity and conflicts are complex and climate change is now an indisputable part of that picture. Its destabilising impacts – including disruptions in food security, reduced access to resources, water and energy, the spread of epidemic diseases and social and economic instability – make it the ultimate threat multiplier. Assessing and anticipating climate risks in the most fragile situations, which risk being caught in a spiral of conflict and climate disaster, should be a priority.

The EU Global Strategy[561] calls for a more comprehensive approach to the EU's foreign and security relations, building stronger links notably between trade, energy, climate, development and security policies. It underlines that financing instruments are "an important element of the toolbox the EU has at its disposal for external action" and that they "should be mobilised in line with agreed political priorities".

Political dialogues and sectoral cooperation are required to address this, with a holistic assessment of each partner country's situation. In particular long-term strategies and climate risks could become standing components of bilateral and regional dialogues, agreements and frameworks. International processes, like the Sendai framework, the SDGs and the World Humanitarian Summit have highlighted the importance of reinforcing synergies with all relevant sectors, therefore reducing the risks of spill-over effects. Finally, peace and stability can be promoted through local and transboundary environmental resource management schemes as well as through support to partner countries in addressing climate-related resource scarcity. Failing to act is not an alternative, because climate change itself will raise numerous similar challenges, affecting resource availability, economic development, political stability and eventually migratory flows, which will become significantly larger than the changes expected due to mitigation of climate change.

A particular challenge of the low carbon transition is that the economic shift necessarily accompanying the changes will reshape the international framework itself. The changes to global energy markets, for example, will impact on the strategic leverage some states exert over others,

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[561] https://europa.eu/globalstrategy/en/global-strategy-promote-citizens-interests

alter international financial flows and require economic diversification in countries traditionally exporting large quantities of fossil fuels[562].

In this context, there may be geopolitical shifts while new dependencies are established. Such shifts will test the established global order particularly within the broad neighbourhood of the EU. Policy actions to address this would be to focus political dialogue and sectoral cooperation on economic diversification, societal, city level and state resilience in vulnerable countries to as to ensure successful transition.

Beyond bilateral and bi-regional schemes, at a moment when multilateralism is under threat, it is also important that EU long term global engagement aims to maintain the issue of climate change high on the agenda of international discussions, including further encouraging the United Nations in general, the United Nations Security Council in particular, to better factor in the climate and security nexus, and to look at options to institutionally strengthen climate risk assessment and management within the UN system.

#### 5.6.1.2 Raw material supply

Non-energy raw materials such as minerals and metals have a relatively smaller contribution to GDP, jobs or trade than other economic sectors, but are the key enablers of all EU value chains and for some key mitigation technologies. Materials are the main cost factor in the manufacturing sector (44%, compared to 18% for labour, 3% for taxes and 2% for energy).[563] Also in the case of energy-intensive industries, materials are the highest or the second highest cost category, with energy costs typically comprising 20-40% (higher in the case of aluminium). For this reason, access to raw material is important for the competitiveness of manufacturing industries.

A risk to the transformation of Europe's industry to net zero emissions is that Europe replaces its dependency on fossil fuels with one on non-energy raw materials, many of which it sources from outside Europe, and for which global competition will become more intense. However, the risks of import dependency do not depend only on the share of imports, but also on the raw material characteristics (e.g. storable or non-storable), uses (e.g. a component of durable equipment or a variable cost) and market (e.g. substitution possibility in supply or demand), as well as the extent to which the raw material can be recycled.

There is a limited amount of studies assessing the dependency of the global effort to reach net zero emissions on the availability of non-energy raw materials, such as metals and minerals. An important reason for this is the high uncertainty related to the future demand of raw materials, due to technological development, material substitution and recycling. As an example of raw materials needed by low carbon technologies, a 3 megawatt wind turbine contains 335 tonnes of steel, 4.7 tonnes of copper, 1200 tonnes of concrete, 3 tonnes of aluminium, 2 tonnes of rare earth elements as well as zinc and molybdenum[564]. Another assessment estimated the raw material requirement of a 3.45 megawatt wind turbine at 567 tonnes of steel, 5 tonnes of copper, 1369 tonnes of concrete, 13 tonnes of aluminium and aluminium alloys, 31 tonnes of polymers, 25.5 ton of ceramics and 3.5 tonnes of electronics while not detailing the amount of rare earths[565].

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[562] OECD (2017). Investing in climate, investing in growth. http://www.oecd.org/env/investing-in-climate-investing-in-growth-9789264273528-en.htm

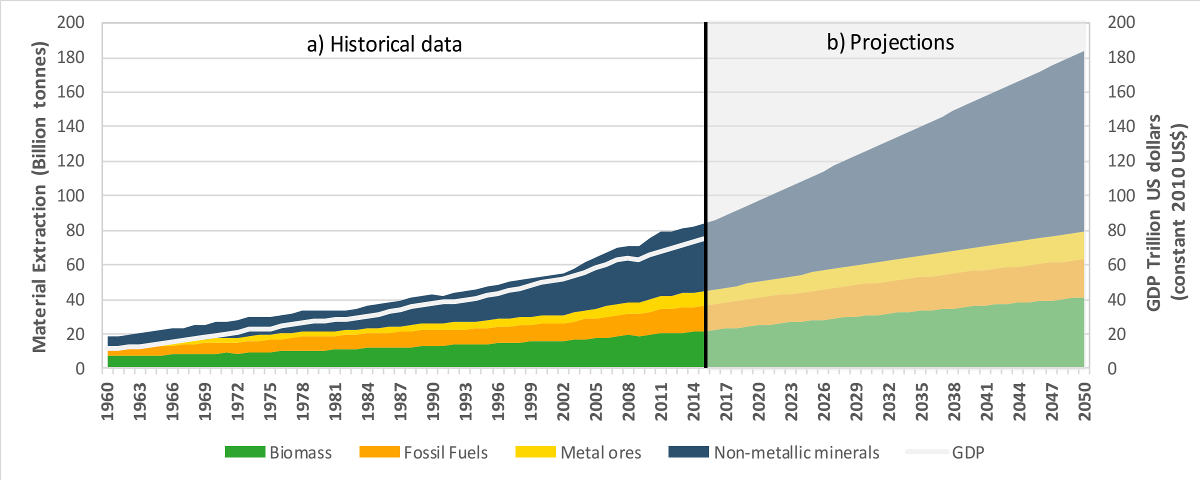
[563] VDI Centre for Resource Efficiency, https://www.resource-germany.com/

[564] http://www.cop23-rawmaterials.com/assets/presentation-1---kirsten-hund_world-bank.pdf

[565] https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/v1263%2045mw_mk3a_iso_lca_final_31072017.pdf

The World Bank projected that demand for metals and minerals increases rapidly with climate ambition[566]. The most significant example of this being electric storage batteries, where the rise in demand for relevant metals, aluminium, cobalt, iron, lead, lithium, manganese and nickel grows by more than 1000 per cent under a 2°C scenario compared to a business as usual scenario (Figure 113).

**Figure 113: Global material extraction by resource type, historical up to 2015 and projected to 2050**



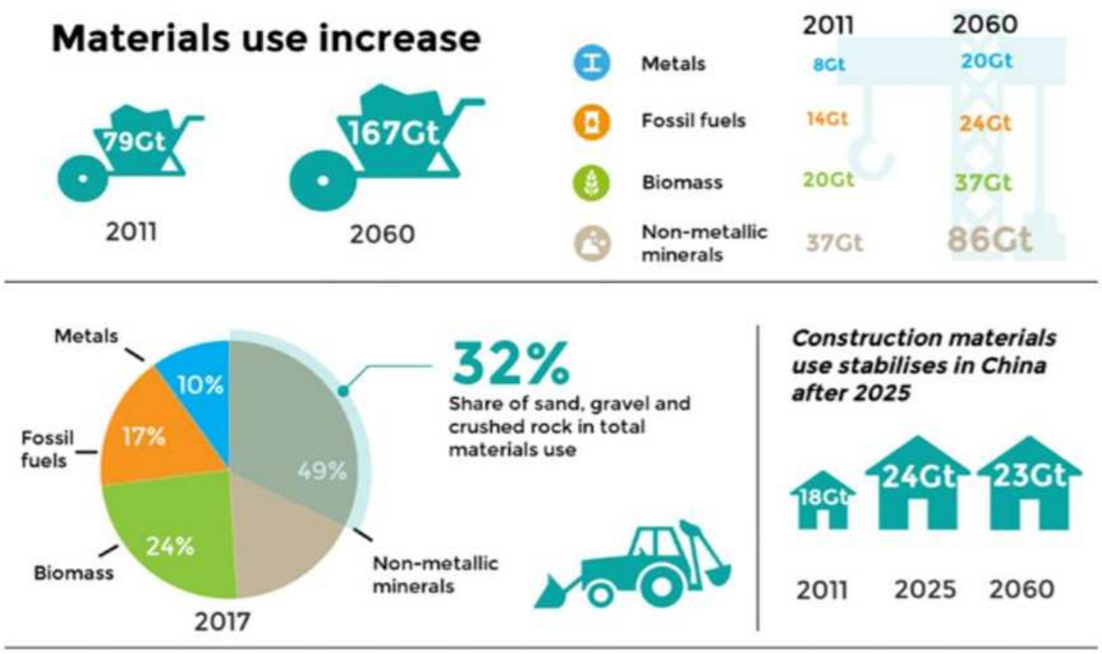

*Source: UN Environment, World Bank.*

The OECD estimates that, despite improvements in materials intensity and resource efficiency and the growth in the share of services in the economy, global material use could more than double from 79 Gt in 2011 to 167 Gt in 2060 (Figure 114).[567] Non-metallic minerals, such as sand, gravel and limestone, represent more than half of total materials use.

566 World Bank (2017), The Growing Role of Minerals and Metals for a Low Carbon Future, http://documents.worldbank.org/curated/en/207371500386458722/The-Growing-Role-of-Minerals-and-Metals-for-a-Low-Carbon-Future

567 OECD (2018), Global Material Resources Outlook to 2060 – Economic drivers and environmental consequences, http://www.oecd.org/environment/global-material-resources-outlook-to-2060-9789264307452-en.htm

**Figure 114: Materials use trends till 2060**




*Source: OECD*[567].

OECD concludes that the growth in materials use, coupled with the environmental consequences of material extraction, processing and waste, is likely to increase the pressure on the resource bases of the planet's economies and jeopardize gains in well-being.

Without addressing the resource implications of low-carbon technologies, there is a risk that shifting the burden of curbing emissions to other parts of the economic chain may simply cause new environmental and social problems, such as heavy metal pollution, habitat destruction, or resource depletion. The International Resource Panel recently assessed these trade-offs[568] [569].

Access to raw materials needed to make low carbon technologies and products will determine EU industry's competitiveness and ability to deliver them at a scale that matches climate ambitions.

Rapid uptake of climate-friendly technologies will increase competition for resources and the EU may face strong increase in competition in global raw materials markets from fast growing economies. Today, production and consumption are shifting towards emerging and developing countries, which on average have higher materials intensity than Europe. Asia has emerged over the last two decades as a major producer and user of raw materials (Figure 115). This increase is mainly due to China's rapid industrialisation and urbanisation, which requires an enormous amount of raw materials such as steel, non-ferrous metals and concrete.

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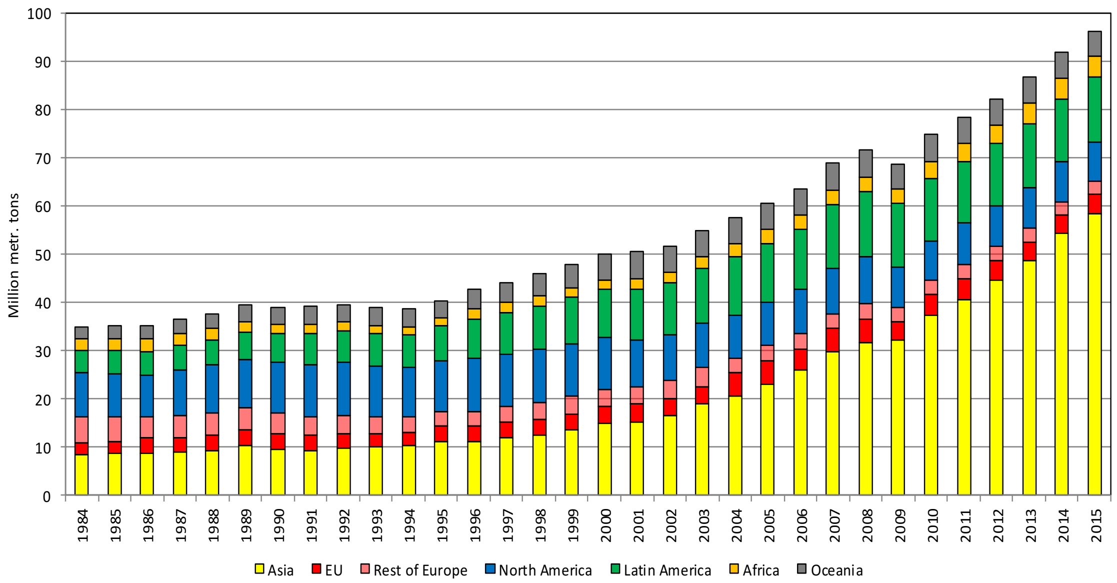
[568] UNEP/IRP (2016), Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production, http://www.un-expo.org/wp-content/uploads/2017/06/Green_energy_choices_The_benefits_risks_and_trade-offs_of_low-carbon_technologies_for_electricity_production-2016UNEP_GEC_web.pdf.pdf

[569] UNEP/IRP (2017), Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies, http://www.resourcepanel.org/file/604/download?token=oZQeI-pe

**Figure 115: Non-Ferrous Minerals production per continent**




*Source: EU Raw Materials Scoreboard.*

In order to safeguard the EU's industrial competitiveness along numerous value chains and to support deployment of low carbon technologies the EU needs to have a sufficient, affordable and sustainable access to raw materials, especially critical raw materials.

The EU economy requires a wide variety of raw materials. The EU has low import dependency for construction materials, several industrial minerals and industrial roundwood, but is heavily import-dependent on many metal ores and natural rubber. Non-metallic minerals represent nearly half of the EU's mass materials. Metal ores only represent a minor proportion of the EU's material consumption in terms of mass, but this understates their high economic and strategic importance[570].

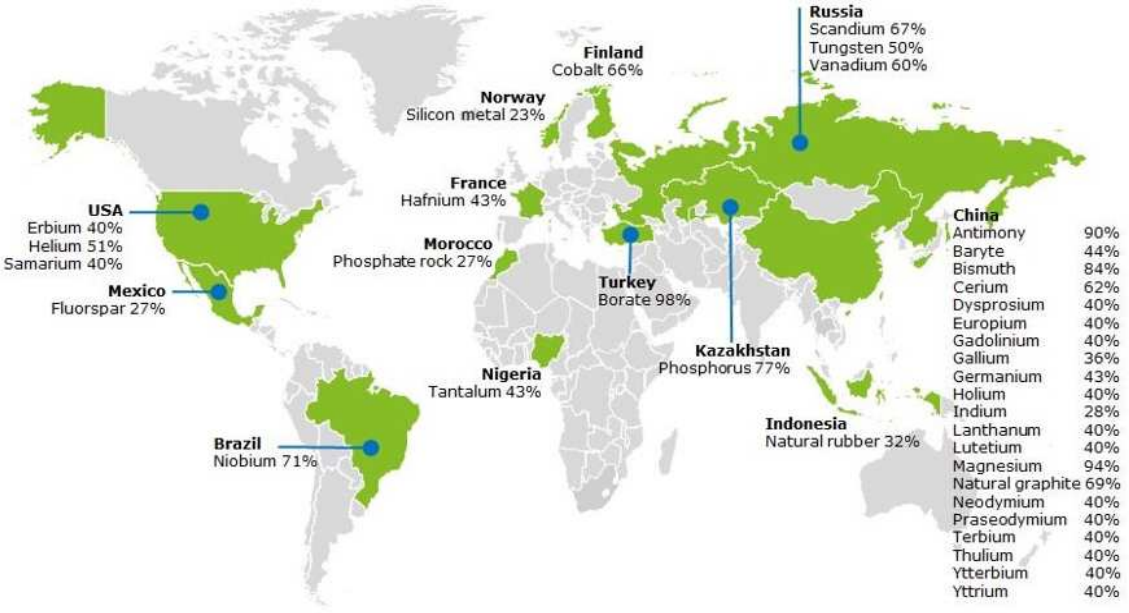
Securing a supply of raw materials will play an increasing role in managing risk in all EU industrial value chains. The EU already monitors the situation through its 3-yearly assessments of critical raw materials. This delivers a risk assessment for EU industry based on economic importance and supply risks criteria and informs policy and business risk mitigation actions. The Commission published the last list of critical raw materials in 2017[571].

The main global producers and suppliers of critical and some non-critical raw materials to the EU are highly concentrated in a few third countries. Many of critical raw materials are located in countries with poor governance and environmental standards (Figure 116).

[570] Raw Materials Scoreboard 2018, https://publications.europa.eu/en/publication-detail/-/publication/117c8d9b-e3d3-11e8-b690-01aa75ed71a1

[571] COM(2017) 490 final, 13.09.2017.

**Figure 116: Largest suppliers of critical raw materials to the EU**




*Source: Study on the review of the list of critical raw materials 2017*[572]

Sustainable and responsible mining and sourcing of raw materials approaches are needed to decouple climate objectives from negative environmental impacts associated with necessary technology materials. This is fundamental in the context of the sustainable development goals.

Circularity of metals and recycling of raw materials from low carbon technologies is an integral part of the low carbon transition. The EU is at the forefront of the circular economy and increasing the use of secondary raw materials. For example, recycling rates of some metals such as iron, aluminium, zinc, chromium or platinum already reach over 50%. For other, especially those needed in renewable energy or high tech applications such as rare earths, gallium, indium secondary production represents only a marginal contribution. Significant amounts of resources leave Europe in the form of wastes and scrap, which are potentially recyclable into secondary raw materials.

However, given the scale of fast growing material demand, primary raw materials will continue to provide a large part of the demand. Also, due to long time spans until these reach their end-of-life stage, recycling opportunities will fully materialise with a lag of several years or, in the case of buildings, several decades.

5.6.1.3 Security of critical energy infrastructure and security of investments

The energy transition raises new security challenges that will have to be properly managed.

Traditional energy technologies are historically composed of control systems tailored to operate the physical networks. These operational technologies become more and more connected to digital technologies and components. This advancing digitalisation makes the energy system smarter, allows the penetration of renewables in the system and enables consumers to actively participate in the energy market achieving higher energy services gains. But digitisation also

[572] https://publications.europa.eu/en/publication-detail/-/publication/6f1e28a7-98fb-11e7-b92d-01aa75ed71a1/language-en

creates an increased exposure to cyber-attacks jeopardizing the data privacy of consumers or the security of supply.

The European Union has already initiated a strategy to promote cyber resilience. After the adoption of the Directive on security of network and information system ("NIS Directive") the Commission proposed in 2017 a cybersecurity package to extend the mandate of the European Union Agency for Network and Information Security (ENISA) and a new European framework to certify the security of IT devices and systems.

However, the energy system has specific characteristics such as real time requirements to react in milliseconds, which prevent the application of standard cybersecurity measures. It combines new technologies with legacy technologies that have a very long life cycle and that were designed well before digitalisation. Furthermore, energy security incidents could lead to cascading effects particularly strong in a European context due to the market coupling of electricity and gas and the numerous physical interconnections in electricity, gas and oil. These cascading effects could be across Member States borders but also across critical infrastructures in a number of Member States and could have devastating effects.

Moreover the current framework at European level does not provide appropriate instruments to effectively respond to new cross-border challenges to physically protect critical energy infrastructure. A more coherent level of physical protection across the Union could significantly improve the security and the level of resilience of the energy system. The aim should be to match the level of physical protection with the level of cybersecurity, which are both of crucial importance for the resilience of the energy system.

Achieving a better preparedness and a higher level of resilience of the energy system for the case that a hybrid threat or cyber-attack occurs will therefore require new policies and initiatives to address adequately the issue of physical and cybersecurity of critical energy infrastructure. In particular, the Commission will help energy operators to better cope to the specific cybersecurity challenges of their sector by adopting next year guidance on cybersecurity in the energy sector. It will be followed by a Network Code on cybersecurity in electricity as requested in the context of the Clean Energy for All European package by the European Parliament and the Council.

In exceptional cases, foreign direct investments (FDI) are problematic when they pose a threat to security or public order. This point has been made in the 2014 Energy Security Strategy and recently by the European Parliament and certain Member States. In such circumstances, FDI may need to be assessed and/or conditioned or prohibited. This is the case where foreign investors – especially but not only when they are state-owned or controlled, including through financing or other means of direction – may seek to acquire control of or influence in European undertakings whose activities have repercussions on critical technologies or infrastructure, such as critical energy infrastructures. Such acquisitions may allow these assets to be used by non-EU parties to the detriment not only of the EU's technological edge but also its security including security of energy supply. The Commission made a proposal for establishing a framework for screening of foreign direct investments into the European Union[573].

### *5.6.2 Markets and Trade*

#### 5.6.2.1 Global leader on clean energy and low carbon policy

Strengthened commitments to climate change mitigation following the conclusion of the Paris agreement, together with increasing concerns over energy security and air pollution, have

[573] COM(2017) 487 final

accelerated the transformation of the energy system across the globe. The EU must stay in the lead in this process, while at the same time ensuring we make full use of the business opportunities resulting from it. Europe's industrial base has benefited from the EU's edge as an early mover, but the competition from other economies is increasing, and the prospects for European companies to enter and expand export markets for e.g. renewable technology is often hampered by restrictions and distortions with reduced market access as a result. The Union's trade policy has an important role to play, so as to enable jobs and growth through the energy transition also in third countries while at the same time facilitating their climate mitigation efforts.

The market opportunities are clear, with a global clean energy market, currently estimated at about EUR 1.3 trillion[574]. For instance, global investment in generating electricity from renewable energy sources is now more than double the level of investment in fossil fuel generation. Looking beyond electricity to the entire energy sector, low carbon sources account for almost 50% of total energy investments. This means that, even if fossil fuels are still essential, their use is rapidly declining in relative terms.

The challenges for EU producers in tapping this market are, however, equally clear. Although the EU has been a leading player in the deployment of renewable energy and the development and manufacture of renewable electricity equipment and in renewable electricity production, we have been overtaken in recent years by other large economies, most notably by emerging economies such as China. In terms of market size, we may soon slip to fourth place worldwide; by 2022, for example, India's investment in renewable electricity is expected to exceed the EU's[575], a milestone already surpassed by the US and China.

The renewable energy market is expected to grow even faster outside the EU than in the EU. For example, while the EU market for renewable electricity would increase by about 450 GW by 2030 and 1500 GW by 2050 (on average across scenarios explored in this analysis – see section 4.2.2.3), global growth should be one order of magnitude higher, up to 10 TW of installed renewables capacities by 2040[576] 577. In fact, the large majority of the electricity production capacity installed in global energy scenarios compatible with the Paris agreement should actually be renewables: close to 80% by 2040 according to WEO 2018[576] and more than 80% by 2050 according to GECO 2018[578]. More than half of these new capacities should be installed in Asia, according to both reports, followed by North America, the EU, and other regions. In addition, the future global market for batteries is also expected to grow fast and be very substantial, increasing from 4 GW[576] currently to between 220 GW and 540 GW in 2040, depending on cost trajectory (WEO 2018)[576], and up to 1000 GW in 2050 (GECO 2018[578], also considering batteries in electric vehicles).

These developments should be anticipated to benefit European industry as business opportunities. In terms of the types of renewable electricity in which EU companies have a competitive advantage, the EU's once strong position in solar power has been significantly eroded in recent years by China. This is important as solar is the main growth technology worldwide. The EU, however, is still a leader in the second biggest growth area – wind power – with a global

574 Advanced Energy Economy Report 2017. https://info.aee.net/aen-2017-market-report, which gives an estimate of USD 1.4 trillion in 2016, converted with an exchange rate of 0.9 USD per EURO.

575 IEA (2017), Renewables 2017, Analysis and forecasts to 2022. OECD/IEA, 2017

576 IEA (2018), World Energy Outlook 2018, Sustainable Development scenario, https://www.iea.org/weo2018/

577 To put this in perspective, total installed electricity capacity in the EU was just under 1000 GW in 2015.

578 Keramidas, K., Tchung-Ming, S., Diaz-Vazquez, A. R., Weitzel, M., Vandyck, T., Després, J., Schmitz, A., Rey Los Santos, L., Wojtowicz, K., Schade, B., Saveyn, B., Soria-Ramirez, A., *Global Energy and Climate Outlook 2018: Sectoral mitigation options toward a low-emissions economy - Global context to the EU strategy for long-term greenhouse gas emissions reduction*, EUR 29462 EN, Publications Office of the European Union, Luxembourg, 2018

investment share of 39% and huge growth in wind energy capacity in the EU and worldwide. All-in-all, despite its strong initial advantage and the fact that the EU still hosts 6 out of the 25 largest renewables energy companies in the world[579], the EU's renewable energy sector faces increased competition from third countries.

EU producers have also to deal with policy-driven barriers to markets, which affect not only EU foreign investment in clean technologies but also trade of raw materials that are essential to develop new technologies, such as copper and lithium (see also section 5.6.1.2). Such barriers include:

- Export restrictions on raw materials used in equipment for generating and supplying renewable electricity;
- Barriers to market access for EU equipment;
- Barriers to market access to electricity grids for producers;
- Closed electricity procurement markets.

The Commission has proposed Energy and Raw Materials Chapters (including renewable energy) in all of its free trade agreements (FTAs) to complement tariff elimination, services liberalisation as well as climate action and trade facilitation provisions in Trade and Sustainable Development Chapters to ensure the openness of the EU's energy market is matched by our trading partners.

The ideal solution would be to tackle these barriers at multilateral level. However, since there are so far no specific provisions tailored to these products following the failure of discussions in the World Trade Organisation (WTO) on energy in the context of the Doha round, the EU is engaged in plurilateral and bilateral initiatives, including pushing for negotiations on an Environmental Goods Agreement (EGA) or including provisions that facilitate the global uptake of climate-friendly technologies in bilateral trade agreements.

#### 5.6.2.2 Trade policy and bilateral trade agreements

EU trade policy contributes in a number of ways to global decarbonisation efforts and support the goals of the Paris Agreement. In particular, bilateral trade agreements have numerous provisions that facilitate the global uptake of climate-friendly technologies. They remove barriers to trade and investment in climate-friendly technologies through early tariff elimination, ambitious liberalisation of environmental services and by addressing non-tariff barriers. For example, green technology annexes in the EU trade agreements with Singapore and Vietnam address non-tariff barriers in green renewable energy such as local content requirements.

Bilateral trade agreements also enable countries to put in place environment-friendly public procurement by promoting environmental considerations, including climate, in the procurement procedure. Public authorities are major consumers and by using their purchasing power to choose climate-friendly goods, or services they can make an important contribution to climate change policies.

Finally, bilateral trade agreements reaffirm the EU’s commitment to the multilateral climate regime under the UNFCCC and Paris Agreement in the Trade and Sustainable Development Chapters with a view to:

- effectively implement the Multilateral Environmental Agreements including the UNFCCC, the Paris Agreement and Kigali Amendment to Montreal Protocol reducing the use of potent greenhouse gases harmful to climate. The EU’s post-Paris agreements such as with Japan, Mercosur or Mexico  aim to include specific provisions relating to the Paris Agreement;

[579] https://www.thomsonreuters.com/en/products-services/energy/top-100.html

- maintain a level playing field, by not lowering environmental standards for the purpose of attracting trade or investment;
- facilitate trade and investment such as in renewable energy and energy efficient goods and services e.g. promotion of standards;
- cooperate on trade-related aspects of climate action, including on related domestic climate policies, customs, regulatory frameworks;
- involve civil society (including environmental NGOs and business, for example in clean-tech sector) in the cooperation, monitoring and implementation of these trade agreement though Trade and Sustainable Development (TSD) platforms (Domestic Advisory Groups).

Trade policy could potentially also support the reduction of the carbon footprint of all products consumed in the EU, including imported ones (see also discussion in section 5.6.2.3). The possibility of matching domestic policies to limit $CO_2$ emissions with a "border tax adjustment" has been debated for over a decade. Trade policy does not prevent the EU from taking effective measures (including taxes) to fight climate change, but the design of these measures needs to fit the characteristics of climate instruments that are already in place in the EU and with the EU's international obligations (including under the World Trade Organisation).

One basic WTO rule is that imported products cannot be treated worse than domestic products (national treatment). A "border adjustment tax" applied on imported products cannot thus be higher than the carbon tax payed by similar products in the EU, just as VAT rates and excise duties apply equally to domestic and imported products.

A theoretical carbon tax on domestically-consumed products, based on their carbon footprint, could be imposed at the border also on imported products. However, this type of tax would necessitate an entire new system of accounting and certification of the carbon content of inputs and production processes, which would need to be applied to any producer anywhere in the world selling its products in the EU. The tax would also have to be adjusted depending on the sources of energy used by each producer at the time of production and the effectiveness of the climate policies of the country of production. This would be clearly unmanageable at this stage.

A border tax adjustment would also not be compatible with the current legislative framework of the EU Emission Trading System (ETS). While a future review of the system could consider whether it is appropriate to prevent carbon leakage through carbon border adjustments fully compatible with the rules of the World Trade Organisation, such a measure would require phasing-out the current system of free allocation, which prevents the risk of carbon leakage in the EU ETS. It is also recalled that ETS is not a tax (as confirmed by the European Court of Justice), and in any event it is not a tax on products but is imposed on producers. This means that a carbon tax applied to imported products would not be matched by any equivalent internal tax, discriminating against imported products and putting the EU in breach of its basic obligations. It is also very unlikely that this breach could be justified by the general exceptions of the WTO (protection of health, conservation of natural resources).

Besides these legal and practical difficulties, there are also policy and political considerations relevant in this regard. In particular, it could be seen as running counter to the spirit of the Paris Agreement, which is founded on the principle of nationally determined contributions.

#### 5.6.2.3 International trade and carbon emissions

Through international trade, the EU and other leading economies can promote higher standards across global markets and contribute to crowding out unsustainable production and consumption patterns (examples: palm oil, timber). Moreover, expenditure at scale on innovative clean technologies in Europe and other advanced economies helps bring down costs and allows other countries to access these technologies at affordable prices within reasonable timeframes (examples: wind, solar, EVs). International competition helps drive down the cost of clean technologies and fosters the global low-emission transition, provided market players are protected from unfair trade practices under the multilateral rules-based framework.

At a global scale, and looking at the long term, Europe will progressively see its share of global population reduce. Similarly, its proportional weight in the global economy will reduce, as emerging market economies are expected to continue growing at faster rates. In 2015, the EU was the largest economy in the world, accounting for 22.7% of world output, while the U.S. represented 20.6% and China 13.3%. By 2050, the shares of the EU, the U.S. and China are expected to amount to 15.1%, 15.2% and 19.8% respectively (based on the macro-economic modelling used in section 4.10.5).

The world has seen an intensification of trade relations, and this has implication for the low carbon transition.

The most obvious and immediate effect of the low carbon transition on trade for the EU would be the significant reduction in imports of fossil fuels. The 80% reduction pathways could reduce net imports of fossil fuels by around EUR 85 billion per annum during 2031-2050 relative to the baseline, while the 1.5°C pathways could generate net annual savings of about EUR 145 billion per annum over the same period. In turn, even oil rich countries can thrive under global action, provided effective economic diversification policies are pursued.[580]

While decarbonisation will require significant investments in the EU energy-intensive industry, leading to some reductions in EU production in the fragmented action scenario, global decarbonisation would probably see a reversal and lead to positive effects on the EU's trade balance for most of the 2020-2050 period if the worldwide playing field is sufficiently levelled and fair for the three pillars of sustainable development (economic, social and environmental).

International trade and globalisation can separate the place of production of emissions from the place of consumption of the goods, besides generating emissions due to transport of traded goods themselves. Global trade has for instance strongly contributed to increased emissions from bunker fuels.

GHG emissions are conventionally allocated to the territory where they occur, thereby ensuring clarity and consistency of international accounts. This is also typically the case for the NDCs as submitted to the UNFCCC. Inventories do not report the emissions related to the consumption of imported goods (which are accounted for in the country of production), but they do report the emissions related to the production of exported goods, which are therefore not consumed domestically. This method of accounting is typically referred to as Production-based accounting (PBA).

PBA has been subject to criticism because it does not adequately represent the GHG emissions impact of changing consumption patterns due to trade and globalisation. It could also potentially open the door to "pseudo-decarbonisation" at the level of individual countries via the outsourcing of carbon-intensive products to third countries that might actually be less carbon efficient than the "outsourcer" country. Overall, such practices could therefore lead to higher GHG emissions at the global level. Some authors have therefore proposed to estimate emissions on consumption-based accounting (CBA) basis. Under this approach, the domestic emissions associated with

[580] OECD (2017). Investing in climate, investing in growth. http://www.oecd.org/env/investing-in-climate-investing-in-growth-9789264273528-en.htm

exports are excluded from a country's inventory, but the emissions related to the production of imported goods are reported in the country where the goods are consumed, not where they are produced. Such CBA exercises rely on estimates using multi-region input-output tables and trade flows and have inherent challenges related to data availability[581].

In this context the decarbonisation effort of the EU (traditionally measured on a PBA basis) has been criticised as being significantly less positive if expressed on a CBA basis. However, CBA is itself open to criticism as it fails to give credit to countries with export sectors that are more carbon-efficient than the world average and therefore contribute to decarbonisation worldwide via their own exports. Put differently, if such countries had not exported and more carbon-intensive countries had produced these goods themselves, global emission would have been higher.

Technologically-adjusted consumption-based accounting (TCBA) seeks to adjust for such differences in carbon efficiency in export sectors, by crediting carbon efficient export countries. By doing so it provides for a more accurate reflection of how international trade impacts global emissions than a pure CBA approach. Studies applying this TCBA methodology find for instance more reductions achieved in the EU than compared to a pure CBA approach[582].

This type of exercise was redone for the European Commission, looking at different impacts of the PBA, CBA and TCBA accounting methods on national emissions. The E3ME macro-econometric model was used for this purpose, which enabled to assess past trends as well as projections under a fragmented action scenario and a global action scenario[583]. GHG emissions considered include energy and process $CO_2$ emissions due to data constraints for non-$CO_2$ emissions and those related to land use. In addition, the Joint Research Centre's Global Energy and Climate Outlook 2018 used the JRC-GEM-E3 model to assess emissions embodied in international trade by using the same methodology[578]. The findings corroborate those described here based on the E3ME model.

The results for the EU indicate that emissions were cut more significantly on a PBA basis (-20.3%) than a CBA basis (-19.5%) between 1996 and 2016. The difference between the two accounting methods is smaller than what other studies have estimated, however. In addition, the TCBA approach resulted in significantly higher reduction for the EU than under either the PBA or CBA methods (-25.3%), which indicates that by 2016 the EU had already contributed significantly to the reduction in emissions of other countries because of the increased trade flow and the improved carbon efficiency of its exports. The absolute level of EU emissions on a TCBA basis are also lower than on a PBA basis because of the carbon efficiency of its exports.

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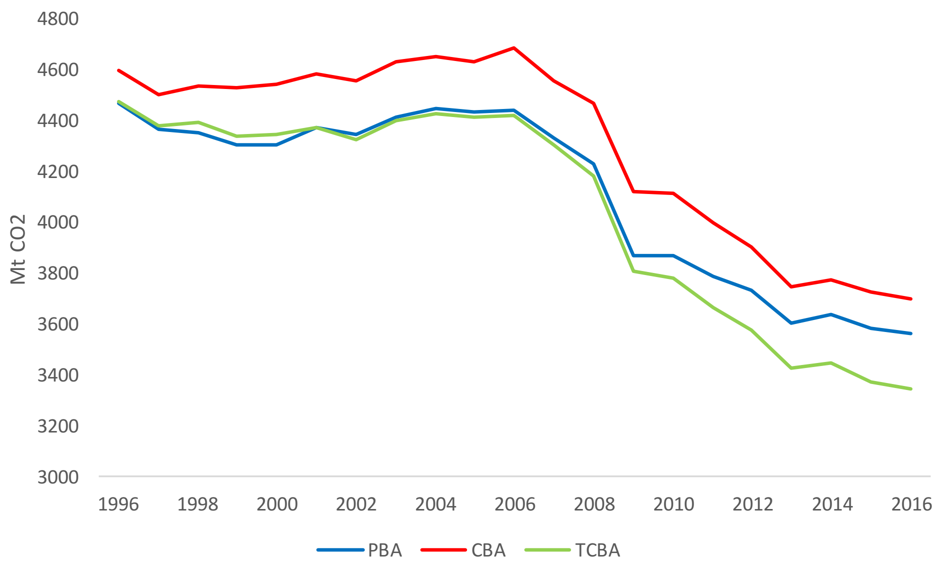
[581] Peters G., Minx J., Weber C., Edenhofer O. (2010), Growth in emission transfers via international trade from 1990 to 2008, Proceedings of the National Academy of Sciences of the United States of America, 2010.

[582] Kander A., Jiborn M., Moran D., Wiedmann T (2015), National greenhouse-gas accounting for effective climate policy on international trade, Nature Climate Change, Letters, March 2015. CBA looks at emission per country by calculating the actual carbon content of consumption domestically produced + the actual carbon constant of imported consumption. Under TCBA, the carbon content of exports (i.e. the carbon emissions that are subtracted from the production-based inventory to derive a consumption-based measure) is based not on the actual carbon content of the exports, but based on the carbon content that such exports would entail if they were produced with a carbon efficiency equivalent to the world average for traded product. The carbon content of imports (i.e. the carbon emissions that are added to the production-based inventory to derive a consumption-based measure) is the same for the CBA and TCBA methodology and is based on actual carbon content.

[583] Cambridge Econometrics, Analysis of Consumption-Based Emissions, forthcoming.

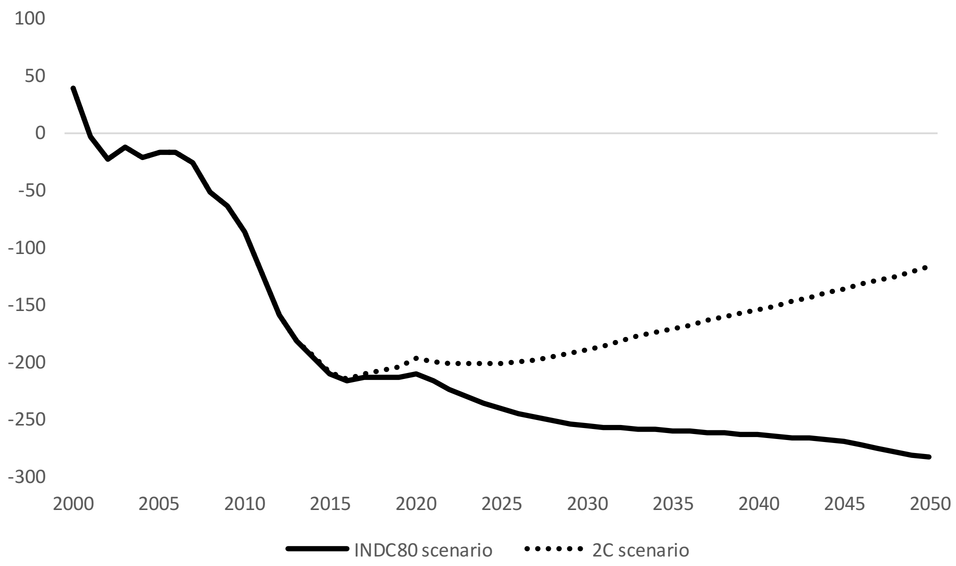
**Figure 117: EU, GHG emissions on a PBA, CBA and TCBA basis**




*Source: E3ME.*

The EU has thus contributed to the decarbonisation of third-countries via the rising efficiency of its economy and exports. Presently EU exports reduce global emissions by a bit more than 200 Mt$CO_2$, compared to a situation where EU exports would be produced locally in the importing countries. Modelling results indicate that if the EU were to reduce its GHG emissions by 80% by 2050 and the rest of the world were to reduce emissions in line with their NDCs, the global reduction in $CO_2$ emissions due to EU exports would further increase to Mt 284 $CO_2$ by 2050. This would be the natural consequence of the EU increasing its relative carbon efficiency compared to third countries. Under a global action scenario, this contribution would be more limited because of the increasing carbon efficiency of other parties' own production, but still be significant at 117 Mt$CO_2$ by 2050 (Figure 118).

**Figure 118: Reduction achieved due to EU net exports and imports, fragmented and global action (TCBA basis)**




*Source: E3ME.*

These estimates using the E3ME model are overall more positive than other exercises and they can certainly be further improved, for instance by including agriculture trade and the associated impacts on emissions, including from land use. However, they also confirm that CBA has shortfalls and that it does not recognise the positive impact the decarbonisation of EU exports on global emissions. CBA studies sometimes are used to conclude that the EU only achieved GHG reduction due to de-industrialisation. This seems incorrect. The EU has not stopped producing industrial goods and its exports may even be contributing positively to global decarbonisation as this analysis shows.

Furthermore, if other countries had achieved emission intensity improvements similar to the EU in globally traded good sectors, EU emissions reductions under CBA would have decreased further. This is of course ultimately the goal of the Paris Agreement, with all countries contributing strongly to the global effort to achieve the temperature objectives. The agreement itself fully recognises this, with a strong transparency framework and a cyclical approach that seeks strengthened commitments over time in order to increase action beyond current contributions. It does so by creating a space for a narrative on action not only as an international obligation under the Paris Agreement, but also as a positive agenda towards sustainable development.

On the other hand, the role of trade and other internationally relevant policies is also of importance. The ongoing economic transition will necessitate access to a new set of resources, opening new trade routes, and potentially closing others. Global value chains will shift requiring an update of applicable rules and regulations. EU trade policy needs to consider this and the EU may contribute to this change itself by setting new standards and re-wiring trade with new free-trade agreements. At the same time the EU needs to be ready to react if global trade or investment rules are being challenged by other players with negative consequences on its competitiveness.

### *5.6.3 Cooperation with third countries*

EU external cooperation is designed to help partner countries develop technical capacity and knowledge for meeting their international climate commitments (including their Nationally Determined Contributions), be equipped for formulating and implementing climate-related policies and projects, and effectively address context-specific, climate-related challenges in their territories. In particular, rising emissions by newly middle-income, emerging economies reinforce the need for cooperation at an early stage to help development process follow a lower carbon intensive path.

The cooperation between the EU and partner countries on climate change issues follows various approaches depending on the national circumstances of the partner country and the legacy of bilateral relations. This includes bilateral and multilateral diplomatic relations, upstream policy dialogues and collaboration, and the use of development policy instruments such as budget support, project-based approaches and blending mechanisms.

Of course, the official dialogue and cooperation between the EU and its Member States and the authorities of the partner countries represent just the tip of the iceberg, whereas climate relations actually arise mainly from exchanges through transnational research programmes, business forums, city networks, and other people-to-people contacts.

The EU’s external cooperation instruments are largely focused on investment and their programmes are multiannual in nature, thus providing a stable and predictable framework over the medium to longer term. This framework is designed to increasingly integrate climate policies, strategies and actions of the partner countries. EU development assistance is mainly delivered through the three largest policy-driven instruments: the Instrument for Pre-accession Assistance (IPA), the European Neighbourhood Instrument (ENI), and the Development Cooperation Instrument (DCI). The European Development Fund, financed by EU Member States separately from the EU budget, and the European Development Bank complete the package of EU instruments for external assistance.

#### 5.6.3.1 Cooperation with major economies

Members of the G20 account for some 80% of global emissions. As a key proponent of international climate action, the EU must help sustain the positive international momentum, cooperation and alliances, beyond political changeovers in individual countries. This priority was identified in HR/VP Mogherini's Global Strategy and has been the central objective for the successful EU climate diplomacy in recent years. Industry and investors in Europe and globally benefit from clear signals and evidence of progress.

Bilateral relations with major economies are usually structured around an official channel for bilateral climate policy dialogue, such as the EU-US Energy Council, the EU-China Bilateral Coordination Mechanism, the EU-South Africa Working Group on Environment and Climate Change and other high-level climate and environment dialogues established under Strategic Partnership Agreements with inter alia Japan. For countries with which the EU has or is negotiating free trade agreements, climate policy dialogues are also pursued within the Trade and Sustainable Development sub-committees, complemented by institutional advisory and monitoring mechanisms. In addition to or in the absence of such existing frameworks, bilateral summits and other official visits create opportunities to exchange on climate policy issues.

Official dialogues are complemented with cooperation activities funded by the Partnership Instrument to advance the Union’s strategic interests and to tackle global challenges with partner countries, for example the Emissions Trading System projects in China and South Korea, the Low carbon business projects in Brazil and Mexico, the India-EU Clean Energy and Climate Partnership, and the EU-Gulf Cooperation Council Energy Technology Network.

Another example is a EUR 25-million programme recently set up by the European Commission and the German Federal Government to support EU’s strategic partnerships for the implementation of the Paris Agreement. By fostering exchanges and collaboration among national and subnational administrations, business communities, the academia and civil society stakeholders from Europe and other major economies, this programme encourages and assists non-European major economies in making their best efforts towards the goals of the Paris Agreement. In a special emphasis, the programme supports analytical work and stakeholder involvement in the development of mid-century strategies.

#### 5.6.3.2 Cooperation projects with low and middle-income countries and partnership with Africa

The strategy and the new integrated Energy and Climate Plans are likely to serve as a role model to other ambitious countries. It will also raise interest for assistance in similarly decoupling economic growth from greenhouse gas emissions in these countries. One way of doing this is through the EU's intensive cooperation on clean energy and low-carbon projects as well as through technical and financial support for developing countries.

The successful low-carbon and climate-resilient transformation of the economy in developing countries requires the mobilisation of private capital and capital market resources from a variety of long-term oriented investors and, more broadly, aligning financial flows with the climate goals. In 2017, the EU and its Member States provided EUR 20.4 billion of climate finance to developing countries. Africa is the biggest recipient (33%, two thirds of which fund activities in South of Sahara countries), followed by Asia (22%), America (16%), non-EU Europe (6%) and Oceania (1%).[584] In July 2018, the European Investment Bank announced that it had already surpassed its 35% external climate finance target, pledged before COP21 as it provided EUR 2.6 billion in 2017 for climate action investments in developing countries, representing over 40% of its lending in these regions.[585] In addition to the financial instruments it manages directly, EU external actions are focusing more and more on investment and private sector involvement and aim to provide a stable and predictable climate-related investment framework.

They do so by combining grants with loans and equities from public and private sources, including bilateral and multilateral development banks. Private investment, alongside and attracted by public investment, is crucial to scaling-up climate finance and closing current finance gaps. In this context, the External Investment Plan, launched in 2016, will mobilise over EUR 44 billion in both the public and private investment.[586] It includes a dedicated fund for Sustainable Development (EFSD). As of July 2018, the EFSD mobilised EUR 800 million in guarantees and EUR 1.6 billion in blending, which will translate into over EUR 22 billion public and private investments in Africa and the EU neighbourhood. With these and other projects globally the EU is trying to pass on knowledge and build capacity, including the development of economic modelling tools, to develop policies, both in the context of the NDCs as well as for long-term strategies.

Furthermore, EU blending facilities operate in various regions (Latin America, Caribbean, Africa, Asia-Pacific). They will also help de-risking investment through innovative financing mechanisms. Leveraging activities will specifically address adaptation – an area that has been traditionally underfunded.

Taking one region as example, Sub-Saharan Africa is a strong priority for EU Official Development Assistance (ODA) and, together with the Western Balkans and the Neighbourhood, attracts the bulk of EU-level climate finance. Flagship infrastructure projects, especially in renewables, tend to focus on countries with particularly enabling environments such as Kenya, Ethiopia and Ghana. In other countries, smaller scale projects targeting both adaptation and mitigation are regularly employed, e.g. under the Global Climate Change Alliance Plus (GCCA+). EFSD climate-relevant projects[587] for Africa are in the planning or very early implementation phase and are expected to bring tangible climate results in the next years.

The EIB has been scaling up renewable energy investments, often co-funded by the EU blending facilities in Africa (e.g. Africa Investment Facility) or through the Global Energy Efficiency and Renewable Energy Fund (GEEREF) co-financed by private investors. Building on the reciprocal commitments that form the basis for EU-Africa partnership relations, the EU and Africa have announced a new Alliance for Sustainable Investment and Jobs between Europe and Africa.[588]

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[584] Activities concerning multiple regions account for 12%, while 11% could not be identified due to unavailable data from multilateral funds and institutions.

[585] For a breakdown of the EU's climate finance 2014-2020, see its *Strategies and Approaches* Submission to the UNFCCC (2018), http://www4.unfccc.int/sites/SubmissionPortal/Documents/201810041701---AT-10-04-EU%20Submission%20on%20Strategies%20and%20Approaches.pdf .

[586] https://ec.europa.eu/europeaid/eu-external-investment-plan-factsheet_en

[588] https://www.africa-eu-partnership.org/en/stay-informed/news/european-commission-unveils-new-africa-europe-alliance-sustainable-investment-and

Mainstreaming climate policy goals as elaborated in NDCs into national development strategies is an important undertaking for developing country partners, as it helps mobilise domestic budget resources and facilitates the alignment of international development assistance programmes on these climate goals through high-level development policy dialogues with key donors. Conversely, donor countries and organisations can and should improve the mainstreaming of climate considerations and NDCs into their development cooperation instruments. To that effect, the EU updated its guidelines in 2016 on the integration of environment and climate change issues into EU international cooperation and development[589]. Belgian, Dutch, French, German, Spanish and Swedish development cooperation organisations are following similar approaches. The NDC Partnership established at COP22 also plays a critical role in promoting and coordinating international support for the implementation of NDCs in developing countries and enhancing aid effectiveness in this context.

#### 5.6.3.3 Cooperation projects with fossil fuel exporting countries

The European Commission is supporting the efforts of Gulf countries, which comprise some of the world's largest producers of oil and gas, to shift away from sole dependency on fossil fuels, through the initiatives with the Gulf Cooperation Council (GCC), the EU-Gulf Cooperation Council Clean Energy Technology network and the EU-GCC Dialogue on Economic Diversification. The emphasis is on sustainable energy transition with the implementation of clean energy plans or the adoption of targets – mainly based on economic diversification strategies, energy efficiency and renewables. For GCC countries to succeed in this process, they will need to put in place an appropriate policy environment to encourage and facilitate private sector development and investment in non-hydrocarbon-dependent sectors. For the past decade, GCC countries have engaged more decisively on a path of transformation towards knowledge-based economies and societies. These efforts were also emphasised in 2015, when all GCC countries presented a commitment to the Paris Agreement.

## 5.7 Interactions with other Sustainable Development Goals

While the EU long-term strategy aims to support the achievement of SDG13 (Take urgent action to combat climate change and its impacts), acting on climate change provides many opportunities to enhance sustainable development. For example, decarbonising energy and transport is associated with improved air quality and health outcomes, especially in urban areas. Enhancing energy efficiency across sectors is associated with multiple economic and social benefits related to comfort, productivity, distributional effects on income and energy poverty alleviation[590]. Similarly, promoting a circular economy (e.g. smarter use of materials such as plastics) can reduce emissions while also contributing to cleaner land and water, and healthier oceans. Limiting methane emissions not only reduces GHG emissions but also air pollutants emissions. Conversely, climate change, if not limited, will become a major social issue with the potential to jeopardise sustainable development goals (SDG) focusing on poverty, hunger and water. Importantly, not acting on climate change and allowing for increase in extreme weather events and disasters compromises development not only in the third countries but also in Europe.

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589 Integrating the environment and climate change into EU international cooperation and development: Towards sustainable development. Guidelines No 6, Tools and Methods Series, Directorate-General for International Cooperation and Development, European Commission.

590 IEA (2014), Capturing the Multiple Benefits of Energy Efficiency, http://www.iea.org/publications/freepublications/publication/Multiple_Benefits_of_Energy_Efficiency.pdf

However, while some synergies are well understood, knowledge about how climate action interacts with all of the 17 Sustainable Development Goals (SDGs) of the UN is still evolving. Identifying further synergies between climate action and sustainable development will help the EU to be a leader in making the case for ambitious climate action, both domestically and worldwide. As countries pursue climate action and sustainable development jointly, the EU can also show leadership by identifying how to manage potential trade-offs.

The close relationship between climate and energy and sustainable development is recognised through the inclusion of climate action and clean energy among the 17 SDGs[591] adopted by the UN General Assembly in 2015. The EU and its Member States have in turn committed to implementing the 2030 Sustainable Development Agenda in full both domestically and internationally, including through the implementation of the Paris Agreement[592].

Although knowledge of how the SDGs interact is still evolving, the literature in this area is growing fast. Indeed, the adoption of the 17 SDGs provides a useful device for identifying synergies, trade-offs and knowledge gaps between any one SDG and the rest. Several studies use the framework of Nilsson et al.[593] which assesses the positive and negative interactions between SDGs on a scale, with 'indivisible' being the most positive relationship.

The IPCC Special Report on 1.5°C employs such a framework to assess the sustainable development implications of mitigation options towards 1.5°C[594]. It concludes that the total number of possible synergies exceeds the number of trade-offs, although their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition.

Strong synergies, with highest confidence, are for instance explicitly listed by the IPPC Special Report on 1.5°C (see figure below) between climate action and SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production), and 14 (oceans). On the other hand, some 1.5°C pathways show potential trade-offs if not carefully managed. This is the case for SDGs 1 (poverty), 2 (hunger), 6 (water), and 7 (energy access).

Some SDGs are associated with high potential for both synergies and trade-offs. A good example is SDG 6 (clean water and sanitation). The demand side appears to have greater potential for synergies since lower energy demand (e.g. through greater efficiency) can reduce water demand from the energy sector, increasing availability for other uses. On the supply side, a switch to a low carbon energy system would have to be managed with care since some low carbon energy systems (e.g. some bioenergy systems) could use water more intensively than the system they replace.

Also SDG16 on life on land shows trade-offs with certain mitigation strategies strongly focussed on biomass potentially having negative impacts on biodiversity. On the other hand, not solving climate change would have dramatic effects on biodiversity. The IPCC Special Report on 1.5°C estimated that with 2°C temperature change 13% of global land area would change from one ecosystem type to another, with 18% of insects, 16% of plants and 8% of vertebrates losing over

[591] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

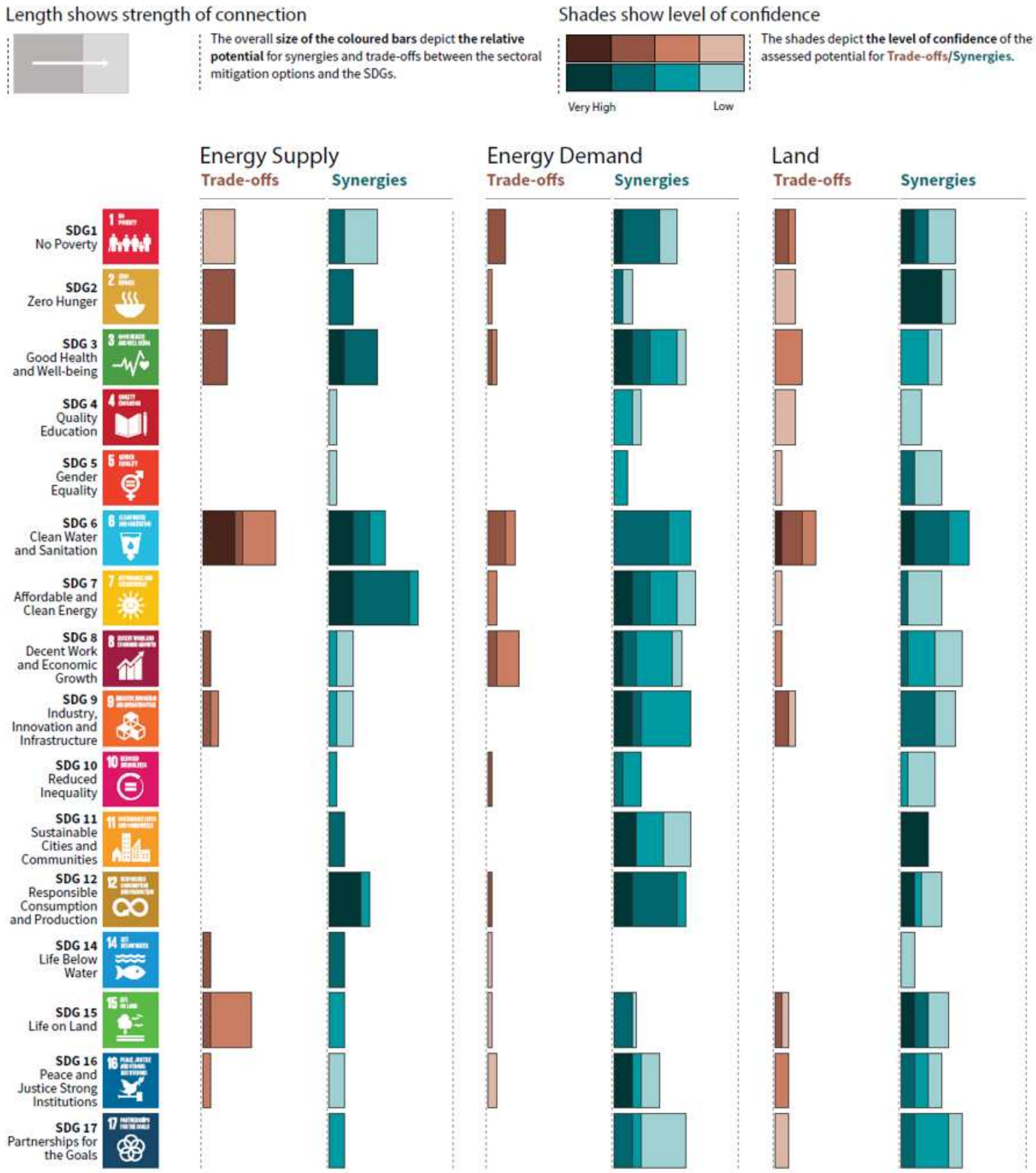
[592] See Council Conclusions on the EU response to the 2030 Agenda for Sustainable Development (June 2017) and on Climate Diplomacy (February 2018) as well as the Communication Next steps for a sustainable European future of the European Commission (COM(2016) 739 final) which maps out how specific EU policies contribute to sustainable development domestically and internationally.

[593] Nilsson M et al. (2018) Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustainability Science*. https://doi.org/10.1007/s11625-018-0604-z

[594] IPCC Special Report on Global Warming of 1.5°C (2018)

half their climatically determined geographic range. Often measures to enhance ecosystems result both in mitigation and adaptation benefits (see also section 5.9.2).

**Figure 119: Indicative linkages between mitigation options and sustainable development using SDGs**




*Notes: The strength of connection between climate mitigation and each SDG is denoted by the length of each bar, while the colour of shading denotes the level of scientific confidence in each interaction (darker colours indicate greater confidence). Individual bars have different colours since they combine multiple mitigation options. See Table 5.3 of IPCC Special Report for complete assessment.*

*Source: IPCC, 2018*[595].

[595] IPCC Special Report on Global Warming of 1.5°C (2018), Figure SPM-4.

Other studies demonstrating the strong linkages between SDGs and demand-side measures in the energy sector include Grubler et al.[596] and McCollum et al[597]. Furthermore, IEA analysis finds that achieving universal access to electricity by 2030 could reduce global greenhouse gas emissions as well as improve health and gender equality, if smart technologies and efficient appliances are used. In this case, the emissions associated with expanded energy access would be more than offset by reductions associated with reduced use of traditional biomass[598].

The IPCC Special Report on 1.5°C also concluded that 1.5°C pathways that include low energy demand, low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs.

The relationship between gender (SDG 5) and climate change and climate policy varies. Women and men affect the climate differently: their consumption patterns are different and they have different $CO_2$ footprints, e.g. through differing mobility patterns, and they are not represented equally in decision-making in this field[599]. Studies show that women and men also have different perceptions and attitudes towards climate change. Women are in general more concerned about this issue and more motivated to act. While women remain underrepresented in environmental, climate and particularly energy decision-making, in some studies men have been found to be more affected in their livelihood by climate mitigation activities in industrialised countries. A recent study in Canada has shown that climate change is a stressor on gendered livelihood activities for both men and women. Men are more likely to be vulnerable to climate change, including heat stress and infectious diseases. Other studies pointed out that in terms of climate change impacts, there is a higher likelihood for women to die in heatwaves, men higher likelihood to be affected by floods[600][601][602]. As more data needs to be gathered on the gendered consequences of climate change and climate policies (an effort driven by the UNFCCC's gender action plan), awareness of these differences will be important in implementing any long-term strategy.

## 5.8 Air pollution benefits from climate action

In terms of health impacts, the reduction of GHG is associated with lower emissions and concentrations of air pollutants, in particular fine particles with a diameter of 2.5 μm or less ($PM_{2.5}$), nitrogen dioxide ($NO_2$) and ozone. These pollutants have significant adverse effects on human health and can cause respiratory and cardio-vascular diseases, among others. They are also at the root of premature deaths. In turn, high ozone concentrations negatively affect plant

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596 Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum D, Rao ND, Riahi K, et al (2018). "A Low Energy Demand Scenario for Meeting the 1.5°C Target and Sustainable Development Goals without Negative Emission Technologies." Nature Energy 3, pages 515–527 (2018)

597 McCollum et al (2018) Connecting the sustainable development goals by their energy inter-linkages. *Environ. Res. Lett.* 13 033006. https://doi.org/10.1088/1748-9326/aaafe3

598 IEA (2017). Energy Access Outlook 2017. From Poverty to Prosperity.

599 http://eige.europa.eu/sites/default/files/documents/Gender-Equality-and-Climate-Change-Report.pdf .

600 Sellers, S. (2018), Climate Change and Gender in Canada: A Review

601 WEDO (2016), Gender and Climate Change: A closer look at the evidence, https://wedo.org/wp-content/uploads/2016/11/GGCA-RP-FINAL.pdf , p. 24-25

602 Studies such as: Neumayer E and Plumper T (2008), "The gendered nature of natural disasters: the impact of catastrophic events on the gender gap in life expectancy 1981-2020" (available at: https://www.tandfonline.com/doi/full/10.1111/j.1467-8306.2007.00563.x ) show that women are more affected by the impact of disasters, e.g. after hurricane Katrina, African American women were among the worst affected by flooding in Louisiana. Similarly, UN studies shown that 80% of people displaced by climate change are women.

growth. Research to quantify the benefits of climate action associated with improved air quality has progressed in recent years and highlights the significant scale of such co-benefits[603] [604]. Separate research has also developed to better quantify the benefits associated with avoided adaptation costs or the benefits of adaptation strategies themselves (see section 5.9).

The table below compares air pollution impact estimates for 2015 with estimates for 2050 in the decarbonisation pathways[605]. The combination of existing air pollution policies as well as ambitious climate policies result in strong reductions of air pollutants by 2050 due to the reduction in energy consumption and shift towards less polluting fuels. This results in strong benefits in air quality, human health and ecosystems impacts. Both the CIRC and 1.5LIFE scenarios have highest benefits (see Table below). The COMBO scenario has somewhat smaller benefits since the reduction in emissions (i.e. PM2.5) are smaller. Premature deaths from PM2.5 and ozone exposure decrease with around 40%. Mortality benefits are valued using the benefit ranges per life year lost, with health damage reduction in the order of magnitude of 140 to 340 billion euro and more by 2050 compared to the impact as experienced in 2015.

[603] See for example European Commission (Joint Research Centre, 2017), *Global Energy and Climate Outlook 2017: How climate policies improve air quality*, GECO 2017. JRC Science for Policy Report.

[604] Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J. V., Van Dingenen, R., Holland, M., Saveyn, B. *Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges*. Nature Communications volume 9, Article number: 4939 (2018). https://doi.org/10.1038/s41467-018-06885-9

[605] The GAINS model uses next to its own data, PRIMES energy projections as input to project air pollutants from the energy system. The methodology applied results in lower estimates for pre-mature deaths than reported in the EEA's *Air quality in Europe — 2018 report*. This estimated for 2015 that $PM_{2.5}$ concentrations were responsible for about 391000 premature deaths per year, and NO2 and O3 concentrations were responsible for respectively around 76000 and 16400 premature deaths per year.

**Table 21: Air pollution control costs and benefits in the EU compared to 2015 in 2050 (EU28).**[606]

| | 2015 | Change by 2050 | | |
|---|---|---|---|---|
| | | CIRC | COMBO | 1.5LIFE |
| SO2 (kton) | 2747 | -2069 | -1975 | -2039 |
| NOX (kton) | 7224 | -5458 | -5307 | -5530 |
| PM (kton) | 1478 | -881 | -848 | -865 |
| Premature deaths ozone and PM 2.5 (1000 cases per year) | 317 | -147 | -142 | -146 |
| Health impacts (million life years lost due to PM2.5) | 5.3 | -2.5 | -2.4 | -2.5 |
| Monetary damage health PM (bn€/yr). Low estimate | 368 | -174 | -168 | -173 |
| Monetary damage health PM (bn€/yr). High estimate | 884 | -418 | -404 | -414 |
| Air pollution control costs (bn€/yr) | 80 | -32 | -36 | -45 |
| SUM pollution control costs & health damage (bn€/yr) | 448 to 964 | -206 to -450 | -204 to -440 | -218 to -459 |
| Eutrophication (Ecosystem area exceeded 1000 km2) | 1016 | -188 | -181 | -190 |
| Acidification (Ecosystem area exceeded 1000 km2) | 100 | -64 | -63 | -64 |

*Note: Estimates for monetary damage based on values per life year lost from IIASA (2017)*[607] *and expressed in EUR 20013. Impacts on morbidity, materials, buildings and crops are not included. Possible impacts of N2O on health are also excluded.*

*Source: GAINS*

The estimates for reduced health damage in the table above only include benefits from reduced mortality (by assigning a value of life years lost in monetary terms). Other types of benefits not estimated are (1) avoided hospital admissions and healthcare costs; (2) reduced number of lost work days resulting from avoided illnesses (3) improved crop yields; and (4) reduced ecosystem impacts. Avoided healthcare costs increase the level of income available for other types of consumption, while reduced work days lost and improved crop yields translate into higher output.

Also impacts on ecosystems are significant notably for acidification where ecosystem areas with exceedance levels would halve by 2050. The trend for eutrophication is positive, though less outspoken given that the primary source of eutrophication is not $N_2O$ emissions but other sources of nitrogen leakage.

## 5.9 Climate change and its impact, how to increase resilience and adaptation

Climate change is already occurring and its impacts are already being felt across Europe: our continent has warmed and will warm faster than the rest of the world. The EU has experienced heatwaves[608], record temperatures and drought during the spring and summer of 2018[609] and also

[606] Due to modelling timing constraints only 3 scenarios were assessed for air pollution.
[607] IIASA (2017). Costs, benefits and economic impacts of the EU Clean Air Strategy and their implications on innovation and competitiveness, Table 5, pg. 15.
[608] Copernicus Programme (2018), The long hot summer just past, https://climate.copernicus.eu/long-hot-summer-just-past

experienced extreme heatwaves in 2014, 2015 and 2017[610]. In Lapland, in the Arctic Circle, the average temperature for July was around five degrees Celsius higher than usual[611]. Last year, the global economic costs of weather-related disasters hit a record of € 283 billion[612].

The IPCC Special Report on 1.5°C builds upon existing knowledge on climate change impacts and adaptation, and paints a clearer picture than ever before. The impacts of human-induced global warming of 1°C are already being felt in the intensity and frequency of some climate and weather extremes. Furthermore, climate models project robust differences in impacts between the present, warming of 1.5°C, and warming of 2°C – every half a degree matters. This underlines the importance of continued climate action (both adaptation and mitigation), not only today but also in the future, as marginal impacts of climate change appear to be significant at any level of warming. In general, climate-related risks are larger at higher levels of warming, and some impacts, such as the loss of some ecosystems, may be long-lasting or irreversible.

Regarding specific impacts, the IPCC Special Report concentrates on identifying differences between 1.5°C and 2°C and finds several striking examples of pronounced drought risk increases, for example in the Mediterranean basin and the Middle East (see Table 22). The Report, in particular, calls for both incremental and transformational adaptation. In particular, it notes that a slower rate of sea level rise under 1.5ºC enables more opportunities for ecological and human systems to adapt. However, it is important to remember that impacts of climate change are already being felt and that global warming of 2°C is likely to be exceeded under current levels of global climate action (for example the current NDCs are thought to be consistent with warming of 3°C by 2100). At the current level of warming (1°C), around 4% of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another, with greater areas affected at higher levels of warming (see Table 22).

While the IPCC report is global in scope, impacts will not be spread evenly across the globe. The report highlights that some regions are at greater risk of drought and precipitation deficit, while others face greater risks from heavy precipitation events (especially in Northern latitudes). The report suggests a transition from medium to high risk of regionally differentiated impacts between 1.5 and 2°C for food security. Reductions in projected food availability are larger at 2ºC than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe and the Amazon. It is clear that the climate change, even with the worst of its effects avoided, will have significant impact on EU humanitarian and civil protection policies.

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609 World Weather Attribution network has estimated that "the probability to have such a heat or higher is generally more than two times higher today than if human activities had not altered climate.", see: https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/

610 https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-8/assessment

611 Finnish Meteorological Institute https://en.ilmatieteenlaitos.fi/press-release/610918514

612 https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/2017-year-in-figures.html ; Estimated global losses due to natural disasters in 2017 stand at US$ 330 billion, of which 97% of losses was weather related This is the equivalent of €283 billion (exchange rate applied 1.13 US$ per €).

**Table 22: Selected Climate Change Impacts to Natural Systems at 1.5°C & 2°C**

| | **At 2°C** | **At 1.5°C** |
|---|---|---|
| **Extreme hot days** | 4°C hotter | 3°C hotter |
| **Sea level rise by 2100** | around 0.1m more than at 1.5°C<br>(less time to adapt) | 0.26-0.77m |
| **Ecosystems** | 13% of global land area changes from one ecosystem type to another | area at risk ~50% lower than at 2°C |
| **Habitat Loss** | 18% of insects, 16% of plants and 8% of vertebrates lose over half their climatically determined geographic range | 6% of insects, 8% of plants and 4% of vertebrates lose over half their climatically determined geographic range |
| **Permafrost thawing** | 1.5 – 2.5 million $km^2$ greater than at 1.5°C | Woody shrubs encroaching into the tundra already at 1°C |
| **Arctic Ocean** | At least one sea ice-free summer per decade | One sea ice-free summer per century |
| **Coral reefs** | largely disappear (>99% loss) | decline by 70-90% |
| **Fisheries**<br>Global annual marine catch (one model) | over 3 million tonnes lower | 1.5 million tonnes lower |

*Greater risk at 2°C than 1.5°C is specified but not quantified*[613]

- Droughts and precipitation deficits;
- Heavy precipitation events;
- Heavy precipitation associated with tropical cyclones;
- Larger area affected by flood hazards due to precipitation;
- Spread of invasive species
- Forest fires
- Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could be triggered around 1.5°C to 2°C of global warming
- Oceans (greater risk at 2°C spanning several impacts including species range shift and impacts of ocean acidification on marine species)

*Note: Impacts above are attributed a confidence level of at least medium in the IPCC report's Summary for Policymakers*

*Source: IPCC Special Report on global warming of 1.5°C*

[613] Some of these impacts are regional rather than global, though regions in this context are large. E.g. heavy precipitation events are projected to be higher in northern hemisphere high latitude/high elevation regions, eastern Asia and eastern North America. More specific phenomena within these categories may be quantified in the underlying IPCC report.

**Table 23: Selected Climate Change Impacts to Human Systems at 1.5°C & 2°C**

| | **At 2°C** | **At 1.5°C** |
|---|---|---|
| **Populations exposed to climate-related risks and susceptible to poverty** | Numbers affected expected to increase | Several hundred million fewer people affected than at 2°C by 2050. |
| **Water stress** | Additional 8% of world's population affected (based on year 2000 population) | Affects up to 50% less of the world's population compared to 2°C |
| *Greater risk at 2°C than 1.5°C is specified but not quantified*[613]<br>• Human health: heat-related morbidity & mortality, ozone-related mortality<br>• Vector-borne diseases (e.g. malaria, dengue): increased risk, shifting geographic range<br>• Crops (cereals, rice): reductions in yields and/or nutritional quality<br>• Reductions in projected food availability<br>• Risks to global aggregated economic growth<br>• Exposure to multiple, compound climate-related risks<br>• Greater adaptation needs | | |

*Note: Impacts above are attributed a confidence level of at least medium in the IPCC report's Summary for Policymakers.*
*Source: IPCC Special Report on global warming of 1.5°C.*

### *5.9.1 The need to adapt in the EU*

Successful mitigation action is the first necessary step to reduce the risk of climate change. However, in parallel, the EU economy as a whole must adapt to the risks that will result from already committed emissions. These risks grow as we lag behind schedule in stabilising global temperatures. Limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people susceptible to poverty by up to several hundred million by 2050. Each 0.5ºC of warming avoided can be significant, increasing the chances of achieving SDGs related to poverty, hunger, health, water, cities and ecosystems. Among others, EU agricultural, Arctic and coastal dependent communities would benefit significantly; adaptation of fragile ecosystems and the services they provide (e.g. coral reefs) would be more effective. In general, overshooting the 1.5ºC limit will make climate-resilient development pathways (CRDPs) more elusive and impacts on water-energy-food-biodiversity links more difficult to manage.

Conventional and incremental approaches to adaptation that do not consider long-term sustainable development or consider adaptation and mitigation separately will not deliver the Paris Agreement. More emphasis on 'transformational' adaptation measures as a complement to 'incremental' adaptation may be required[614]. These adaptation measures and options may include not only "hard" structural and physical measures (e.g. coastal protection, infrastructure) but also

[614] Transformational adaptation, according to the IPCC (2014 AR5, Chapter 14: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap14_FINAL.pdf) "seeks to change the fundamental attributes of systems in response to actual or expected climate and its effects, often at a scale and ambition greater than incremental activities. It includes changes in activities, such as changing livelihoods from cropping to livestock or by migrating to take up a livelihood elsewhere, and also changes in our perceptions and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems". See also EEA 2017 climate, impacts and vulnerability report and 2016 EEA report on Urban adaptation to CC in Europe.

"soft" social policies (e.g. awareness, health services) and governance improvements (e.g. implementation, cross-sector coordination, mainstreaming). A combination of both "hard" and "soft" adaptation may produce best results[615], and joining efforts from several EU Member States may also improve protection, e.g. monitoring and mapping jointly coastal areas for a more reliable early warning of extreme weather[616].

It is necessary to better integrate long-term planning of emissions reduction and adaptation because:

a) **Adaptation provides opportunities and economic and social stability** – climate change will interact with other socio-economic developments[617]. It can be expected that climate change adaptation projects or the impact of climate extremes will involve a higher level of public intervention than today[618], which calls for effective and efficient adaptation strategies, particularly at local scale. Public resources may be severely drained if the climate reaches certain tipping points[619]On the other hand, both public and private investments in adaptation provide opportunities and risk management opportunities that can spur the creation of market niches: e.g. for climate services or green infrastructure. In addition, supporting adaptation in developing countries may also bring stability and security within the EU's borders.

b) **There are co-benefits and trade-offs between mitigation and adaptation** – so both policies must be developed together as components of any credible long-term climate action. Early integration of both adaptation and mitigation in coherent climate-resilient development pathways entails that specific vulnerabilities are factored in when a given economic sectors starts implementing a decarbonisation strategy. Adaptation must ensure that low-emission agricultural techniques withstand higher temperatures, it must lead to renewable electricity networks that are climate-proof and protect forests so that they keep functioning as carbon sinks. Transformative climate action in cities, in particular, depends on the right mix of mitigation and adaptation actions to both protect citizens against climate impacts and enable emissions reduction within stringent legal and budgetary boundaries.

(c) **Adaptation improves the functionality and resilience of human and natural systems**. Effective adaptation action reduces both the vulnerability and exposure of natural ecosystems and communities to the risks associated with climate extreme events (floods, wildfires, hurricanes, etc.), and improves their capacity to recover and re-establish after a climate-related perturbation. These aspects ensure that the functionality of ecosystems (e.g. absorption of CO2) is maintained over the long-term, or at least that such functionality is recovered shortly after an extreme event. In 2013, the European Commission adopted an EU Adaptation Strategy to tackle climate change risks to the EU economy and society. The Adaptation Strategy focuses on developing better knowledge and understanding of climate impacts, climate proofing of specific sectoral policies and the promotion of action by Member States and cities through non-legislative means. The

[615] OECD (2015), Climate Change Risk and Adaptation - Linking Policy and Economics, http://dx.doi.org/10.1787/9789264234611-en

[616] For example, a new European seabed map stitched together from surveys originally made for navigation has improved storm surge forecasts in the North Sea. See: http://www.emodnet.eu/improving-storm-surge-modelling-north-sea

[617] EEA (2017), Climate change, impacts and vulnerabilities in Europe 2016, https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016

[618] Daniel Bailey (2015), The Environmental Paradox of the Welfare State: The Dynamics of Sustainability, New Political Economy, 20:6, 793-811, DOI: 10.1080/13563467.2015.1079169

[619] Steffen et al 2018, Trajectories of the Earth System in the Anthropocene,, Proceedings of the National Academy of Sciences Aug 2018, 115 (33) 8252-8259; DOI: 10.1073/pnas.1810141115

recent evaluation of the Strategy highlighted the urgency for action because of the important risks facing the EU in certain economic areas[620]. For instance:

- By the end of the century, under a high emissions scenario[621] and without specific adaptation measures undertaken, the EU could experience a welfare loss of around 2% of GDP per year by 2100, i.e. EUR 240 billion per year from only six impact sectors assessed[622]:
    - Weather-related disasters could affect about two-thirds of the European population annually (351 million people per year)[623], compared with 5% of the population between 1981-2010. This would increase the related fatalities per year by fifty times by the year 2100 (from 3 000 deaths per year presently, to 152 000 deaths per year by 2100)[624];
    - Flooding alone may cost EU countries up to EUR 1 trillion per year in damages by the end of the century. Most of this would be due to coastal flooding (up to EUR 961 billion). Damages from river flooding could also rise to up to EUR 112 billion compared to EUR 5 billion today, and there is considerable increase in river flood risk for Europe even under a 1.5º C warming scenario[625]. This could also affect transport infrastructure. By the end of the century, under a high warming scenario, about 200 airports and 850 seaports of different size across the EU could face the risk of inundation due to higher sea levels and extreme weather events.
- As regards agriculture, and aside from the impacts of increasing temperatures, the OECD includes four Member States (France, Spain, Italy and Greece) as countries at risk because of water shortages[626]. In a 2°C scenario before 2100, irrigated crop yields are projected to decline in most regions of Europe, with rain-fed yields depending on changes in water availability[627]. At EU level, the prolonged drought of 2018 has triggered higher CAP advanced payments and derogations from greening requirements.[628] Repeated droughts in Europe will have repercussions for climate mitigation policies: the water and carbon cycles are interlinked because $CO_2$ rates in the atmosphere increase when terrestrial water storage diminishes: major droughts may cause drastic regional reductions in land carbon sinks[629]. Drought is already ravaging Europe's soils, whose moisture shows a marked decreasing trend

[620] Report from the Commission to the European Parliament and the Council on the implementation of the EU Strategy on adaptation to climate change.

[621] In this section, the term "high emissions scenario", unless specified otherwise, refers to the IPCC's Representative Concentration Pathway (RCP) 8.5. In the RCP 8.5 scenario, greenhouse gas emissions continue to rise throughout the 21st century.

[622] JRC (2018), Climate Impacts in Europe, Final report of the JRC PESETA III project. doi:10.2760/93257. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/climate-impacts-europe

[623] Forzieri et al. (2017), Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study, https://doi.org/10.1016/S2542-5196(17)30082-7

[624] High emissions scenario, in this particular case, means scenario SRES A1B.

[625] Alfieri et al, Climate 2018, 6, 16; doi:10.3390/cli6010016: https://www.mdpi.com/2225-1154/6/1/6/pdf

[626] OECD (2017), Water Risk Hotspots for Agriculture, http://dx.doi.org/10.1787/9789264279551-en

[627] Commission Staff Working Document: Evaluation of the EU Strategy on Adaptation to Climate Change SWD(2018)461final.

[628] Commission Press release – "Commission offers further support to European farmers dealing with droughts", Brussels, 2 August 2018. http://europa.eu/rapid/press-release_IP-18-4801_en.htm

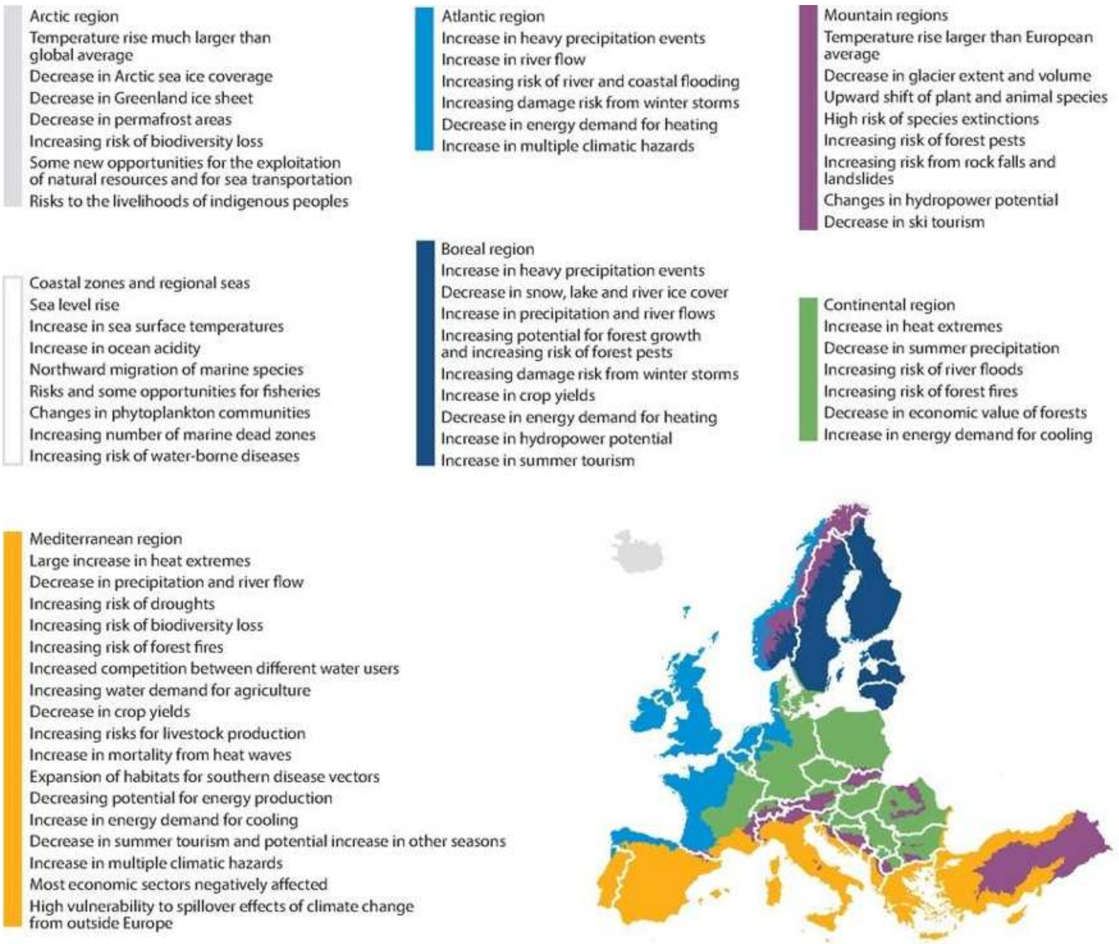
[629] Humphrey et al. (2018), Sensitivity of atmospheric $CO_2$ growth rate to observed changes in terrestrial water storage, https://doi.org/10.1038/s41586-018-0424-4

over the 1979-2017 period[630]. Furthermore, moisture decrease is a crucial factor in the ferocity and expanded reach of recent forest fires (that would jeopardise viability of forests as carbon sink).

In addition, climate-change related risks can also have implications on the assessment of medium-term inflation outlook by central banks. Recently, the European Central Bank (ECB) stated that catastrophic climate change could force the ECB to rethink its current monetary policy framework[631].

Looking at risks from a more territorial angle, evidence is mounting on the distributional effects of climate impacts across Europe. Impacts and opportunities will not be equally spread across the EU territory, as shown in the map[632] below:

**Figure 120: Risk of climate change impacts across Europe**




*Source: EEA.*

[630] Copernicus Climate Services (C3S): European State of the Climate 2017: https://climate.copernicus.eu/climate-2017-european-wet-and-dry-indicators

[631] Speech by Benoît Cœuré, Member of the Executive Board of the ECB, at a conference on "Scaling up Green Finance: The Role of Central Banks", organised by the Network for Greening the Financial System, the Deutsche Bundesbank and the Council on Economic Policies, Berlin, 8 November 2018

[632] Source: [617]

There are specific climate risks that are of major concern to some EU regions and communities. In the absence of adaptation, for instance[633]:

- While Europe as a whole will be more prone to flood risk (with mean annual river flow set to increase), water stress will be more pronounced in Southern European regions[622], and may well cause tensions between different users of dwindling reservoirs and aquifers. Under 2°C warming, median river flows in Mediterranean regions are expected to fall in all four seasons.
- Higher temperatures by the end of the century are expected to have various impacts such as a 10-15% loss in outdoor labour productivity in several Southern European countries as well as increases in heat-related mortality.
- Habitat loss and forest fires are also serious risks. 16% of the present Mediterranean climate zone (an area half the size of Italy) could become arid by the end of the century. Drier soils in the Mediterranean also increase the area prone to forest fires.
- Loss of Alpine tundra, even at 2°C could have important impacts on water regulation (including for human consumption), as well as economic impacts including in the tourism sector.
- Specific risks (e.g. hurricanes, sea level rise, extreme heat) threaten to unravel EU efforts to support its nine Outermost Regions, most of them small and isolated islands. The impacts of hurricanes Irma and Maria on the Caribbean in 2017, and notably on St-Martin, Guadeloupe and Martinique (three of the EU's outermost regions) came as a stark warning of the potential impacts such regions face.
- Big cities are more vulnerable than rural areas. They concentrate people and assets, and are thus heavily exposed to the impacts of climate change. European cities participating in the Global Covenant of Mayors are particularly vulnerable to floods and sea level rise, extreme heat, water scarcity and droughts, and extreme precipitation and storms.[634]

### *5.9.2 Mitigation and adaptation: co-benefits and trade-offs*

Measures to cut emissions can undermine resilience to climate change in certain contexts, and vice versa. On the other hand, there are adaptation measures that are also beneficial for decarbonisation (e.g. protection of certain coastal ecosystems that both tackle sea level rise and remove CO2). A recent OECD report[635] highlights that climate investments and projects must consider the links between adaptation and mitigation to minimise climate risk: the greater the perceived risks of a project, the higher the returns investors will demand, and the higher the costs passed onto end users and government sources of funding. The report provides a summary of potential synergies and trade-offs between adaptation and mitigation measures:

633 Where not otherwise specified, information provided comes from Commission Staff Working Document: Evaluation of the EU Strategy on Adaptation to Climate Change SWD(2018)461final.

634 Global Covenant of Mayors (2018), Global Aggregation Report, https://www.globalcovenantofmayors.org/wp-content/uploads/2018/09/2018_GCOM_report_web.pdf .

635 OECD (2017), Investing in Climate, Investing in Growth, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264273528-en

**Table 24: Co-benefits and trade-offs between adaptation and mitigation**

| | Positive for mitigation | Potential trade-off with mitigation |
|---|---|---|
| **Positive for adaptation** | Reduced deforestation: sequesters carbon and provides ecosystems services<br><br>Agricultural practices (e.g. no till) that can sequester carbon while boosting farmers income<br><br>Wetland restoration: carbon sequestration and reduced flood risk<br><br>Renewable energy – wind and solar: lower water use than thermal generation | Desalination: addresses water shortage but is energy intensive<br><br>Increased irrigation: helps farmers manage variable precipitation but can be energy intensive<br><br>Construction of hard defences: reduces the risk of extreme events, but greenhouse gases are embodied in the construction<br><br>Air-conditioning: reduces the impact of high temperatures and help, but is energy intensive |
| **Potential trade-off with adaptation** | Inappropriate expansion of biofuels: could exacerbate food price shocks if biofuels displace crops<br><br>Hydropower: could increase the complexity of managing water resources | N/A |

In some areas, the potential to maximise the mutual reinforcement between adaptation and mitigation should guide long-term EU efforts to decarbonise and climate-proof the economy. Examples for ecosystems, energy and cities are mentioned below.

Land and coastal ecosystems

Terrestrial and marine ecosystems globally absorb around 50% of anthropogenic emissions[636]. The rest remains for prolonged times in the atmosphere, increasing greenhouse gas concentrations and causing climate change.

This absorption capacity has its own limits. In case of oceans this uptake is associated with increased acidification, having negative impacts on marine biodiversity. In case of terrestrial ecosystems, ecosystem degradation and deforestation actually result in significant greenhouse gas emissions, while being detrimental for biodiversity. Preserving and restoring terrestrial and marine ecosystems contribute both to mitigation and adaptation (for example, they contribute to water retention, control floods and protect against erosion or air quality).

In general, the joint implementation of adaptation and mitigation strategies contribute to the health, functionality and resilience of ecosystems, and therefore improve the availability and delivering of goods and services to EU citizens. Many environmental, welfare and climate objectives may be reached simultaneously through ecosystem-based initiatives[637]. For example, marine vegetated habitats (seagrasses, salt-marshes, mangroves and others) contribute 50% of

[636] Around 50% globally, according to A. P. Ballantyne, C. B. Alden, J. B. Miller, P. P. Tans, J. W. C. White. Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. Nature, 2012; 488 (7409): 70 DOI: 10.1038/nature11299

[637] Faivre et al. 2018; https://doi.org/10.1016/j.ijdrr.2017.12.015

carbon storage in marine sediments despite occupying only 0.2% of the ocean surface globally. They reduce wave energy and raise the seafloor, and as such moderate the impacts of sea level rise and contribute to safeguard people, infrastructure, and property along coastlines[638].

Land restoration, reforestation and reduced and avoided degradation in forests, as well as rehabilitation of wetlands, contributes to and increased land use sink. Forests offer a good example of the co-benefits that can arise from coordinated adaptation and mitigation. Indeed, EU forests absorb the equivalent of just over 400 million ton $CO_2$ (see section 4.7.1), or almost 10% of total EU greenhouse gas emissions each year. At the same time, they lower temperatures, act as a buffer for hydrological extremes and purify water, which means they are also crucial in adapting to climate change. Recent case-studies in Ireland, Spain and the Czech Republic have shown that adaptation measures and good forestry practices enhance the role of forests as carbon sinks[639]. It is important to act with a long-term perspective because aging and degraded forests, agro-forestry systems and more recent forest plantations all require adaptation planning today in order to withstand a changing climate.

Energy

Due to climate change alone, and in the absence of adaptation, annual damage to Europe's critical infrastructure could increase ten-fold by the end of the century under business-and-usual scenarios[640], from the current EUR 3.4 billion to EUR 34 billion. Losses would be highest for the industry, transport, and energy. One of the greatest challenges is how to assess impacts on energy production which may occur as a consequence of the projected increase in the intensity of extreme weather events, as research gaps include economic modelling of extreme events and vulnerabilities of transmission infrastructure[641].

Impacts on renewable energy sources are of specific concern, given their critical contribution to emissions reduction. There is some evidence on impacts on hydropower production due to water scarcity, but also on wind, solar, biomass[642]. As regards hydropower in particular, the main mechanisms through which climate change can affect hydropower production are changes in river flow, evaporation, and dam safety[643]. For Europe, most studies show a positive effect of climate change impacts on hydropower for Northern Europe and a negative effect for South and Eastern Europe[643 644 645 646 647]. The extent to which climate change affects hydropower in Europe as a whole differs among the studies from almost no effect[644] to decreases of 5-10% by the end

[638] Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change, 3 (11), pp. 961-968 (2013).

[639] European Forest Institute – 2018 https://www.efi.int/publications-bank/climate-smart-forestry-mitigation-impacts-three-european-regions

[640] Forzieri et al (2018), Escalating impacts of climate extremes on critical infrastructures in Europe, Global Environmental Change 48, 97–107,

[641] Chandramowli et Felder (2014), Impact of climate change on electricity systems and markets – A review of models and forecasts, https://doi.org/10.1016/j.seta.2013.11.003

[642] See COACCH 1st synthesis report.

[643] Mideksa and Kalbekken (2010), The impact of climate change on the electricity market: A review, https://doi.org/10.1016/j.enpol.2010.02.035

[644] Hamududu and Killingtveit (2012), Assessing Climate Change Impacts on Global Hydropower, doi:10.3390/en5020305

[645] Lehner et al.,(2005), The impact of global change on the hydropower potential of Europe: a model-based analysis, https://doi.org/10.1016/j.enpol.2003.10.018

[646] Van Vliet et al,(2016), Power-generation system vulnerability and adaptation to changes in climate and water resources, https://doi.org/10.1038/nclimate2903

[647] Teotónio et al.(2017), Assessing the impacts of climate change on hydropower generation and the power sector in Portugal: A partial equilibrium approach, https://doi.org/10.1016/j.rser.2017.03.002

of the century or even before[645] [648]. Adaptation measures in hydropower production could offset these impacts in Europe on a yearly average (not for all months of the year): e.g. by increasing efficiency[646] or water storage[649]. As regards solar and wind energy, there are studies that indicate that production might be negatively affected on some regions in the EU[650] [651] [652].

Thermoelectric generation will be under more pressure in Southern European regions where their water cooling needs may no longer be met: they may generate up to 20% less under a 3ºC scenario; 15% less in a 2ºC world. [641]Thermal electricity generation may suffer most from water stress in the near term in the Mediterranean, France, Germany and Poland[653].

While the magnitude of these impacts is not expected to jeopardise Europe's long-term decarbonisation path, it may entail higher costs and different regional energy mixes, unless adaptive measures are deployed such as increased plant efficiencies, replacement of cooling systems and fuel switches[646]. Private stakeholders in the energy system and EU and national policies should reinforce the right market framework to ensure that the climate impacts do not jeopardise the EU’s stability and security of energy supply. Transitions in the electricity sector should encompass both mitigation and adaptation planning, if they are to sustain and secure a sustainable water–energy nexus in the next few decades.

Cities

The need to integrate adaptation and mitigation pathways is most apparent in the transformation of European cities. They are home to 360 million people, i.e. 73% of Europe’s population, and account for 80% of the continent’s energy consumption and for 85% of Europe’s GDP[654]. Yet, only around 40% of EU cities with more than 150.000 inhabitants have adopted adaptation plans to protect citizens from climate impacts. Globally, a 2015 OECD report recognises that, in spite of the important role local authorities have to deliver climate resilience through regulatory frameworks and incentives, “support for urban adaptation remains uneven”[615].

Trade-offs between mitigation and adaptation goals must be avoided in cities. In general, for example, densification may benefit emissions reduction (e.g. less transport needs), but can also increase vulnerability to regional climate impacts (e.g. more people and assets in less space when a flood occurs). Cities also suffer from higher temperatures than the surrounding areas, due to the concentration of built environment (“heat island effect”).

There are opportunities to optimise climate action when developing joint mitigation and adaptation in urban planning. For example, urban green spaces and green infrastructure can deliver adaptation benefits and absorb emissions and pollution. Cities will also be major clients for climate services and emerging businesses may provide solutions to city planners that combine

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[648] Chandramowli et Felder (2014), Impact of climate change on electricity systems and markets – A review of models and forecasts, https://doi.org/10.1016/j.seta.2013.11.003

[649] Berga (2016), The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review, https://doi.org/10.1016/J.ENG.2016.03.004

[650] Karnauskaset al. (2018), Southward shift of the global wind energy resource under high carbon dioxide emissions, https://doi.org/10.1038/s41561-017-0029-9

[651] Tobin et al. (2018 ), Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming, https://doi.org/10.1088/1748-9326/aab211

[652] Jerez et al. (2015), The impact of climate change on photovoltaic power generation in Europe, https://doi.org/10.1038/ncomms10014

[653] Behrens et al. (2017): Climate change and the vulnerability of electricity generation to water stress in the European Union, https://doi.org/10.1038/nenergy.2017.114

[654] HELIX - https://www.helixclimate.eu/

optimal mitigation and adaptation ideas. Cities that prioritise resilient and low-emission urban development at once will enjoy a competitive advantage and attract investments[655].

### *5.9.3 EU adaptation action in the global context*

There is a growing need to translate into policy the growing evidence about transboundary climate risks arising from climate change impacts in countries outside the EU. By definition, national vulnerability assessments tend to ignore or underestimate climate risks brought about by the global economy. Today, this is an emerging research area with few quantitative assessments and unstable terminology: the evaluation of the EU Adaptation Strategy points at the need to gather more knowledge.

In one of the few efforts to quantify cross-border impacts conveyed via trade in the EU, available only for some sectors, climate impacts in third countries conveyed through negative impact on trade flow may increase EU ”domestic” losses by up to 20%[622]. As regards climate and migration, recent findings confirm a relationship between climate change and fluctuations in asylum applications in the EU: asylum applications could increase by 28% by the end of the century (an average of 98,000 additional asylum applications per year)[656].

Lack of climate action in third countries will propagate to Europe not only via people displacement and trade, but also via financial flows and value chain disruptions. The importance of these risk pathways and the range of indirect impacts facing the EU in the future will vary depending on future socio-economic scenarios[657], as well as on the level of future climate change. Economic and climate intelligence on global value chains and trade flows will be crucial to prioritise support for the adaptive capacity of fragile partners[658].

In recognition of these transboundary effects of climate change, the EU's external policy has embraced climate diplomacy and recognised the need to provide structural, long-term but flexible approaches to climate resilience, especially to its most vulnerable partners such as Small Island Developing States (SIDS) and Least Developed Countries (LDCs). In the 2016 Global Strategy[659], the EU recognises climate change as a global challenge because climate-induced fragility in EU partners exacerbates conflicts and undermines Europe's security.

In developing countries, adaptive capacity determines the degree to which decarbonisation can make progress. The Paris Agreement established a global goal on adaptation in parallel to mitigation responding to the increasing demands from developing countries to support climate change resilience as a component of sustainable development: as a bottom line from which to cut their emissions as they catch up with the developed world. Both adaptation and mitigation will be part of Paris' ambition cycle as of 2023 and the EU, as a party, will be reporting on progress to make both pillars of climate action mutually reinforcing and synergetic.

The EU balances adaptation and mitigation through climate action mainstreaming into development and cooperation programmes with partner countries. In particular, this relates to the programmes on energy, agriculture, infrastructure, water, forestry and disaster risk reduction. The budget allocated to interventions focusing on adaptation accounted for slightly more than half of the EU external cooperation spending on climate change over the period 2014-2017.

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655 E3G (2014), "Underfunded, underprepared, underwater? Cities at risk".

656 Missirian et al.(2017), Asylum applications respond to temperature fluctuations, Science 358, 1610–1614 (2017), DOI: 10.1126/science.aao0432

657 also known as shared socio-economic Pathways (SSPs) under the IPCC nomenclature.

658 For instance third countries with which the EU has signed trade agreements http://ec.europa.eu/trade/policy/countries-and-regions/negotiations-and-agreements/

659 EU's global strategy: *Shared Vision, Common Actions* (EU, 2016).

# 6 ROLE OF DIFFERENT ACTORS IN THE ACHIEVEMENT OF LOW CARBON AND ENERGY TRANSFORMATION PATHWAYS

## 6.1 Role of Member States

National Governments have a crucial role to play in the low carbon and energy transition. Implementing the acquis as described in section 2.3.1, requires Member States to make key decisions with respect to security of supply, network infrastructure, energy efficiency and renewable energy policies as well as research and innovation. Moreover, they need to decide on their energy mix and enter regional cooperation. Circumstances are thus different in Member States, with sectoral composition, existing infrastructure and economic development all different in the EU's Member States. To prepare for an orderly transition it is also important that national Governments develop their long term strategy and engage with all relevant stakeholders.

This is also recognised by the Paris Agreement which asks all Parties to communicate, by 2020, their mid-century, long-term low GHG emission development strategies.

The Governance of the Energy Union and Climate Action Regulation asks the Commission to prepare by early 2019 a proposal for a Union long-term strategy, and for Member States to submit by 1 January 2020 their long-term strategies.

Against this background, the Commission's decision to present already in 2018 the proposal for the European Long Term Strategy is based on its wish to lead by example as regards the preparatory process, entailing a wide stakeholder consultation, development of a robust analytical framework and assessment of a broad range of credible pathways for the entire economy, and, subsequently, to allow a comprehensive and inclusive debate on its proposal. This would also allow considering the positions and visions of all Member States before delivering the final EU strategy to the UNFCCC. Therefore, the adoption of the proposal for the EU LTS by the Commission should not be seen as the end of a process but a beginning of the road towards the submission of the EU LTS to the UNFCCC by 2020.

Several Member States signed the declaration[660] to achieve net zero emissions at latest in 2050 pushing for an ambitious approach in the Commission's proposal. Some Member States have already delivered their national LTS to the UNFCCC, some work intensively on them so they will be well positioned to discuss the Commission's proposal.

The Governance of the Energy Union and Climate Action Regulation asks the Commission to take into account the Member States' draft National Energy and Climate Plans (NECPs) and foresees the need for ensuring consistency between National Energy and Climate Plans (NECPs) and the national LTS.

With national draft plans still under development, this assessment already incorporates in its baseline the collective targets for 2030 foreseen in the Governance of the Energy Union and Climate Action Regulation. The 2030 national objectives set in the Plans will play a key role for the national LTS and vice versa and the long term decarbonisation perspective will play a key role for the NECPs. The requirements in the Governance Regulation of public participation and consultation as regards both the national plans and the long-term strategies should ensure that local and regional actors are involved in their development, contributing to the broad acceptance

[660] Green Growth Group (2018): Common statement on the long-term strategy and the climate ambition of the EU. https://www.ecologique-solidaire.gouv.fr/sites/default/files/2018.06.25_statement_ggg_climat.pdf

of the NECPs and the national LTS. Also, both Governance and UNFCCC processes will interlink and influence each other in the future through updates.

## 6.2 Role of regional and local authorities

Today, 75.6% of the EU28 population live in urban areas (cities and towns and suburbs) and that proportion is expected to remain largely stable until 2050. City governments have therefore a particular, important and increasing role to play in implementing and enforcing climate mitigation and adaptation policies. Urban resource planning can lead to cities that are environmentally-friendly, energy-efficient, encourage low-carbon forms of mobility – notably walking and cycling – and are more resilient to climate-induced hazards[661]. The EU encourages them to engage in long-term planning exercises, such as through the Covenant of Mayors[662], and many have started these processes[663]. Cities such as Copenhagen, Paris, Stockholm and London[664] are taking bold climate action. For instance, they have pledged, together with 14 cities of the C40 network of world megacities[665], to "enact regulations and/or planning policy to ensure new buildings operate at net zero carbon by 2030 and all buildings by 2050". Through the Urban Agenda for the EU, Partnerships on Climate Adaptation and Energy Transition, city governments are also encouraged to implement joint actions tackling the climate and energy challenge."

Local and regional authorities also play a pivotal role in achieving the Energy Union objectives. The Governance of the Energy Union and Climate Action Regulation facilitates the involvement of all governance levels in addressing energy and climate policies by creating a permanent Multilevel Climate and Energy Dialogue in Member States: European cities and regions have proven to be important delivery agents for the European transition towards a more decentralised, energy-efficient, decarbonised and resilient energy system. A permanent and regular dialogue on climate and energy among all levels of governance and relevant stakeholders will deliver various benefits: continuous political support, ownership, feedback loops, shared responsibility as well as a better implementation of the necessary actions.

[661] UNEP, IRP (2018), The Weight of Cities Resource Requirements of Future Urbanization, http://www.resourcepanel.org/reports/weight-cities
[662] https://www.covenantofmayors.eu/
[663] In a 2015 DG ENER/Committee of Regions survey of Covenant cities 84% of the 836 respondents called for a long term targets for the initiative. Of these 48% preferred the 80-95% GHG reductions by 2050, circa 25% carbon neutrality, 5% other targets and 23% did not specify.
[664] https://www.eceee.org/all-news/news/news-2018/c40-cities-targets-net-zero-carbon-buildings-by-2030/
[665] https://www.c40.org/

**The Covenant of Mayors for Climate and Energy**

Covenant of Mayors for Climate and Energy (launched in 2008) has grown into the world's largest voluntary movement of over 9000 municipalities committed to meet or exceed the EU GHG mitigation targets, to improve their resilience against negative effects of climate change as well as to promote access to sustainable energy. Cities voluntarily commit to develop local strategies and plans on mitigation and adaptation in order to implement the EU climate and energy targets and accept accountability for progress. The cities in the Covenant of Mayors provide also a channel to deploy innovative energy transition solutions tested under the Smart Cities and Communities programme. The participatory process underpinning these initiatives as well as e.g. local energy communities makes it easier to win public support for the transition and deriving projects such as new infrastructure.

After gradual expansion to over 50 countries, the Covenant of Mayors and a similar initiative, the Compact of Mayors merged in 2016 to create the Global Covenant of Mayors for Climate and Energy. This initiative, strongly supported by the Commission, has enabled building strategic alliances and partnership for a bottom-up transition to a global low-carbon and climate-resilient economy, keeping the momentum to meet the goals of the Paris Agreement and the sustainable development goals at the core of the 2030 Agenda.

The proposal for the next multiannual financial framework (MFF) of the EU makes an ambitious commitment for climate mainstreaming across all programmes, with a target of 25%, which will help spending a significant part of the proposed budget of the regional and cohesion policy on climate objectives. In this context, information and access to the EU funding for local level, for example, through the new Urban Investment Support service URBIS, and creation of regional investment advisory hubs can further increase cities' capacity to mobilise investments for the clean energy transition. Furthermore, the share of EU funding directly available for municipalities is proposed to increase under the Urban Agenda cohesion policy proposal for the next programming period 2021-2027 as the urban earmarking under the European Regional Development Fund is increased from 5% in the current period to 6% in the next period in light of the encouraging results of this type of activities.

Going forward, there are several areas that will require further attention:

- In terms of governance, cities in countries where local climate plans are compulsory (e.g. Denmark, France, Slovakia and the UK) are about twice more likely to have a mitigation plan and about five times more likely to have an adaptation plan than cities in other EU countries[666]. This indicates that national binding requirements are more effective than voluntary schemes to develop local climate plans.
- There are remaining data limitations and gaps on local emission inventories, climate mitigation and reporting, needed to facilitate local quantitative assessment exercises – which would also closely need to link to adaptation planning.
- National plans are likely to be more successful if the planning and implementation capacity of regional and local governments has been taken into account.
- Awareness and quantification of the co-benefits (e.g. health, clean air, environment) of fighting climate change are important to stimulate the cross-sectorial transition described above.

[666] D. Reckien et al., How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28, Journal of Cleaner Production, 26 March 2018, https://www.sciencedirect.com/science/article/pii/S0959652618308977?via%3Dihub

To support local authorities in making the most of the opportunities and challenges of the transition, national and EU initiatives and policies are clearly of importance. They cover a wide range such as how National Energy and Climate Plans are developed, what national initiatives and legislation exist regarding local planning for climate mitigation and adaptation action, capacity building initiatives, emission data availability allowing cities to make own emission inventories, initiatives regarding access to finance and fiscal and economic policies including those that are addressing environmental externalities such as air pollution.

## 6.3 Role of business and civil society

Achieving the EU's climate and energy objectives will require contributions from every part of the economy and from individual citizens. Hence the policy process at all levels of the society is key to regulate and achieve that change. In preparation for the EU's long-term GHG emissions reduction strategy, the Commission has carried out a public consultation in the summer of 2018, seeking input from all stakeholders (see section 7.1). Strong public participation and ownership will not only help accelerate the implementation of current commitments in the EU, but can also help strengthen global efforts in the short, medium and long term.

Non-state initiatives have increased significantly but the magnitude of their impact remains difficult to quantify. Quantification of impacts depends on the baseline chosen, the methodology for assessing additionality or overlaps of voluntary actions with policies, and the assumptions made about the future scaling up of effort or membership. For instance UN Environment Gap Report assessed additional emissions reductions made so far by non-state actors: in the order of 0.2-0.7 $GtCO_2$ per year by 2030 compared to full NDC implementation[667]. It estimates that international climate initiatives involving state and non-state actors could materially contribute to greenhouse gas reductions, going much beyond the NDCs. As a share, most global voluntary initiatives are taking place in Europe, with a focus on the core sectors of transport, energy efficiency and agriculture. These are key for the deep decarbonisation envisaged under the Paris Agreement.

Some businesses have started taking action in identifying their own pathways to reach emissions reduction of 80%, 95% or full GHG neutrality. As part of the open public consultation (see section 7.1), different sectors provided their own analyses for change. For instance, power sector organisations propose ambitious pathways leading to full decarbonisation, industry sector organisations focus on the role of alternative fuels, transport and residential sectors on energy efficiency improvements. They also shed light on new technologies.

With a view to the future, the practice of preparing such plans needs to be taken up by more business of all sizes and from various sectors. These plans should clearly identify the opportunities and provide sectoral knowledge, e.g. on which disruptive technologies they expect to become economically viable and within what timeframes. This will help governments and fill data limitations and gaps, open possibilities for measuring and reporting the impact of voluntary climate action, while also helping direct sustainable finance and ensuring targeted investments in innovation and competitiveness.

Civil society will need to continue increasing its role of creating awareness among citizens about long-term decarbonisation, including action that can be taken at individual level and lifestyle choices that each citizen can make. It plays a unique role in providing best practice examples and holding businesses and other non-state actors accountable to their commitments and to avoid greenwashing. Civil society organisations have already come forward to support countries, local governments and businesses to come up with and understand long-term plans, even beyond 2050. Examples for this are a number of tools released by for instance the 2050 Pathways initiative[668] or WWF's LIFE-Maximiser project[669]. Synergies between civil society, enterprises and public authorities already exist. For example, according to the Eurostat Community Innovation Survey 2014[670], the main driver of eco-innovation ("innovation with environmental benefits") was companies' reputation, before costs of energy and raw materials and regulation. This means that enterprises are aware about citizens' concerns about climate and environmental issues and actually take action to adapt to customers' requests and to be (or seem) more friendly to the climate and the environment For instance, as part of the open public consultation, respondents anticipated mobility in people's daily life to see the biggest change to address climate change (see section 7.1). Public authorities contribute to this virtuous circle by providing transparency tools (e.g. eco-labels) that empower citizens and committed enterprises.

**Overcoming obstacles for non-state climate action and long-term planning**

In order to encourage climate action from non-state actors, states can help them overcome the most common challenges they face, in particular when they are volunteering to do more than is required by regulators. The key obstacles identified globally (UNFCCC, 2017[671]), but also applicable to Europe, include the lack of access to funding, recognition, organisational capacities and knowledge.

An important contribution governments can make is to set the enabling environments (that for example explicitly acknowledge the partnership principle) as well as long-term plans and visions that provide certainty and allow non-state actors to make ambitious decisions.

Governments can thus create the conditions for non-state action to prosper, by developing regulatory frameworks, by facilitating access to finance, by providing systems for reporting and tracking and by providing visibility to the climate and energy action that is achieved.

Working together, learning from each other and scaling up successful approaches, are essential. Targeted programs or platforms for different sectors are good practice for enabling and creating relevant knowledge and organisational capacity. Strengthening these platforms, promoting the cooperation between stakeholders and the sharing of experiences are crucial to accelerate and scale up climate action.

The need for non-state action to be recognised and promoted can be addressed, by reporting schemes that may also provide access to further opportunities and investments, but also through individual award schemes, highlighting the successes of frontrunners.

[668] https://www.2050pathways.org

[669] http://www.maximiser.eu

[670] Eurostat (2014), Community Innovation Survey 2014, https://ec.europa.eu/eurostat/web/microdata/community-innovation-survey

[671] UNFCCC (2017), Yearbook of Global Climate Action 2017, p. 28

# 7 ANNEXES

## 7.1 Synopsis report on consultation activities

Following the invitation by the European Council in March 2018 and a similar request by the European Parliament to present "a proposal for a strategy for long-term EU greenhouse gas emissions reduction in accordance with the Paris Agreement" the Commission has undertaken several stakeholder consultation actions.

A 12-week online survey analysed in the sections below was held as well as a two-day high-level stakeholder consultation event held in Brussels in July 2018 (analysed in section 7.1.6). A number of position papers were also received (analysed in section 7.1.5). All types of stakeholders were invited to participate in the consultation.

These activities aimed at collecting views and opinions on the technological and socio-economic pathways that should be explored for a long-term EU greenhouse gas emissions reduction strategy, as well at gathering factual information, data and knowledge, including drivers, opportunities and challenges relevant in the context of the long-term strategy.

### *7.1.1 Methodology and tools of analysis of the online public consultation*

The open public consultation (OPC) consisted of a questionnaire of 74 questions uploaded on the EU Survey Platform[672] . All citizens and organisations were welcome to participate. The public consultation was open from July 17th 2018 to October 9th 2018.

The responses were checked for coordinated groups of responses, being identical or very similar in key aspects. Four such coordinated groups of responses were detected: (1) of 4 individuals in Germany with links to the land-use sector; (2) of 4 organisations in the petroleum and fuels sector in Spain and Portugal; (3) of 9 respondents including individuals and two NGOs; and, (4) of 4 individual respondents from the same NGO. In the context of the number of responses (2805), these are not judged to have a significant influence on the results.

The results are quantitatively analysed in the following sections. For each question analysed, the number of respondents (n) is indicated [n=x]. Open questions were analysed using a keyword coding based approach. By determining key issues and words raised in responses, grouping these by themes and translating and searching for these in all languages, the frequency of the issue could be identified.

In this report references are made to the questions in the Open Public Consultation questionnaire, these are included as [PCXX], with XX representing the question number in the questionnaire.

References are also made to a category of respondents named 'Private enterprise, professions, trade and business associations'. This category represents the combined responses from three groups of respondents in the OPC survey, namely: (1) Private enterprise; (2) Professional consultancy, law firm, self-employed consultant; and, (3) Trade, business or professional association.

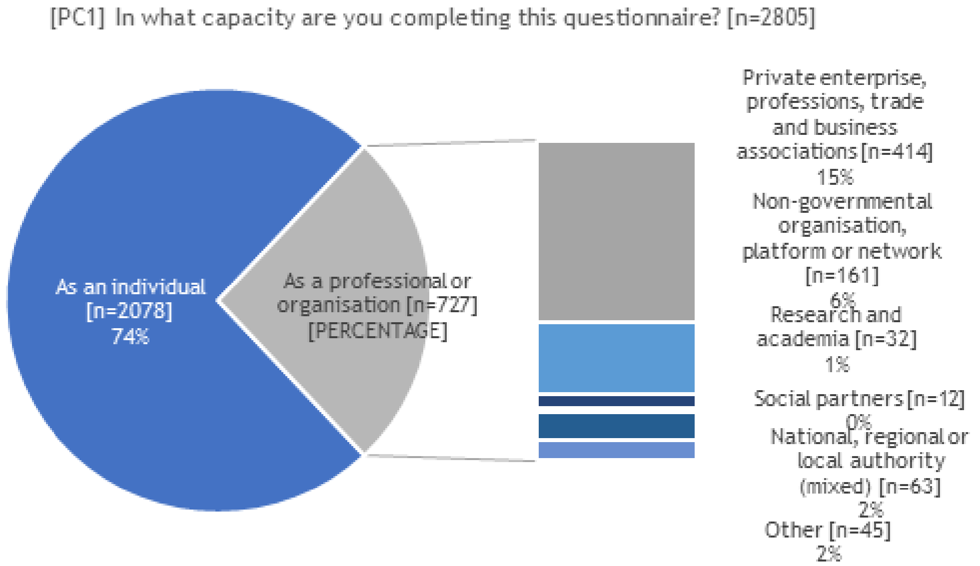
### *7.1.2 Type and number of stakeholders participating in the online public consultation*

The aim of the public consultation was to gather feedback from the general public regarding the EU's long-term strategy for the reduction of greenhouse gas emissions. In total, 2 805

[672] https://ec.europa.eu/clima/consultations/strategy-long-term-eu-greenhouse-gas-emissions-reductions_en

respondents replied to the survey. Figure 121 shows the split of respondents per category (individuals vs. professionals, organisations) and per stakeholder group.

**Figure** 121: Type of stakeholders in the public consultation




*Source: Open Public Consultation.*

With regards to geographic coverage, respondents covered 27 of the 28 EU Member States. The countries with the highest response rate were Germany, Belgium and Spain. In addition to the EU respondents, there were also 82 respondents that identified themselves as non-EU.

### *7.1.3 Main results on the general stakeholder opinion on long-term reduction of greenhouse gases and the Paris Agreement*

The following section outlines the main results and key messages as provided by the respondents under each section of the survey. An extensive report on the public consultation covering all questions is also to be published[673].

Respondents were asked [PC11] how much the EU should contribute to achieving the Paris Agreement objectives (with a view towards 2050). More than half of the respondents, both individuals and organisations, considered that the EU should already achieve a balance between emissions and removals in the EU by 2050 (see views by respondent type in Table 21).

Of the 13 EU Member States[674] that responded to the consultation either through the OPC questionnaire or through a position paper, ten had a position on this subject, two were in favour of 80% reductions, two for 80-95% reductions and six for a balance in emissions (net zero) by 2050.

[673] https://ec.europa.eu/clima/policies/strategies/2050_en

[674] On behalf of the Member State or a national government entity

**Table 25: General stakeholder opinion on the EU's contribution to the Paris Agreement objectives, per respondent type**

| Respondent type | Reduce greenhouse gas emissions in the EU by 80% by 2050 compared to 1990 levels | Reduce greenhouse gas emissions in the EU more, within the range of 80 to 95% by 2050 compared to 1990 levels | Achieve already a balance between emissions and removals in the EU by 2050 |
|---|---|---|---|
| as an individual in your personal capacity [n=2024] | 16% | 32% | 53% |
| in your professional capacity or on behalf of an organisation [n=612] | 16% | 31% | 54% |
| *Of which:* | | | |
| Private enterprise, professions, trade and business associations [n=332] | 20% | 37% | 43% |
| Non-governmental organisation, platform or network [n=146] | 5% | 18% | 77% |
| Research and academia [n=30] | 17% | 20% | 63% |
| Social partners [n=12] | 17% | 42% | 42% |
| *Of which:* Trade unions [n=6] | 17% | 33% | 50% |
| National, regional or local authority (mixed) [n=55] | 18% | 29% | 53% |
| Other [n=37] | 16% | 30% | 54% |

*Source: Open Public Consultation.*

### *7.1.4 Summary and key messages of sector/issue specific questions*

#### 7.1.4.1 The low-carbon transition from the consumer perspective

Given the important role of consumer choices in decarbonising the economy, respondents were asked a set of questions in this section regarding how they expect their daily lives will be affected by the transition to a low-carbon economy and their willingness to adopt certain new technologies. The questions covered topics such as housing, waste generation, transport and the consumption of goods and services.

Many respondents (56%) expect the largest changes in the daily lives of consumers to be related to mobility.

Several questions in the open public consultation addressed the issue of mobility. The main findings include:

- When asked about purchasing a vehicle that does not run on petrol or diesel, more than two thirds of respondents supported this option (some supported the option only if sufficient refuelling infrastructure were available).
- 80% of respondents would consider using car-sharing services – including if an easy-to-use and affordable service were in place.
- Many respondents would also consider avoiding private cars for short trips and opt for public transport (47%), but some respondents highlight the importance of accessibility and regularity of service (43%).
- Another alternative presented to respondents for short trips were (electric) bikes and other active mobility modes – 58% of respondents would consider using such alternatives and one third would consider using such alternatives if proper bike lanes were in place.
- With respect to longer distances, respondents were asked whether they would consider avoiding flights or cars whenever alternatives were available. Over 80% of respondents agreed (out of which a large majority only agreed if a convenient alternative was available).
- When respondents were asked whether better urban planning would reduce the use of private cars and reduce congestion in urban areas, some 60% agreed but highlighted the importance of combining urban planning with better public transport.
- Finally, more than half of the stakeholders expected that IT tools would reduce mobility needs to some extent.

When asked about different ways of reducing energy consumption and related $CO_2$ emissions in buildings, many respondents expected the following measures to be of priority: improving the energy performance of buildings through insulation, triple glazing, installing heating and water boilers that run on renewables, installing heating and cooling equipment and using electrical appliances with the best energy performance label and buying carbon free electricity or generating their own renewable energy.

On the topic of waste separation, almost all respondents stated that they sort their waste; and a considerable share of respondents (54%) mentioned that adapted infrastructure and financial incentives would improve the rate of people that separate their waste.

When questioned about the importance of raising awareness about the impact of food consumption on the climate, almost all respondents agreed that this was important. Furthermore, a large majority of respondents (over 80%) stated that they would consider the impact of their food purchases on greenhouse gas emissions (out of which an important share would consider their impact if the necessary information was available); and many respondents (74%) would consider changing their diets.

Respondents were also concerned about the environmental impact of their decisions when buying products or services. 55% of respondents stated that they consider the impact of such decisions but that they often lack the necessary information to assess the impact. Even a higher share of the respondents (79%) considered it important to buy products and services from companies that produce goods and services in a greenhouse gas neutral manner.

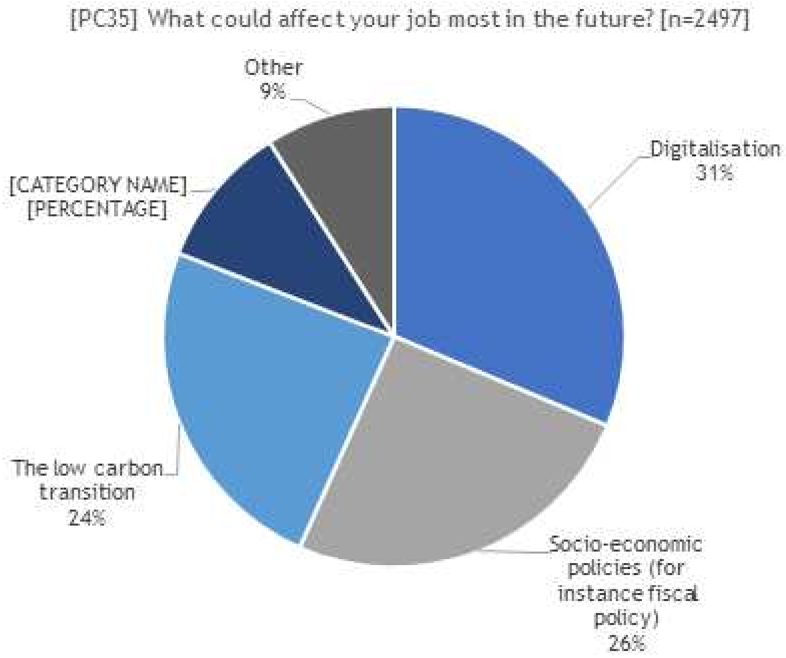
7.1.4.2 Expectations and opinions on changes in work and the economy

*Employment and a socially fair transition* `

Stakeholders were asked about the effect of the low carbon transition on employment. There was an almost equal split between respondents that expected the transition would create jobs and respondents that either had no opinion or did not know what the effect of the transition would be.

When asked about the factors or trends that could affect jobs most in the future, the highest ranked factor overall was 'digitalisation' followed by 'socio-economic policies' and 'the low-carbon transition'(see Figure 122). Those responding in their professional capacity or on behalf of an organization put a stronger emphasis on the low-carbon transition (45%) than those replying in their individual capacity (18%).

**Figure 122: Stakeholder opinion on the factors and/or trends that will affect jobs in the future [only one answer possible]**



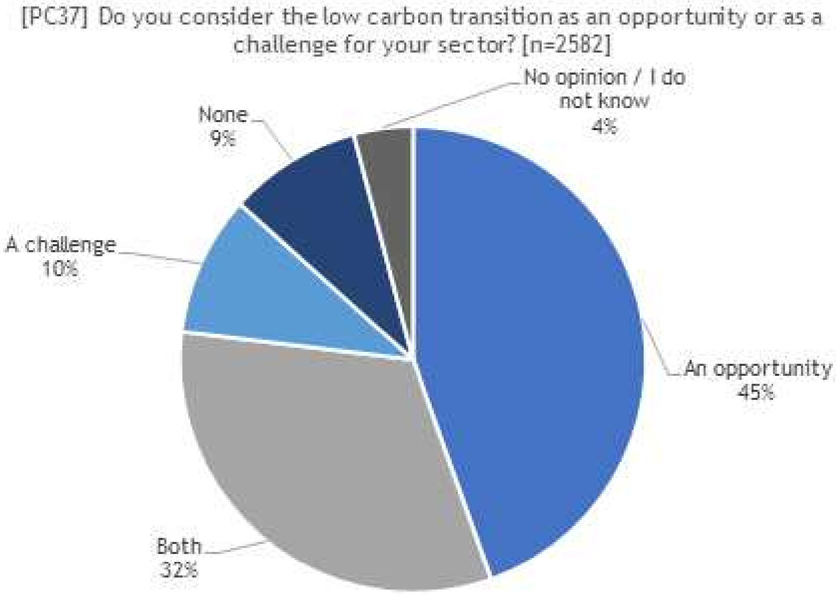

*Source: Open Public Consultation.*

When asked whether they or their sectors would benefit from training in the context of the energy and low-carbon transformation, 40% of respondents fully agreed with the benefits of training and close to 40% of respondents expected that training would be beneficial to some extent.

*The impact on the low-carbon transition on certain sectors*

Around 45% of respondents expect that the low-carbon transition represents an opportunity for their sector and some 10% considered the transition to be a challenge (see Figure 123). Non-governmental organisations and research and academia considered the transition as an opportunity to a larger extent than private enterprises, professions, trade and business associations where a majority perceived it as both an opportunity or a challenge.

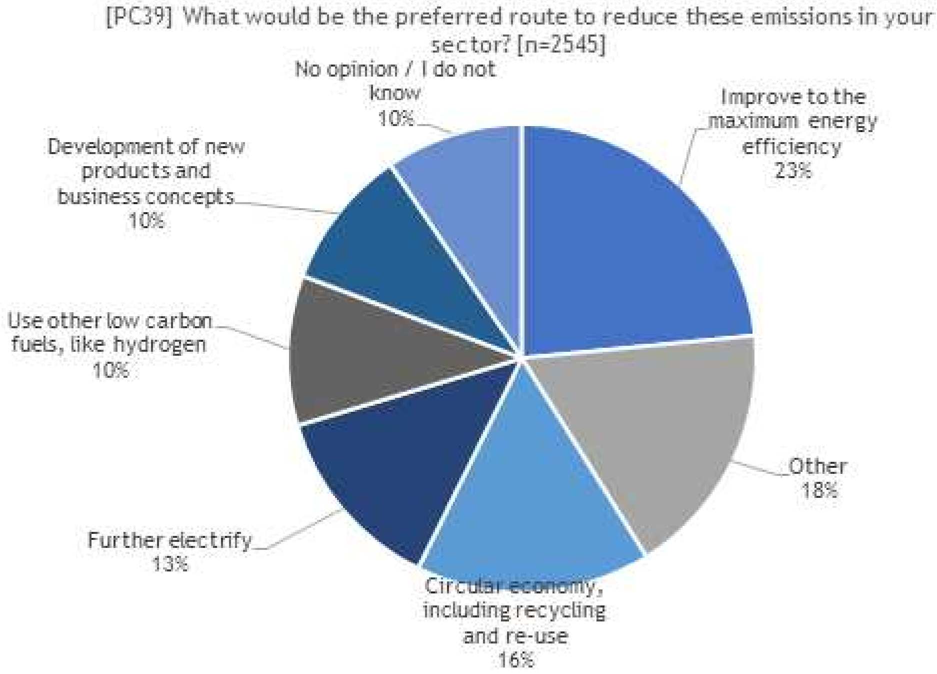
**Figure 123: Stakeholder opinion on whether the low-carbon transition represents an opportunity or a challenge**




*Source: Open Public Consultation.*

When asked about the potential of their sector to reduce greenhouse gas emissions by 2050, close to half of respondents said that their sector could reduce emissions by more than half or entirely. Moreover, when asked how their sector could potentially reduce greenhouse gas emissions, over 20% of respondents expected that this could be achieved through improved energy efficiency. Others expected that the circular economy, further electrification, low carbon fuels (like hydrogen), and new products and business concepts could help (see Figure 124). In addition, many respondents (40%) expected that they (or their sector) will invest in innovative low-carbon technologies as a priority.

**Figure 124: Stakeholder opinion on the means to achieving greenhouse gas emission reduction**

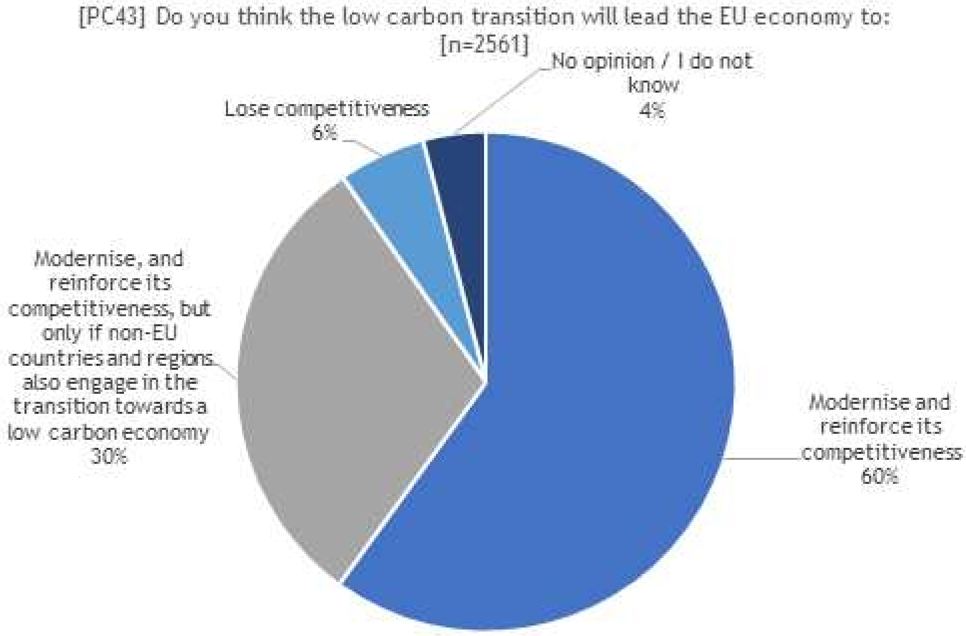



*Source: Open Public Consultation.*

On further integrating their sectors with other sectors in order to decrease emissions and increase efficiency, around 40% expected that this was possible and a similar proportion had no opinion or did not know. The respondent group with the highest proportion (75%) expecting that further integration would help was in the private enterprises, professions, trade and business organisations group.

Many respondents (60%) expected the low-carbon transition to modernise and reinforce the competitiveness of the EU, while close to a third of stakeholders expected this to happen only if non-EU countries and regions also engage in the low-carbon transition (see Figure 125). Stakeholders belonging to the non-governmental organization, platform or network category were the most positive to the low-carbon transition for modernization and competitiveness in general (82%), whereas private enterprises, professions, trade and business organisations (48%) emphasized the need for non-EU countries and regions to also engage in the low-carbon transition.

**Figure 125: Stakeholder opinion on the impact of the low-carbon transition on EU competitiveness**




*Source: Open Public Consultation.*

Regarding the impact of the low-carbon transition on EU modernisation and growth, more than half of the respondents expected the transition to help the EU modernise and grow. An additional 21% of respondents expect this to happen in case of public support and 19% in case of non-EU countries and regions engagement in the transition.

Stakeholders were also asked, in an open question format, '[PC45]: How can opportunities and challenges (in particular related to carbon intensive sectors or regions) be addressed? What key economic transformations should the EU pursue to achieve a low carbon and resilient economy?'. In total, n=1 523 responses were received.

- Energy was raised by n=1 018 (67%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Renewable energy (as part of a clean or green energy system) [n=378] represented an opportunity for EU industry but also a challenge in terms of scaling up renewable energy rapidly, while many respondents agreed on the need to phase out fossil fuels [n=322]. Other themes raised included energy efficiency in buildings and the importance of smart grids and energy storage.
- Mobility and transport emissions were raised by n=759 (50%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Cars and road transport [n=285] were perceived almost equally as an opportunity (cleaner air) and challenge (to reduce the use of individual vehicles), clearly linked to the need to expand and improve public transport [n=210]. Other issues raised included electrification of transport (including the necessity to provide sufficient charging infrastructure), the need for improved cycling infrastructure and fuelling infrastructure for alternative fuels (such as hydrogen).
- Public policy related issues were raised by n=1 448 (95%) respondents, therefore almost every respondent saw some role for government action, with a variety of related issues. Respondents expressed strong opinions on taxes (carbon), pricing (Emissions Trading System) and fiscal policy, including subsidies [n=567], the majority arguing that policy

should create an enabling market framework to promote the clean energy transition. Public investment [n=498] was considered an opportunity to support research and development, but also a challenge in terms of picking ‘picking winners’. Other issues raised included the role of planning and spatial policy.

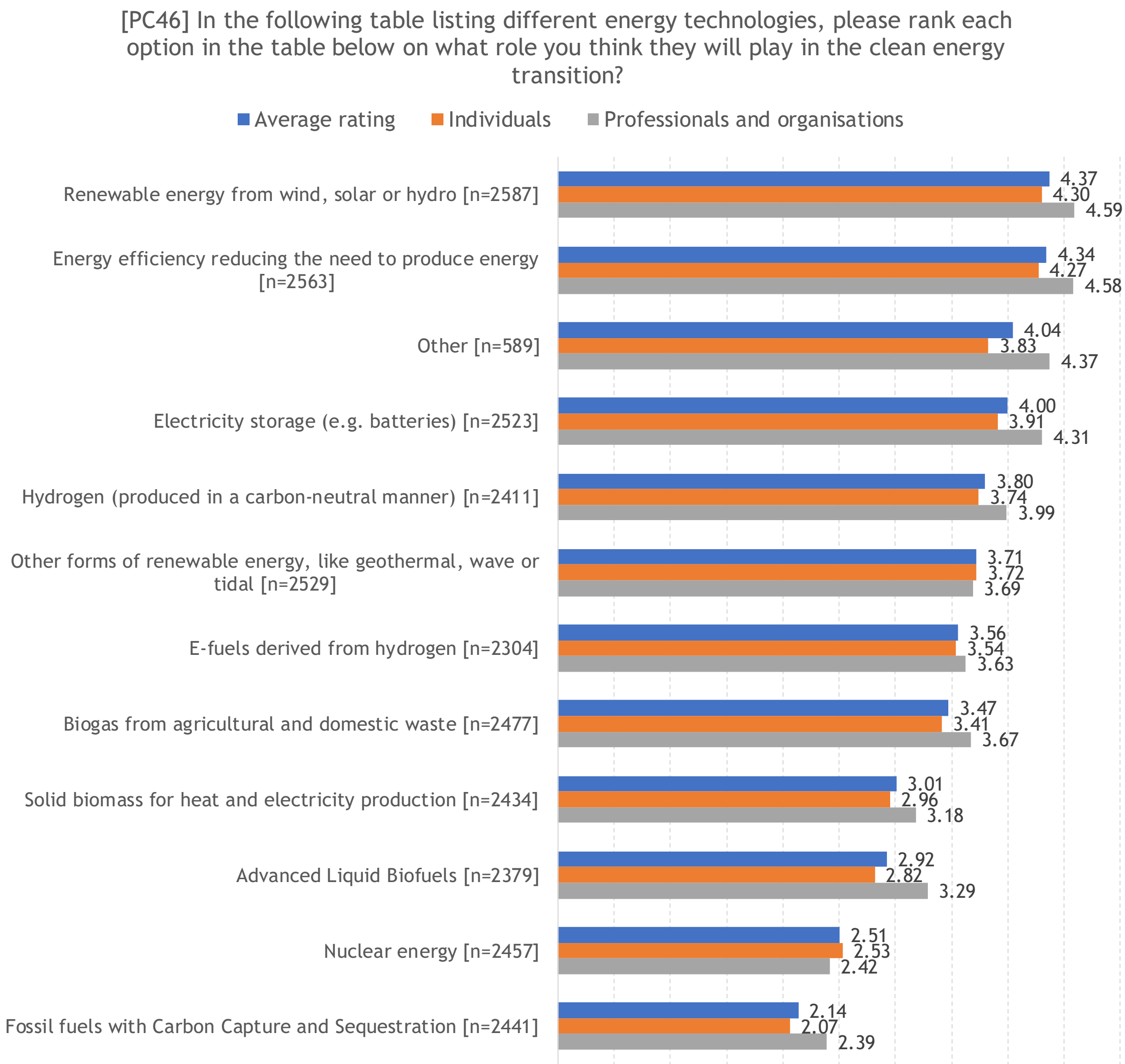
- Specific emissions related issues were raised by n=404 (27%) respondents, with carbon capture, storage, use and/or removal, particularly through forestry, identified as the most important issue among this group [n=135 respondents].
- Specific economic sectors were identified by n=913 (60%) respondents with a variety of sectors singled out, sometimes perceived as both opportunities and challenges. Waste management, recycling, re-use and circularity in practice [n=274] was perceived as an opportunity to move towards a circular economy, while sustainable production [n=196] was perceived as an essential need for industry, many identifying that sustainability should be introduced at the product design stage (low energy use, recyclability, durability).
- Paradigm shift (such as major changes to production or consumption patterns) was identified as a key factor by n=997 (65%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Economic models – encompassing sustainable consumption and production, circular and life cycle thinking [n=843] were raised by many respondents, such as challenging the concept of infinite growth. Consumer behaviour [n=358] was identified as important, representing both a challenge and opportunity to modify consumer behaviour by improving awareness and understanding on climate impacts.

#### 7.1.4.3 Expectations and opinions on the future of the energy system

When asked to rank[675] the importance of energy technologies in the clean energy transition, respondents indicated that renewable energy was the most preferred technology with the highest average rating of 4.37 (see the average rating, including the ranking of technologies in Figure 126). The least important role was envisaged for fossil fuels with carbon capture and sequestration with the lowest average rating of 2.14.

[675] In the survey, respondents were asked to rank each technology on a scale of 1 (important) to 5 (not important). For the scope of this analysis, the ranking system was inversed for ease of readability. The technologies with the highest average rating (or score) are therefore the most important technologies and the ones with the lowest average rating (or score) are the least important.

**Figure 126 : Stakeholder ranking of energy technologies (from 1 (not important) to 5 (important))**




*Source: Open Public Consultation.*

Finally, respondents were requested to answer, in an open question format, the following questions: [PC47] 'What are the biggest opportunities, including for the wider economy? What are the biggest challenges, including as regards public acceptance or the availability of land and natural resources, related to these future developments?'

- Energy was raised by n=1031 (76%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Renewable energy (as part of a clean or green energy system) [n=455] was perceived as representing an opportunity to create new jobs but also a challenge in terms of its intermittency, while energy efficiency [n=376] was predominantly regarded as an opportunity, such as balancing increased energy demand and reducing energy costs. Other issues raised included energy storage, smart grids and energy cost and affordability. On balance respondents tended to perceive these as opportunities but with challenges to their implementation.
- Mobility and transport were raised by n=470 (35%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Electric vehicles are generally

seen as an opportunity to reduce noise and air pollution, but also a challenge in ensuring the sustainability of the source of the electricity, many respondents also seeing the mobility sector as a challenging sector to decarbonise, especially with regards to aviation and shipping.

- Education and research related issues were raised by n=575 (43%) respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Innovation and research [n=359] was perceived as an opportunity to create new jobs and growth, but also a challenge in terms of investment needs. Funding and investment [n=221] was expected to be a challenge in terms of mobilising sufficient funding from both public and private sources. Opportunities were noted for the European Investment Bank and the European Investment and Structural Funds to invest in research and infrastructure projects. Other issues raised included acceptance and human adaptability, and education and public awareness.

- Public policy related issues were raised by 93% [n=1253] respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Taxes and fiscal policy, including subsidies [n=314] was perceived as an opportunity to shift production and consumption patterns (tax reform) but also a challenge in terms of fossil fuel subsidies distorting competition. Public investment – including in research and development (R&D) [n=278] was perceived as an opportunity to leverage private investments and support investments in key infrastructure, whilst it was also viewed as a challenge in terms of the overall cost of the investments needed

- Issues relating to the wider economy were identified by 54% of respondents [n=731], with a variety of sectors singled out, sometimes perceived as both opportunities and challenges. Sustainable production [n=503] was perceived as an opportunity to stimulate a circular economy, but also a challenge in terms of incentivising companies and industries to change production patterns. Trade and economic growth [n=402] was perceived as an opportunity for strengthening European competitiveness globally (by developing new technologies) but also entailing challenges related to international competition.

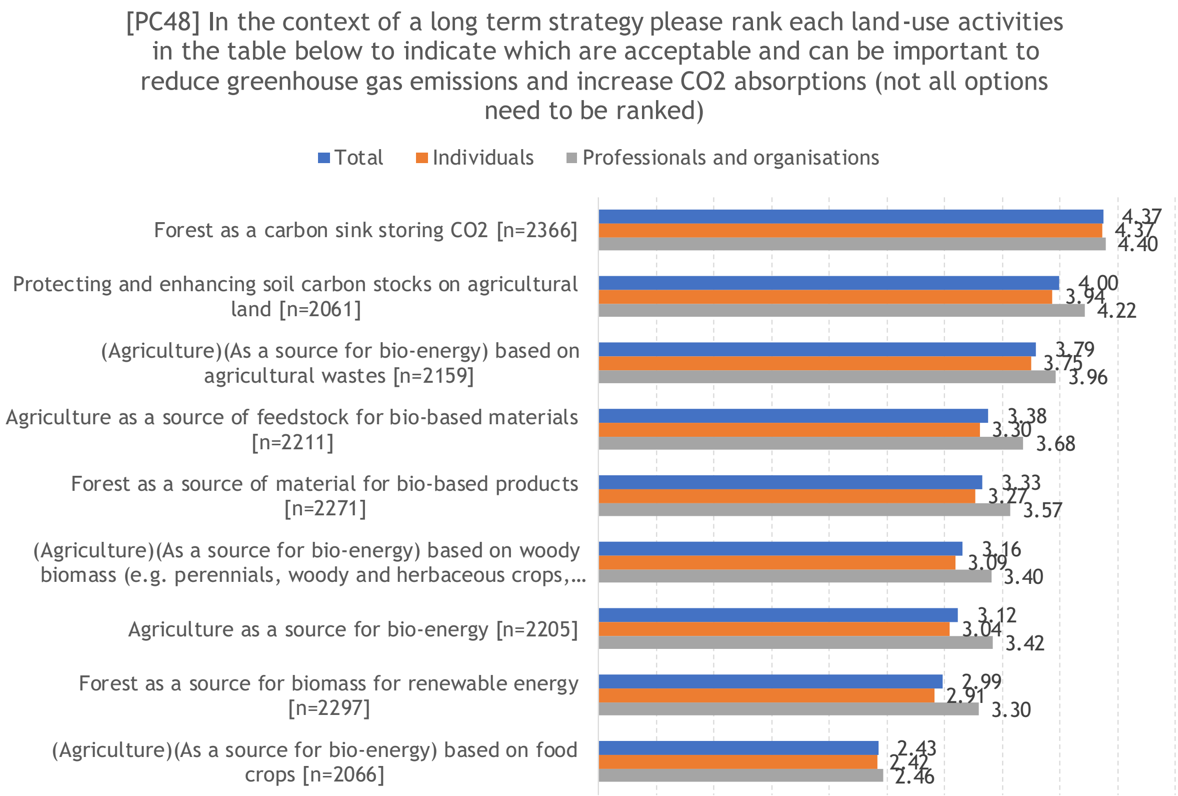
- Sustainability concerns were raised by 66% [n=892] respondents. Destruction of natural spaces (including deforestation, and the loss of biodiversity due to monoculture plantations) was raised by many respondents, [n=794] highlighting challenges such as the conversion of prime forests into forest plantations and soil degradation, while preserving natural spaces was identified as an opportunity for adaptation. Biomass sourcing [n=237] was considered an opportunity to support the bioeconomy and create jobs in rural areas, whilst also entailing challenges relating to biodiversity and land availability concerns.

- Paradigm shift (such as major changes to production or consumption patterns) was identified as a key factor by 66% [n=883] respondents, with a variety of issues, sometimes perceived as both opportunities and challenges. Economic models – encompassing sustainable consumption and production, circular economy and degrowth [n=624] was perceived as both an opportunity and challenge to shift to more sustainable consumption patterns and means of production. Lifestyles and work, including “fair transition”, local economies and inequalities [n=434] represented both opportunities (creation of green jobs) as well as challenges in terms of economic consequences for specific regions and industries.

#### 7.1.4.4 Stakeholder opinion on the role of forests and land use

Respondents were asked to rank activities in the land use sector and their importance in terms of reducing greenhouse gas emissions (see Figure 127). Stakeholder ranked the role of forests as carbon sinks as the most acceptable and important land-use activity to increase CO2 absorption with the highest average rating of 4.37 while the least acceptable activity was agriculture as a source for bio-energy (based on food crops) with the lowest average rating of 2.43.

**Figure 127: Stakeholder ranking of land-use activities (from 1 (not important) to 5 (important))**




*Source: Open Public Consultation.*

Respondents were also asked to comment, in an open question format, on the role, possibilities and challenges related to the land-use sector: [PC49] 'What should be the role of the land-use sector in reducing emissions and increasing absorptions? For what purposes should biomass be used most to reduce greenhouse gas emissions? How and which sustainability concerns should be addressed?'. This question received n=1042 responses.

On the question of the role of the land-use sector in emissions reduction a handful of key themes emerged in responses:

- Increasing forest areas and improving forest management were among the main focuses of respondents, with almost all respondents recognising the key role that forests play as carbon sinks.
- Reduced livestock production was identified as an important way in which emissions could be reduced, as both a large emitting activity and as part of a needed shift in diet.
- In particular, soils and also peatlands were identified as important carbon sinks that could play an important role in emissions reduction and absorption.
- Other issues also mentioned, although less frequently, included the potential for urban farming and the need for Bio-Energy Carbon Capture and Storage (BECCS).

On the question of for which purposes biomass should be used for emissions reduction, the following key themes emerged from responses:

- Opposition to the use of biomass for energy was amongst the most commonly expressed views with many respondents sceptical of the emissions reduction/neutrality and finding food production the key purpose of cropland.
- Local production and consumption was preferred by respondents, particularly in context of using forest residues or industrial wastes as fuels for heating.
- Construction and furniture materials were amongst the preferred uses for biomass.
- Other issues raised, but less frequently, included the possibility for biomass to be used to improve soil carbon retention and to produce bioplastics.

Sustainability concerns were common to many responses, with the following key themes emerging:

- Biodiversity concerns, from continued expansion of agricultural land, or increased production of energy crops.
- Tropical deforestation, was raised as a key issue, with fears that EU demands for biofuels for transport was causing indirect land-use change in third countries.
- Not to convert land from food to energy production, was noted as an important social sustainability concern.

#### 7.1.4.5 Facilitating the low-carbon transition through education, research and innovation

This section addressed the central role of accelerating research and innovation to facilitate the transition to a low-carbon economy. Respondents indicated that awareness raising to change attitudes, values and mind-sets could best be done at school through education alongside local and regional and national and EU wide campaigning. Moreover, the energy, industry and transport sectors were considered those on which R&D efforts should focus on primarily in the coming decade to best support the low carbon transition.

Respondents answered the following questions in an open question format: [P52] 'On which cross-sectoral domains should R&D efforts focus in the coming decades? Is there a particular need for large scale deployment of certain innovative technologies? Is there a different role for authorities and private sector in support?'. Respondents [n=1 042] focused mainly on:

- Renewable energy was mentioned by 59% [n=611] of respondents.
- Energy efficiency, included in [n=506 responses], should be targeted and improved both for industry and regular consumers (such as efficiency in buildings).
- Industrial processes, covered by [n=333 respondents], should receive further attention, especially to target sectors and industries with process emissions. In this context, several respondents mentioned the importance of CCUS technologies.
- Mobility and transport - electrification, charging stations, hydrogen, public transport – was deemed important by [n=325 respondents]. Electrification was the most common theme in this category.
- Energy storage - batteries, decentralized storage and supply, was highlighted by [n=199] respondents.
- Hydrogen, mentioned by [n=188] respondents, should be further improved to develop technologies such as hydrogen fuel-cells and power-to hydrogen for energy storage, but also to decarbonise the transport sector.

#### 7.1.4.6 Financing the low-carbon transition

More than half of the respondents indicated that the sector in which they are active requires significant additional investments to undertake the transition to a low carbon economy, with almost half of respondents acknowledging that there is a financing gap in their sector. In addition, over 40% of stakeholders highlighted that companies are not transparent enough about climate change and the low carbon transition and the financial risks that they face due to these changes. With regards to financial risks there was a significant difference between respondent groups: only 17% of the individual respondents believed companies were sufficiently transparent, compared to 52% of those responding on behalf of a private enterprise, profession, trade of business organisation.

Respondents were asked about their opinion on the public sector's involvement in ensuring adequate financing for the low carbon transition. A large share agreed that the public sector should be more involved in ensuring adequate financing, either through direct investments (32%) or by ensuring more low cost finance for sustainable investments (51%).

#### 7.1.4.7 Meta trends

Respondents were asked which trends currently shape our societies that are important for reducing greenhouse gas emissions. A vast majority of stakeholders considered the economic transition towards a more circular economy, digitalisation and the shared economy positive trends enabling the reduction of greenhouse gas emissions. The views were relatively more dispersed when talking about the importance of further interdependency of sectors across borders through globalisation, with a fairly even distribution of respondents being either positive (37%), negative (27%) or neutral (37%) to this trend.

#### 7.1.4.8 Actors of the low carbon transition

In this section, respondents were asked which non-state actors would have the biggest impact on their sector's contribution to deliver on the EU's ambition [n=2405]. About a third of the respondents expected towns and cities would have the most impact and some comparable shares indicated regional governments and businesses. However, when looking at the responses of private organisations and businesses[676], close to half of respondents (45%) expected businesses to have the most impact. Respondents were further asked to provide examples, in an open question format, of types of initiatives of particular importance to underline the role of such actors in the low carbon economy and energy transition. Examples included:

- Infrastructure and spatial planning was identified as one of the crucial areas for action by regional government, towns and cities.
- Action at different levels of governance, was noted as important, whilst EU and national level seen as playing an important role in rule setting and major decisions, an important role was foreseen for other actors in spatial planning (regional government) and in more practical day-to-day issues (local/city government).
- Energy generation was identified by around 1/3 of respondents as an important area for action and initiative with many examples focusing on local, decentralised renewable energy generation (primarily solar PV), either by individual citizens or through cooperatives or associations.

[676] Sub-category 'Private enterprise, professions, trade and business associations' (n=322).

#### 7.1.4.9 Adaptation

Respondents were asked to rank which actions they thought would be necessary to prepare for and adapt to the likely effects of climate change in their place of living. Respondents [2 321] indicate an overall high level of importance given to all adaptation measures. Adapting agriculture to the changing climate, better understanding of the security effects of climate change on the EU and increasing the amount of green areas in cities to cope with heatwaves and floods were ranked as the top three measures.

Finally, respondents were also asked, in an open question format, which adaption measures were of particular importance for their sector, and why [PC64] [n=704]. Key themes mentioned included:

- Greater preparation is needed, was a common theme across every sector, with few if any respondents believing they were already well prepared.
- Awareness raising was noted by many as an important step, with a strong perception that few (including policy makers) really understood the impacts of climate change, the risks and vulnerabilities it would bring and the types of actions that would be needed.
- Adaptation measures were highlighted for a handful of specific cases, including an increase in number of green areas and trees in cities, improved insulation and cooling of buildings, and improved insurance.
- Mitigation as adaptation was highlighted by some respondents, with one of the key adaptation measures being to mitigate emissions sufficiently that less adaptation would be needed.
- Better understanding how climate change impacts in third countries might affect the EU, such as changed migration patterns or resource scarcity, was also mentioned by some respondents.

#### 7.1.4.10 Stakeholder opinion on the role of $CO_2$ removal and storage

Respondents were asked to estimate and rate the role of various $CO_2$ removal and storage methods and technologies in the EU in delivering negative emissions, taking into account issues such as economic and technical feasibility, storage potential, environmental integrity and social acceptance.

Amongst the five proposed measures direct air capture received the lowest average rating, while other measures, intensive afforestation and woody perennial plantations were in the top three. The most important method of capture for individuals is intensive afforestation, while for professionals it is other options. Options mentioned by professionals include: improved land and forest management, the protection and restoration of forests and natural ecosystems (including reforestation), BECCS, biochar, CCU, pre-combustion capture, the sea as a carbon sink and oceanic algal blooms.

Carbon Capture and Storage (CCS) in onshore or offshore geological sites were ranked as the least important carbon storage technologies, while respondents estimated increased permanent stock in plants and soils and other methods to be the most important. Once again, professionals opted for other options over the methods presented in the table, while individuals rated increased permanent carbon stock in plants as the most important method. The other methods highlighted by professionals include: restoration of forests and natural ecosystems, CCU, BECCS, carbon stocks in the sea, bio char and wood products.

Finally, respondents were asked to comment on, in an open question format, [PC72] 'What main barriers do you see currently preventing the large scale deployment of CCS, including on how to use it to generate negative emissions? What are the particular challenges related to biomass CCS? What type of CCU (Carbon Capture and Utilization) would lend itself to create long term storage? Are there other technologies that should also be considered? What policies do you think the EU should pursue to better help development and deployment?' Respondents [n=705] highlighted the following aspects as being important:

- On barriers to large scale CCS: Efficiency and scalability [n=163], public support and acceptability [n=62] and economic viability [n=49] were listed.
- Challenges to BECCS (bioenergy carbon capture and storage) [n=165] was an important point of discussion among the responses, with major concerns expressed over the actual emissions savings achievable with this technology, many doubted that negative emissions could be achieved and that it may in fact be counterproductive given the energy inputs needed (in its value chain) and diversion of resources from other technologies.
- Carbon Capture and Use [n=212] was identified as a potential opportunity, particularly in the area of building and construction materials, fuels and for specific industrial sectors such as steel, cement and chemicals. However, there were considerably more doubts over the efficiency, cost and feasibility of applying CCU in the power generation sector, as well as some opposition to further CCU in the oil and gas sector.
- Other technologies that could be considered: renewable energy [n=284], ecosystem-based carbon capture (such as re- or afforestation)
- There was also a significant minority arguing that CCS was no solution and a more fundamental paradigm shift was needed to avoid emissions in the first place.
- With regards to policies, the need for more pilot projects and research [n=190] was highlighted, as well as further policy discussions on, for instance, the EU-ETS function and pricing and in public funding of elements of the CCS value chain (e.g. transport and storage infrastructure).

### *7.1.5 Results of the position paper analysis submitted to the consultation*

*Stakeholders*

In addition to the OPC questionnaire, stakeholders could also submit position papers. In total, 173 papers were submitted by the end of the OPC, of which 39 already did in reaction to the consultation of the roadmap[677] [678].

*Results*

*Roadmap consultation papers*

Submissions under the roadmap consultation covered a broad range of topics. Some stakeholders outlined their support for an EU strategy that is in line with the 1.5°C goal of the Paris Agreement, with the long-term goal of Europe attaining net-zero emissions by 2050. The majority of respondents did however rather emphasise considerations and elements to be included in the strategy. Common views were the need to ensure a global rule-based order (level playing

[677] https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-3742094_en

[678] In total, 39 papers were submitted but one submission was removed as it did not comply with the European Commission's rules for publishing feedback

field) for climate action, the need to invest in further innovation, ensuring a just transition, continue to put energy efficiency first, the cost-effectiveness of continued use of the existing gas-infrastructure and the prominent role of the EU ETS. Moreover, several stakeholders underlined the importance of ensuring transparency in the drafting process of the Strategy, both with regards to modelling, methodologies and assumptions.

*National, regional or local authority (20 papers)*

Six Member State governments (DK, FR, NL, PT, SE, UK) and NO submitted individual attachments to the consultation. In addition, 14 members of the Green Growth Group[679] submitted a joint statement. A number or local and regional authorities also took the opportunity to express more detailed opinions under the consultation. Within this stakeholder group there was in general strong support for an EU long-term strategy with a net-zero target by 2050 in order for the strategy to be compatible with the 1.5°C target of the Paris Agreement, or for the strategy to explore at least one pathway compatible with such a target. The need to build on and take into account the conclusions of the IPCC's Special Report on the 1.5°C target was further emphasised. Moreover, several Member States further advocated for a revision of the consistency of the current 2030 target with the 1.5°C temperature goal of the Paris Agreement and the EU's revised long-term target.

*Trade, business or professional association (49 papers)*

Attachments from this stakeholder category covered a broad range of topics, reflecting the variation of sectors covered. Approximately 20 stakeholders expressed support for an EU long-term target of net-zero emissions/carbon neutrality by 2050. Several stakeholders also pointed to the need for the EU to revise its 2030 target. However, representatives from in particular the industrial, energy and employment sectors also emphasised the need of aiming for realistic targets in relation to cost-efficiency, competitiveness and employment security (in the context of a "just transition"). These are not necessarily incompatible with an ambitious 2050 goal, but need to be taken into consideration. Several submissions highlighted the key role of the EU ETS in driving the energy transition. Another aspect brought up by many stakeholders was the need for the Strategy to promote and ensure long-term stability and predictability for actors and investors on the market. With regards to specific technologies, the need to put efficiency first was raised together with its cost-effective advantages, as well as the need to promote the further development of CCUS technology. Furthermore, achieving a full decarbonisation of the power sector in combination with further electrification was also promoted as crucial measures to reduce emissions. The gas-sector further emphasised both the medium-and long-term benefits of fuel switching from coal to gas – not only could gas provide stability in the grid to complement intermittent renewable energy sources, but the possibility of using already existing infrastructure would promote the cost-efficiency of the energy transition. Moreover, the need for the Strategy to adopt a technology neutral approach, or at least to the extent possible avoid to pre-empt future technological advances.

*Non-governmental organisation, platform or network (22 papers)*

Several stakeholders in this category argued for the EU to set as its long-term target to attain net-zero emissions by 2050 (or earlier), in light of the 1.5°C target of the Paris Agreement. In this context many alluded to the (then forthcoming) IPCC Special Report on the 1.5°C. Additionally, some stakeholders also advocated for a revision of the 2030 target. From the environmentalist groups, a strong emphasis was given to the land use sector and the role or restoring, protecting and preserving forests and other ecosystems. In this context, two stakeholders emphasised the

[679] Comprising of 16 EU Member States and Norway

share of global emissions attributed to livestock farming and consumption of related products and promoted a transition towards a plant-based diet. The importance of further promoting and strengthening investments for research and development of clean technologies was also highlighted across the stakeholder group. Not only will such investments be necessary to achieve the necessary emission reductions, but also for the EU to retain its competitiveness and leadership role internationally.

*Private enterprise (14 papers)*

All stakeholders but two in this category which submitted additional attachments operate in the energy sector. Only one enterprise expressed a firm view on the long term target, advocating to aim for carbon neutrality by 2050 and also called for a strengthening of the 2030 target to 45%. Several companies commented on the prominent role of the EU ETS as the main tool to steer European and sectorial decarbonisation, with some companies advocating an increase in its scope and strengthening of the trading scheme. Moreover, there was also a strong emphasis on the importance of decarbonising the power sector and to aim for further electrification. CCUS technology was also frequently mentioned as an enabling tool to further reduce emissions, requiring more investment in research and development and an enabling policy framework.

*Research and academia (3 papers)*

Three entities provided input under this category. They focused on food and nutrition security, assessment of additional mitigation potentials of certain sectors in the EU, and road transport.

*Professional consultancy, law firm and self-employed consultant (2 papers)*

Two individual consultants provided input. The first entry presented a review of European and international climate policies and the second entry discussed and outlined the future for a specific hydrogen technology.

*Other (24 papers)*

Several individuals and groups of concerned citizens provided additional input to the OPC. Topics covered included, inter alia, the presentation of alternative or, according to the authors, disregarded technologies and innovations, the need to reduce meat consumption and the moral imperative to reduce our overall ecological footprints.

### *7.1.6 Results of the stakeholder consultation conference*

A stakeholder conference was held on 10th and 11th July, at the Université libre de Bruxelles[680]. More than 1000 people attended.

The discussion on the EU's vision for a modern, clean and competitive economy was welcomed by all speakers and panellists. It highlighted the need to have a unified European vision ahead of COP24. Europe's Long Term Strategy for Greenhouse Gas (GHG) emission reduction will not only guide European efforts in the coming decades and serve as an example for other nations and important stakeholders.

A number of themes were addressed. Some of the most important themes regard the trends of the energy sector, the regulatory environment in the EU, as well as the social dimension of the low-carbon transition. Overall, there is consensus on the need for an ambitious long-term strategy, with many participants acknowledging that in practice this means net zero emissions at some

[680] The programme of the event is available at: https://ec.europa.eu/info/sites/info/files/decarbonisation_hlc_juillet_2018_programmes_a3_v03_web_1.pdf .

point, perhaps as early as 2040, but according to most around 2050. It was recognised that this strategy should focus mainly on the long-term in order to help decision-makers focus on the long term, despite their everyday distractions. As a result, the strategy should specifically include attention for measures creating negative emissions. It should help set milestones for the short- and medium-term also in order to stimulate timely action. Most panellists emphasised the need to view the transition ahead as an opportunity, rather than a cost or a threat. In order to demonstrate that, the cost of inaction should be communicated more clearly.

More specifically, many panellists agreed that the key to realising the transition lies in energy efficiency and renewable energy, these being able to deliver 80-95% of the total change required. Electrification of heating and transport, digitisation and the further growth of solar and wind energy were seen among the major developments needed. Other technologies such as nuclear fission and fusion, hydrogen, CCS and natural gas were all also discussed, as potential bridges or future hopes for a low or zero carbon future. Yet traditional sources of energy still account for a large share of the energy mix, so the focus should not only be on electrification, but also making all energy cleaner. It was noted that despite progress on EU policy there remain important steps still to be taken in many sectors. Particular areas that will be challenging include end-user sectors such as heating and transport, and important technologies such as CCS lagging significantly behind. In addition, discussions on the role and use of natural resources noted that agriculture and forestry have a crucial role to play in meeting food and resource needs, whilst contributing to decarbonisation and potentially acting as carbon-sinks.

Since climate change is not only a European problem, but a global concern, panellists agree that Europe must collaborate with its partners and show leadership. The EU also faces a lot of competition, though, notably from China. This means that while transitioning towards a low-carbon economy, Europe needs to stay competitive. To achieve this, there must be investment in infrastructure, research and the labour force. Moreover, we need to ensure that supply and value chains and innovators stay in Europe. Now is the time to build a comparative advantage in areas that will be of value in the future (e.g. digitalisation, battery production). Furthermore, when thinking about the future, we have to account for a mix of solutions (there is no 'one' solution). This is why it is important to keep the conversation open and to consider diverse viewpoints. Engaging citizens and gaining their support for the developments that are taking place was highlighted by a number of panellists. Communications and regulation were cited as significant drivers of citizen engagement. Beyond that, panellists called for a cohesive regulatory framework that cuts across all sectors and that reduces the overlaps between different countries. Regulation should encourage private investment and business opportunities, while discouraging the business (and consumer) behaviour that needs to be phased out. Although some panellists called for a stronger price signal on carbon, the oil & gas industry believes that it is already heavily taxed and is not in favour of an increase in carbon pricing.

Affordability was also an important angle to the discussion, whilst some renewable energy and energy efficiency solutions are low or negative cost, it is clear that not all low carbon options are of this nature and there are significant implications for existing industries and households. These should not be forgotten as millions of Europeans today are energy poor. In general, it is important to keep in mind all the possible disruptions that a transition can cause and how to address them in a fair, just and responsible way.

## 7.2 Details on methodology and modelling

### *7.2.1 Description of analytical models used*

**MAIN MODEL SUITE: PRIMES, GAINS, GLOBIOM, GEM-E3, E3ME**

The main model suite used for the scenarios presented in this assessment has a successful record of use in the Commission's energy and climate policy impact assessments. It is the same model suite used for the 2020 and 2030 climate and energy policy framework, as well as for the 2011 Commission's decarbonisation Roadmaps. The model suite has been strongly enhanced over the past years in terms of more granular representation of both energy system and GHG emissions and removals, and the detail of representation of technologies. The model suite covers:

- **The entire energy system** (energy demand, supply, prices and investments to the future) and all GHG emissions and removals.
- **Time horizon:** 1990 to 2070 (5-year time steps)
- **Geography:** individually all EU Member States, EU candidate countries and, where relevant Norway, Switzerland and Bosnia and Herzegovina.
- **Impacts:** on all energy sectors (PRIMES and its satellite models on biomass and transport), agriculture (CAPRI), forestry and land use (GLOBIOM-G4M), atmospheric dispersion, health and ecosystems (acidification, eutrophication) (GAINS); macro-economy with multiple sectors, employment and social welfare (GEM-E3).

The models are linked with each other in such a way, so as to ensure consistency in the building of scenarios (Figure 128). These inter-linkages are necessary to provide the core of the analysis, which are interdependent energy, transport and GHG emissions trends.

Detailed model descriptions can be found on the DG CLIMA website[681], as well as in the Impact Assessments accompanying Clean Energy for All proposals[682] (notably in the Impact assessment of the revised Energy Efficiency Directive[683]).

The modelling suite was recently updated, with an extension of the time horizon till 2070, addition of a new buildings module, improved representation of electricity sector, more granular representation of hydrogen and synthetic fuels produced with electricity ("e-fuels"), as well updated interlinkages of the models to improve land use and non-$CO_2$ modelling.

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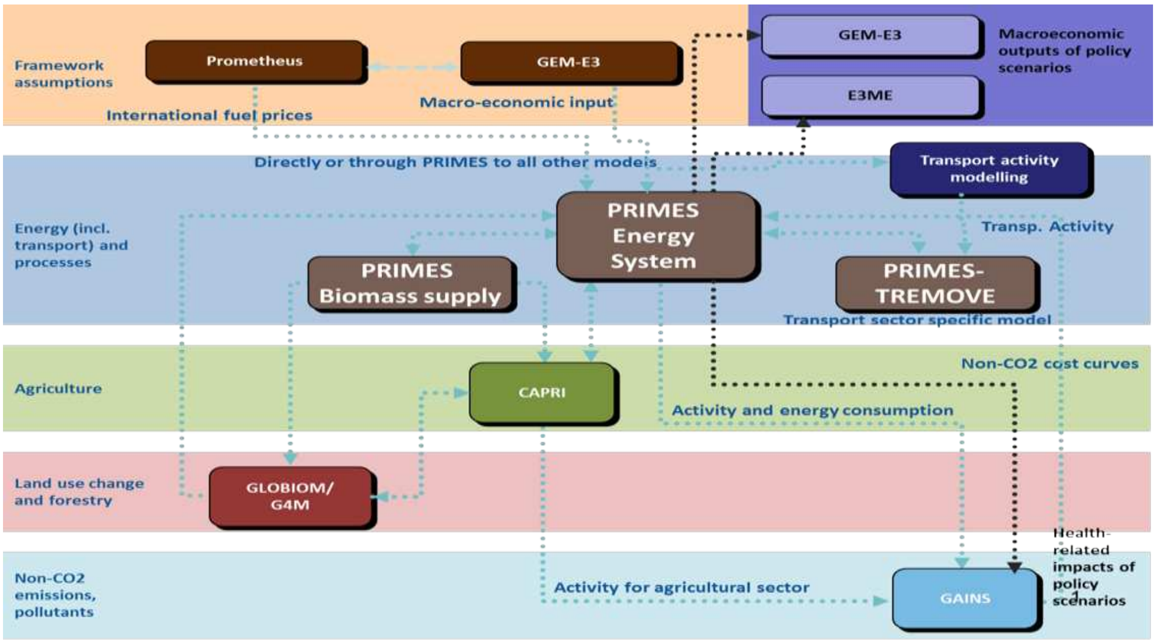
681 http://ec.europa.eu/clima/policies/strategies/analysis/models_en#Models.

682 https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition

683 https://eur-lex.europa.eu/resource.html?uri=cellar:56466305-b7f6-11e6-9e3c-01aa75ed71a1.0001.02/DOC_2&format=PDF

**Figure 128: Interlinkages between models**




*Source: E3MLab/ICCS*[684].

## MACRO ECONOMIC MODELLING

The results of these energy-system scenarios served as input for the macroeconomic modelling. The assessment of the macro economic impacts of various decarbonisation pathways was performed using JRC-GEM-E3[685], E3ME[686], and QUEST[687]. In addition, the energy-system scenarios also serve as input for assessing the health implications of the scenarios, via the model GAINS.

## FORECAST

The above model suite was complemented by the bottom-up industry model FORECAST[688]. It is based on a simulation approach considering the dynamics of technologies and socio-economic drivers. The model allows addressing various research questions related to energy demand in industry, including scenarios for the future demand of individual energy carriers, like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions, as well as abatement cost curves and ex-ante policy impact assessments.

Energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are modelled as cross-cutting technologies. The energy-intensive processes module covers 76 individual processes and products regarding their production output and specific energy consumption.

Saving options unfold their total impact on energy consumption and GHG emissions by diffusing through the modelled technology stock and, thus, reducing the specific energy consumption or

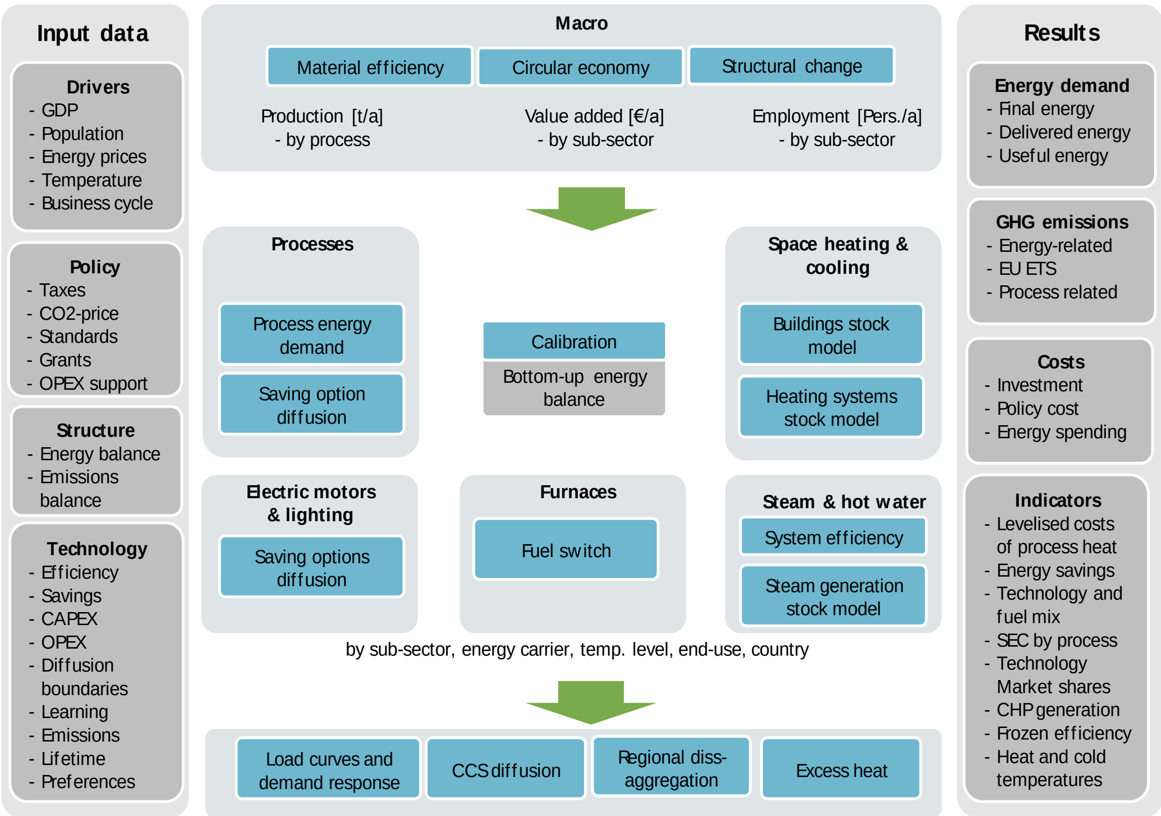
[684] http://www.euclimit.eu/Default.aspx?Id=2
[685] https://ec.europa.eu/jrc/en/gem-e3/model
[686] https://www.camecon.com/how/e3me-model/
[687] https://ec.europa.eu/info/business-economy-euro/economic-and-fiscal-policy-coordination/economic-research/macroeconomic-models_en
[688] Fleiter et al (2018), A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model, https://doi.org/10.1016/j.esr.2018.09.005

specific process-related emissions of individual production processes. Saving options can be incremental changes as well as radically new production processes. The diffusion of saving options is based on the payback time, which depends on energy savings, energy prices and the carbon price.

The FORECAST model is designed as a tool that can be used to support strategic decisions. Its main objective is to develop scenarios for the long-term development of energy demand and greenhouse gas emissions for the industry. The model considers a broad range of mitigation options combined with a high level of technological detail. The future production capacity by product and the choice of production processes are exogenous input to the model, while the investment in energy efficiency measures and heat supply technologies are based on a detailed simulation of investment decisions.

Detailed model description of FORECAST can be found in Annex 1 of the report summarising the relative modelling work performed for the Commission.[689] Figure 129 shows the simplified structure of FORECAST.

**Figure 129: Overview of the bottom-up model FORECAST**




*Source: FORECAST.*

## *7.2.2 Construction of scenarios*

### 7.2.2.1 Baseline scenario developed with PRIMES, GAINS, GLOBIOM suite

In order to assess the trajectory that is entailed by the recent policies and objectives adopted, a Baseline scenario was developed. As described in Section 2.2.2, EU and its Member States have

[689] ICF & Fraunhofer ISI (2018), Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation, forthcoming

recently agreed to strengthen the set of policies and mandatory objectives that already guide EU's decarbonisation and energy transformation up to 2030. In addition, these policies will continue pushing further GHG emissions reduction, and increasing energy savings and renewable energies deployment after 2030, either because they do not have a "sunset clause" (notably ETS, and since recently, Article 7 in revised EED), or because of the technological learning and cost reductions that they are expected to induce. Moreover, most actions in the energy system have long-term impacts (e.g. construction of well-insulated houses, efficient power plants or other types of infrastructure). The Baseline captures these dynamics, but it needs to be emphasised that no intensification of policies post-2030 was assumed and no target for GHG emissions reduction in 2050 was set.

Baseline scenario largely builds on the Reference scenario 2016 (REF2016)[690], keeping the macroeconomic projections, fossil fuels price developments and pre-2015 Member States policies as implemented in REF2016[691]. It applies the same decision-making and cost-accounting discount rates as REF2016 (see more information on this topic in Section 2.6.1 of REF2016 publication).

The Baseline assumes the achievement of the energy and climate 2030 targets[692], as adopted by EU leaders on October 2014[693], further refined on May 2018 with the agreement on the Effort Sharing Regulation and enhanced on June 2018 with the agreement on the recast of Renewable Energy Directive and the revised Energy Efficiency Directive. The Baseline thus incorporates several major recently agreed pieces legislation as well as recent Commission proposals:

- The revised EU ETS Directive (Directive (EU) 2018/410) which entered into force on 8 April 2018[694].
- The LULUCF Regulation (Regulation (EU) 2018/841) which entered into force on 9 July 2018[695].
- The Effort Sharing Regulation (Regulation (EU) 2018/842) which entered into force on 9 July 2018[696].
- The Energy Performance of Buildings Directive (Directive (EU) 2018/844) which entered into force on 9 July 2018[697], according to which new buildings are assumed to be nearly zero-energy buildings as of 2020;

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690 The "EU Reference Scenario 2016 – Energy, transport and GHG emissions - Trends to 2050" publication report describes in detail the analytical approach followed, the assumptions taken and the detailed results, see: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

691 Also the same assumptions are kept throughout all PRIMES scenarios on heating and cooling degree days which reflect the impact of climate change; but the possible effects on availability of hydropower or biomass are not captured.

692 The 2030 climate and energy framework did set three key targets for the year 2030: (a) at least 40% cuts in greenhouse gas emissions (from 1990 levels), (b) at least 27% share for renewable energy, and (c) at least 27% improvement in energy efficiency. They built on the 2020 climate and energy package.

693 Conclusions of the European Council of 23 and 24 October 2014.

694 Directive 2010/31/EU of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814.

695 Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU.

696 Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013.

- The Commission proposal for the recast of the Renewable Energy Directive[698]. In its agreed version by the European Parliament and the Council on June 14th 2018 it features a 32% overall RES EU target;
- The Commission proposal for the revision of the Energy Efficiency Directive[699]. In its agreed version by the European Parliament and the Council on June 20th 2018 it features 32.5% overall Primary Energy Consumption and Final Energy Consumption target (compared to 2007 Baseline), as well as a continuation of Art 7 of EED post-2020 without a sunset clause;
- The Commission proposal for the revision of the Eurovignette Directive[700];
- The Commission proposal for the revision of Combined Transport Directive[701];
- The Commission proposal for the revision of Clean Vehicles Directive[702];
- Regulation on electronic freight transport information[703]
- The Commission proposal for new $CO_2$ standards for LDVs[704] and HDVs[705].

It does, however, foresee a continuation of policies impacting non-$CO_2$ emissions, as included in the REF2016, but updated to include the impact on non-$CO_2$ emissions from reductions in fossil fuel consumption in Baseline.

Importantly, the Baseline incorporates an update of technology assumptions as conducted under the ASSET project[706] and, concerning transport, as conducted for the purpose of the recent Commission's legislative proposals[707].

Baseline has been specifically built for the purpose of the development of long-term decarbonisation scenarios. It does not reflect specific, short-term Member State policies, and, in particular, no consultation with the Member States has taken place to verify that current or updated policies are adequately represented, as currently being developed under the NECPs.

[697] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

[698] COM/2016/0767 final/2 - 2016/0382 (COD)

[699] COM/2016/0761 final - 2016/0376 (COD)

[700] COM/2017/0275 final 2017/0114 (COD)

[701] COM/2017/0648 final - 2017/0290 (COD)

[702] COM/2017/0653 final - 2017/0291 (COD)

[703] COM(2018) 279 final

[704] COM/2017/0676 final - 2017/0293 (COD)

[705] COM/2018/0284 final

[706] Modelling scenarios for development of the energy system is highly dependent on the assumptions on the development of technologies - both in terms of performance and costs. While these assumptions have been traditionally developed by the modelling consultants, based on a broad and rigorous literature review, the Commission is increasingly seeking a review of these technologies by stakeholders to make them even more robust and representative of the current projects as well as experts' and stakeholders' expectations. This is why a dedicated project was launched by the Commission in early 2018 to ensure robustness and representativeness of the technology assumptions in model PRIMES by reaching out to relevant experts, industry representatives and stakeholders, who are in possession of the most recent data in the different sectors. The project was concluded in July 2018 and its final report (including the finalised technology assumptions) is available here: https://ec.europa.eu/energy/en/studies/review-technology-assumptions-decarbonisation-scenarios

[707] RICARDO, 2016, Improving understanding of technology and costs for $CO_2$ reductions rom cards and LCVs in the period to 2030 and development of cost curves, https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_co2_technologies_and_costs_to_2030_en.pdf

#### 7.2.2.2 Decarbonisation scenarios developed with PRIMES, GAINS, GLOBIOM suite

The Commission's analysis based on the PRIMES, GAINS, GLOBIOM model suite explores eight economy-wide scenarios to achieve different levels of ambition, covering the potential range of reduction needed in the EU to contribute to the Paris Agreement's temperature objectives of between *the well below 2°C*, and *to pursue efforts to limit to 1.5°C temperature change*. This translates into GHG emissions reduction for the EU in 2050 (compared to 1990) in the range between -80% (excluding LULUCF) and -100% including LULUCF (i.e. achieving net zero GHG emissions). All decarbonisation scenarios are based on the Baseline and have identical technology assumptions. The general logic of the decarbonisation scenarios is presented in section 4.1.

The decarbonisation scenarios can be split into three different categories, depending on the level of GHG emissions reduction achieved. The pathways examined in each scenario category aim to show how the desired level of reductions can be delivered if the current policy framework (presented in the Baseline) is further intensified post-2030, each time intensifying the deployment of certain technologies (or consumer choice in one scenario) in order to obtain stylised, explorative pathways.

1. Scenario Category 1: contains scenarios achieving emissions reduction contributing to Paris Agreement goal of *well below 2°C*, translated into a target of -80% GHG in 2050 (excluding LULUCF) and a continuing GHG emission reduction trend after 2050 towards net zero GHG emissions. Five pathways were considered, building on the Baseline Scenario. Three of them focused more on the higher penetration of decarbonised energy carriers (requiring a significant change in energy supply sectors), while two put more emphasis on the demand side.
    a. Scenarios with GHG reductions driven by decarbonised energy carriers:
        i. Electrification (ELEC), including as key action electrification of the energy demand and thus higher electricity supply
        ii. Hydrogen (H2), including as a key action deployment of e-hydrogen in the energy demand sectors and thus hydrogen production on the supply side
        iii. E-fuels (P2X), including as a key action deployment of e-fuels (e-gas and e-liquids) in the energy demand sectors and thus e-fuels production on the supply side.
    b. Scenarios with demand driven GHG reductions:
        iv. Energy Efficiency (EE), including as a key action energy efficiency in buildings, industry and transport
        v. Circular Economy (CIRC), including as a key action circular economy in the industry and (to a more limited extent) in transport
2. Scenario Category 2: A scenario (COMBO) combining the pathways of Scenario Category 1 on a moderate basis, aiming for further emissions reduction beyond the ambition of *well below 2°C*. No specific emissions reduction target was assumed for this scenario, but by construction, the emissions reduction fall between the ones of Scenario Category 1 and Scenario Category 3, seeing a continuing GHG emission reduction trend after 2050 towards net zero GHG emissions.
3. Scenario Category 3: Highest GHG reductions scenarios, contributing to Paris Agreement goal of *pursuing efforts to limit to a 1.5°C temperature change*, translated to a target of around -100% GHG (including sinks), i.e. net zero GHG emissions in 2050. The two scenarios of this category build on the COMBO scenario and assume further intensification of the implementation of actions and technologies included in that

scenario. In addition, net-zero emissions are achieved by compensating with negative emissions for the “harder to abate” emissions (e.g. agriculture[708], transport), with one of these two scenarios assuming changes in lifestyles compared to today, further reducing GHG emissions.

i. Negative Emissions Technologies (1.5TECH), including as a key complementary action the development of negative emissions as of 2050 (in significant amounts).

ii. Sustainable Lifestyles (1.5LIFE), including as a key complementary action the change in consumer choice[709] in transport and circular economy in the industry.

Although each scenario, by construction, promotes certain elements stronger than others, the scenarios are not examined as extreme options (e.g. the “hydrogen economy”, the “e-fuels economy”, etc.), but as feasible/realistic pathways for the future based on current knowledge.

The projections of all eight scenarios tend to be quite close - almost identical - until 2030. This is because they share the same policy drivers. The differences start becoming more visible post-2030 and in particular closer to 2050 when deployment of different energy carriers and level of demand becomes more differentiated, low carbon technology costs further reduce depending on deployment, existing infrastructure (be it power generation plants, industrial sites or buildings) is replaced or refurbished. This also reflects the inertia of the energy system and the economy as a whole. Projections start diverging even more post-2050.

In all scenarios, deep decarbonisation is required for the ETS sectors, such as power and industry. The purpose of the scenarios is to show the technological transition pathways available to these sectors. In the modelling, technology choices by enterprises in the ETS sectors are driven by (i) a carbon price and (ii) the scenario specific context. The development of the carbon price is a key driver for these scenarios to reduce emissions but not the only one.

Carbon price represents a stylised price signal. It triggers the cost-effective deployment of zero carbon technologies and alternative fuels by the power sector and industry. Cost-effective choices in the power sector are of particular importance in scenarios where demand for electricity is very high. However, which particular alternative fuel is chosen (for instance, whether hydrogen, e-gas, or electricity is preferred) also depends on the technological and infrastructural context of the scenario. This context is the result of coordinating policies, which develop infrastructure and pursue R&D&I on enabling technologies, as well as setting producer expectations, consumer preferences and public acceptance. These coordinating policies are what varies across scenarios. As a result, industrial maturity and availability of technologies and alternative energy carriers vary per scenario.

[708] The scenarios modelled scenarios have not taken into account the potential of marine resources. The emissions could be offset by switching to other food production sectors which are already greenhouse gas emission negative, such as aquaculture production from shellfish and seaweed

[709] As to the term of consumer choice it is important to emphasise that some consumer choice is part of “energy efficiency family” of measures – when it concerns reduction of energy consumption per specific activity. Consumer choice can also be in the “circular economy family” – when it relates to reducing waste, recycling, reusing. Finally, consumer choice might mean also reducing an activity (e.g. not taking a flight because of the carbon footprint or taking instead the train) and such measures were modelled in 1.5LIFE scenario.

The stylised carbon price assumed increases significantly under all scenarios, reaching 28 EUR/t$CO_2$ in 2030 and then increasing to 250 EUR/t$CO_2$ in 2050 under the 80% reduction scenarios and 350 EUR/t$CO_2$ under the scenarios that achieve net zero GHG emissions by 2050. Real carbon price developments will be different and depend on numerous factors, including the deployment of other policies and how they impact technology costs and deployment. For this assessment with the PRIMES model suite it was not chosen to vary for instance other policy levers and see how carbon prices would be impacted.

In the following, the specific characteristics and assumptions underlying the modelling of all eight scenarios are presented, specifying which are common and which are pathway specific.

*Scenario Category 1*

The scenarios achieving emissions reduction *well below 2°C* have many similar characteristics. Table 1 in Section 4.1 summarises the common characteristics and assumptions of Scenario Category 1, which are also briefly discussed below.

Power decarbonisation

Continuing and further intensifying EU efforts to achieve the 2030 energy and climate targets, extend and enhance the current trend of decarbonisation of the power sector in the long-term. The power sector achieves decarbonisation mainly by the increasing deployment of renewables, complemented by a stable and slightly increasing nuclear generation and a limited[710] installation of CCS units in the few remaining fossil fuels based power generation plants. Production of district heating and industrial steam also decarbonises, mainly through the use of renewable energy.

Electrification

This, in turn, facilitates the increasing electrification of the final energy demand, as progressively electricity becomes an affordable and zero-carbon energy carrier. In industry, the gradual increase of carbon prices post-2030renders fossil fuel energy carriers increasingly unfavourable. Transport (especially light-duty vehicles) and buildings switch partly to electricity, driven by specific drivers supporting the decarbonisation objectives. For transport in particular, electrification is driven by the assumption of more stringent $CO_2$ standards post-2030 and policies encouraging shift to lower emission transport means and modes supporting electrification (e.g. rail). For buildings, it is the multiple benefits of heat pumps (deployment of renewables, energy efficiency and emissions abatement) that drive their deployment, in particular in highly insulated, new and refurbished, buildings.

[710] Due to limitations in geological storage and transport infrastructure of $CO_2$.

**Table 26: Major common characteristics of Scenario Category 1**

**Level of Ambition**

- Around -80% GHG emission reductions in 2050 (excluding LULUCF)

**Main Common Assumptions**

- Market Coordination for infrastructure deployment.
- Significant learning by doing for low carbon technologies.

**No Regret Options**

- Intensification of Energy Efficiency post-2030 across the energy system.
- Average renovation rate of buildings post 2030 is minimum double than the historical rates.
- Smoothened electricity consumption patterns, driven by increased self-consumption, demand response and digitalisation (making smart appliances/building control functions wide-spread.
- Development of electricity storage for better integration of RES
- Moderate circular economy measures, with increased resource efficiency and improved waste management compared to today

**Renewable Energy**

- High penetration of RES in Power Generation, but also in heating & cooling.
- Increase in the advanced biofuel (and bio-methane) mandate in Transport, reaching at least 25% in total transport fuels (excluding electricity and hydrogen) by 2050.
- Biomass imports limited post-2030, close to 2015 levels (approx. 12 Mtoe)

**Power Sector**

- Power is nearly decarbonized by 2050.
- Nuclear still plays a role in the power sector.
- CCS deployment faces limitations until 2050. These are relaxed post-2050.

**Transport Sector**

- Higher intensity of policies post-2030 relative to the Baseline.
- Measures increasing the efficiency of the transport system (i.e. digital technologies, connected, cooperative and automated mobility, smart pricing, encouraging multi-modality and shifts to lower emission transport modes).
- Ambitious $CO_2$ standards for LDVs and HDVs in all scenarios.
- Connected, cooperative and automated mobility.

**ETS**

- Common carbon price for all scenarios in Scenario Group 1.

Deployment of renewables and more flexible power system

The decarbonisation of the power sector is due largely to the mass deployment of variable RES, especially wind and solar. To facilitate the integration of variable RES, the EU's power system becomes more flexible thanks to an extension and improved operation of the grids, including the interconnectors, the installation of significant storage capacity, and the increased contribution of demand response. While developments till 2030 are driven by the RES targets, the main driver post-2030 is the relative competitiveness of available technologies, taking into account the price signal delivered by the carbon price. The renewable energy sources are increasingly used in heating and cooling, as well as in transport, where the emergence of advanced biofuels (including biogas) is the main enabler. Their penetration though is limited by their economic and production potential, the constraints related to the sustainability criteria of biomass and competing uses in non-energy applications in industry (wood and bio-feedstock).

Energy efficiency

Another major trend appearing in all scenarios is the decreasing energy intensity of the energy system, due to regulatory incentives for energy efficiency, as well as cost-effectiveness of such measures in the decarbonisation context. The intensification of the 2030 policy framework, together with technology improvements and electrification, to name some of the main factors, greatly boost energy efficiency in industry, buildings and transport. This is further supported by digitalisation, making smart appliances/building control functions wide-spread.

Despite the many similarities across these scenarios, differences do exist. The common features described above lead to significant GHG emissions reduction, but not up to the desired levels. Reducing the remaining emissions require additional actions, especially in the sectors where emissions are “harder to abate”, such as in industry (iron & steel, chemicals, non-metallic minerals) and transport (heavy-duty vehicles, aviation, waterborne transport). Literature review and discussions with stakeholders identified the availability of different options to mitigate these emissions, which are reflected in the differences between the scenarios.

In the ELEC scenario, electricity becomes the vector for reducing emissions in the sectors where emissions are harder to abate. In transport, more stringent $CO_2$ standards are assumed for LDVs compared to the other scenarios of this category (e.g. 16g $CO_2$/km in 2050 and zero from 2060 for cars), driving electrification faster. The scenario also assumes penetration of battery HDVs for shorter distances and trucks with pantographs for longer distances. Electric HDVs have a more significant share than in other scenarios, especially concerning heavy goods vehicles for shorter distances and busses. Electrification of inland navigation (inland waterways and national maritime) and aviation remains a niche solution. Electrification of rail is further intensified. The strong penetration of efficient heat pumps is driving further emissions reduction in buildings. For industry, the effort focuses on strong electrification where fuel shift is possible, and in particular of high-temperature industrial process heat.

H2 scenario foresees high deployment of hydrogen in final uses in transport, buildings and industry, benefiting from possible applications that are currently known. This is facilitated by properly adjusting the gas distribution grid and heating equipment to accommodate high shares of hydrogen (allowing for a mix up to 50% in gas distribution in 2050 and 70% in 2070). Dedicated infrastructure is assumed to facilitate high shares of hydrogen in transport. Additionally, the blending of biogas quantities in the gas distribution grid, further reduces the quantity of fossil-based natural gas, therefore, providing low carbon distributed gas to the final consumers (for heating uses in buildings, industry and for heat production). Moreover, the scenario assumes direct use of hydrogen in high-temperature industrial furnaces, produced locally via electrolysers. In transport, some competition between hydrogen and electricity takes place for cars and vans, the main difference coming from vehicles that cannot run on batteries, such as long mileage cars, coaches and trucks. The hydrogen refuelling infrastructure, assumed to be deployed by 2050 in this scenario, facilitates the uptake of hydrogen for these uses. The requirements for hydrogen in the demand-side sectors increase the electricity needs of the system; on the other hand, the hydrogen production and its use/storage in the grid provides at the same time medium to long-term energy storage capacity. This is particularly important, as the large majority of additional electricity required by the electrolysers to produce the hydrogen comes from variable renewable energy sources.

The P2X scenario is similar to the H2 scenario, but hydrogen becomes mainly an intermediate feedstock for the production of e-fuels (e-gas and e-liquids). E-fuels have the advantage of having the (almost) same chemical properties as their fossil counterparts. However, their production is energy intensive, as a further transformation step is required, after the hydrogen is produced via the electrolysers. Moreover carbon feedstocks are required, their future availability at the required quantities being quite uncertain[711]. The distributed gas in this scenario constitutes of a combination of e-gas and biogas to provide end-users with a distributed gas of identical quality as today, but with very low remaining emissions. For the transport sector, the use of e-liquids would allow for the reduction of emissions in transport modes where emissions reduction are costly, in particular where electrification is difficult or where developing an alternative technology/infrastructure (fuel cells and hydrogen infrastructure) requires significant changes. The use of e-fuels in transport would reduce the biofuel requirements of the transport sector, leaving biomass available for other uses, such as for heat, electricity and as a feedstock. Towards 2050, hydrogen is produced by electrolysis, e-gas in methanation plants and e-liquids via various chemical routes, notably the methanol route and the Fischer-Tropsch process. To be carbon neutral, both e-gas and e-fuel production use $CO_2$ captured from the ambient air and biomass-using power plants. The production of e-fuels implies that this scenario sees an even higher electricity demand than the H2 scenario, the highest one among all scenarios, as the production of e-fuels requires a further transformation step after the production of hydrogen. The production of e-fuels, however, also provides medium to long-term storage services for the additional electricity generation requirements, which are mainly satisfied through additional variable renewable energy investments.

The above scenarios focus on alternative energy carriers. Two more scenarios focus more on demand-driven GHG emissions reduction.

<u>In the EE scenario</u>, high levels of energy efficiency are pursued in all sectors, going beyond electrification options and intensifying the use of energy efficiency technical options, especially in the residential sector and industry. Energy consumption is thus reduced in all final consumption sectors and particularly in buildings. The latter is driven by strong improvements of energy performance of buildings, higher and more in-depth renovation rates, strong improvements in heating and cooling equipment (as well as for water heating, cooking) and electric appliances, as well as the deployment of Building Automation and Control Systems. Energy efficiency improvements are also observed in industry, with higher efficiency of furnaces and in low enthalpy heat uses, as well as with the increase of waste heat recovery mechanisms. In transport, energy efficiency is achieved by the higher electrification of transport, very similar to the ELEC scenario, combined with an intensified modal shift towards rail, waterborne transport and collective transport modes in the urban environment.

<u>The CIRC scenario</u> is the one where GHG emissions reduction are driven by measures outside the energy system. Although very close in the concept with EE scenario, reductions are not driven by energy savings, but mainly by the more general concept of resource and material efficiency. Recycling and re-use, product and process innovation, improved waste management,

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[711] The uncertainty in regards to the availability of resources to produce the carbon molecule used to produce clean hydrocarbons should be emphasized. In particular this becomes an increasingly important issue when considering the decreasing $CO_2$ emissions and thus the reduced amounts of carbon available in the system. Its origin may be biogenic, coming e.g. from the burning of biomass, or from the air through air capture. There will also be some remaining emission sources from distributed process emissions that might be used for the capture and use of carbon (like lime, bricks, ceramics, clinker). The constraints in the availability of carbon are considered and accounted for in PRIMES. The biogenic origin of the carbon molecule is identified in the model and comes from capturing $CO_2$ from biomass burning installations. It is modelled endogenously, and thus respects availability constraints regarding both biomass and $CO_2$ to capture. The air capture origin of the carbon molecule does not consider land constraints. This is a result of the technological assumptions for the long-term, implying relatively low land use for air capture.

cascading use of materials and material substitution, are the main drivers of the reductions[712]. Two sectors demonstrate the impacts of going along this pathway:

- Industry benefits from increased and improved recycling, less contamination and downgrading of materials and material substitution (especially via 3D printing), reduction of the need especially for virgin materials (steel, non-ferrous metals, plastics, paper, construction materials) and shift of production to the less energy demanding and lower carbon intensity secondary materials (higher recycling). Therefore primary industrial output reduces in volumes, although at the same time industrial value chains have an increased value added focused on recycling and re-use, requiring increased services, leading to reduced energy consumption and GHG emissions. The assumed impact on primary production for the modelling in CIRC is illustrated in the below table.
- Transport benefits from integrating the sharing economy and connected, cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service. The vehicle fleet is smaller relative to the Baseline, but it is utilised more, it displays higher occupancy rates, and it is renewed faster. The reduced vehicle fleet also has secondary impacts on the industrial output of materials used in the car industry. Finally, improved logistics and shifts from long-distance freight to near-sourcing is assumed, together with shifts towards rail and waterborne transport. In energy terms, there is no reliance on hydrogen or e-fuels in the transport system, but biomass use increases coming in part from biomass that is not needed to reduce industrial emissions.
- In energy terms, there is increased waste heat recovery, and conversion of remaining waste material into useable heat, electricity or fuel. Improved management and collection of organic waste and biomass cascading, leading to the use of more sustainable biomass either as a feedstock or for the production of biogas in local bio-refineries[713].

**Table 27: Assumed impact of circular economy on energy intensive industries primary production in the CIRC scenario**

| | 2050 |
|---|---|
| | **Reduction of volumes (% change from baseline projection)** |
| Iron & Steel | -6% |
| Non Ferrous | -3% |
| Chemicals | -9% |
| Paper & Pulp | -12% |
| Non Metallic Minerals | -8% |

The differences in the five pathways examined, apart from the drivers for achieving the desired GHG emissions reduction, also have important implications for infrastructure, regarding both changes needed in existing infrastructure and additional needs for new infrastructure.

[712] The assumptions regarding the dynamics of the circular economy are somewhat conservative, as they consider continued expansion of circularity also after 2050; therefore, 2050 is not the peak (over the projection period) of the circular economy development in the CIRC scenario.

[713] Due to the similar main characteristics of EE and CIRC, focusing more on demand-driven emissions reduction and sharing only two low carbon energy carriers (electricity and biomass), a conscious choice was made to push more electricity consumption in EE and more biomass consumption in CIRC, in order for the two scenarios to present a sufficient variance in their results. As electrification is a means of improving energy efficiency, notably in residential and transport, this option fits more with the energy efficiency goal of EE. The CIRC does not focus on energy efficiency primarily and thus did not need electrification as much as the EE. However, CIRC could also assume similar electrification as the EE, which would then result in lower biomass use.

All scenarios require significant new investments in power infrastructure and recharging/refuelling infrastructure for vehicles and the only difference among scenarios is the required scale. The H2 and P2X scenarios allow the use of existing infrastructure for gas, thus allowing the use of existing heating equipment for buildings and industry. In transport, rolling out of refuelling infrastructure for H2 is needed at a large scale, in particular in the H2 scenario. The P2X scenario also allows the use the existing infrastructure for liquids and requires the relatively lower deployment of recharging/refuelling infrastructure for vehicles. ELEC and EE require in many cases replacement of existing equipment especially for long distance, and heavy duty transport and require the use of high quantities of biofuels or technological developments which are today at a low level of readiness. Finally, going even beyond the infrastructure, CIRC assumes a change in the business model of road transport and industry, and requires improved waste management practices.

The needs for infrastructure investments is also a major factor determining the speed at which different sectors can decarbonise. As an example, for the industry, ELEC and EE deliver emissions reduction faster as there is a lot of potentials that can be harnessed early, but then there is a plateau as for deeper emissions reduction technological breakthroughs are needed. CIRC delivers steady emissions reduction over the horizon, as the economy becomes circular. On the other hand, P2X and H2 require the decarbonisation of a significantly large power sector and, for H2 scenario, the investments in direct hydrogen applications. These two scenarios also depend on an additional factor, technological competitiveness. Electrolysis and direct hydrogen applications, but also electrification of high-temperature furnaces and capture of $CO_2$ from the air, are expected to become competitive technologies closer to 2050.

Table 1 in section 4.1 provides an overview of scenario construction. Table 28 below summarises the main differences in scenario assumptions.

**Table 28: Main differences in assumptions of Scenario Category 1**

| Sector | ELEC | H2 | P2X | EE | CIRC |
|---|---|---|---|---|---|
| **Buildings** | Promoting use of electricity for heating. | Promoting use of carbon neutral gases. | Promoting use of carbon neutral gases. | High rate and depth of renovations Further improved energy efficiency in appliances. | Reduced renovation costs due to material efficiency and substitution. |
| **Industry** | Electrification for part of high temperature heat. | Direct use of hydrogen in high temperature furnaces. | | Further improved energy efficiency in industrial heat applications and equipment.<br><br>Waste heat recovery. | Changing industrial value chain, more circular, more recycling, reduced primary industrial output on average 10%.<br><br>Waste heat recovery. |
| **Transport** | Optimistic learning assumptions for batteries.<br><br>Standards for cars reach 16 gCO2/km (WLTP cycle) in 2050 and become zero from 2060 onwards. | Optimistic learning assumptions for fuel cells.<br><br>Large scale availability of H2 refuelling stations.<br><br>Standards for cars reach 18 gCO2/km in 2050 | Standards for cars reach 30 gCO2/km in 2050 | Further improved energy efficiency of vehicles.<br><br>Higher model shift towards rail, waterborne transport and collective transport modes in the urban environment.<br><br>Standards for cars reach 23 gCO2/km in 2050 | Integrating the sharing economy and connected, cooperative and automated mobility.<br><br>More efficient logistics.<br><br>Standards for cars reach 30 gCO2/km in 2050 |
| **Other** | | Share of hydrogen in distributed gas of up to 50% in 2050 and 70% in 2070.<br><br>Hydrogen production provides indirect electricity storage. | Share of e-gas in gas distribution grid up to 60%.<br><br>E-gas production provides indirect electricity storage. | | |

The pathways examined in Scenario Category 1 achieve the emissions reduction for the *well below 2°C* target, i.e. a 80% greenhouse gas emissions reduction (excluding LULUCF) by exploring the possibilities offered by the leading paradigm/solution/technology of each scenario. They do not, however, propose this one solution as the preferred option for all applications. To achieve the emissions reduction through "one solution" in many cases, a scenario would need to strongly exploit the economic potential of a certain pathway for a specific sector. This creates the danger of lock-in/overreliance on a specific technology, which may not be able to deliver further emission reductions if required. Moreover, such focused technology pathways may require using extreme solutions, due to the lack of other options within the specific pathway, thus possibly ignoring solutions from other pathways that have lower costs if higher ambition is required. Such a technology specific scenario may also lead to further improvements of a specific technology – and lower developments in another technology reflecting economies of scale due to learning and mass production. The default development pathways chosen for the techno-economic characteristics are therefore “middle-way” pathways except for technologies, which are required regardless of the scenario, and therefore follow an optimistic development.

*Scenario Category 2*

COMBO is a scenario offering an alternative approach to the pathways examined in Scenario Category 1, aiming to combine effective solutions for each sector/mode from the paradigms/solutions/technologies explored by specific scenarios in Category 1. Such a scenario would require spreading of investments and more moderate deployment of different technologies than the technology-specific solutions as explored in Scenario Category 1 scenarios.

COMBO serves as a bridge between Scenario Category 1 and Scenario Category 3. It indicates how far emissions reduction can go using a set of technology/solutions per sector as identified in Scenario Category 1.

It does not push for extreme deployment of specific technologies or actions. It neither focuses on the development and deployment of specific negative emission technologies by 2050, nor promotes actions incentivising the uptake of CO2 in our land sink. It does not include consumer choice changes. These are options explored in Scenario Category 3, achieving net zero GHG emissions.

The only pathway that was not included in the COMBO scenario is the one of circular economy. The reasons for this choice were purely technical. The main difference of CIRC with the other scenarios is resource efficiency, captured in the modelling mainly by assuming reduced industrial output (in volumes). Including CIRC in COMBO would complicate the identification of cause and effect of emissions reduction in the latter. Furthermore, the assumed levels of output reduction in CIRC can be considered conservative compared to the circular economy literature; thus including even weaker assumptions than CIRC on circularity (in line with the treatment of the other pathways in COMBO), would not offer additional insights. Thus, it was preferred to include circular measures only in the 1.5LIFE scenario, which has similar features with CIRC.

*Scenario Category 3*

Pursuing net zero GHG emissions requires, on top of the options examined above, even stronger measures. Based on existing literature, the main additional options to consider are: investing significantly in negative emission technologies (BECCS, direct air capture as well as better land use management fostering increased absorption of $CO_2$ in the natural sink) and changing lifestyles facilitating higher sustainability. In order to better understand the impact of these choices, two different scenarios and one sensitivity were produced.

Both scenarios are based on COMBO, with the explicit additional measures described below. The drivers of COMBO remain the same or are further intensified. Firstly, $CO_2$ standards for new cars, vans and buses are assumed to be zero starting from 2040. Secondly, the limitations assumed on CCS (due to acceptance, storage availability, transport infrastructure, etc.) are partly relaxed and CCU is introduced (notably related to the storage of biogenic $CO_2$ in plastic material which is not incinerated but recycled). This makes sequestration of $CO_2$ a more economic option, resulting in a larger amount of $CO_2$ ending up stored either underground or in materials. The drivers to enhance the energy-related renovation rate and depth of renovations in buildings were also intensified.

The last remaining – and hardest to abate emissions – mainly coming from agriculture, road freight, aviation and cement processes, are dealt in the scenarios in two different ways.

The scenario 1.5TECH assumes limited additional incentives to improve the land use sink. Instead it focuses on technical solutions to achieve net-zero GHG emissions. It increases CCS aiming to lower more the remaining emissions. Similarly it applies more use of e-gases and fuels based on air captured or biogenic $CO_2$ to reduce remaining emissions. It applies negative emission technologies via biomass coupled with CCS and the storage of biogenic $CO_2$ in material.

The scenario 1.5LIFE takes an alternative approach, by trying to address the issue of emission abatement by focusing more on demand-side measures, as well as increased take up by the land-use sink. It assumes that consumers start making different choices on certain carbon-intensive activities, leading to more sustainable lifestyles. Towards 2050, the demand for air transport is reduced relative to the Baseline as significant shift takes place to rail[714] and significantly increased modal shift takes place towards lower emission transport modes for both passenger and freight transport. Also, there is an assumption that shifts in food preferences by consumers continues towards less animal based products[715]. Due to a behaviour focusing on rational use of energy, demand for heating and cooling is lower compared to other scenarios. Increased modal shift takes place towards lower emission transport modes for both passenger and freight transport. The latter is also linked to improved city planning, improved logistics, integrating sharing economy and connected, cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service (see section 4.4.2 for resulting impacts on transport demand). This scenario includes also the drivers and assumptions of the circular economy scenario, complementing the lifestyle changes with changes in product design and business models, aiming to achieve higher resource efficiency. Moreover, it explicitly introduces on top of the above incentives to improve the land use sink. This relates to improved forest management activities that increase sequestrations, improved agriculture practices that improve soil carbon and afforestation.

Finally a sensitivity was included that looks into impacts on biomass requirements, fully building on the above two scenario. On one hand it builds fully on scenario 1.5LIFE, with the combination of changing consumer preferences, increased modal shift, a more circular economy and a high incentive to enhance the LULUCF sink. One the other hand it applies many of the technology options driven to the maximum in 1.5TECH, but with a focus on options that do not require biomass. This scenario tries to see how net zero GHG emissions could be achieved while limiting biomass demand increases. This scenario is referred to as 1.5LIFE-LB and discussed in more detail in section 4.7.2. If not explicitly mentioned all results shown in this assessment refer to 1.5LIFE.

## FORECAST scenarios

Specifically for the case of industry, detailed scenarios were developed using the model FORECAST for the future evolution of energy demand and greenhouse gas emissions of the EU's industry sector under varying assumptions with regard to technology innovation and diffusion.

Eight scenarios were explored[716], which can be organised in four scenario groups differentiated by the type of mitigation options and the level of ambition in GHG mitigation:

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[714] A part of intra-EU air trips for leisure and personal reasons would be shifted to rail and coaches and a reduction in the distance travelled for extra-EU trips would also take place. The number of the business trips would be reduced thanks to the adoption of video/tele conferencing facilities.

[715] The diet applied is Diet 4, as described in more detail in section 4.6.2.

[716] ICF & Fraunhofer ISI (2018), Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation, forthcoming

1. Scenario Group 1: Incremental improvement
2. Scenario Group 2: Best available techniques
3. Scenario Group 3: Decarbonisation scenarios (~80%) with varying technology focus including innovations (> TRL4):
    a. Focus CCS
    b. Focus clean gas (renewable hydrogen and synthetic methane)
    c. Focus bioeconomy & circular economy
    d. Focus electrification
4. Scenario Group 4: "balanced mix" of the above-mentioned supply/mitigation options with varying level of ambition (~80%/~95%)

**Figure 130: Overview of the FORECAST scenarios.**

| | Scenario name | Main scenario philosophy |
|---|---|---|
| no innovations | 1) Ref | **Existing technologies** and **incremental improvements** in **energy efficiency** and **fuel switch** towards natural gas and some biomass. Slow continuation of past trends regarding recycling. |
| | 2) BAT | Like scenario 1, but with complete diffusion of **today's best available technologies** with regard to energy efficiency where technically applicable. Fast development of recycling. |
| GHG reduction >80%. (ref. 1990) Including innovations with TRL >4 | 3a) CCS | **Decarbonisation, focus on** CCS, but also use of other mitigation options (energy efficiency innovations & BAT). |
| | 3b) Clean gas | **Decarbonisation, focus on renewable hydrogen and synthetic methane**, but also use of other mitigation options (radical process innovations & BAT). |
| | 3c) Bioeconomy & circular economy | **Decarbonisation, focus on biomass as fuel and feedstock.** Comprehensive implementation of **circular economy** beyond todays practices and downstream **material efficiency.** Also use of other mitigation options (radical process innovations innovations & BAT). |
| | 3d) Electrification | **Decarbonisation, focus on direct use of electricity**, but also use of other mitigation options (radical process innovations innovations & BAT). |
| | 4a) „Balanced mix" -80% | **Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -80%, on a track towards deeper decarbonisation beyond 2050. Not using CCS and limited biomass. |
| | 4b) „Balanced mix" -95% | **Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -95%, CCS allowed, but limited biomass use. |

*Source: FORECAST.*

Scenarios 1 and 2 illustrate possible GHG emission pathways and mitigation potentials including only technologies that are available today. They are explorative, in the sense that GHG reductions are a result of best available techniques (BAT) potentials (scenario 2) and past trends (scenario 1). Scenario 1 can be interpreted as a baseline scenario to which the results of scenario groups 2-4 can be compared. In terms of diffusion of today's BAT, scenario 2 is ambitious; still, it does not allow new disruptive technologies to enter the market. These two scenarios are not further discussed in this assessment.

Scenario groups 3 and 4 were constructed to achieve a minimum GHG reduction of 80% compared to 1990. Scenarios in group 3 can be considered as more extreme pathways, aiming to achieve the level of ambition mainly via the technology they are focusing upon. Scenarios in group 4 achieve their respective target by taking advantage of all technological pathways in a balanced way. The scenario philosophy is summarised in Figure 130.

In more detail:

The CCS scenario includes large scale diffusion of CCS and innovative energy efficiency measures. It is the only scenario including CCS, except for the Mix95[717] where some selective applications of CCS are also allowed for the sectors of non-metallic minerals and refineries. It has strong assumptions on the availability of enabling transport and storage infrastructure for CCS, as well as improved public and political acceptance of CCS.

The CleanGas scenario assumes hydrogen and e-gas[718] entering the fuel mix, plus again innovative energy efficiency measures. As an assumption, both energy carriers are assumed to be exclusively produced via electrolysis[719] using electricity from renewable energy sources. Conventional gas in the gas grid is reduced to 20%. Production of ethylene, methanol and ammonia switches to hydrogen-based production routes, as well the steel industry shifts to direct reduced iron production using hydrogen. Finally, naphtha is decreasingly used as feedstock.

The BioCycle scenario includes a number of measures, starting from significant fuel-switching to sustainable biomass, innovative energy efficiency and low-carbon production technologies, as well as implementation of comprehensive circular economy approach throughout the entire value chain. In particular, it is assumed that material losses are reduced, material efficiency improves and material substitution takes pace, increased recycling and re-use of materials and changes in use-behaviour. These assumptions lead to decreased demand for certain materials compared to the other scenarios from Group 3: -10% for steel, -23% for cement, -12% for ethylene and -40% for ammonia. As the scenario aims to explore whether it is possible to achieve the desired ambition by switching to biomass, no supply limitations were considered for this specific scenario, quantities to be supplied most likely via imports and cascading use of biomass (from product to fuel).

In the Electric scenario, energy efficiency measures are combined with switching processes to using electricity directly (direct reduced electricity in iron & steel) or indirectly (production of ethylene via methanol). Similar to the biomass scenario, this scenario tries to assess the potential of electrification assuming the required amounts of electricity are available. Electricity is assumed to be carbon-free, supported by large scale deployment of RES-E technologies and an electricity market design allowing for demand response and electricity prices being competitive with other fuels.

Mix80 combines in a more balanced way the main solutions of the above scenarios and tries to identify a more cost-efficient way to meet the desired reductions. It includes the innovative energy efficiency measures, low carbon production innovations, hydrogen, electrification, moderate circular economy and material efficiency improvements (less ambitious than BioCycle only in the case of chemicals[720]). On the other hand it excludes the use of CCS, limits biomass to 2015 levels and does not consider clean gas in the gas grid.

[717] The role of CCS in Mix95 is mainly to address some very difficult to decarbonise processes by other means (e.g. lime and clinker). This is a result of the radical transition taking place in all sub-sectors, based mostly on the substitution of fossil fuels by carbon-free energy carriers.

[718] The constraints in the availability of carbon, discussed in footnote 711, are not captured by FORECAST. Sufficient carbon feedstock is assumed to be available (and transportable), although this is somehow considered in the prices, e.g. if direct air capture of $CO_2$ would be needed, the costs of synthetic methane might be substantially higher than the ones assumed (from a "simpler" $CO_2$ source).

[719] According to the system boundary defined, both hydrogen and synthetic methane are accounted for as energy carriers, which are produced outside the industry system. Consequently, CAPEX for e.g. electrolyser is not included, however, it is considered via the price of hydrogen and synthetic methane.

[720] For Chemicals, ethylene production is assumed to remain constant, while ammonia production decreases by around -20%.

The final scenario, Mix95, builds on Mix80, but adds a number of additional elements. CCS is added in major remaining process emissions (lime, bricks, ceramics, clinker). Gas is assumed to be decarbonised, as 95% of conventional gas is assumed to be replaced by clean gas in the gas grid – even more than in CleanGas scenario. Steam generation technologies are replaced prematurely, there is an increased diffusion of innovative low carbon technologies in steel, chemicals and cement, as well as faster transformation of buildings and transport sectors, reducing the demand for conventional fuels. The latter is assumed to result in the halving of output in refineries compared to all other scenarios (apart from that, all other circular economy aspects are assumed to be the same with Mix80). Finally, a more ambitious recycling of plastic products is assumed.

### *7.2.3 Limitations in the modelling exercise.*

While the modelling exercise has been performed to the highest quality standards, one should interpret the modelling results with caution. All models, independent of their complexity, are stylised approximations of reality. Modelling results are based on highly uncertain assumptions, especially when the projection goes up to a long-term horizon such as 2070. The future development of the economy, the availability, costs and performance of the technologies[721], market imperfections, fuel prices and emission abatement cost curves are among the main uncertainties.

Although most relevant recent adopted legislation (or proposed by the Commission) has been included as part of the Baseline for this exercise, all other elements of the scenarios are based on the Reference scenario 2016 assumptions. Therefore, many of the newest national policies and developments have not been captured (e.g. recent coal phase-out announcements). In the same context, short-term macroeconomic and forecasts of world fossil fuel prices (key input into energy-system modelling) may be considered in some cases as outdated. However, as the main focus of the exercise is the period 2050-2070, the changes in the short term are unlikely to have significant impacts on the main findings of the modelling[722].

The PRIMES scenarios in this study have a normative rather than a forecasting character. They indicate cost-effective pathways towards the achievement of given 2050 decarbonisation objectives, assuming perfect operation of energy markets[723] and economic actors/consumer willingness to invest in new technologies, with only certain bias reflecting non-economic considerations (via discount rates and cost curves). Consequently, while the micro-economic foundations (limited resources available to economic actors) and technology outlooks (difficulty in switching to more costly technologies in the absence of policy drivers) are included in the modelling methodology, the specific investment/energy consumption decisions might be different from what may be observed in reality. For example, construction of a nuclear reactor or extensive electricity transmission lines, while identified as cost-effective by the model, might not happen because of consumer acceptance/land availability issues.[724] Similarly, a decision to renovate the house even with certain payback in a reasonable time might not happen because of split incentives between landlord and tenant, or a car with best fuel-efficiency performance will not be purchased because of other preferences/commodities or missing incentives (e.g. in case of company cars). All scenarios assume favourable conditions enabling cost-effective

[721] In particular, data on future technology costs are highly uncertain and thus investment results should be interpreted with caution and more in a comparative manner across scenarios.

[722] Long term energy price and technology assumptions are much more important in this aspect.

[723] Notably by assuming that all investment costs are recuperated via end-user prices

[724] The PRIMES model nonetheless takes into account limitations for the developments of e.g. nuclear reactors based on country policies and space availability e.g. within existing nuclear sites.

decarbonisation including the removal of non-market barriers and successful coordination of actors with different aspirations.

The investment expenditures reported by PRIMES include the majority of energy-related costs. However, although the model includes investment and cost recovery of all types of infrastructure, the final report of total amounts of investment expenditures does not include bio-refineries, oil refining, oil distribution and upstream exploration and production of oil and gas. The model also does not include investment in roads, railways, ports and airports infrastructure and in systems facilitating sharing of vehicles etc., as these are out of the scope of the model. Investment or hidden costs related to behavioural or organisation structural changes or in sectors outside energy are not part of the calculation of investment expenditures either. Generally, the model does not include the full investment expenditure of industrial plants and buildings, but only the parts that relate to energy and efficiency and to a certain extent to the additional investment expenditure to change process technology in the industry. For transport, the model shows total investment expenditure in vehicles, ships, aircraft and trains and not only the energy part of this equipment.

For the hydrogen and e-fuels the investment costs in their production assets (electrolysers, methanation plants) are fully captured in the model. It is, however, assumed that the power sector does not pay for the indirect storage service allowed for by the storage of hydrogen, e-gas and e-liquids in their respective distribution systems. This storage allows using electricity for hydrogen and e-fuel production at times when the maximum renewables are available and when the marginal cost of the system is lowest. This indirect electricity storage allows for smoothing the net load curve, maximise the contribution of variable renewables and improve system reliability. Thus, consumer electricity prices can be lower than otherwise, but partly due to the non-payment for the indirect storage services. However, the power system, hence the electricity consumers, do pay for the direct storage services using power-to-X technologies and of course batteries, hydro pumping and others. Also, the modelling assumes full exploitation of the electricity grids to share balancing services and to access remotely located renewable sources without obstruction. A limitation of the modelling is that the model does not represent trade of hydrogen and e-fuels between the countries, although electricity trade is fully endogenous. Thus, the model ignores the possible returns to scale if the facilities producing the e-fuels were concentrated and eventually located on specific sites with access to significant electricity and gas hubs. The costs and prices of the e-fuels do recover all types of cost in the value chain, including for transmission, distribution and storage, but do not benefit from possible optimisation of the location of production facilities in Europe.

Some cost aspects that relate to consumer choice are subjective and difficult to estimate. Most of the decarbonisation scenarios create so-called disutility to the consumers, as they alter their behaviour to an eventually less “comfortable” solution. It can be a very small change, for example, necessity to charge the electric vehicle during a certain period (instead of having it all the time available if running on liquid fuels) or inconvenience during house renovation. It can also be a bigger change, for example when a consumer decides to give up on a journey (because of its carbon footprint), not own but share a vehicle (in the context of mobility as a service) or restricts their comfort (reduction of temperature). The disutility associated with such actions is always subjective, and estimations of such costs are only approximations; they are used as an (approximate) measurement of the required behavioural changes. This is why the energy system costs the results of the scenarios are reported without disutility costs.

Finally, although the main model suite covers in detail most relevant parts and aspects of the economy concerning the focus of this exercise on a EU28 level, certain aspects of the economy have not been captured in the modelling, like the availability and prices of raw materials, costs related to resilience / adaptation to climate change and investments in transport infrastructure. Modelling results though were complemented with a number of additional modelling runs, using the bottom-up industry model FORECAST and macroeconomic models (JRC-GEM-E3, E3ME and QUEST)) to assess a range macro-economic issues stemming from the analysis of the energy transition, including growth, employment and non-EU countries actions.

These macro-economic models face their own limitations in that they are not tailored to make detailed projections on sector-specific developments, including for example to those related to the transformation of the automobile industry from internal combustion engines to electric and self-driven cars. Instead, they are structured to assess the impact of specific policies as a deviation from baseline, which makes the definition of the baseline itself critical. As used in this context, the models were used to assess the impact of the energy transition and decarbonisation of the economy. As such, the models therefore do not factor in other phenomena that are likely to impact the EU economy in the coming decades, including the development of artificial intelligence, digitalisation or other technological trends. The baseline of the models do nevertheless integrate expected population and labour force trends (including in particularly the ageing of the EU population) and projections regarding total factor productivity growth. No sensitivity analyses were conducted regarding these factors, which are common for the baseline across the macro-economic models.

## 7.3 EU contribution to the Paris Agreement's temperature objectives

Many recent studies have examined cost effective global pathways to well below 2°C and report results at global level. A small number of studies report results at regional level for different world regions including the EU. These tend to confirm that reducing EU domestic greenhouse gas emissions by at least 80% below 1990 levels would still be consistent with a global pathway for keeping warming well below 2°C.

For instance the Horizon 2020 projects LIMITS[725] and AMPERE[726] examined different scenarios, comparing multiple models operated by different teams around the world. A 2018 summary by the Netherlands Environment Assessment Agency, which selects only scenarios that have 66% likelihood or more to limit global warming to 2°C and where global cost-optimal mitigation begins in 2020 or later[727], finds the average reduction for the EU, including the LULUCF sector, to be 74% below 2010 levels which is around 78% below 1990 levels.

This finding is also supported by analysis conducted by the Netherlands Environmental Assessment Agency and JRC for this report[728]. Pathways keeping global warming by 2100 compared to pre-industrial below 2°C with a probability of at least 66% see EU reduce GHG emissions, including LULUCF, by 76% to 84% below 1990 levels in 2050 the more ambitious pathway being associated with a scenario that limits technology options related to CCS.

[725] Kriegler et al., 2014, Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change 90, 24–44.

[726] Riahi et al., 2015, Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, 8–23

[727] van Soest et al. (2018) Global and Regional Greenhouse Gas Emissions Neutrality. *Netherlands Environmental Assessment Agency* report no. 2934. http://www.pbl.nl/en/publications/global-and-regional-greenhouse-gas-emissions-neutrality In this case, well below 2°C refers to scenarios associated with atmospheric greenhouse gas concentrations of around 450 parts per million $CO_2$ equivalent. Scenario's that saw global peaking in 2010 and subsequent emission reductions were not retained, given that global emissions profiles of these projections were too high compared to actual emissions.

[728] Esmeijer K., den Elzen M.G.J., Gernaat D., van Vuuren D.P., Doelman J., Keramidas K., Tchung-Ming S., Després J., Schmitz A., Forsell N., Havlik P. and Frank, S. (2018), 2 °C and 1.5 °C scenarios and possibilities of limiting the use of BECCS and bio-energy. PBL report 3133, PBL Netherlands Environmental Assessment Agency, The Hague.

In contrast, to achieve a 1.5°C pathway, global projections typically foresee the world reaching net zero emissions well before 2100, or rather just before 2070, using net negative emissions both to compensate for remaining emissions from sectors that are hardest to decarbonise as well as to remove $CO_2$ actively from the atmosphere after 2070. Analysis conducted by the Netherlands Environmental Assessment Agency [740] and JRC[729] for this report projected similar global projections[728]. These projections see the EU reduce emissions, including LULUCF, to 91% to 96% below 1990 levels by 2050.

The main options for achieving net negative emissions involve the land sector, through a combination of reducing deforestation drastically, enhancing the forest sink by applying forest restoration and afforestation, and using biomass & CCS (BECCS) as an energy technology and provider of negative emissions. Regions with a large LULUCF sink, high biomass potential and/or high CCS potential are therefore often assumed to achieve zero emissions first in cost-optimal modelling assessments. This means that the EU is not the first large emitter to achieve net zero emissions in most of the cost optimal global scenarios [727].

These 1.5°C pathway scenarios rely on achieving net negative GHG emissions on a global scale after 2070. Projections that try to avoid the need for net negative emission pathways towards the end of the century achieve reductions on a global scale close to net zero GHG by 2050.

The above pathways for well below 2°C and 1.5°C cover all major sectors and greenhouse gases (the so called Kyoto basket of greenhouse gases[730]). This includes the land sector (which as well as a source can also be a net sink of $CO_2$ in the EU, leading to net absorptions of $CO_2$) and the international aviation and maritime sectors which are proportionally attributed to the regions modelled.

Many stakeholders have warned against the over-reliance on negative emission technologies. Many have underlined the need for the EU to achieve zero GHG emissions by 2050 or even earlier.

Scientific assessments, including those of the IPCC, have also reiterated several times that delaying action increases the likelihood of missing temperature goals, increases reliance on rapid emissions reduction afterwards and increased the need for negative emissions, and is ultimately more costly than acting sooner.

There are therefore good reasons why the EU should act in line with the more prudent projections that try to limit net negative global GHG emissions in the 2nd half of the century.

From a precautionary standpoint, there is a strong argument for the whole world to reduce emissions more quickly than the median scientific estimates suggest is necessary, and for the EU to take the lead in encouraging this.

Human-induced warming reached 1°C in 2017, and the best estimates of the remaining emissions compatible with 1.5°C are still subject to significant variation. Large uncertainties remain, including earth-system feedbacks like the impact of permafrost thawing and uncertainties of the

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[729] JRC (2018), Global Energy and Climate Outlook 2018 (GECO 2018), forthcoming. It should be noted that the GECO scenarios are not a pure global cost efficient scenario because some differentiation in action is maintained by scaling the carbon price on the basis of GDP per capita. All countries are assumed to implement a carbon price from 2020, but the price for developing and emerging economies is lower. By 2030, advanced and emerging economies are assumed to implement the same carbon price, with a 'discount' maintained only least developed countries and India. By 2050 the carbon price is assumed to be equal globally.

[730] These are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and the so-called F-gases (hydrofluorocarbons and perfluorocarbons and sulphur hexafluoride)

warming related to non-$CO_2$ emissions. Applying the precautionary principle it is better to show ambition early on if it would turn out that budgets are reviewed downward again.

From an economic perspective, acting early represents an opportunity for change and innovation. A net zero GHG world requires scale-up of a number of innovations in energy, transport and industry, but can also be accelerated by breakthroughs in General Purpose Technologies such as Information & Communications Technology, artificial intelligence and biotechnology[731]. Looking at high ambition can therefore be a crucial part of creating this enabling environment. On the other hand, delayed action can increase the risks of lock-in to carbon intensive infrastructure[732] [733].

Finally, a number of studies[734] [735] have attempted to measure different regions' contribution to global action using a number of potential metrics including purely equity based principles, which may have nothing to do with economic achievability of mitigation efforts.

Höhne et al (2018)[734] distinguish for instance between approaches based on *technical necessity* (including cost optimisation and use of indicators such as emissions per capita, or per unit of GDP), and approaches based on *moral obligation* (such as measures that takes countries' income levels or historical emissions into account).

On emissions intensity metrics, the EU is already a strong performer. The EU has the lowest GHG emissions per unit of GDP of all major world economies[736] and is among the low middle in terms of GHG per capita.

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[731] OECD (2017). The Next Production Revolution: a report for the G20. http://www.oecd.org/governance/the-next-production-revolution-9789264271036-en.htm

[732] See for example Seto et al (2016) Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources* Vol. 41:425-452. https://doi.org/10.1146/annurev-environ-110615-085934 $CO_2$

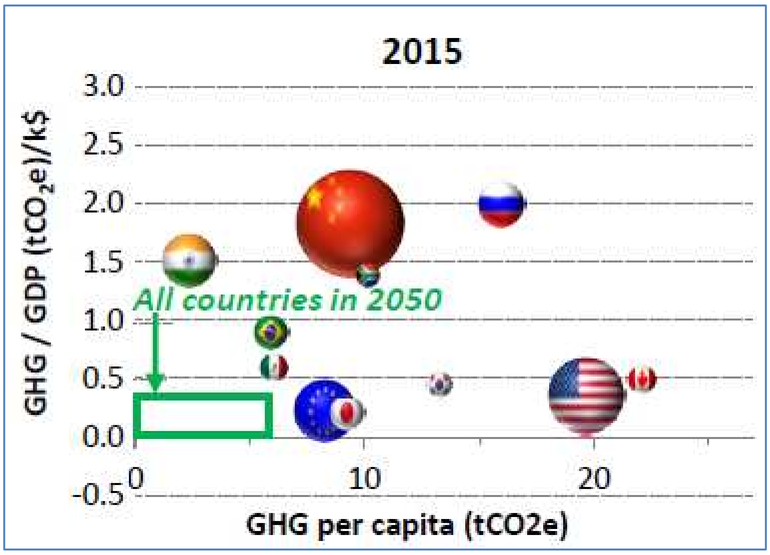
[733] Luderer *et al* (2018) Residual fossil $CO_2$ emissions in 1.5–2 °C pathways *Nature Climate Change* volume 8, pages626–633. https://doi.org/10.1038/s41558-018-0198-6

[734] Höhne et al (2018) Assessing the ambition of post-2020 climate targets: a comprehensive framework, *Climate Policy*, 18:4, 425-441, DOI: 10.1080/14693062.2017.1294046

[735] Robiou du Pont et al (2017) Equitable mitigation to achieve the Paris Agreement goals *Nature Climate Change* volume 7, pages 38–43

[736] Series *GHG per GDP emissions* from EDGAR database v4.3.2. Available at: http://edgar.jrc.ec.europa.eu/ http://edgar.jrc.ec.europa.eu/overview.php?v=CO2andGHG1970-2016&dst=GHGgdp&sort=asc9

**Figure 131: GHG emissions intensity vs GDP per capita for major economies**




*Source: JRC Global Energy & Climate Outlook (GECO) 2017*[737].

Robiou du Pont et al (2017) [735] estimated the necessary 2050 reductions using a number of different metrics to achieve globally well below 2°C, as well as 1.5°C. These resulted in an EU reduction on average of around -75% for the 2°C and -90% for the 1.5°C objective by 2050 compared to 1990, if the global allocation method was based on convergence towards equal annual emissions per person. The 1.5°C pathway used did allow for negative emissions later on in the century. If it would not allow for negative emissions later in the century, a per capita convergence would see required emissions reduction converge towards -100% by 2050. Similarly if the global allocation method was based on the need for higher mitigation for countries with high GDP per capita a 1.5°C objective would typically see EU targets of little less than -100%. Only approaches that were taking into account the level of historical per capita emissions tended to allocate negative reduction targets (higher than 100%) for the EU by 2050, not taking into account the feasibility of such reductions.

## 7.4 Global $CO_2$ budget

### *7.4.1 Global carbon budgets in light of the IPCC Special Report on 1.5°C*

There is a near-linear relationship between the cumulative $CO_2$ emissions in a given period and the increase of the global temperature during this period, compounded by the further impact of other greenhouse gas emissions. This relationship permits to infer the maximum remaining $CO_2$ budget (also called carbon budget) that can be released into the atmosphere while keeping global temperature below 2°C or 1.5°C, taking into account also the expected future non-$CO_2$ emissions.

The IPCC Special Report on 1.5°C reflects advances since the previous IPCC report (the Fifth Assessment Report – AR5). It provides new estimates of the remaining $CO_2$ budget (defined as cumulative $CO_2$ emissions from the start of 2018 until the time of net-zero global emissions) and quantifies the major factors (both scientific uncertainties and methodological choices) which affect any budget estimate.

[737] JRC (2017), Global Energy and Climate Outlook 2017 (GECO 2017), doi:10.2760/474356

Using updated calculations comparable with those of AR5 budget estimates, the IPCC 1.5°C report gives central estimates of the remaining carbon budget of around 1170[738] $GtCO_2$ for a 66% chance of keeping the temperature increase below 2°C and 580 $GtCO_2$ for a 50% chance of keeping temperatures below this 1.5°C by 2100. These estimates are around 300 $GtCO_2$ higher than those of AR5 due to advances in understanding and scientific methods.

The main sources of uncertainty around these central budget estimates are related to the temperature response to $CO_2$ and non-$CO_2$ emissions (+/- 400 $GtCO_2$) and the level of historic warming[739] (+/- 250 $GtCO_2$). Furthermore, Earth System feedbacks (such as release of $CO_2$ and methane from permafrost thawing) could reduce this budget further, out to 2100 (-100 $GtCO_2$ best estimate).

The remaining carbon budget estimate is also affected by the chosen measure of global temperature. AR5 budget estimates were based on mean surface air temperature (SAT). Using an alternative measure (Global Mean Surface Temperature – GMST, which includes the surface temperature of the ocean itself, not just the near surface air temperature) increases the central estimates to 1320 $GtCO_2$ for a 66% chance of keeping the temperature increase below 2°C and 770 $GtCO_2$ for 1.5°C (also 50% chance). Either temperature measure (GMST or SAT) is equally correct in scientific terms. With ocean water surface temperature warming a little less fast than air temperature, temperature measured by SAT is consistently around 0.1°C higher than GMST[740]. This means that warming of 1.5°C measured as GMST is equivalent to 1.6°C when measured as SAT. While the scientific literature uses both measures, the 1.5°C Special Report uses predominantly GMST.

In addition to the above factors, the remaining carbon budget is affected by future levels of non-$CO_2$ emissions. The 1.5°C Special Report estimates that this could alter the budget estimate by 250 $GtCO_2$ in either direction (based on a range of scenarios). It is important to note that, unlike the scientific uncertainties described above, this variation can be thought of as a (global) policy choice since it is influenced by mitigation action. More mitigation of non-$CO_2$ gases (such as methane and nitrous oxide) can increase the carbon budget.

A quantitative estimate of all these variations and uncertainties is presented in Table 2.2 of the IPCC Special Report on Global Warming of 1.5°C.

These estimates are assuming a 2°C or 1.5°C peaking temperature. More uncertainty is added in case of temporary exceedance of the carbon budget for a given warming threshold, followed by net negative emissions to bring cumulative $CO_2$ emissions back to within the carbon budget and reduce temperatures to below 2°C or 1.5°C. This greater uncertainty is due to knowledge gaps on ocean thermal and carbon-cycle inertia in a context of decreasing $CO_2$ atmospheric concentrations.

### *7.4.2 Emission pathways in light of the IPCC Special Report on 1.5°C*

The IPCC Special Report on 1.5°C finds that if all anthropogenic GHG emissions were reduced to zero immediately, any further warming beyond the 1°C already experienced would likely be less than 0.5°C[741]. However, given that this scenario is not realistic, it is necessary to consider which emissions reduction pathways are consistent with the remaining emissions budget for

[738] http://report.ipcc.ch/sr15/pdf/sr15_spm_approved_trickle_backs.pdf
[739] IPCC estimates warming in the period 2006-15 to be 0.87°C above the level of 1850-1900 but with a likely range of +/- 0.12°C.
[740] See Section 1.2.1.1 of the IPCC 1.5°C Special Report for details
[741] See Chapter 1 of the IPCC Special Report on Global Warming of 1.5°C

limiting warming to well below 2°C or 1.5°C – including pathways that rely on negative emissions technologies to compensate for residual GHG emissions or correct temporary temperature overshoots.

The Special Report's revised central estimates of the carbon budget are around 300 $GtCO_2$ higher than assessments made in AR5 due to methodological improvements. Since the revised carbon budget estimates of IPCC Special Report on 1.5°C are based on extremely recent literature[742], most global and regional emissions reduction pathways are based on approaches consistent with AR5 estimated budgets rather than the budgets of the Special Report. This includes those produced by the JRC and Netherlands Environmental Assessment Agency in the context of this document (see section 7.3).

New assessment of the literature on both budgets and pathways is expected to begin immediately, to inform the publication of the IPCC's sixth Assessment Report in 2020-2022. Once the revised budget estimates of the IPCC Special Report on 1.5°C are taken into account, new pathways may indicate that it is possible to remain consistent with well below 2°C or 1.5°C while reducing emissions more slowly than AR5-based pathways might indicate, or more importantly that maintaining the same short-term pace as AR5-based pathways could reduce the need for net negative GHG emissions later this century.

For instance, a recent study by Kriegler et al. (2018)[743] compares for different budget estimates how they could be achieved, and to which extent they can avoid temperature overshoot and/or the need to use carbon dioxide removal technologies. It finds that for 1.5°C budgets near the upper end of the revised IPCC's budget estimates[744], it may be possible to achieve these with emission pathways without carbon dioxide removal technologies, but only if the steepest possible global emissions reduction are pursued.

Even in the absence of updated projections, it is clear that there are no grounds for complacency. To place the IPCC Special Report on 1.5°C budget revisions in context, 300 $GtCO_2$ is equivalent to around 8 years of current global emissions, and any central budget estimate is subject to an uncertainty range of at least this magnitude in either direction. Therefore, the precautionary case for faster reductions is compelling. A budget increase of 300 $GtCO_2$ could postpone the necessary timing of global net zero emissions by 1-2 decades at most and would not postpone the more immediate task of reducing emissions compared to today's levels. In a scenario where all countries achieve only their NDC pledges under the Paris Agreement, even the IPCC's largest central estimate of the likely 2°C budget would be exceeded at around 2050 and the new 1.5°C budget (50% likelihood) of the IPCC would be exceeded well before 2040[745].

## 7.5 The specificities of methane emissions and other short-lived climate pollutants

*Short-lived and long-lived climate pollutants*

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[742] It should be noted however, that the basic science underpinning the revised estimates is not new. See for example Figure 2.3 of the IPCC Fifth Assessment Report, Synthesis Report.

[743] Kriegler E, Luderer G, Bauer N, Baumstark L, Fujimori S, Popp A, Rogelj J, Strefler J, van Vuuren DP. 2018 Pathways limiting warming to 1.5°C: a tale of turning around in no time? Phil. Trans. R. Soc. A 376: 20160457. http://dx.doi.org/10.1098/rsta.2016.0457

[744] The study finds that for budgets of 650 $GtCO_2$ and higher, the steepest emissions reduction scenario can be achieved without using Carbon Dioxide Removal Technologies.

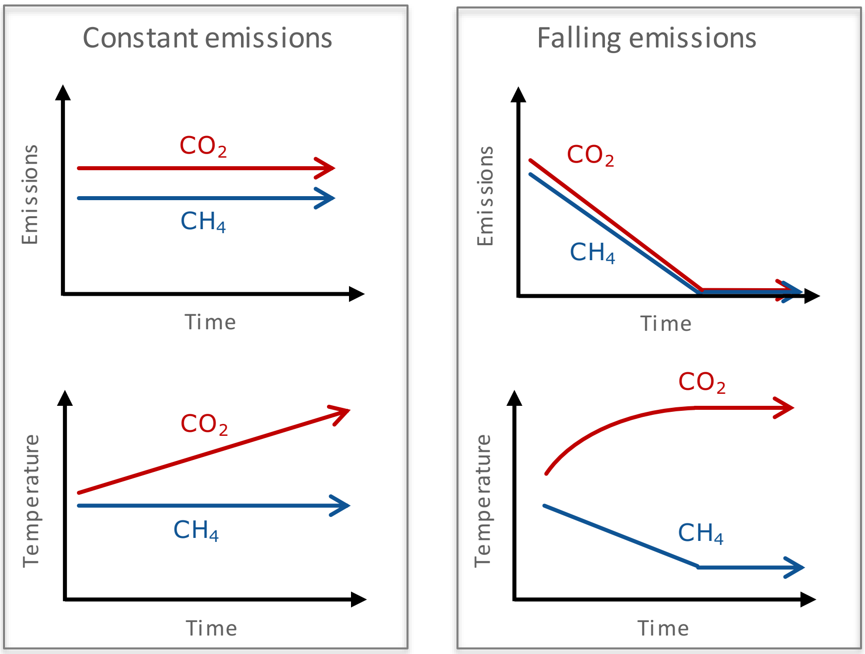
[745] Refers to the GMST-based budgets from Table 2.2 of the IPCC Special Report on 1.5°C. 1320 $GtCO_2$ for 66% chance of 2°C and 770 for 50% chance of 1.5°C. See also Section 7.4.1.

The warming potential of a GHG varies according to the characteristics of the gas. Warming potential of a gas is determined by two main factors: the intensity of the near-instantaneous radiative forcing, and its time of residence in the atmosphere. Both factors differ significantly across greenhouse gases. To illustrate, one molecule of methane causes instantaneous radiative forcing an order of magnitude stronger than $CO_2$, but it remains in the atmosphere for a much shorter time (around a decade). Most of the HFCs, who behave similarly, and methane are therefore called *short-lived climate pollutants* (SLCP). By contrast, gases that remain in the atmosphere for much longer period, often centuries and even millennia such as $CO_2$, $N_20$, $SF_6$, $NF_3$, as well as some HFCs and PFCs are called *long-lived climate pollutant* (LLCP).

*Responsiveness of temperature on SLCP and LLCP emissions reduction*

Reductions in the level of SLCP emissions lead to fast drops in concentrations, thus translating into relatively fast decreases in additional warming. By contrast, even if emissions of LLCPs stop, these gases remain in the atmosphere for a significant period of time. Consequently, the warming effect of past emissions continues for a long time (Figure 132).

**Figure 132: Temperature response to $CO_2$ and $CH_4$ emissions**




*Source: Adapted from Allen et al. (2017)*[746].

The Global Warming Potential 100 (GWP100) is the most used metric to compare the warming potential of different GHGs over a period of 100 years. GWP100 as used in the 4th Assessment Report of the IPCC is also the metric used in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. As such, GWP100 is the most common metric used in policy: parties, including the EU, that committed to NDCs with explicit GHG reduction targets under the Paris Agreement for a basket of GHGs have done so typically using GWP100 as the metric to aggregate and compared GHG emissions and reductions.

[746] Allen et al. (2017), Climate metrics under ambitious mitigation, Oxford Martin School, briefing November 2017.

GWP100 is defined as the sum[747] of radiative forcing over a time horizon of 100 years of one kilogram of a certain gas emitted today, relative to the accumulated radiative forcing of one kilogram of $CO_2$ emitted today over this same 100 year time period[748].

By definition, the GWP of $CO_2$ is therefore always one. The cumulative radiative forcing of methane ($CH_4$) as defined in the 4th Assessment Report of the IPCC is 25 times higher than of $CO_2$, but most of the radiative forcing occurs early in the 100 year time period used for the assessment. By con²trast, the radiative forcing caused by $CO_2$ is more constant. Furthermore, parts of the $CO_2$ remain in the atmosphere beyond the 100 year time horizon. If the GWP were to be estimated for a shorter period of time, then the cumulative radiative forcing of $CH_4$ compared to $CO_2$ would be significantly higher in relative terms: 72 times for a 20 year period in the 4th Assessment Report of the IPCC (see table below).

**Table 29: Lifetimes, radiative efficiencies and GWPs relative to $CO_2$ as presented in the IPCC 4th Assessment report.**

| **Chemical Formula** | **Lifetime (years)** | **Radiative Efficiency (W m–2 ppb–1)** | **Global Warming Potential for Given Time Horizon** | | |
|---|---|---|---|---|---|
| | | | **20-yr** | **100-yr** | **500-yr** |
| $CH_4$ | *12* | 0.00037 | *72* | *25* | *7.6* |
| $N_2O$ | *114* | 0.00303 | *289* | *298* | *153* |
| **Selected number of Hydrofluorocarbons** | | | | | |
| HFC-134a | *14* | *0.16* | *3830* | *1430* | *435* |
| HFC-143a | *52* | *0.13* | *5890* | *4470* | *1590* |
| **Selected number of Perfluorinated compounds** | | | | | |
| $SF_6$ | *3200* | *0.52* | *16300* | *22800* | *32600* |
| $NF_3$ | *740* | *0.21* | *12300* | *17200* | *20700* |
| PFC-14 | *50000* | *0.10* | *5210* | *7390* | *11200* |

*Source: Based on IPCC, 4th Assessment report, Working Group I, Section 2.10, table 2.14.*

GWP100 therefore tends to overestimate the temperature response in the long run of the current emission of a SLCP compared to an emission of a LLCP. However, the converse also holds: GWP100 tends to underestimate the temperature response in the short term of an emission today of a SLCP compared to an emission of a LLCP.

The choice of time period to assess warming potential has policy implications. If the primary concern is to stabilise temperature change in the long run, e.g. by the end of this century, then a reducing in annual emissions of SLCPS today has a similar effect to a reduction in a couple of decades, as long as this shift to annual emissions reduction has taken place by somewhere the second half of the century.

However, such flexibility does not exist for LLCPs such as $CO_2$ for which temperature impacts being determined by the cumulative emissions, including the emissions of the past. If the cumulative emissions are too high to reach a certain temperature goal, then only active removal

[747] Technically it is rather the integral of radiative forcing over time.

[748] IPCC (2007) Fourth Assessment Report https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

of these LLCPs from the atmosphere will lead to the achievement of a certain temperature goal within the century. That is why many projections require net negative $CO_2$ emissions in the second half of the century to compensate for excessive $CO_2$ emissions in the past.

These difference in warming potential might result in the conclusion that all focus in the short term should be to reduce LLCPs rather than SLCPs, to avoid the need for negative emissions later on where possible. Such a conclusion would, however, be short-sighted. Several reasons can be put forward to explain this:

First, with temperatures already up by over 1°C, there is a serious risk of overshooting temperature goals. This danger looms particularly large for the 1.5°C goal for which most projections already assume some level of overshoot of temperatures during this century. Reducing SLCPs as soon as possible can contribute to avoiding these overshoots, or to limit their magnitude. Second, a reduction of emissions like $CH_4$ - for instance, from sectors like agriculture, the energy system and the waste management system - will require a sustained effort over time, and can benefit from behavioural changes, all that cannot be achieved in a short amount of time. Third, any remaining emissions of SLCP like $CH_4$ will continue to have a warming impact. So the lower they eventually become, the lower their warming impact by the end of the century, but also the larger the remaining allowed cumulative budget for LLCPs becomes. Finally, some SLCPs are air pollutants or air pollutant pre-cursors and their reduction will lead to improvement of air quality.

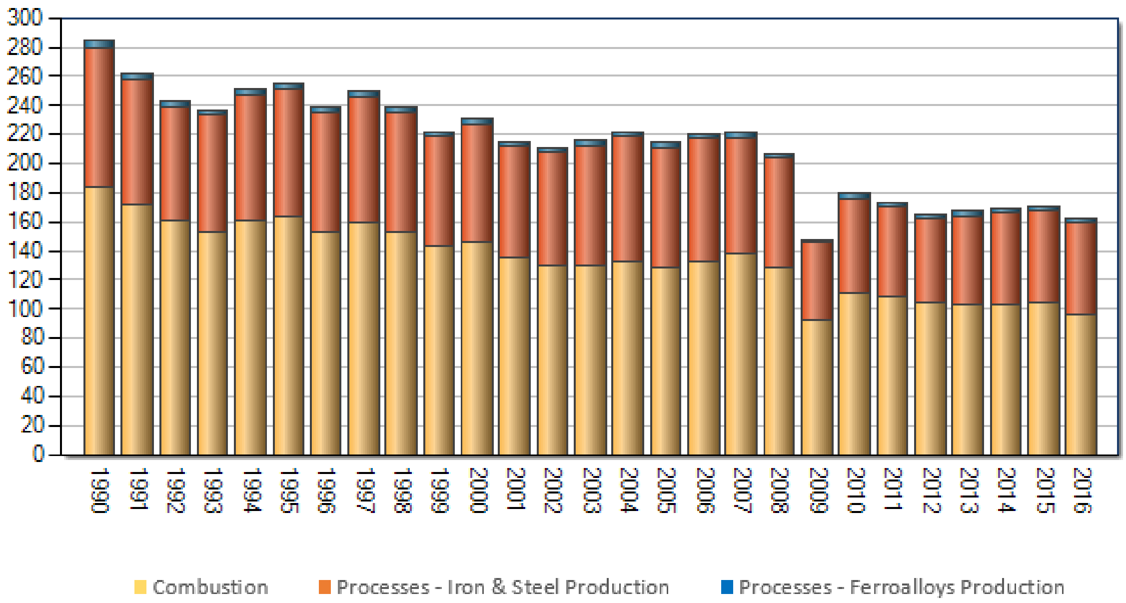
A number of stakeholders have argued that the GWP should be adjusted towards a 20 year time horizon and to thereby focus more mitigation effort on methane. Such a change would increase the relative importance of methane in our policy framework - but would also provide a metric that, in relative term, would downgrade the need to reduce LLCPs like $CO_2$. While no metric can perfectly capture the differences in temperature dynamics between GHGs over time, GWP100 is a transparent and well-known metric which provides a relatively good representation of the importance of the different gases for the achievement of our temperature goals and the perspective of the Paris agreement. The assessment as undertaken in this report is therefore using the GWP100 metric.

## 7.6 Sectoral Industry Transformation

### *7.6.1 Iron & Steel*

As an energy-intensive industry, the European steel industry accounted in 2016 for about 7% of the verified emissions of all stationary installations of the European Union and around 22% of industrial emissions excluding combustion (Figure 133).

**Figure 133: EU28 Historical GHG Emissions for Iron & Steel Sector (in $MtCO_2eq$)**




*Source: EEA*[749].

Steel making consists of two main processing routes, each having about equal share in the steel making process in Europe: primary steel making (60% share), based on the iron ore reducing process in a blast furnace (BF), and secondary steel re-melting (40% share), either using direct reduced iron or scrap metal in an electric arc furnace (EAF). The majority of the emissions come from the iron reduction process, where there is a chemical reaction between carbon and iron ore, producing molten iron, which is then converted to steel. Therefore the two main methods to decarbonise steel is either to increase the use of secondary steel making route, which can be even almost carbon free in the case of low carbon electricity generation, or to reduce the carbon intensity of the BF route.

The efforts so far to reduce the emissions from the BF route have mainly focused on resource efficiency (energy and material), as well as improved process control. Therefore the additional potential for improvement through technological improvements (mainly via energy efficiency) of the specific process are diminishing.[750]

In general, studies[751] [752] indicate that without direct reduced iron (DRI) or CCS and CCU, the shift away from BF to EAF (using scrap metal) can lead to sector emissions reduction around 25-30% compared to 2010[753]. In the cases of hydrogen, electrolysis or CCS and CCU the reductions can be much higher. One of the alternatives for deep decarbonisation so far seems to be the

[749] https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer
[750] ICF (2015), Study on Energy Efficiency and Energy Savings Potential in Industry and on Possible Mechanisms, https://ec.europa.eu/energy/sites/ener/files/documents/151201%20DG%20ENER%20Industrial%20EE%20study%20-%20final%20report_clean_stc.pdf
[751] Boston Consulting Group (2013), Steel's Contribution to a low-carbon Europe 2050 https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050.aspx
[752] Otto et al. (2017), Power to Steel: Reducing $CO_2$ through the integration of renewable energy and hydrogen into the German Steel Industry, https://doi.org/10.3390/en10040451
[753] A maximum share of 44% for EAF is assumed in the Roadmap of the Steel Industry.[751]

replacement of BF route by EAF using DRI,[754] reducing the carbon intensity of the specific process by 30-36% when based on conventional methods and fuels.[751 755]

If the DRI is produced via either hydrogen or electrolysis iron ore reduction it allows for electrification of the most energy-intense step in iron making[756], leading to reductions up to 85-95%.[757 758] However, it has to be noted that nowadays, due to the high cost of gas, there is very limited production of DRI in Europe, that has therefore to be imported; in addition most of EAF in Europe requires the use of DRI in combination with scrap metal.

There are currently three projects on hydrogen-based steelmaking announced in the EU: HYBRIT, SALCOS and H2Future/Susteel. While the first two aim at using today's available direct reduction technology, the H2Future project plans to use the plasma smelting reduction technology. These technologies do not require the use of CCS and CCU as $CO_2$ emissions are avoided.

Another alternative is to combine a technology using natural gas with CCS. This has the potential to significantly bring down steel's emissions and reductions to around 80%, for example with the deployment of technologies like HIsarna (smelting reduction) or ULCORED (direct reduction) – both connected to CCS (or CCU).

The shift from primary steelmaking to secondary smelting of steel scrap depends on various factors, including the availability and quality of scrap metal within the EU market and on the quality of the final product[759]. Europe has a large stock of steel, nevertheless there are many factors that significantly reduce the amounts of steel that can be recycled, most importantly low collection rates, losses in the processes, downgrading of steel and copper contamination.[760] Moreover, increasing amounts of scrap have been exported from the EU with the subsequent loss of potential resources.[761]

These issues can be resolved to a large degree by improving circular economy practices, thus significantly increasing the availability of scrap, so that the secondary route can increase its share from around 40-45% today up to 85% in 2050, according to some studies[762]. The combination of these measures can reduce the emissions of the sector by around 75%, as primary production would continue to serve the rest of demand. Demand side measures in the context of the circular

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754 DRI can be considered as a source of clean iron units that can be used both in the EAF and the BF route.

755 European Commission (2018), European Steel. The Wind of Change, https://publications.europa.eu/en/publication-detail/-/publication/fb63033e-2671-11e8-ac73-01aa75ed71a1/language-en.

756 Under the ULCOS program, supporting low-energy primary steel making, this is known as ULCOWIN and ULCOLYSIS.

757 EUROFER (2014), A Steel Roadmap for a low carbon Europe 2050, http://www.nocarbonnation.net/docs/roadmaps/2013-Steel_Roadmap.pdf

758 ECOFYS & Fraunhofer ISI (2018), Impact on the Environment and the Economy of Technological Innovations for the Innovation Fund (IF), https://publications.europa.eu/en/publication-detail/-/publication/669226c7-b6ff-11e8-99ee-01aa75ed71a1/language-en/format-PDF/source-77120765

759 Today the secondary steel melting of steel scrap is mainly used for relatively basic construction steels, which can tolerate a less precise composition.

760 According to BCG (2013)[751] the maximum share of scrap steel based on current practices is 44%. This is also related to the contaminants that are present in the scrap steel, which make the steel produced from recycled steel of lower quality than virgin steel.

761 Iron and steel is the most traded waste and scraps by mass. In 2016 about 18 million tons were exported by the EU, 3 million were imported and 27 million were traded among EU Member States. See indicator 18 in the Raw Materials Scoreboard (http://rmis.jrc.ec.europa.eu/?page=scoreboard#/ind18).

762 Material Economics AB (2018), The Circular Economy, http://materialeconomics.com/latest-updates/the-circular-economy

economy could then further reduce steel produced by the primary route, like increased use of aluminium in manufacturing and reduction of the number of circulating cars due to transport becoming a service.[763]

The main technological pathways, with projects under development, emissions reduction and market entry are summarised in Table 30:

**Table 30: Low Carbon Projects under development in Iron & Steel**

| Technology option | Examples | TRL | Max. emissions reduction | Market entry |
|---|---|---|---|---|
| **DRI RES-H2** | HYBRIT, GrINHy, H2Future, SuSteel, SALCOS | 7 | up to 80% | 2030/2035 |
| **DRI RES-Electrolysis**[764] | SIDERWIN, ULCOWIN | 6 | up to 90% | 2025/2030 |
| **Bath smelting**[765] | HIsarna | 5-6 | up to 20% | 2025[e] |
| **Top gas recycling**[766] | ULCOS-BF, IGAR | 7 | up to 30% | 2020/2025 |
| **Carbon capture and usage** | Carbon2Chem, Steelanol | 5-7 | case specific: an LCA is needed for each project to determine the GHG reduction potential. | 2025/2030 |
| **Near net shape casting** | Castrip, Salzgitter, ARVEDI ESP | 8-9 | up to 60% | 2015 |

*Source: Ecofys & Fraunhofer ISI* [758 767].

Overall, studies performed for the Iron & Steel Sector indicate a large range of possible GHG reductions.[768] The roadmap commissioned by the steel industry[769] reports possible reductions ranging between 10% and 36% by 2050 compared to 2015[770], but without the use of CCS or CCU. The inclusion of the latter options could further increase the reductions to 60%, under certain limiting assumptions. Other breakthrough solutions, like the direct use of hydrogen, were not considered in that roadmap.

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[763] In the context of a circular economy, the reductions in demand could possibly reach the point where the available scrap steel would be able to cover most of the demand.

[764] SALCOS can also operate with a mixture of H2 and natural gas, with TRL 7-9, emissions reduction up to 95% and expected market entry 2020/2025.

[765] Higher potentials with CCU/S: up to 80%.

[766] Higher potentials with CCU/S. up to 60%.

[767] An updated version of the table can be found in the forthcoming report: ICF & Fraunhofer ISI (2018), Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis, forthcoming

[768] Umweltbundesamt (2018), Comparative analysis of options and potential for emission abatement in industry, https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-07-16_climate-change_19-2018_ets-7_analyse-minderungspotenzialstudien_fin.pdf

[769] Boston Consulting Group (2013), Steel's Contribution to a low-carbon Europe 2050 https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050.aspx

[770] Own estimate based on the results of the study.

The analysis performed by PRIMES has a more positive view on the possible reductions in iron and steel. In the case of the scenarios achieving 80% GHG reduction, the energy related $CO_2$ emissions in iron & steel are projected to decrease between 81% (in the EE scenario) up to 92% (in the H2 scenario) compared to 2015. The 1.5°C scenarios are projected to deliver even higher emissions reduction up to 97% (see Table 31).

**Table 31: Total $CO_2$ emissions reduction in Iron & Steel by 2050 compared to 2015**

| Iron & Steel | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **Total $CO_2$ Emissions** | -60% | -88% | -92% | -88% | -82% | -91% | -90% | -97% | -97% |

*Source: PRIMES.*

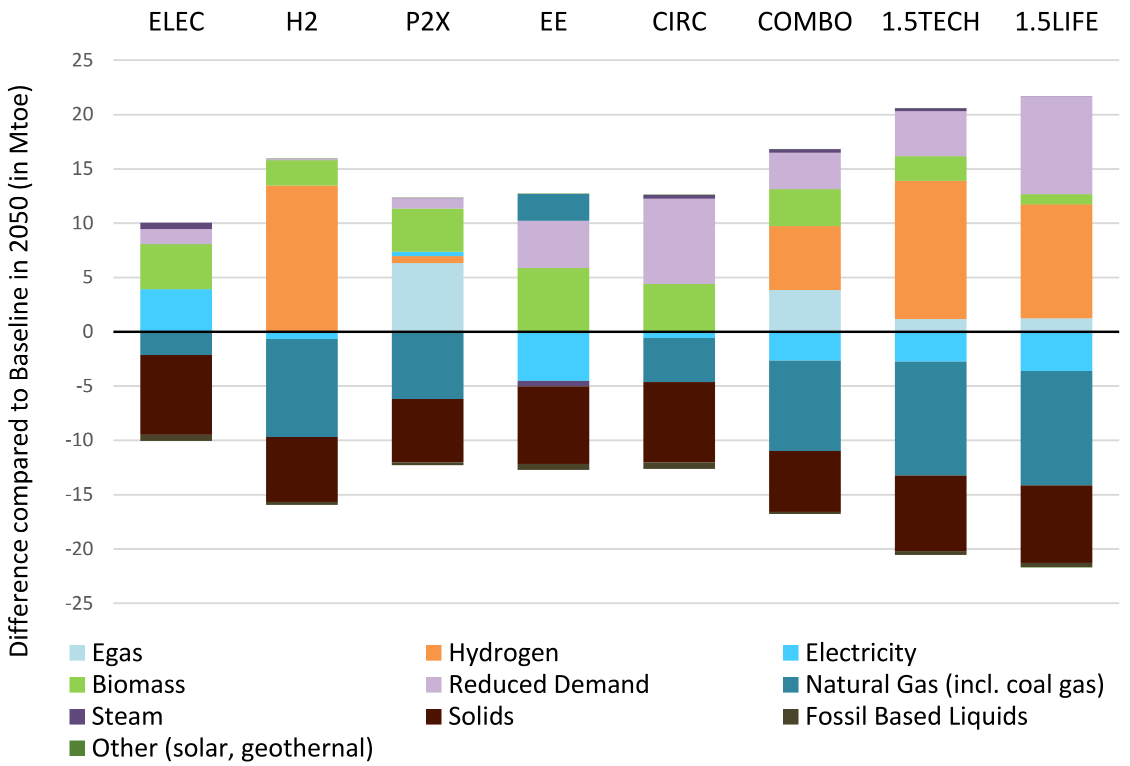
Figure 134 shows the different energy mixes in the scenarios compared to the Baseline. The sector had a final energy consumption of around 50 Mtoe in 2015[771] and a projected demand in Baseline of 42 Mtoe in 2050, out of which 14 Mtoe of electricity, 9 Mtoe of natural gas, 9 Mtoe of biomass and 8 Mtoe of solid fossil fuel.

The Baseline achieves the GHG emissions reduction by switching to less carbon intensive fuels in energy combustion, notably from solids to biomass and electrification to a certain extent, as well as by reducing energy demand by further improving energy efficiency.

The scenario results confirm, as for most industries, that several alternative options exist for this sector in the context of the -80% ambition, with solids almost eliminated from the fuel mix. The direct use of hydrogen together with circular measures that would increase the availability of scrap metal and thus the use of the secondary production are the solutions deployed additionally for achieving net zero GHG emissions reduction.

[771] Source: Eurostat

**Figure 134: Differences in final energy consumption in Iron & Steel compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

The complementary bottom-up analysis using FORECAST leads to similar conclusions as with PRIMES[772]. The GHG emissions reduction compared to 2015 for the 80% ambition scenarios range between 69% (BioCycle Scenario, the weakest scenario to deliver the desired emission reductions) up to 88% (CleanGas scenario), with the Mix80 scenario delivering 88% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 96% reductions (see Table 32).

**Table 32: Total GHG emissions reduction in Iron & Steel by 2050 compared to 2015**

| Iron & Steel | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Energy related GHG emissions (without CCS)** | -56% | -88% | -70% | -84% | -88% | -97% |
| **Process GHG emissions (without CCS)** | -37% | -80% | -57% | -80% | -84% | -91% |
| **Total GHG emissions (with CCS)** | -85% | -88% | -69% | -83% | -88% | -96% |

*Source: FORECAST.*

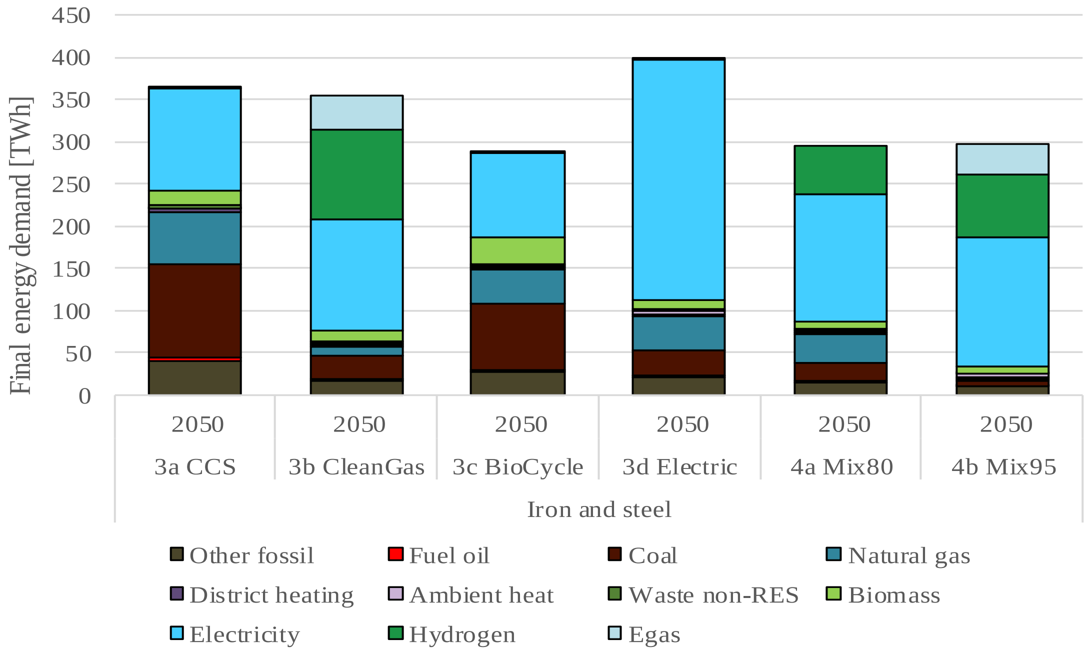
The drivers for GHG emissions reduction in the FORECAST scenarios are listed below. Figure 135 presents the final energy demand by process, showing the move from the BF route to EAF and other technologies under development today.

[772] Considering always the differences between the two models and the scenario approach followed in each case.

- For all scenarios energy efficiency innovations (near net shape casting, top-gas recycling) and faster increase of EAF (mainly used for construction steel).
- CCS allows retaining current fuel mix (with less coal due to energy efficiency) with a slightly increased role for biomass. About 54 $MtCO_2$ are captured and stored in 2050.
- In CleanGas, reductions are achieved by hydrogen based direct reduction replacing 88% of the BF steel production route and the consumption of distributed gas, which is assumed to have only 20% of conventional gas.
- BioCycle foresees significant amounts of biomass used for co-firing, high quality EAF allowing shares for new products, reinforced steel, material efficiency and substitution (steel replaced by biomass-based products in construction).
- In Electric, about 80% of conventional BF production in 2050 is substituted by direct reduction based on electrolysis (assumed to be available after 2030).
- Mix80 combines the solutions of carbon free steel (via hydrogen based direct reduction, plasma and electrolysis steel) with recycling and material efficiency solutions of BioCycle (less ambitious though).
- Mix95 builds on Mix80, fully replacing BF steel by the alternative routes (instead of just 80-90%) combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid.

Scenarios CleanGas, Electric, Mix80 and Mix95 report a significant increase in electricity consumption, either for the production of hydrogen or due to the increased used of the EAF route. Compared to 2015, where electricity consumption was around 115 TWh, electricity production for direct use may more than double, ranging between 100 TWh for BioCycle up to 282 TWh in the case of Electric. The more balanced scenarios Mix80 and Mix95 report consumption around 150 TWh. Accounting also for the electricity required for the production of feedstocks, clean gas and hydrogen, electricity consumption increases exponentially, reaching 1,064 TWh for CleanGas, 690 TWh for Electric and Mix95 and 550 TWh for Mix80.

**Figure 135: Final energy demand in the iron & steel industry by energy carrier (excluding production of feedstocks, clean gas and hydrogen)**



*Source: FORECAST.*

The identified solutions imply certain challenges.[757] Most of the technologies discussed in this section for deep decarbonisation have a low technology readiness level (TRL), thus more R&D will be required before commercialisation of these technologies. For the shift from the BF route, existing facilities will need to be replaced by new plants, while - since these plants will be mostly electrified - a very high share of carbon-free electricity is necessary to deliver the high emissions reduction. The transformation to nearly zero steel making is possible, see for example Figure 140, but it will take time and determination, starting from now, and spreading the technologies across the sector, so the total steel production is nearly zero carbon in 2050. As for the increased recycling and other circular economy measures, concentrated policies across Europe will need to be introduced.

**Figure 136: Staged transformation of a steel plant to hydrogen reduction and electric arc furnace through use of natural gas in transition stages in SALCOS**


*Source: SALCOS*[773].

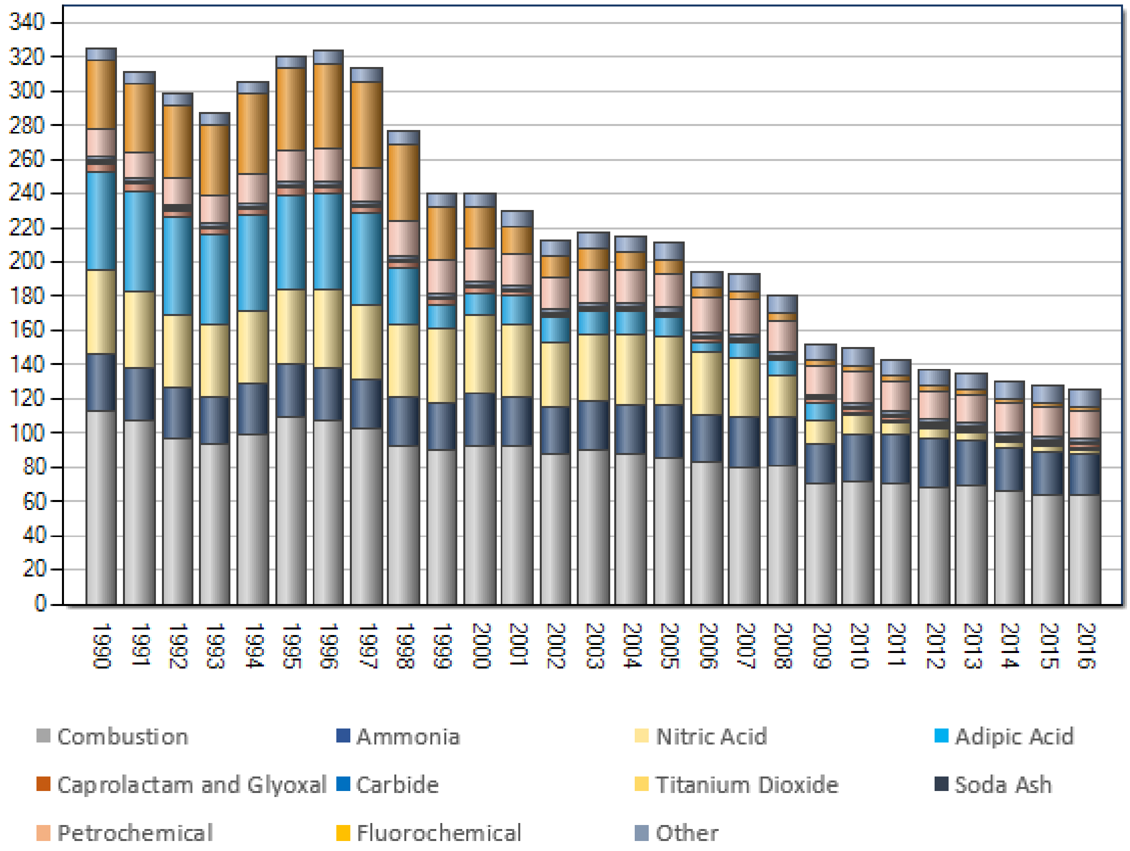
At the same time this transition presents significant opportunities for the industry, as it can further modernise, reducing its costs along with its carbon intensity. The replacement of older plants could allow for opportunities of industrial symbiosis e.g. with chemical industries for the production of plastics or fertilisers, in which case application of CCS or CCU could provide economic co-benefits.

[773] https://salcos.salzgitter-ag.com/. SALCOS plans to proceed in stages: (Status quo) add a natural gas based direct reduction plant for iron ores to the actual plant layout at the integrated site in Salzgitter. The direct reduced iron from this plant is to be fed to the existing blast furnaces ($CO_2$ reduction: 10%, as natural gas used for reduction has a certain amount of hydrogen content). (Stage 1a and b) Additionally, large amounts of hydrogen may be fed to the process, replacing the needed natural gas partly. The hydrogen will be produced via electrolysers operated with power from renewable resources. ($CO_2$ reduction: 18%). (Stage 2) Addition of an electric arc furnace plant, to be fed with the direct reduced iron from the then already existing direct reduction plant ($CO_2$ reduction: 26%). (Stages 3a and 3b) Further steps are principally based on the same approach as the steps before, leading to the complete transformation of steelmaking from the blast furnace/basic oxygen technology to direct reduction/electric arc furnace route in the decades to come. The maximum $CO_2$ reduction possible by the SALCOS concept in this ultimate configuration is 95%.

### 7.6.2 *Chemicals*

The European chemicals industry accounted in 2016 for around 4% of the verified emissions of all stationary installations of the European Union and 14% of industrial emissions excluding combustion[774] (Figure 137).

**Figure 137: EU28 Historical GHG Emissions for Chemicals Sector (in MtCO$_2$eq)**




*Source: EEA.*

Chemicals is a very complex, wide and diverse sector, with even more diverse subsectors. The petrochemical and the basic inorganic subsectors produce the organic (olefins, alcohols, aromatics) and inorganic (ammonia, chlorine) building blocks for the chemical industry. The polymer (plastics) and specialty chemical (paints, dyes) subsectors produce intermediate or end user products, while the consumer chemicals (soaps, cosmetics) are sold to end customers.[775] Petrochemicals, basic inorganic and polymer subsectors account for roughly 70% of the sectors GHG emissions, and therefore these are the subsectors most studies focus upon.

Analysis for this report and other studies[750 775 776 777] indicate that energy efficiency improvements and fuel switching can reduce significantly emissions in 2050 compared to 2010 by 55-60%, largest share of reductions coming from fuel switching[778].

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[774] Some chemical company data are reported under the fuel combustion category; hence, actual emissions of the chemical industry may be higher.

[775] ECOFYS & CEFIC (2013), European Chemistry for Growth, http://www.cefic.org/Documents/RESOURCES/Reports-and-Brochure/Energy-Roadmap-The%20Report-European-chemistry-for-growth.pdf.

[776] JRC (2017), Energy Efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry,

Deeper emissions reduction are also technically possible, 85% or even above, but would require change of feedstock, application of CCS and CCU technologies and increased recycling. In particular, the lower use of fossil-based feedstock, replaced by the use of hydrogen, bio-based material and recycled materials, show strong potential for emissions reduction. Although many new business opportunities are created, at the same time significant investments would be needed so that industrial plants could adapt to this business model.

The potential of bioeconomy is not clear, with conflicting evidence. Bio-based ammonia and methanol production may not have a high potential, unless low cost e-gas is available, contrary to the bio-based production of cracker products (from naphtha to e.g. bio-ethanol), assuming though increased availability of sustainable biomass in Europe.[775] [779] [780] On the other hand, the use of low carbon hydrogen and $CO_2$ as feedstock for the production of low-carbon methanol shows strong potential for emissions reduction, but has a number of pre-requisites including wide availability of affordable renewable energy.[750] [781]

It is particularly worth highlighting the importance of improved recycling of plastics. Today only 60% of plastics is recovered in average in Europe, with 60% used for energy recovery purposes. Plastic waste can be significantly reduced by increasing the mechanical and feedstock recycling[782] up to 60-70% of yearly plastic waste volumes.[762] [780] Another study finds that out of the 106 Mt of chemicals delivered to customers, up to 60% can be recycled and re-used.[783] This would require standardisation, improved collection and sorting and would result in both more limited use of raw material (of fossil origin)[784], as well as less energy, since recycled plastic is a less energy demanding process. As a result a cascading use of plastics would be introduced, with downgrading (with mechanical recycling) or upgrading (with feedstock recycling) or after the plastics have degraded to energy recovery.

Moreover the chemical industry can be an ideal consumer of the $CO_2$ produced in its own processes or from other industrial sectors (iron & steel, cement, refineries), leading to the avoidance of emissions if embedded in long lived material or at least the reduced use of fossil fuel[777]. As an example the production of methanol from hydrogen and $CO_2$ is identified as a beneficial option, assuming that it is economic in the future. Certain studies calculate the potential for capturing and storing or using $CO_2$ to 90% for petrochemicals, basic inorganics and polymers and 75% for specialty and consumer chemicals.[775]

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https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/energy-efficiency-and-ghg-emissions-prospective-scenarios-chemical-and-petrochemical

[777] Dechema (2017), Low carbon energy and feedstock for the European Chemical Industry, https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf

[778] According to [750], the economic potential of energy efficiency is much lower than the technical one.

[779] In EU the two main bio=based materials available for the production of bio-chemicals are straw and forest products.

[780] ECOFYS & Berenschot, 2018, Chemistry for Climate, https://www.vnci.nl/Content/Files/file/Downloads/VNCI_Routekaart-2050.pdf

[781] Ramboll (2018), Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, forthcoming, https://ec.europa.eu/clima/events/stakeholder-event-carbon-capture-and-utilisation-technologies-technological-status_en

[782] Mechanical recycling refers to the mechanical processing of waste plastics to produced recycled polymers. Feedstock recycling refers to the chemical or thermal processes breaking down polymers into products that can directly replace raw material.

[783] Accenture (2017), Taking the EU chemicals industry into the circular economy, https://www.accenture.com/us-en/_acnmedia/PDF-45/Accenture-CEFIC-Report-Exec-Summary.pdf

[784] According to [775], EU production of polymers could reduce by 7%

The main technological pathways in the chemicals sector, with projects under development, emissions reduction and market entry are summarised in Table 33:

**Table 33: Low Carbon Projects under development in Chemicals**

| Technology option | Examples | TRL | Max. emissions reduction | Market entry |
|---|---|---|---|---|
| **CCU – Methanol** | Carbon International Iceland | 6-7 | Eliminates (almost) all emissions, if renewable power is used and depending on the (accounting of the) source of $CO_2$, and the energy used to capture the $CO_2$. | 2030[785] |
| **CCS for ammonia** | Capturing of process emissions from syngas production already happening. | 6-7 | (Almost) all process emissions, which forms typically 2/3 of the $CO_2$ emissions of ammonia production | 2025 |
| **Hydrogen based ammonia** | Renewable electricity → $H_2$, turned into $NH_3$ | 6 | (Almost) all emissions | In the near future |

*Source: Ecofys & Fraunhofer ISI* [758 767].

Many of the above potentials can be realised if chemical plants are installed together in industrial parks with plants from the chemical or other sectors, sharing their energy and material resources.[777]

Overall, studies performed for the chemicals sector indicate strong GHG reduction possibilities.[768] The most recent study by the chemicals sector[777] explored options towards a carbon-neutral future for the industry, including synergies and opportunities of industrial symbiosis with other process industries, in which the chemical industry can valorise side streams and waste from other sectors. The three scenarios assessed different ambition levels, on top of a business as usual scenario. The theoretical maximum potential identified by the industry would allow for a reduction of $CO_2$ emissions up to 210 $MtCO_2$ annually (max) in 2050 compared to 2015 (175% of $CO_2$ emissions reduction). The other two ambition levels considered corresponded to 59% and 84% of the anticipated emissions in 2050. The focus in these scenarios was mainly the utilisation of alternative carbon feedstock (mainly electrolytic hydrogen, $CO_2$ and bio-based raw materials), together with further electrification of processes and energy efficiency. A particular issue noted in the study is that the considered hydrogen based technologies require high amounts of low carbon electricity, up to 4900 TWh for the max scenario, 1900 TWh for the second most ambitious one.[786]

PRIMES projects emissions reduction along the above lines. In the case of the scenarios achieving 80% GHG reduction, $CO_2$ emissions in chemicals are projected to decrease between 64% (in the P2X scenario) up to 70% (in the CIRC scenario) compared to 2015. The 1.5°C GHG scenarios deliver negative emissions (see Table 34). These negative emissions are achieved due to a combination of additional use of CCS and the potential of $CO_2$ storage in materials. In

[785] Moderate plant already operational in Iceland.
[786] The electricity demand is mainly driven the high electricity intensity of electrolysis to produce hydrogen.

particular, the 1.5°C scenarios include the possibility of sequestering in petrochemical materials, such as plastic[787], $CO_2$ captured in the power sector (including onsite CHP plants and industrial boilers) or in industrial processes in sectors other than chemicals (this illustrates the possibilities of symbiosis in industry and the role of CCU). If biomass based, these will result in negative $CO_2$ emissions in industrial processes of the chemicals sector, as long as the plastic is not incinerated but rather re-used, recycled or landfilled.

**Table 34: Total $CO_2$ emissions reduction in Chemicals by 2050 compared to 2015**

| Chemicals | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **Total $CO_2$ Emissions** | -43% | -67% | -69% | -64% | -65% | -70% | -71% | -143% | -118% |

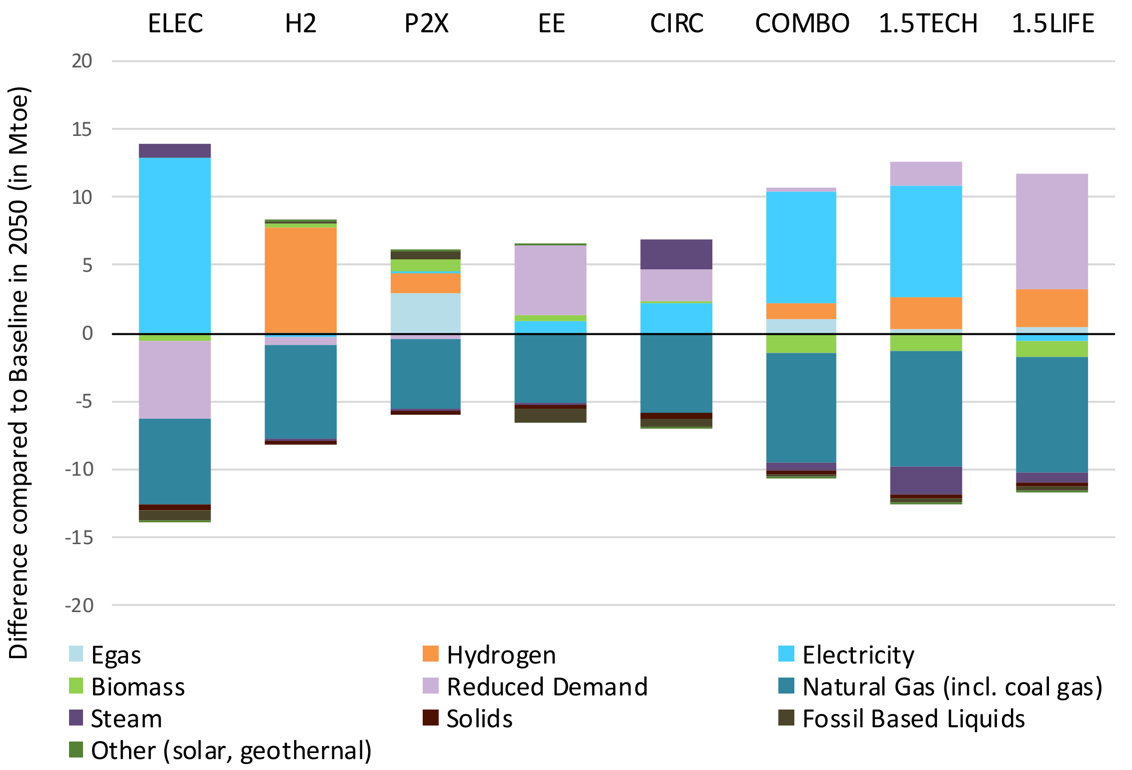
*Source: PRIMES.*

Figure 138 illustrates the differences in the fuel mix by scenario and compares to the Baseline. The Baseline achieves its GHG emissions reduction through energy efficiency, which significantly carbon intensive fuels, together with increased use of biomass. Final energy consumption drops in from 51 Mtoe in 2015[788] to 39 Mtoe in 2050 in Baseline projections, with 16 Mtoe electricity, 9 Mtoe steam, 9 Mtoe natural gas and 3.5 Mtoe biomass. In the chemicals sector also, PRIMES confirms the existence of many available options for the sector in the context of the -80% ambition, with the further reduction of natural gas appearing in all scenarios. Electrification together with demand side measures (energy efficiency, circular economy) are the deployed solutions for achieving net zero GHG emissions reduction in the PRIMES scenarios.

[787] Storage into materials may also be in minerals (through a process called mineralisation) or new materials. In the case of plastics, storage of $CO_2$ implies the re-use, recycling or landfilling of these plastics at end of life. Otherwise, their incineration would lead to $CO_2$ emissions.

[788] Source: Eurostat

**Figure 138: Differences in final energy consumption in Chemicals compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

The complementary bottom-up analysis using FORECAST leads to similar conclusions as with PRIMES, showing also the high potential of emissions reduction using CCS in chemicals. The GHG emissions reduction compared to 2015 for the 80% ambition scenarios range between 63% (BioCycle Scenario) up to 90% (CCS scenario), with the Mix80 scenario delivering 76% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 91% reductions (see Table 35).

**Table 35: GHG emissions reduction in Chemicals by 2050 compared to 2015**

| Chemicals | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Energy related GHG emissions (without CCS)** | -21% | -84% | -74% | -74% | -76% | -95% |
| **Process GHG emissions (without CCS)** | -2% | -63% | -40% | -63% | -68% | -80% |
| **Total GHG emissions (with CCS)** | -90% | -77% | -63% | -70% | -73% | -91% |

*Source: FORECAST.*

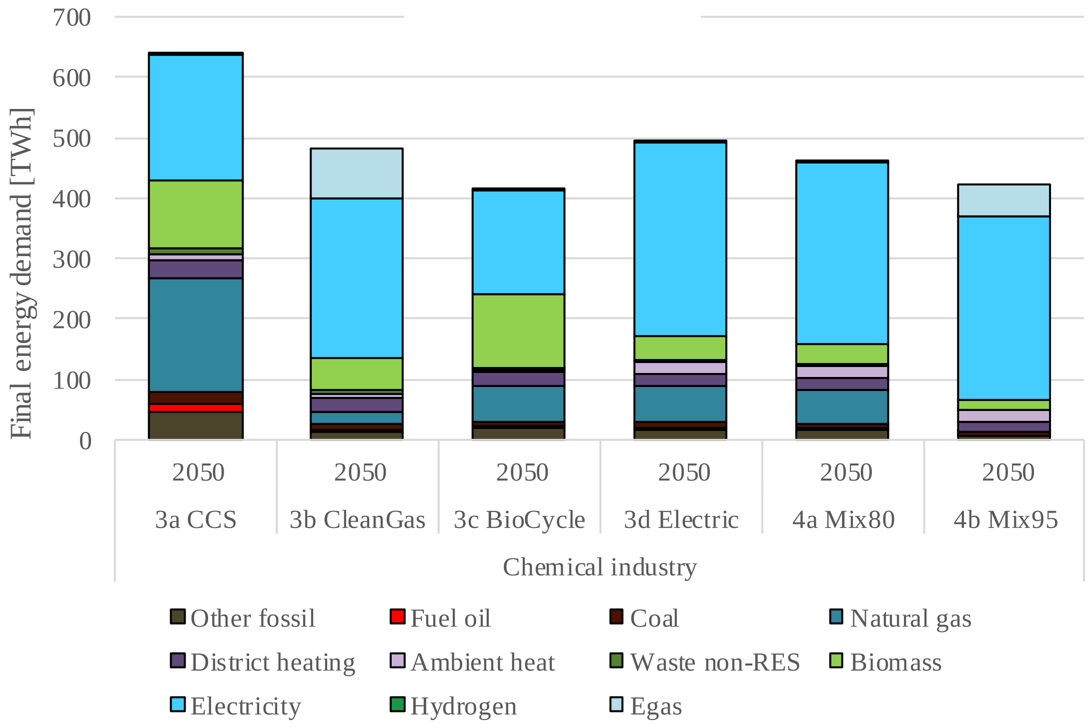
The drivers for GHG emissions reduction in the FORECAST scenarios are listed below. Figure 138 presents the final energy demand by process, showing the significant decrease in consumption in the ethylene process, some of it being permanent and some shifting mainly to methanol-based ethanol, using hydrogen (for methanol). Similarly ammonia in all scenarios, except BioCycle, is produced via the hydrogen route. In more details, it is assumed:

- For all scenarios energy efficiency innovations (for chlorine oxygene depolarised cathode, catalytic cracking of naphtha, use of selective membranes).

- In CCS natural gas is the dominant fuel, while CCS is used for ammonia, ethylene and methanol. About 85 $MtCO_2$ are captured and stored in 2050.
- In CleanGas, reductions are achieved by utilisation of alternative feedstock (hydrogen for ethylene, ammonia and methanol) and the consumption of distributed gas, which is assumed to have only 20% of conventional gas. Also CCU applications for capturing $CO_2$ to be used as feedstock with hydrogen for the production of methanol and subsequently ethylene.
- BioCycle foresees significant amounts of biomass and biogas, together with the use of biomass as a feedstock for producing methanol and subsequently ethylene. Moreover the scenario includes a number of circular economy measures (ambitious plastics recycling, bio-based plastics, substitution of plastics by bio products, reduced fertiliser demand, material efficiency).
- In Electric, use of electric boilers and electrolytic hydrogen replacing up to 80% naphtha and natural gas as feedstock for the production of ethylene, ammonia and methanol.
- Mix80 reductions are driven by combining the utilisation of alternative feedstock (hydrogen for ethylene, ammonia and methanol) with the circular economy solutions of BioCycle (but less ambitious ones).
- Mix95 builds on Mix80, combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid and hydrogen fully replacing naphtha and natural gas as feedstock.

Similarly to Iron & Steel, scenarios CleanGas, Electric, Mix80 and Mix95 report a significant increase in electricity consumption, either for the production of hydrogen or due to increased used of electric processes. Compared to 2015, where electricity consumption was 181 TWh, electricity production for direct use may increase by 78%, ranging between 169 TWh for BioCycle up to 323 TWh in the case of Electric. The more balanced scenarios Mix80 and Mix95 report consumption around 300 TWh. Accounting also for the electricity required for the production of feedstocks, clean gas and hydrogen, electricity consumption increases radically, reaching 1,097 TWh for CleanGas, 1,080 for Mix95, 1,016 TWh for Electric and 849 TWh for Mix80.

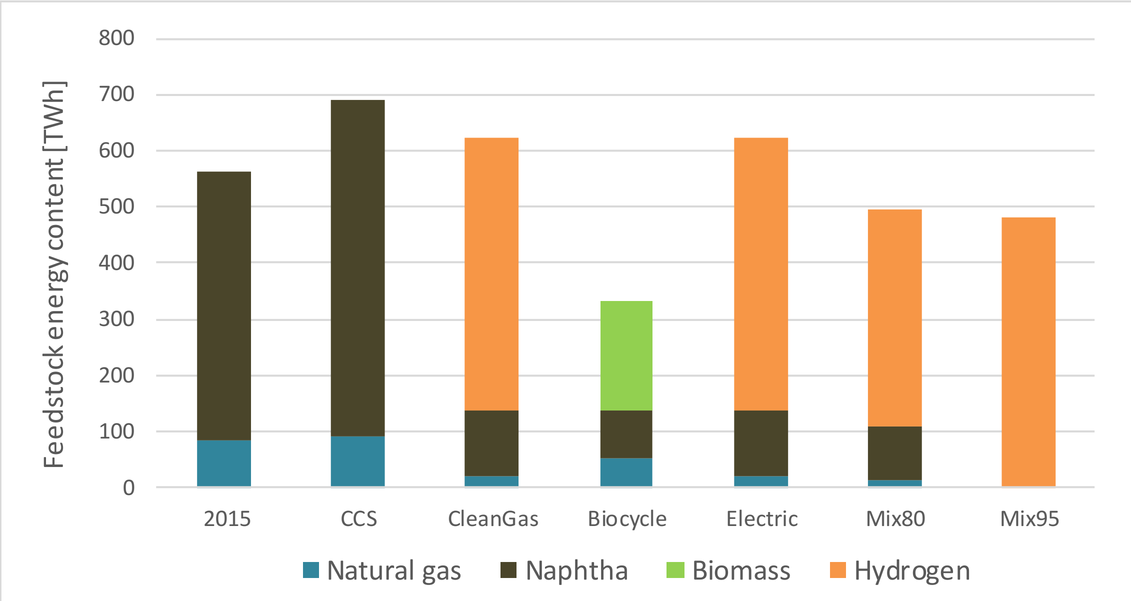
**Figure 139: Final energy demand in the chemical industry by energy carrier (excluding production of feedstock hydrogen and clean gas)**




*Source: FORECAST.*

A particularly interesting aspect of the chemical industry is its feedstocks. The main commercial method of producing ethylene is through steam cracking of a variety of hydrocarbon feedstock, with naphtha, ethane and LPG being the main ones. Ammonia is produced via the Haber-Bosch synthesis, using hydrogen mainly generated via steam reforming form natural gas. In order to decarbonise, the fossil feedstock either needs to be replaced by carbon-free hydrogen (in FORECAST assumed to be produced through electrolysis with carbon free electricity) or by bio-based feedstock, or to be used with CCS (for permanent storage) or CCU for storage in materials, which at the end of their life-time would either be re-used, recycled or landfilled (not incinerated). If CCU is used with biogenic material then this leads to negative emissions. Figure 140 presents the developments in the chemical feedstocks across scenarios. In CCS nothing changes, but $CO_2$ emissions are stored. In Biocycle fossil feedstock is substituted by biomass (without CCS) and due to the increased circularity total feedstock input reduced, while in CleanGas, Electric and the Mix scenarios feedstock is substituted by hydrogen.

**Figure 140: Energy Content of feedstock demand for ethylene, ammonia and methanol production by type of feedstock and scenario in 2050**




*Source: FORECAST.*

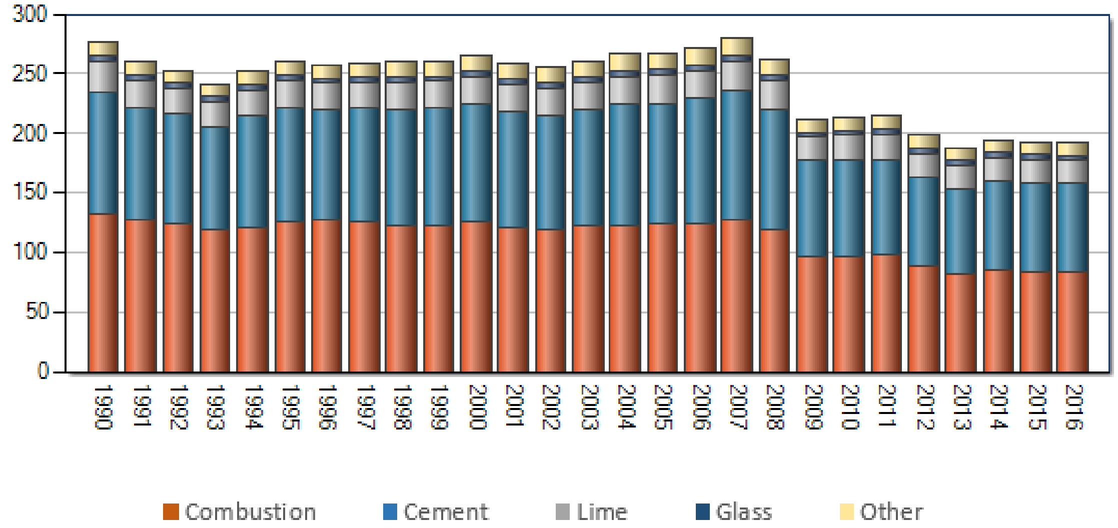
To conclude, the major challenges for the chemical industry are feedstocks, process emissions and the high share of natural gas. Overall, the analyses performed indicate towards three pathways for the chemical industry:

- Circular economy, combined with increased use of bio-based material as feedstock. The limitations of this approach seem to be on the access to sufficient sustainable biomass feedstock.
- Electrification, combined with the use of hydrogen as feedstock. This pathway tends to have very high investments in renewable generation, electrolysers and other infrastructure, thus possibly being the highest cost pathway, but at the same time is the one with the highest reduction of emissions.
- CCS may be a less costly route and combined with biomass it leads to the generation of negative emissions (via BECCS). It does entail though risks of lock-ins, if industry rellies most on this technology, while it needs to surpass public acceptance issues and solve the infrastructure problem of transportation and storage of $CO_2$.
- A combination of these options seem to be the most promising approach. Industrial symbiosis can further support this option, as it can provide for the high demand for hydrogen and $CO_2$ as feedstock, together with other benefits related to the provision of heat, waste management etc.

### *7.6.3 Non-metallic minerals*

Together, cement and lime sectors accounted for about 8% of total greenhouse gas (GHG) emissions in the scope of the EU Emissions Trading Scheme (ETS) in 2016 and for about 28% of industrial sector emissions within the ETS. In 2016, $CO_2$ emissions in the cement industry were about 112 $MtCO_2$, while they were at about 30 $MtCO_2$ in the lime industry (Figure 141).

**Figure 141: EU28 Historical GHG Emissions for Non-Metallic Minerals Sector (in $MtCO_2eq$)**




*Source: EEA.*

The sector of non-metallic minerals is an energy intensive sector, which includes three main subsectors: cement, glass and ceramics. Together with the iron & steel and the chemicals sectors, they account for 70% of total industrial emissions. Cement (and lime) is the main emitting subsector, responsible for 80% of the sector's emissions. The remaining emissions of the sector originate from glass and ceramics.

Cement has two main sources of $CO_2$ emissions: the burning of fossil fuels in the clinker/lime furnace and the process related emissions from the decarbonisation of the limestone. Together these two sources make up about 85% of total $CO_2$ emissions of the entire Portland Cement production value chain.

By using today's best available techniques, mitigation potentials are limited, including energy efficiency[750], fuel switching to less carbon intensive fuels (namely biomass) and reducing the clinker content in the cement. For instance, the remaining thermal efficiency potential until 2050 is estimated to be less than 10%.[789] Thus, breakthrough technologies are essential to achieve the necessary reductions, which together with circular measures (resource, material and product efficiency) and CCS or CCU, can reduce emissions up to 75% compared to 2010.[790]

A similar reduction potential is assessed on a global level by IEA[791], where it is found that the integration of CCS and CCU in the cement production can reduce global cement emissions between 2014 and 2050 by 48%, while new technologies for the reduction in the clinker to cement ratio in cement by 37%. On the other hand, although the UK Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 for cement[792] identifies a similar very high potential for

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789 CSI and ECRA (2017), Development of State of the Art Techniques in Cement Manufacturing, https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Development-of-State-of-the-Art-Techniques-in-Cement-Manufacturing

790 CEMBUREAU (2013), The role of Cement in the 2050 Low Carbon Economy, https://cembureau.eu/media/1500/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf

791 IEA, 2018, Technology Roadmap. Low Carbon Transition in the Cement Industry, https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf

792 WSP, Parsons Brinckerhoff, DNV GL (2015), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Cement,

CCS and CCU, leading to 62% of reductions, it finds less benefits in reduction of the clinker content, at around 5-10%. Both studies identify also the fuel switch to biomass as an important emissions reduction solution.

The options for the EU lime industry seem similar to the ones of cement.[793] Two thirds of GHG emissions are attributed to process emissions, the rest being energy related. Although the energy related emissions can be addressed to a large extent by energy efficiency, electrification and use of low carbon fuels, process emissions require as in the case of cement the capturing of $CO_2$, either to be stored underground (CCS) or to be used (CCU).

The big uncertainty in cement, highlighted in the sometimes contradicting expectations on how much the carbon intensity of cement can be reduced, is related to the generally low TRL of the many innovative technologies that are in the stage of R&D today. These options range from new raw materials to new cement alternatives, but even extend to the more efficient use of concrete in the construction sector, when considering the entire value chain. There are various concepts under development, with a large number of concepts and projects covering different ambition in reducing cement carbon intensity, from 30% to even 90%, and with the tendency to have specific applications.

Low carbon cements are substances made from alternatives to Portland clinker, which can be produced using less energy and release fewer emissions in productions. Some novel cements can even lead to reinforced concrete.[794] One of the most advanced binders is claimed to be Solidia, which, based on company claims, could possibly reduce $CO_2$ emissions up to 70%[795] compared to the standard ones. This is mainly achieved by altering the raw materials used, thus reducing process and combustion emissions. So far, these cements have been slowly penetrating the market. Experts justify this for a variety of reasons, most notably the existing regulatory framework, which is based on the Portland cement, their low technological maturity and the limited applications they may have, e.g. precast concrete.

Significant potential lies also in the increased material efficiency and substitution,[762] in the context of a circular economy, not considered in most analyses. Although cement cannot be recycled as other material, there is an opportunity to recover up to 30-40% of unused clinker from concrete at end to life, replacing new cement. If used to produce higher strength aggregates, the recovered cement can replace up to 80% of new cement in construction, saving almost half the $CO_2$. Moreover, if building components could be re-used and buildings designed for disassembly, the need for new cement production would decrease. Another alternative is wood-based construction, since timber can have similar applications to reinforced concrete. Despite though the obvious benefits in carbon savings, it is often viewed that wood-based construction entails more risks due to its reduced stability, ability to handle compression and shorter lifecycle. In general though, an opportunity lies here, which needs further assessment compared to other options.

The main technological pathways in the cement/lime sub-sector, with projects under development, emissions reduction and market entry are summarised in Table 36:

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https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf

[793] ECOFYS, 2014, A competitive and Efficient Lime Industry, https://www.eula.eu/sites/eula.eu/files/publications/files/A%20Competitive%20and%20Efficient%20Lime%20Industry%20-%20Technical%20report%20by%20Ecofys_0.pdf

[794] Chatham House (2018), Making Concrete Change, https://www.chathamhouse.org/sites/default/files/publications/research/2018-06-13-making-concrete-change-cement-lehne-preston.pdf

[795] http://solidiatech.com/wp-content/uploads/2018/05/ERA-Discovery-FINAL.pdf

**Table 36: Low Carbon Projects under development in Cement & Lime**

| Technology option | Examples | TRL | Max. GHG emissions reduction | Market entry |
|---|---|---|---|---|
| **Low carbon cement (-50%) (new binder)** | Celitement | 6 | 50% | 2022 |
| **Less carbon cement (-30%) (new binder)** | Aether | 6-7 | 30% | 2020 |
| **CCS Post combustion** | | 8-9 | 95% | 2022 |
| **CCS (direct separation)** | LEILAC project | 5-6 | ~70%* | 2025 |
| **Low Carbon cement (-70%) (CCU: $CO_2$ absorbing concrete)** | Solidia | 8 | 70% | 2020 |

** only process related emissions*

*Source : Ecofys & Fraunhofer ISI* [758 767].

The European glass and ceramics industry accounted in 2016 for around 2% of the verified emissions of all stationary installations of the European Union and around 6% of its industrial emissions excluding combustion.

Moving to the decarbonisation potential of the glass and ceramics sub-sectors, this is mainly centred around the drying and firing process. Certain energy efficiency improvements can be performed, but their potential is found limited due to the advances the past period. As both sub-sectors today use mainly natural gas for producing heat, the biggest reductions can be achieved by switching the fuel to electricity or biogas. In the case of glass use additional reductions can be achieved through the use of CCS, as well as with increased recycling, re-use and other circular interventions.

In UK Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 the maximum potential reductions compared to 2012 were around 60% for ceramics[796] and 90-96% for glass[797] (higher reductions corresponding to the inclusion of CCS and CCU). The 2012 Roadmap of the ceramics industry identifies a potential of reducing emissions by 78% compared to 1990 levels, requiring electrifications of half the kilns, while the other half retrofitted to clean gas.[798]

The main technological pathways in the glass/ceramics sub-sector, with projects under development, emissions reduction and market entry are summarised in Table 37:

[796] WSP, Parsons Brinckerhoff, DNV GL (2015), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Ceramic Sector, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416676/Ceramic_Report.pdf

[797] WSP, Parsons Brinckerhoff, DNV GL (2015), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416675/Glass_Report.pdf

[798] Cerameunie (2012), The Ceramic Industry Roadmap. Paving the way to 2050, http://www.cepi.org/system/files/public/documents/publications/environment/2011/roadmap_final-20111110-00019-01-E.pdf

**Table 37: Low Carbon Projects under development in Glass and Ceramics**

| Technology option | Examples | TRL | Max. emissions reduction[799] | Market entry |
|---|---|---|---|---|
| **RES Electrification** | - | 5-8[800] | up to 80% | 2015/2020 [e] |
| **Oxy-fuel combustion incl. heat recovery[801]** | OPTIMELT | 7[e] | up to 60% | 2025[e] |
| **Waste heat Recovery** | Organic Rankine Cycle | 8-9[802] | up to 15%[803] | - |
| **Batch preheating** | | 8 | up to 15% [e] | - |
| **Recycling[804]** | - | 9 | up to 60% | - |

*Source: Ecofys & Fraunhofer ISI [758 767].*

In the case of the scenarios achieving 80% GHG reduction, the $CO_2$ emissions in non-metallic minerals are projected to decrease between 61% (in the ELEC scenario) up to 71% (in the CIRC scenario) compared to 2015. The 1.5°C scenarios deliver 83-86% reductions (see Table 38). Reduction in process emissions are mainly achieved by the application of CCS.

**Table 38: Total $CO_2$ emissions reduction in Non Metallic Minerals by 2050 compared to 2015**

| Non-metallic Minerals | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **Total $CO_2$ emissions** | -28% | -61% | -68% | -66% | -63% | -71% | -69% | -83% | -86% |

*Source: PRIMES.*

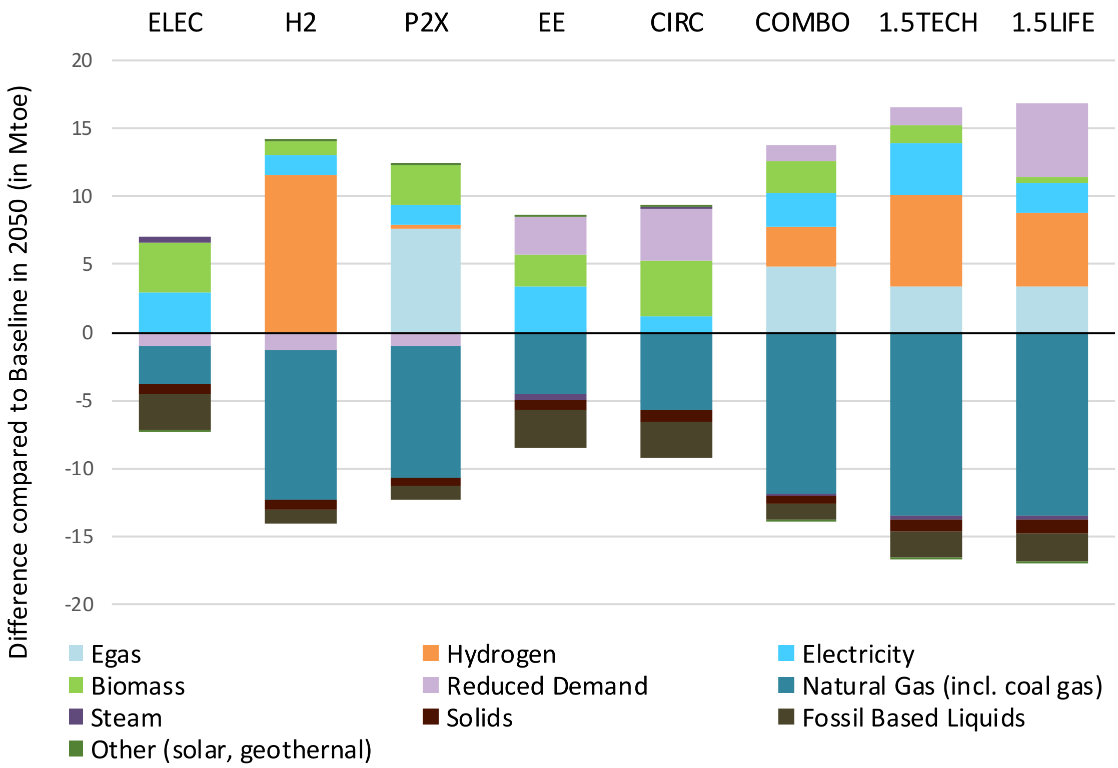
The changes of fuel mix by scenario are reported in Figure 142, which indicates the differences in energy consumption compared to the Baseline. The Baseline achieves its GHG emissions reduction through a combination of energy efficiency, together with increased use of biomass and natural gas. The sector had a final energy consumption of 34 Mtoe in 2015[805] and a projected demand in baseline of 31 Mtoe in 2050, out of which 15 Mtoe natural gas, 5 Mtoe of biomass, 6 Mtoe of electricity.

PRIMES confirms a similar pattern of emissions reduction in the scenarios meeting the -80% ambition, based notably on strong reductions of natural gas and increased use of biomass. Electrification, enhanced energy efficiency and primarily the use of hydrogen and e-fuels are additional possibilities, which emerge in scenarios involving new fuels and in particular in the

799 Reductions partly lower for ceramic industry (e.g. gasification of biomass up to 29%, oxy-fuel firing/oxygen enrichment up to 12.5%).
800 Lower TRL in the ceramic industry (5-6). Higher TRL in the glass industry (8).
801 Mainly for glass industry. Example for container glass.
802 Lower TRL in the ceramic industry for special projects e.g. DRYficiency project (around TRL 5).
803 Mainly for glass industry.
804 Mainly for glass recycling.
805 Source: Eurostat

1.5°C scenarios. For abating industrial process emissions in this sector, CCS seems to be the preferred option according to the PRIMES projections.

**Figure 142: Differences in final energy consumption in Non-Metallic Minerals compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

The complementary bottom-up analysis using FORECAST leads to similar conclusions as with PRIMES, with CCS being again the most effective solution. The GHG emissions reduction compared to 2015 for its -80% decarbonisation scenarios range between 45% (the Electric Scenario) up to 81% (CCS scenario), with the Mix80 scenario delivering 56% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 86% reductions (see Table 39). About 120 $MtCO_2$ are captured and stored in 2050 in CCS scenario and 39 $MtCO_2$ in the case of Mix95.

**Table 39: GHG emissions reduction in Non-Metallic Minerals by 2050 compared to 2015**

| Non-Metallic Minerals | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Energy related GHG emissions (without CCS)** | -52% | -83% | -88% | -69% | -71% | -95% |
| **Process GHG emissions (without CCS)** | 9% | -26% | -43% | -28% | -45% | -45% |
| **Total GHG emissions (with CCS)** | -81% | -50% | -62% | -45% | -56% | -86% |

*Source: FORECAST.*

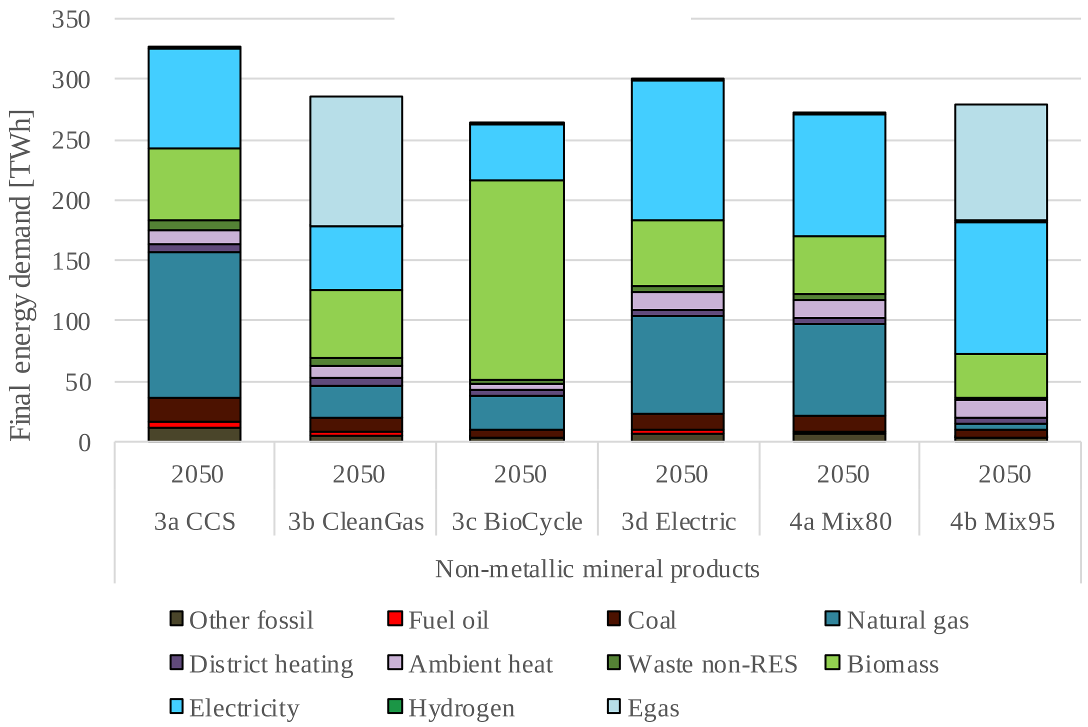
The drivers for GHG emissions reduction for cement and lime in the FORECAST scenarios are listed below.

- For all scenarios energy efficiency innovations (low-carbon cement types, re-carbonating cement/concrete) and material efficiency through a reduction in the clinker share.
- In CCS the fuel switch is driven by prices, with post-combustion and direct separation CCS in place.
- In CleanGas, reductions are achieved by using more biomass and RES-waste and consuming more distributed gas, which is assumed to have only 20% of conventional gas.
- BioCycle foresees higher amounts of biomass and RES-waste, together with circular economy measures (concrete recycling and re-use, efficient concrete use, material substitution by biomass, carbon reinforced concrete).
- In Electric, cement is produced through electric clinker kilns.
- Mix80 combines the recycling and material efficiency solutions of BioCycle with fuel switching to low carbon fuels.
- Mix95 adds to Mix80 CCS for lime and conventional clinker, combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid.

The drivers for GHG emissions reduction for the glass and ceramics in the FORECAST scenarios are listed below.

- For all scenarios energy efficiency innovations (oxy-fuel and use of waste heat) and faster increase in recycling of glass containers.
- In CCS there is a fuel switch to natural gas, but economic applications of CCS are restricted only for the late-combustion in the glass sector. There is also an increase in flat glass recycling.
- In CleanGas, reductions are achieved by the consumption of distributed gas, which is assumed to have only 20% of conventional gas. There is also an increase in flat glass recycling.
- BioCycle foresees higher amounts of biomass, together with circular economy measures (re-use of glass and more efficient glass use).
- In Electric, electric furnaces replaces gas. There is also an increase in flat glass recycling.
- Mix80 combines electric furnaces with the recycling and material efficiency solutions of BioCycle.
- Mix95 is similar to Mix80, combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid.

**Figure 143: Final energy demand in the non-metallic minerals industry by energy carrier**



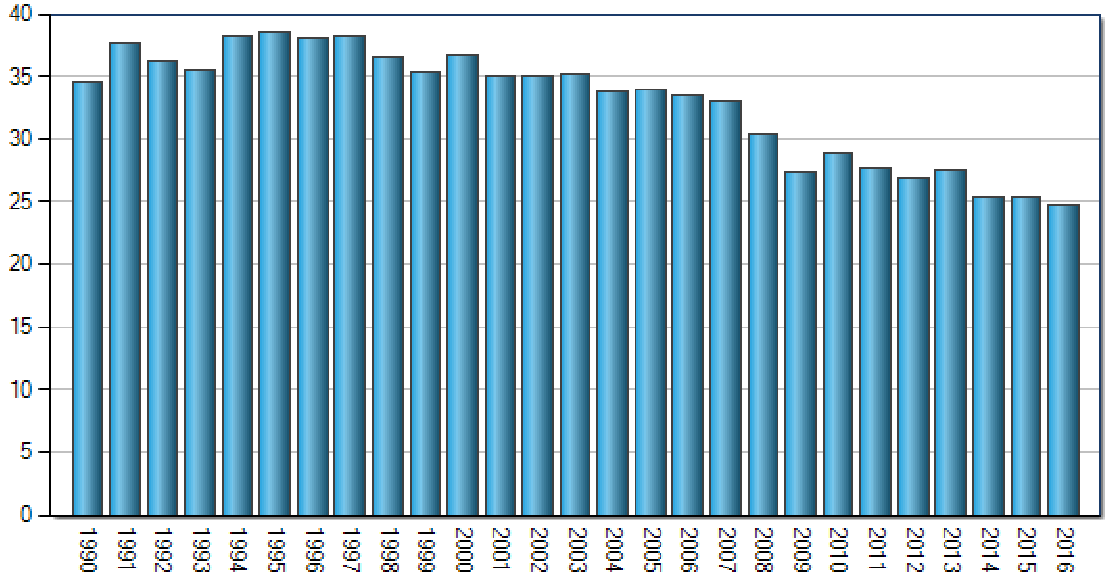

*Source: FORECAST.*

The analysis confirms that the non-metallic minerals industry, and in particular the cement and lime production, is one of the hardest to abate source of emissions. Without CCS, the success in decarbonising the sector will depend on the diffusion speed of low carbon cements and fundamental improvements in material efficiency and recycling in the construction industry. These in turn may require significant changes in current value chains and business models.

### *7.6.4 Pulp & Paper*

The European pulp and paper industry accounted in 2016 for around 1.5% of the verified emissions of all stationary installations of the European Union and around 5% of industrial emissions excluding combustion (Figure 144).

**Figure 144: EU28 Historical GHG Emissions for Paper & Pulp Sector (in $MtCO_2eq$)**




*Source: EEA.*

This sector produces paper and pulp, the wood-based resource used to produce paper. Pulp is produced mechanically, chemically or from recycled paper, with its intended quality determining the processing steps and the raw materials to be used. Drying the paper web is then the important energy-consuming process in paper mills.

The two main mitigation pillars for pulp & paper are improving energy efficiency and switching to low-carbon fuels and electricity. The European Paper industry has greatly improved its energy efficiency over the last decades using waste heat and improved drying techniques. In addition, fuel switching from fossil fuels to renewable sources like biomass (and electricity) has already taken place to a significant extent, but there is further potential.

When it comes to decarbonising the paper industry, the industry has the advantage of having direct access to bio-based materials. In addition, the paper industry only generates energy-related, but no process-related emissions (like for example the cement industry) which are much more difficult to reduce. Finally the demand for steam in the paper industry is quite flexible in terms of the energy carrier used for its production (in contrast to furnaces in the high-temperature range, e.g. in the steel industry). The above allow for many possibilities regarding fuel-switching to low carbon fuels, which can be performed purely on an economic basis. The full electrification of the sector seems particularly appealing, as the sector could be used to increase flexibility of the energy system e.g. by providing demand side flexibility[806]. The competition for biomass with other sectors may prove a challenge for the future.

Another opportunity for paper and pulp is the Black liquor gasification (BLG). This is a technique used in pulp mills to generate surplus electricity or bio fuel. In the black liquor gasification process concentrated black liquor is converted into inorganic compounds (mainly sodium and sulphur) suitable for the recovery of cooking chemicals and combustible fuel gas

[806] CEPI (2017), Investing in Europe for Industry Transformation, http://www.cepi.org/system/files/public/documents/publications/innovation/2017/roadmap_2050_v07_printable_version.pdf

comprising primarily hydrogen and carbon monoxide. BLG is often discussed in the context of the future paper factory becoming a biorefinery.[807]

Recycled fibre quality can be improved by improving the collection, sorting (e.g. by filler content, brightness, fibre length) and Ecodesign for recycling. This will allow more efficient treatment and refining of fibres. New recycling technologies like the before mentioned steam forming without wetting and drying could even further decrease energy demand in the paper industry. Digitalisation might also provide the next generation of efficient recycling technologies.

The main technological pathways in the pulp and paper sector, with projects under development, emissions reduction and market entry are summarised in Table 40:

**Table 40: Low Carbon Projects under development in Paper & Pulp**

| Technology option | Examples | TRL | Max. emissions reduction | Market entry |
|---|---|---|---|---|
| **New drying techniques** | Impulse drying[808] | 8-9 | up to 20% | 2020[e] |
| **Foaming of fibrous materials** | | 5 | n.a. | 2025 |
| **Black liquor gasification** | | 8-9[e] | up to 11% | 2020[e] |
| **Enzymatic pre-treatment** | | 6-8 | up to 5% | 2025[e] |
| **Heat recovery** | e.g. paper[809] | 9 | up to 5% | - |

*Source: Ecofys & Fraunhofer ISI* [758 767 758]

A number of studies of possible pathways for the decarbonisation of the sector have been performed.[768 810] The European forest fibre and paper industry has recently expressed the position that the above mentioned measures can lead to an 80% decarbonisation of the sector compared to 1990, while at the same time increase its added value in Europe by 50%.[806]

The analysis performed by PRIMES provided mixed possibilities for the industry, depending on the pathway.[811] In the case of the scenarios achieving 80% GHG reduction, the emissions in non-ferrous are projected to decrease between 65% (in the EE scenario) up to 87% (in the P2X scenario) compared to 2015. The 1.5°C GHG scenarios deliver much higher reductions at 94% (see Table 41).

[807] JRC (2015), Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/best-available-techniques-bat-reference-document-production-pulp-paper-and-board-industrial

[808] Selected options like for example “superheated steam drying” can have lower TRLs (e.g. 3-5 in WSP Parsons Brinckerhoff (WSP) und DNV-GL 2015d). The example shown here is for “impulse drying”.

[809] Also for mechanical pulp.

[810] JRC (2018), Prospective scenarios for the pulp and paper industry, http://publications.jrc.ec.europa.eu/repository/bitstream/JRC111652/kjna29280enn_jrc111652_online_revised_by_ipo.pdf

[811] For the CIRC and 1.5 LIFE scenarios a 30% reduction in the output of pulp was assumed, due to increased recycling and digitalisation, with the wood saved used in construction instead to substitute cement and other materials. In PRIMES CCS in pulp and paper is not applied except in CHP installations. Emissions of these installations are recorded under the power sector.

**Table 41: Energy related $CO_2$ emissions reduction in Pulp & Paper by 2050 compared to 2015**

| Pulp & Paper | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions reduction** | -67% | -79% | -83% | -87% | -65% | -77% | -91% | -94% | -94% |

*Source: PRIMES.*

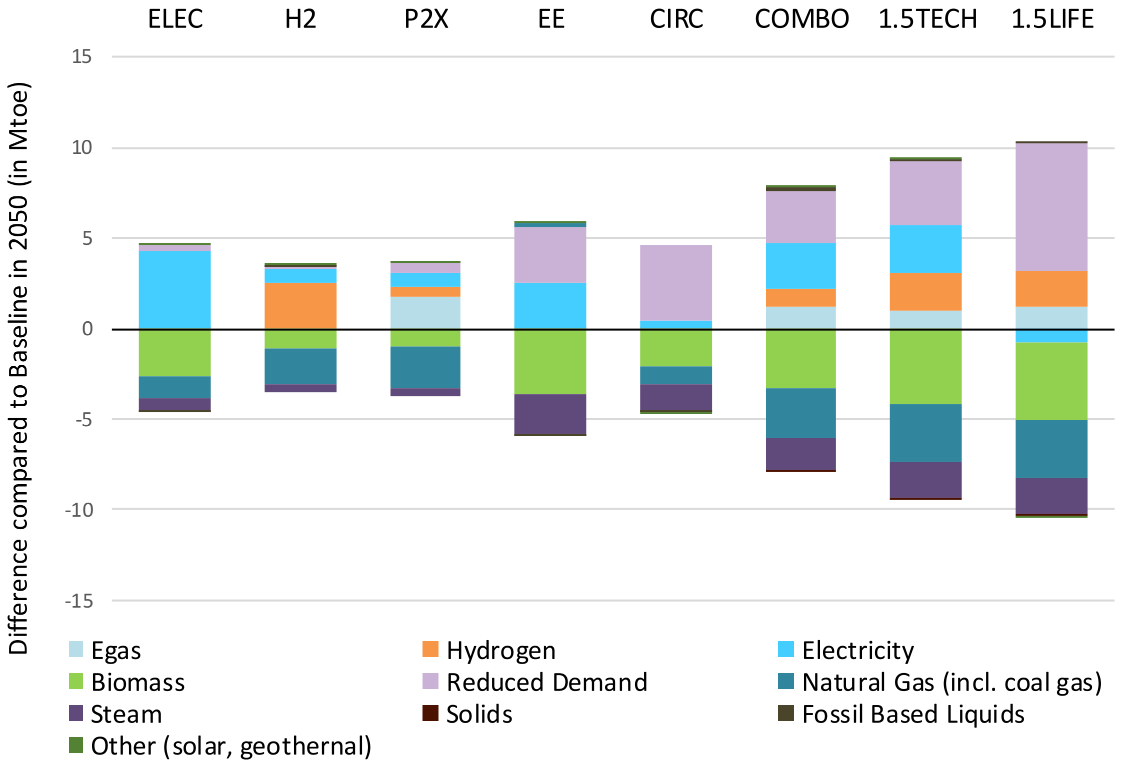
The sector had a final energy consumption of 34 Mtoe in 2015[812] and a projected demand in Baseline of 25 Mtoe in 2050, out of which 11 Mtoe of electricity, 8 Mtoe of biomass, 3.5 Mtoe natural gas and 2.5 Mtoe of steam.

The changes in fuel mix are reported in Figure 145 by scenario, measured as differences in energy consumption compared to the Baseline. Further electrification in this sector, combined with enhanced energy efficiency and the use of e-gas and biogas seem to be a valid combination for reducing emissions.

In the CIRC and 1.5LIFE scenario, the reduction of total final demand due to energy efficiency improvement and the recycling of paper imply a significant reduction of demand for energy products, compared to the Baseline. The scenarios achieving 80% GHG reduction show that a single solution is not sufficient to drive deep emissions reduction. Measures regarding the amount and the type of paper material used in the economy, in particular for packaging, and digitalisation, which may replace paper, can further reduce the demand for paper and pulp, and thus energy demand and GHG emissions.

[812] Source: Eurostat

**Figure 145: Differences in final energy consumption in Pulp & Paper compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

FORECAST produced a range of lower GHG reduction potentials compared to PRIMES for the pulp and paper sector. The GHG emissions reduction compared to 2015 for its -80% decarbonisation scenarios range between 42% (the Electric Scenario) up to 99% (CCS scenario), with the Mix80 scenario delivering 50% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 88% reduction (see Table 42).

**Table 42: GHG emissions reduction in Pulp & Paper by 2050 compared to 2015**

| Pulp & Paper | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Total GHG emissions**[813] | -98% | -50% | -50% | -42% | -50% | -88% |

*Source: FORECAST.*

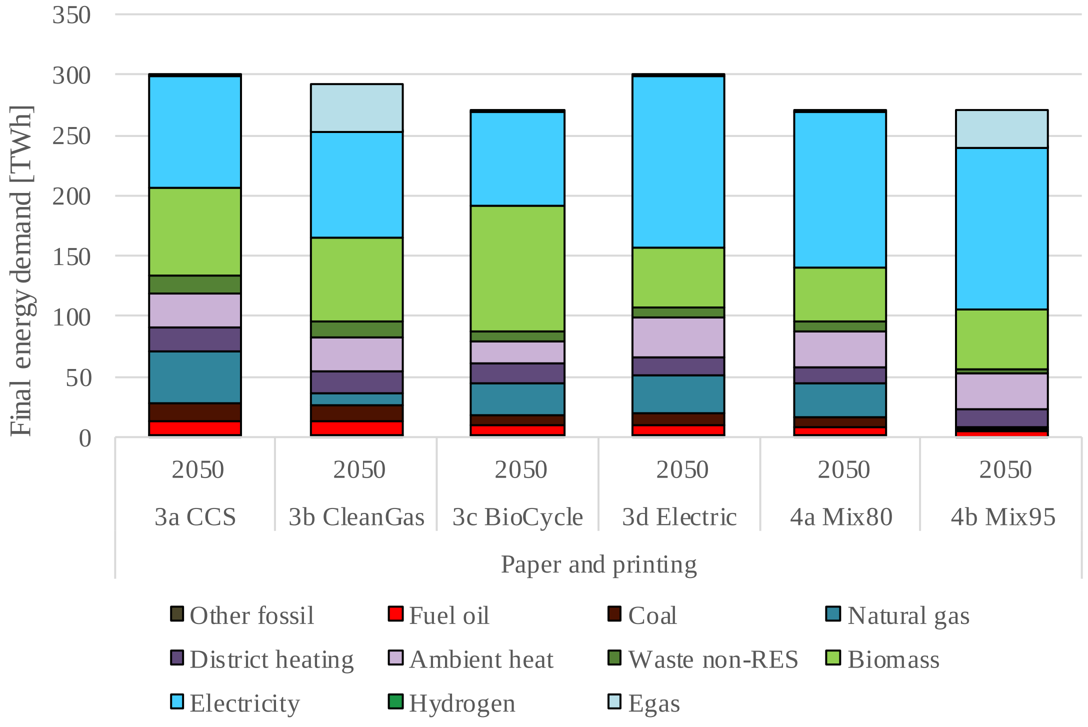
The drivers for GHG emissions reduction in the FORECAST scenarios are listed below. Figure 146 presents the final energy demand by energy carrier.

- For all scenarios energy efficiency innovations (enzymatic pre-treatment, innovative paper drying, black liquor gasification) and ambitious recycling.
- In CCS Scenario, CCS is adopted by big emitters closer to 2050. About 20 Mt$CO_2$ are captured and stored in 2050.
- CleanGas GHG reductions are driven by the consumption of distributed gas, which is assumed to have only 20% of conventional gas, together with biomass.

[813] The reason for the high reduction in the CCS scenario is that by deploying CCS even to only half the paper mills (to the bigger emitters), together with the biomass in the energy mix, results in BECCS thus leading to negative emissions.

- In BioCycle, there is a strong focus on biomass, together with strong circular economy measures (maximum paper recycling and re-use, wood fibre products replace plastics, improved material efficiency).
- In Electric, electric boilers and heat pumps are the main drivers.
- Mix80 is based on the combination of Electric and BioCycle (without the extensive use of biomass).
- Mix95 is similar to Mix80, combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid.

**Figure 146: Final energy demand in pulp & paper by energy carrier**




*Source: FORECAST.*

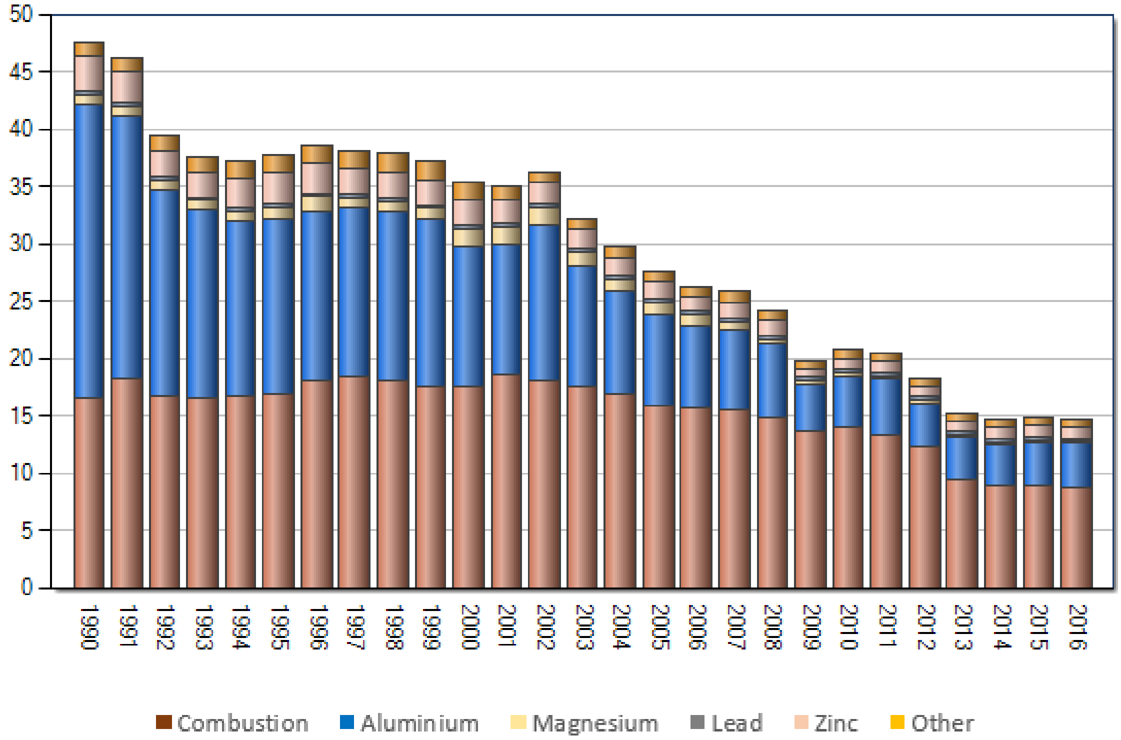
The scenarios confirm the high potential of the industry to decarbonise through electricity and biomass. If the large paper mills are also equipped with CCS then the industry can generate negative emissions and compensate other, hard to abate, emissions, like process emissions in other industries.

The FORECAST scenarios also indicated a risk for lock-in due to the upcoming necessary investments to replace old installations in the coming decade. If proper incentives are not in place, like a sufficiently high $CO_2$ price, industry may continue to invest in fossil fuel based steam generation with a lifetime of 20-30 years.

### *7.6.5 Non-ferrous metals*

The non-ferrous metals sector covers base metals (aluminium, copper, lead, zinc, nickel and tin), precious metals (gold, silver, etc.) and the so-called technology metals (molybdenum, cobalt, silicon, selenium, manganese, etc.). Aluminium production covers the largest part of the emissions of the sector, after combustion (Figure 147).

**Figure 147: EU28 Historical GHG Emissions for Non-Ferrous Metals Sector (in $MtCO_2eq$)**




*Source: EEA.*

As an electricity-intensive industry the European aluminium sector accounted in 2016 for around 1% of the verified emissions of all stationary installations of the European Union and around 2% of its industrial emissions excluding combustion. In aluminium production, two main process routes can be distinguished: primary aluminium production from bauxite and the much less energy-intensive aluminium production using scrap and electricity as main inputs. The gradual electrification of fossil-fuel based processes has led to the significant decrease of emissions and increase of the energy efficiency of the sector.

Conventional aluminium smelting from ore is a multi-stage, energy-intensive process. Of the main process stages, electrolysis via the Hall-Héroult (H-H) route is the most energy intensive one (with a share of 83%), with alumina production from bauxite being the next more intensive (15%), but also the main generator of solid / effluent waste.

A project that has attracted attention in the sector is "the Elysis process". In May 2018, Alcoa and Rio Tinto announced the World's first "carbon-free" aluminium smelting process, called "Elysis". The emerging technology is currently producing metal at the Alcoa Technical Center, near Pittsburgh, USA.[814] Alcoa and Rio Tinto launch new Joint Venture for larger scale development and commercialization of the process. The development is being supported by Alcoa, Rio Tinto, the Government of Canada, the Government of Quebec and Apple, with a combined investment of $CAN188 million. The technology is expected to become commercially available around 2024.

Perhaps the highest potential for reductions for both aluminium and copper, complementing the emissions reduction to be achieved in the primary production, is the shift to more secondary

[814] https://elysistechnologies.com/en#unprecedented-aluminium-partnership

production through further recycling and re-use. This could then bring significant benefits, as the recycling of aluminium reduces energy consumption by 95% and emissions up to 98%. Moreover it opens up the possibilities for fuel switching to the least carbon-intensive fuel for use in combustion, be it electricity, clean gas or biomass.

Re-use of existing aluminium is seen as an interesting opportunity for making "order-of-magnitude" carbon/energy savings per tonne of metal. Recycling also offers substantial resource efficiency and other environmental benefits. Today aluminium recycled from end-of-life products covers 27%, according to one study[762] with the possibility to increase up to 55%, or slightly above 50% according to a different source[815]. The key barriers are the ability to isolate and gather this recyclable material easier and the infrastructure to handle it, as this would prevent its down-cycling and enable the production of high-quality secondary aluminium. At the same time it is important to reduce the losses of aluminium throughout its use cycle, as 25-30% of aluminium is estimated to be lost.

Energy efficiency could also bring some further reductions both in cost and in energy consumption for aluminium. There are some promising technologies, which could deliver overall energy savings up to 45% but they have very low TRL. A more advanced solution, currently in pilot phase, is the carbo-thermic reduction (non-electrolytic process), which could deliver around 20% energy savings.

CCS does not seem to be an option of first priority for the non-ferrous metals due to the smaller size of the installations and emissions in comparison to the sectors discussed so far.

The main technological pathways in the non-ferrous metals sector, with projects under development, emissions reduction and market entry are summarised in Table 43:

**Table 43: Low Carbon Projects under development in Non-ferrous Metals**

| Technology option | Examples | TRL | Max. emissions reduction | Market entry |
|---|---|---|---|---|
| **Low emission electrolysis** | HAL4e | 5-6 | n.a. | 2023 |
| **Inert anodes/wetted drained cathodes** | | 5 | up to 35% | 2020/2025 |
| **Magnetic billet heating** | | 5-9[816] | n.a. | 2010/2020[817] |
| **Waste heat recovery[818]** | | 8-9 | n.a. | - |

*Source: Ecofys & Fraunhofer ISI* [767].[758 767].

Overall, studies performed for the non-ferrous sector indicate the possibility for limited GHG reductions.[768] Nevertheless, according to the 2012 vision of the aluminium industry[819], a decarbonised power sector could reduce the direct emissions of the industry by 70% and the total

[815] JRC (2018), Raw materials scoreboard 2018, https://publications.europa.eu/en/publication-detail/-/publication/117c8d9b-e3d3-11e8-b690-01aa75ed71a1
[816] Lower TRLs in the copper industry (5), higher TRLs in the aluminium industry (8-9).
[817] 2020 for the copper industry.
[818] Example for copper.
[819] European Aluminium Association (2012), An aluminium 2050 roadmap to a low-carbon Europe, https://european-aluminium.eu/media/1801/201202-an-aluminium-2050-roadmap-to-a-low-carbon-europe.pdf

emissions (including indirect) up to 79% by 2050. But for this to happen research into new technologies is needed to eliminate direct emissions attributable to carbon anode consumption, while also recycling rates for aluminium should further increase (saving up to 95% of the energy required in primary production). On the contrary, copper sector supports that its production process has almost reached its technological plateau and the opportunities for further energy reductions are very limited, with a reduction of carbon emissions by 25% by 2050 being a realistic estimate.[820]

The analysis performed by PRIMES provided mixed possibilities for the industry, depending on the pathway. No significant changes were assumed in technologies or highly increased recycling rates of aluminium. In the case of the scenarios achieving 80% GHG reduction, the emissions in non-ferrous are projected to decrease between 68% (in the EE scenario) up to 87% (in the H2 scenario) compared to 2015. The 1.5°C scenarios deliver much higher reductions, between 93-94% (see Table 44).

**Table 44: Energy related $CO_2$ emissions reduction in Non-Ferrous Metals by 2050 compared to 2015**

| Non-ferrous | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions reduction** | -53% | -72% | -87% | -84% | -68% | -69% | -90% | -94% | -93% |

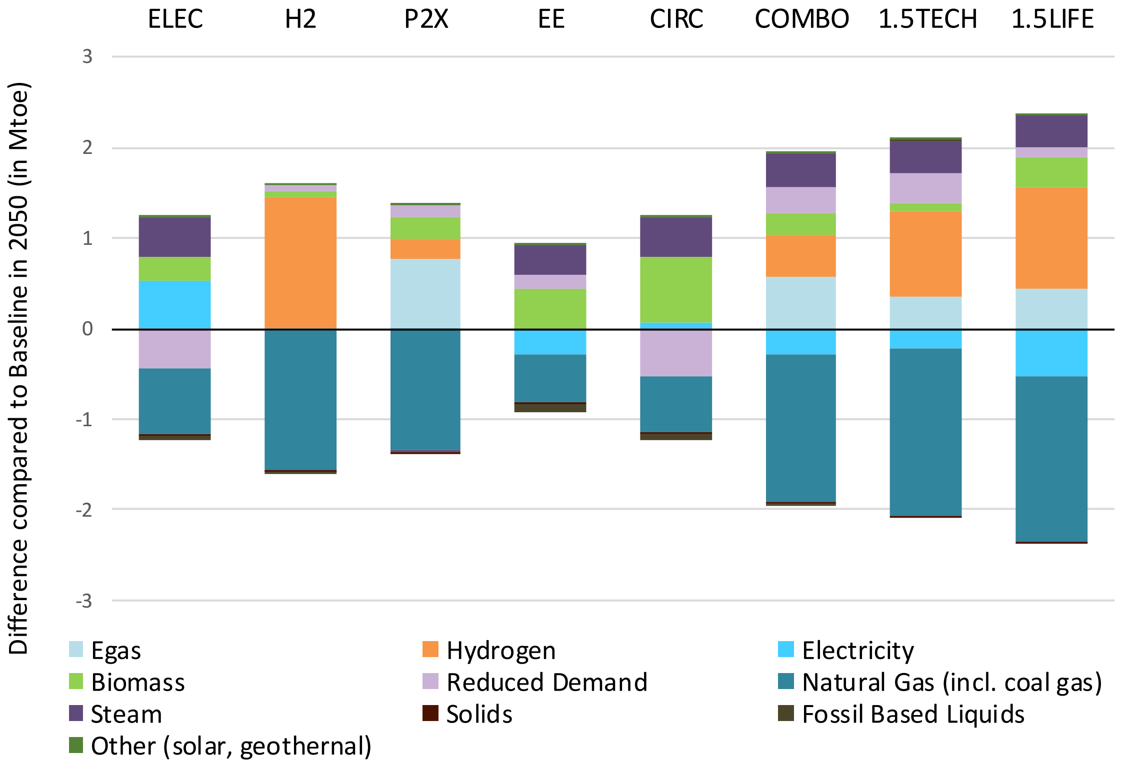
*Source: PRIMES.*

The sector had a final energy consumption of 9.5 Mtoe in 2015[821] and a projected demand in Baseline of 8 Mtoe in 2050, out of which 5.5 Mtoe of electricity and 2 Mtoe natural gas. The main drivers for these reductions are reported in Figure 148, which indicates the differences in energy consumption compared to the Baseline. In general, overall energy consumption levels change little; the differences between scenarios are more related to fuel switching to lower carbon intensity fuels.

[820] European Copper Institute (2014), Copper's Contribution to a Low-Carbon Future, https://copperalliance.eu/benefits-of-copper/sustainable-development/low-carbon-future/

[821] Source: Eurostat

**Figure 148: Differences in final energy consumption in Non-Ferrous compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

FORECAST results confirmed the more limited possibilities of emissions reduction for this sector, compared to the other industry sectors, noting though at the same time that the sector has already significantly reduced its emissions compared to 1990. The GHG emissions reduction compared to 2015 for its -80% decarbonisation scenarios range between 33% (the CCS Scenario) up to 47% (CleanGas scenario), with the Mix80 scenario delivering 41% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 57% reductions (see Table 45).

**Table 45: GHG emissions reduction in Non-Ferrous by 2050 compared to 2015**

| Non-Ferrous Metals | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Energy related GHG emissions (without CCS)** | -52% | -80% | -67% | -62% | -62% | -94% |
| **Process GHG emissions (without CCS)** | -11% | -11% | -17% | -11% | -17% | -17% |
| **Total GHG emissions (with CCS)** | -33% | -47% | -43% | -38% | -41% | -57% |

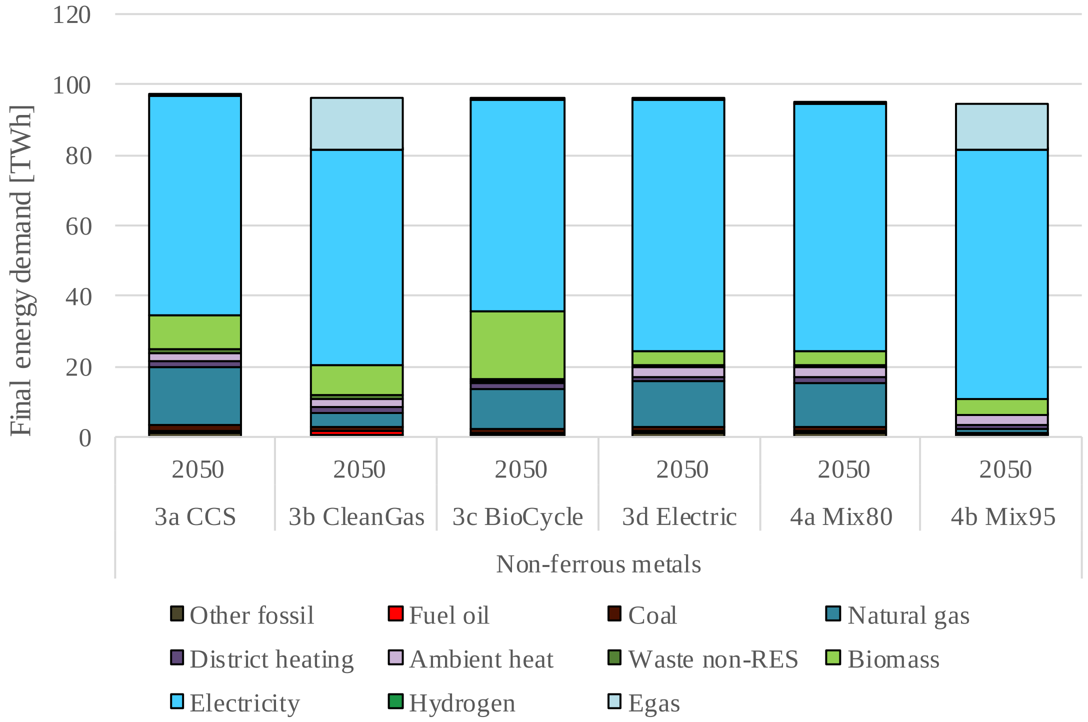
*Source: FORECAST.*

The drivers for GHG emissions reduction in the FORECAST scenarios are listed below. Figure 149 presents the final energy demand by energy carrier.

- For all scenarios energy efficiency innovations (Hal4E, inert anodes & wettable cathodes, magnetic billet heating) and faster increase of recycling.
- In CCS Scenario, natural gas remains dominant.

- CleanGas is based on the consumption of distributed gas, which is assumed to have only 20% of conventional gas.
- In BioCycle, there is some switch to biomass and biogas, plus an increase in recycling rates due to higher quality in sorting.
- In Electric, induction heating in foundries and electric furnaces drive the reductions.
- Mix80 is based on the Electric scenario, together with an increase in recycling rates.
- Mix95 is based on Mix80, combined with the assumption of having 95% clean gas (replacing natural gas) in the gas distribution grid.

**Figure 149: Final energy demand in the non-ferrous industry by energy carrier**

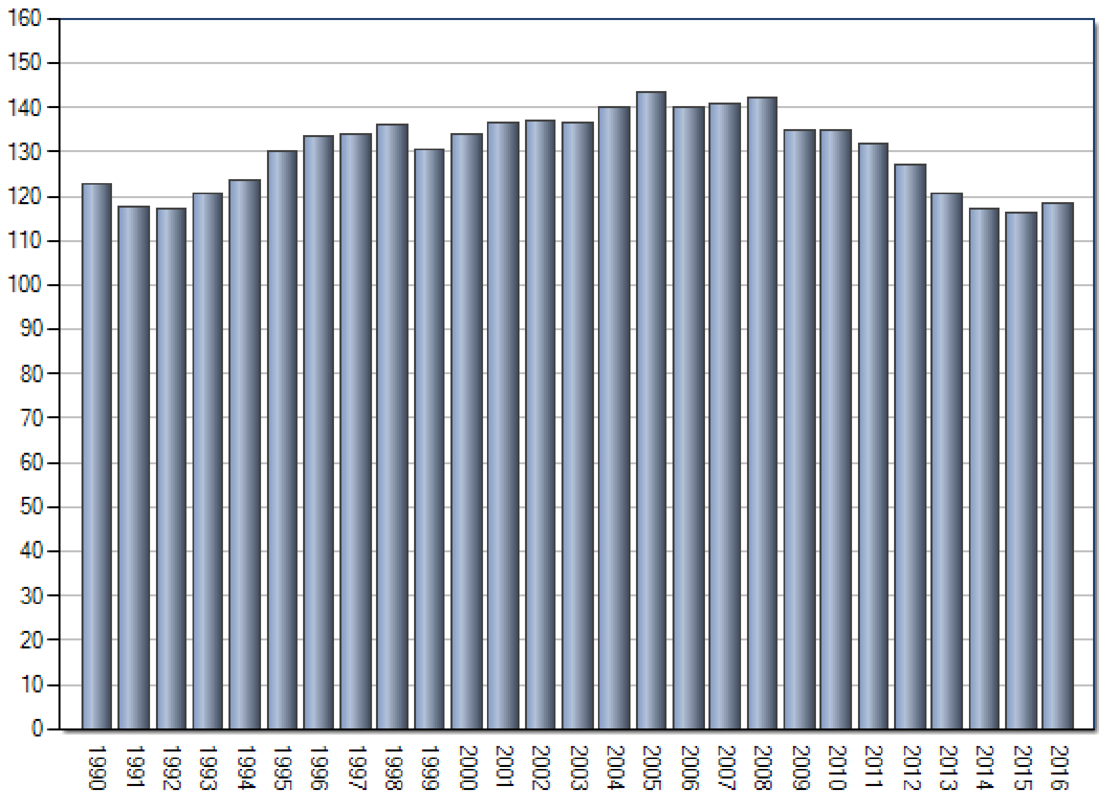



*Source: FORECAST.*

### *7.6.6 Refineries*

As an energy-intensive large industry, the European refineries accounted in 2016 for around 7% of the verified emissions of all stationary installations of the European Union and around 23% of industrial emissions excluding combustion (Figure 150).

**Figure 150: EU28 Historical GHG Emissions for Refineries Sector (in $MtCO_2eq$)**




*Source: EEA.*

The petroleum refineries sector is composed of two key groups: the refined petroleum products and the coke oven products. Refined petroleum products accounted for 92% of the sector's emissions. They are derived from crude oils, which are distilled in the refinery into a number of fractions (petroleum gases, naphtha, asphalts and residue). Depending on the refinery's complexity these fractions can be upgraded into commercial products, like kerosene and gasoline.

Between 1992 and 2010, EU refineries have increased their energy efficiency by 10%, picking most low hanging fruits. Still BAT techniques in 3 major categories of the refining process have the potential to reduce refinery emissions by 25%.[822] [823] Moreover improved waste heat recovery can deliver 10% further reductions.

A major opportunity for the refineries seems to lie in the CCS technology, due to usual large size of the refineries, producing large amounts of $CO_2$ at high concentration. The ideal target for CCS is the methane reformation unit, producing hydrogen and a $CO_2$ stream at very high concentration, almost at 100%. The surplus hydrogen produced[824] can then be used as a fuel elsewhere. Application of CCS to other refinery processes can still significantly reduce emissions

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[822] WSP, Parsons Brinckerhoff, DNV GL (2015), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Oil Refining, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416671/Oil_Refining_Report.pdf

[823] Concawe (2018), Low Carbon Pathways. $CO_2$ efficiency in the EU Refining System 2030/2050, https://www.concawe.eu/wp-content/uploads/2018/04/Rpt_18-7.pdf

[824] Normally hydrogen is used in the refineries themselves, thus only the required amounts of hydrogen are produced. For using it as a fuel elsewhere capacities of Steam Methane Reforming need to be expanded.

between 90-96%, though these technologies have not reached the commercial stage still. Towards 2050, electrolysis is expected to be competitive with steam reforming, with uncertainty on which technology will prevail, depending also on the underlying variable costs (fuels, emissions).[825]

Demand side trends and measures, will also lead to reduced consumption of fossil-fuel based liquids in transport and thus also to reduced emissions.

The main technological pathways in the refineries sector, with projects under development, emissions reduction and market entry are summarised in Table 46:

**Table 46: Low Carbon Projects under development in Refineries**

| Technology option | Examples | TRL | Max. emissions reduction | Market entry |
|---|---|---|---|---|
| **Carbon Capture and Storage** | Lacq/TOTAL | 8-9 | 60% (net; 90% gross reduction) | 2025 |
| **RES-H2** | | 7 | up to 50% | 2020 |
| **Bio-based refinery** | REPSOL approach | 6 | up to 30% | 2025 |
| **Power to Gas/Liquid (synthetic fuels)** | | 6 | 80% | 2025 |
| **Advanced biofuels** | | 8-9 | n.a. | 2020 |

*Source: Ecofys report* [758 767 758]

According to a recent study published by the refining industry, a combination of energy efficiency, low carbon electricity and CCS could lead to emissions reduction up to 70% compared to 2012.[823]

The analysis performed by PRIMES projected similar results. In the case of the scenarios achieving 80% GHG reduction, the energy related $CO_2$ emissions in refineries are projected to decrease between 77% (in the H2 scenario) up to 80% (in the CIRC scenario) compared to 2015. The 1.5°C scenarios can lead to higher reductions, up to 90% (see Table 47).

**Table 47: Energy related $CO_2$ emissions reduction in Refineries by 2050 compared to 2015**

| Refineries | Baseline | ELEC | H2 | P2X | EE | CIRC | COMBO | 1.5 TECH | 1.5 LIFE |
|---|---|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions reduction** | -47% | -79% | -77% | -78% | -79% | -80% | -83% | -90% | -90% |

*Source: PRIMES.*

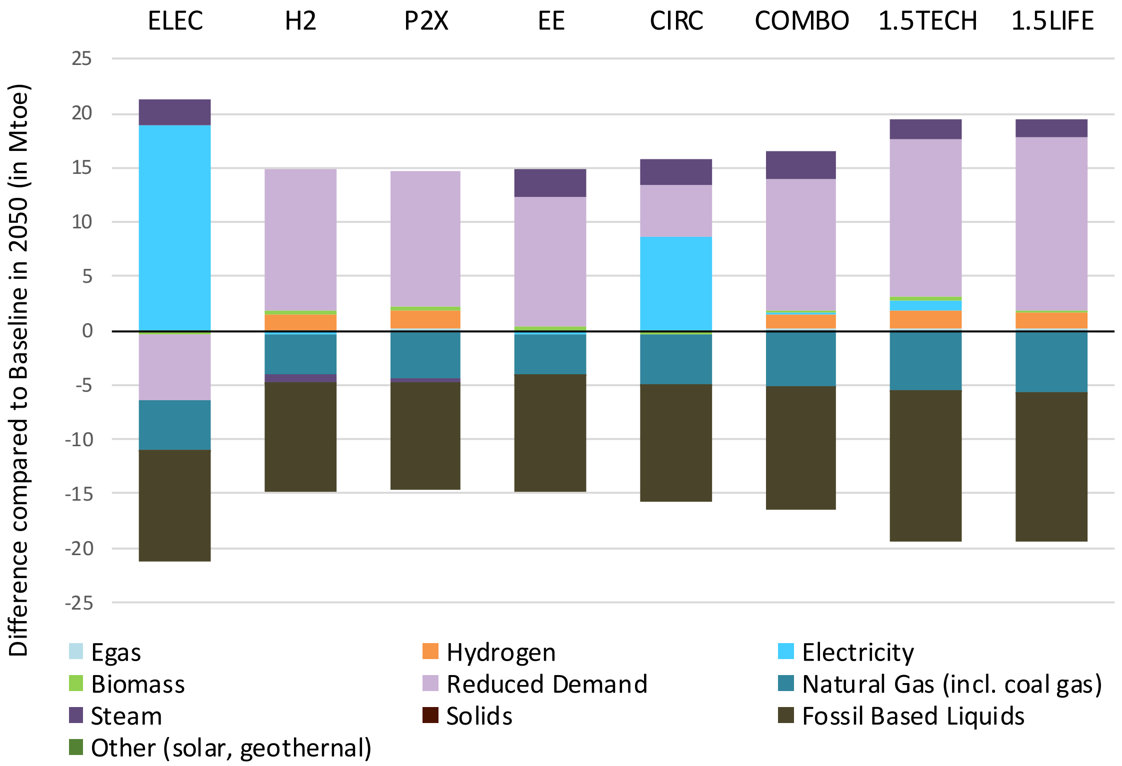
The sector had a final energy consumption of 46 Mtoe in 2015[826] and a projected demand in Baseline of 32 Mtoe in 2050, out of which 18 Mtoe of fossil liquids, 6 Mtoe natural gas, 4 Mtoe of steam and 3 Mtoe of electricity. The main drivers for these reductions are reported in Figure 151, which indicates the differences in energy consumption compared to the Baseline. In general, the main differences come by a significant decrease in final energy demand, up to almost 50% in 1.5 LIFE, related also with the increase in Electric Vehicles and corresponding decrease in fuel

[825] ASSET project (2018), Sectorial integration long-term perspective in the EU energy system, https://ec.europa.eu/energy/en/studies/asset-study-sectorial-integration

[826] Source: Eurostat

consumption. ELEC and CIRC are the only scenarios which reduce emissions not by demand reductions (energy efficiency) in the sector, but by fuel substitution of fossil liquids by electricity.[827].

**Figure 151: Differences in final energy consumption in Refineries compared to Baseline in 2050 by fuel and scenario**




*Source: PRIMES.*

The analysis using FORECAST indicates the possibility for high reductions. The GHG emissions reduction compared to 2015 for its -80% decarbonisation scenarios range between 71% (the Electric scenario) up to 83% (CCS scenario), with the Mix80 Scenario delivering 71% GHG reductions. Finally, the more ambitious Mix95 scenario delivers 96% reductions (see Table 48).

**Table 48: Total GHG emissions reduction in Refineries by 2050 compared to 2015**

| Refineries | CCS | CleanGas | BioCycle | Electric | Mix80 | Mix95 |
|---|---|---|---|---|---|---|
| **Total GHG emissions** | -83% | -79% | -77% | -71% | -71% | -96% |
| **Energy related GHG emissions (gross)** | -70% | -79% | -77% | -71% | -71% | -96% |
| **Process GHG emissions (gross)** | -83% | -85% | -90% | -89% | -89% | -98% |
| **Total GHG emissions (net)** | -83% | -79% | -77% | -71% | -71% | -96% |

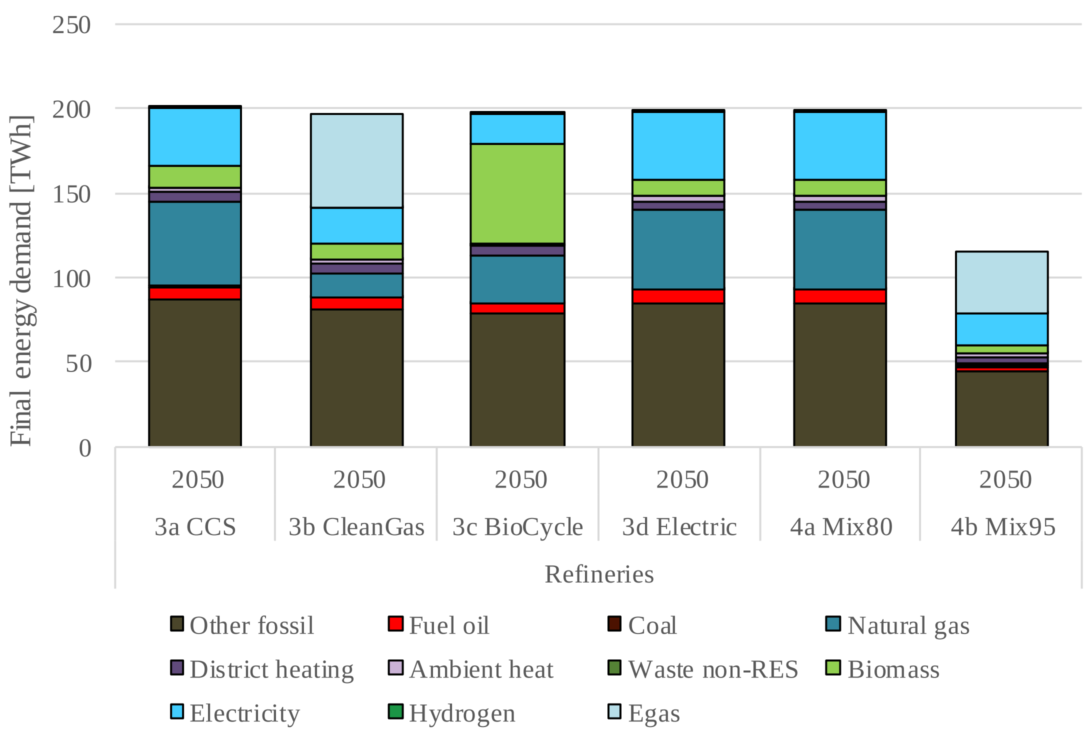
[827] This is because electrification of certain industrial processes is less efficient than thermal processes in high-temperature applications and at the same time reduces the potential of energy savings through heat recovery.

*Source: FORECAST.*

The drivers for GHG emissions reduction in the FORECAST scenarios are listed below. Figure 152 presents the final energy demand by energy carrier.

- For all scenarios energy efficiency innovations, but most importantly significant penetration of EVs, reducing the demand for diesel and gasoline.
- In CCS, reductions are achieved by the installation of post-combustion CCS and oxy-fuel CCS technologies, combined with faster switch to natural gas as energy carrier. About 14 Mt$CO_2$ are captured and stored in 2050.
- CleanGas, combines the consumption of distributed gas, which is assumed to have only 20% of conventional gas, with blue fuel synthesis to capture $CO_2$ and use them for the production of e-fuels (for the remaining non-electric vehicles).
- BioCycle foresees significant amounts of biomass used as feedstock and for heating of columns. Moreover, biofuels are produced to serve the remaining liquid fuel demand;
- In Electric, columns are heated by electricity.
- Mix80 is based on fuel switching to electricity.
- Mix95 adds CCS to the remaining emissions of Mix80, combined with the assumption of having only clean gas (no natural gas) in the gas distribution grid. About 7 Mt$CO_2$ are captured and stored in 2050. Final energy demand decreases strongly because this is the only scenario assuming a strong decrease in consumption of oil production in the economy as a whole, and thus less production in refineries.

**Figure 152: Final energy demand in the refining industry by energy carrier**



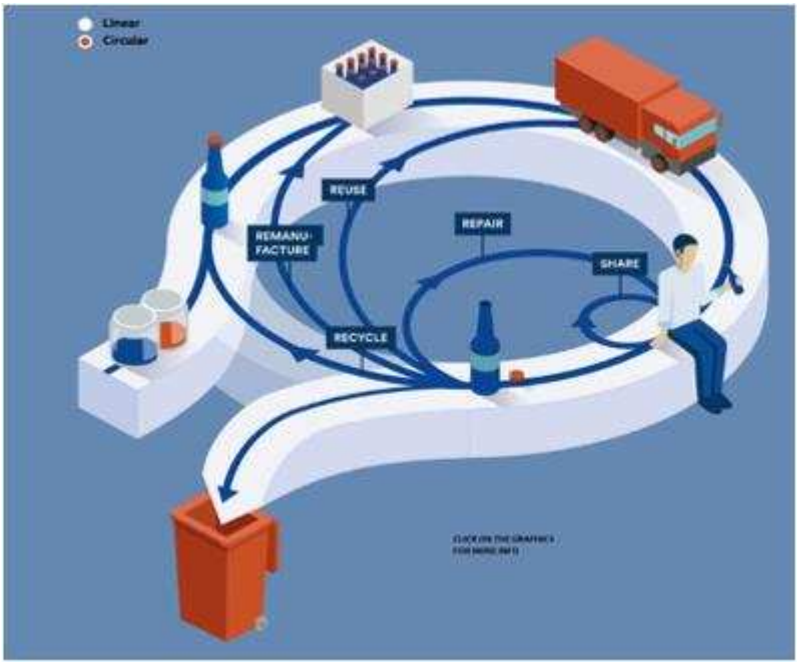

*Source: FORECAST.*

In the context of the Paris agreement, reduced demand for fossil fuel based fuels should be expected and may prove as a challenge to the industry. At the same time though opportunities arise in the refining of clean molecules, which would allow refineries to be integrated into local economic value chains for the production of heat, hydrogen and synthetic fuels, biofuels and $CO_2$.[828] This will allow refineries to continue supplying the market with fuels and remain competitive in an international context. Note though that in these cases, like the production of synthetic fuels, emissions reduction can be achieved only if electricity is carbon free.

### *7.6.7 Circular Economy: The opportunities for industry*

Circular economy presents a great potential for emissions reduction and many other opportunities for the industry. Ambitious demand side measures in the form of materials recirculation, increased product efficiency and circular business models can reduce emissions significantly in heavy industry by up to 60% in 2050 compared to 1990.[762] It offers opportunities for a more efficient use of materials, complementing the efforts in increasing energy efficiency and reducing costs. To reap these benefits significant changes need to take place in our economy (see Box 1).

**Figure 153: A circular economy**

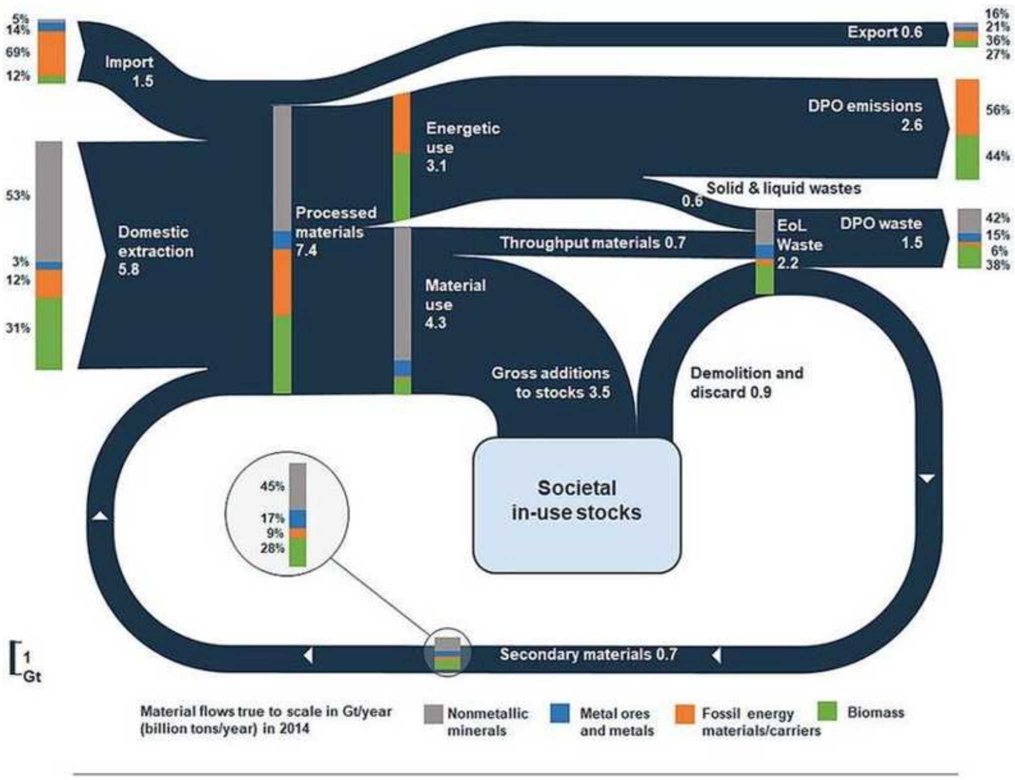



*Source: European Parliamentary Research Service* [829].

[828] CIEP (2018), Refining the Clean Molecule, http://www.clingendaelenergy.com/publications/publication/refinery-2050-refining-the-clean-molecule

[829] http://www.europarl.europa.eu/thinktank/infographics/circulareconomy/public/index.html

**Figure 154: Material flows in the economy (EU-28, 2014)**




*Source: Mayer et al (2018)*[830].

[830] Mayer et al (2018), Measuring progress towards a Circular Economy - a monitoring framework for economy-wide material loop closing in the EU28, Journal of Industrial Ecology, doi: 10.1111/jiec.12809

**Box 1: The Circular Economy**

The current economic model is close to linear, often described by extraction, production, use and disposal. In a circular economy raw materials are sourced sustainably and used for production more efficiently, taking into consideration from the product design phase the use, repair, disassembly, remanufacturing and reuse of the products. After a certain level of degradation, the components of the product are gradually recycled, each component allowing for a possibly different number of reuse cycles (Figure 153). This way a circular economy minimises waste, especially when the materials used are fully recyclable. It also reduces extraction of new raw materials.

In order to transit to a circular economy it is also necessary to revisit the existing value chain model of our economy. The current model could lead to a moderate circular economy, with increased recycling and some limited reuse. To reap the benefits of circular economy though, certain changes need to take place in the value chains. Products will be decreasingly bought and consumed; instead they will have increased durability and be leased, rented or shared by the consumers. Industrial and manufacturing processes will be redesigned so that material loss in the production and between the different lifecycles phases of each product or material are minimised. Cascading use of material will lead to a diversified reuse across the value chain, for example cotton clothing first reused as second hand apparel, then as fibre-fill in upholstery in the furniture industry and later in stone wool insulation for construction ("Towards the Circular Economy", 2013, Ellen McArthur Foundation).

A major objective of the circular economy is to retain value within the economic system (value-retention processes). In a circular economy companies may sell less new products than in the current linear one. At the same time though value creation opportunities will arise, both in terms of cost reductions and the increase of services offered together with the product. In terms of costs, due to the reverse cycle, energy, material and labour costs per product are expected to be reduced. New services, enabled by the digitalisation of the economy, will facilitate reusing or sharing the use of products, while offering advanced lifetime prolongation options for the products and logistical support via reverse logistics. This will maximise the utility of the customers, while significantly reducing environmental impacts.

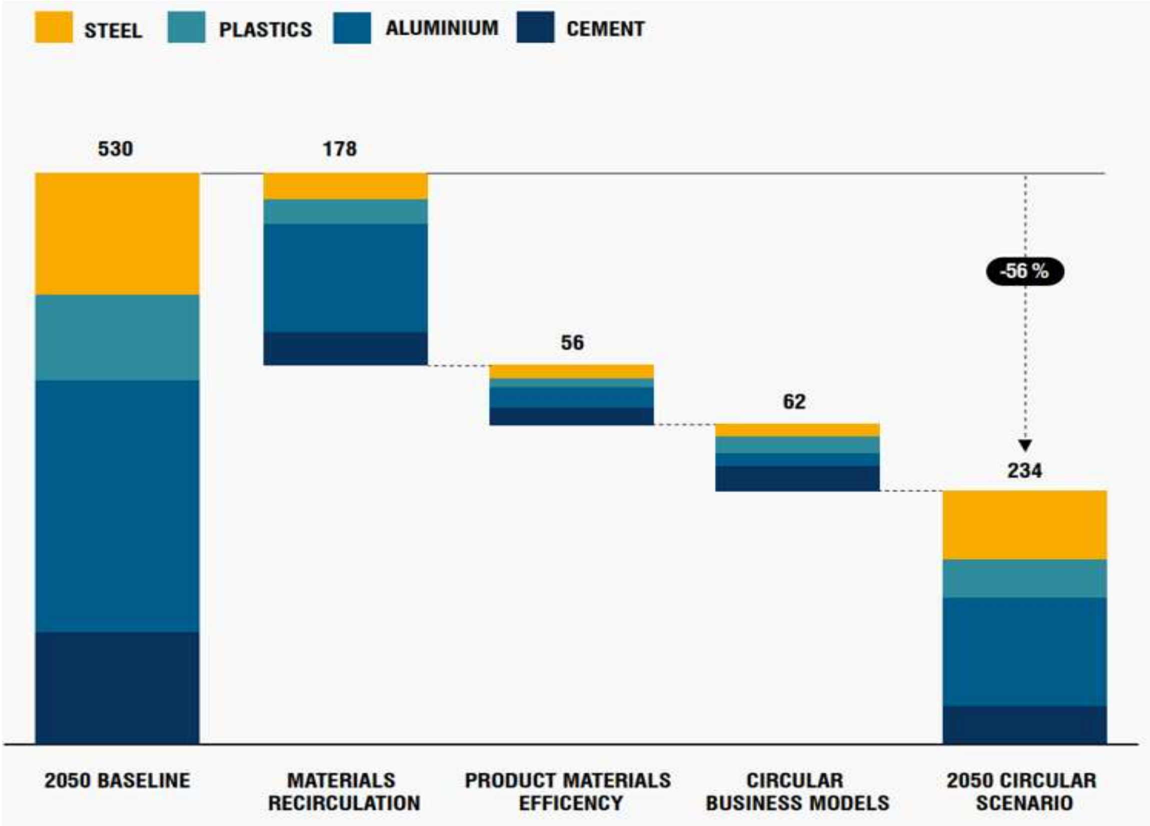
What would be the impact of these changes? These changes will have a number of impacts on the economy, the environment, the GHG emissions and the energy system. Improved waste management allows materials to go back into the economic cycle, thus, reducing the input of raw materials. The quantities of virgin material used as feedstock will reduce, part of it replaced by increased recycled and uncontaminated material, which requires much less energy and carbon intensive processes for its processing, and part from the cascading use of material and reduced material loss during the processing phase. Industries will enter partnerships, sharing their infrastructure and their material inputs / outputs / waste in the context of increasing trends of industrial symbiosis. Mobility will become a service, with cars shared and operated in fleets, increasing the occupancy rates of cares and reducing their numbers and thus the material required for their production.

As part of its continuous effort to transform Europe's economy into a more sustainable one and to implement the ambitious Circular Economy Action Plan, in January 2018 the European Commission adopted a new set of measures (COM(2018) 29 final), including:

- a Europe-wide EU Strategy for Plastics in the Circular Economy,
- a Communication on options to address the interface between chemical, product and waste legislation that assesses how the rules on waste, products and chemicals relate to each other,
- a Monitoring Framework on progress towards a circular economy at EU and national level. It is composed of a set of ten key indicators which cover each phase – i.e. production, consumption, waste management and secondary raw materials – as well as economic aspects – investments and jobs - and innovation.
- A Report on Critical Raw Materials and the circular economy that highlights the potential to make the use of the 27 critical materials in our economy more circular.

The Material Economics report[762] identifies four materials and two value chains, accounting for more than half of industrial $CO_2$ emissions today, that could significantly reduce their emissions by 2050. Increased recycling and reduced losses during production in steel, plastics, aluminium and cement can deliver about 40% reductions in emissions (Figure 155). Additional reductions can be achieved by the reduced material used for buildings and cars, when these are used and produced more efficiently.

**Figure 155: EU Emissions reduction potential from a more circular economy**




*Source: Material Economics* [762].

**Box 2: Circular Economy Examples**

*Short-loop recycling of plastics in vehicle manufacturing:* Renault initiated a collaboration with multiple stakeholders with the aim of establishing a closed loop for plastics maintained wholly within the local automotive industry. As a result 36% of the total mass of a new vehicle is made from recycled materials; in a new Espace 20% of plastic is from recycled material. (Source: Ellen Macarthur foundation)

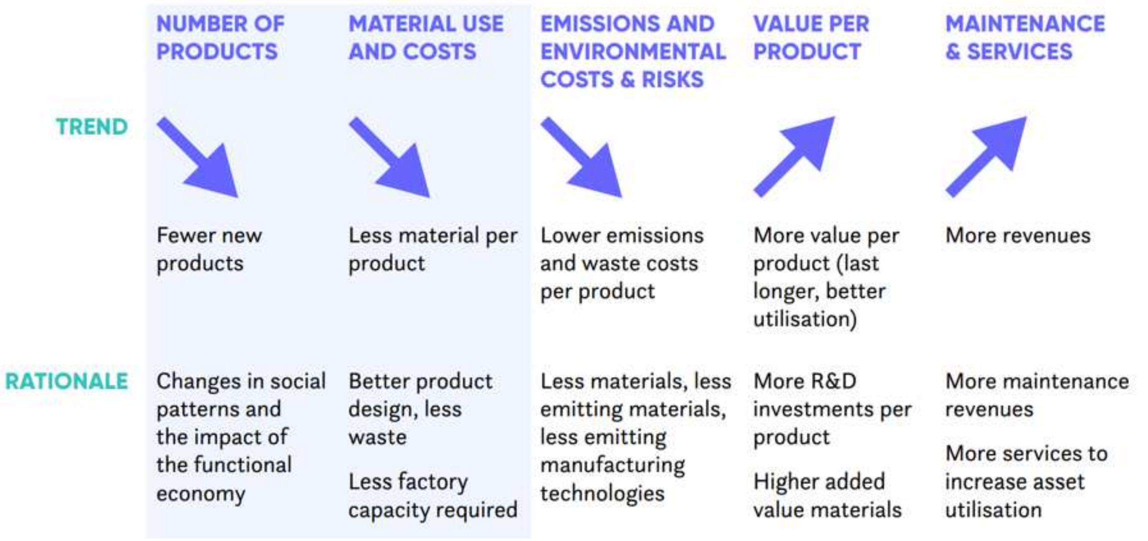
*Re-using old bricks to build a greener future:* “Gamle Mursten” (“Old Bricks”) is a large-scale cleantech production company with patented cleaning technology for reusing building waste without the use of any chemicals, saving more than 95% of the energy otherwise used to manufacture new bricks. (Source: State of Green)

*Product as a service*: HP is gradually moving into the product as a service business model by focusing on leasing, renting and other service contracts for ink, print and PC services. Compared with conventional business models, printers using this service generate up to 67 percent less materials consumption per printed page. (Source: HP)

Quantification of the impacts of circular economy in industry with PRIMES confirms the high economic and emissions reduction potential of this pathway. The CIRC scenario assumes an average reduction of physical output for most energy intensive industries around 10% by 2050, although the sectoral value added is retained at the same level assuming higher valued products. Moreover it assumes other circular economy measures, like increased recycling and reuse, improved waste management and reduced losses of material. Combined with moderate energy efficiency and fuel-switching, compared to the other scenarios, it leads to a scenario which achieves the 80% ambition at the least energy related investment cost.[831]

Circular economy is a big opportunity to create new markets, new technologies and new synergies (see Figure 156, Box 2).[832] In a moderate form it will improve waste management and reduce primary raw material required. A more ambitious approach, bringing additional changes in the current supply chains, utilisation patterns and product design for more re-usable and recyclable products, can deliver significant more benefits. A very ambitious approach could lead to even full circularity, but this would require also significant behavioural changes and deep business model transformation. Any level of ambition though does require a relevant level of changes to the regulatory framework and significant investment and innovation to create the proper conditions that could foster the development of a circular economy.[833] [834]

**Figure 156: Circular economy impacts on industry**




*Source: Climact.*

While the EU is at the forefront of the circular economy transition increasing the use of the secondary raw materials, a lot remains to be achieved in order to make the economy truly circular. In addition, these high recycling rates for a number of materials cannot cover the demand for these metals due to long product life-cycles (e.g. in buildings) and significant ongoing accumulation of products in households, although in some cases (e.g. steel, glass, paper) relatively large quantities of used material are being made available due to non-perishable nature

[831] The energy related investment costs do not include certain additional costs that would be related to circular measures, like the improved of material collection methods, handling and transporting material for preparing their reuse etc.

[832] Climact (2018), Net Zero By 2050: From Whether to How, https://europeanclimate.org/wp-content/uploads/2018/09/NZ2050-from-whether-to-how.pdf

[833] Climate Strategies & DIW Berlin (2018), Filling gaps in the policy package to decarbonise production and use of materials, https://climatestrategies.org/wp-content/uploads/2018/06/CS-DIW_report-designed-2.pdf

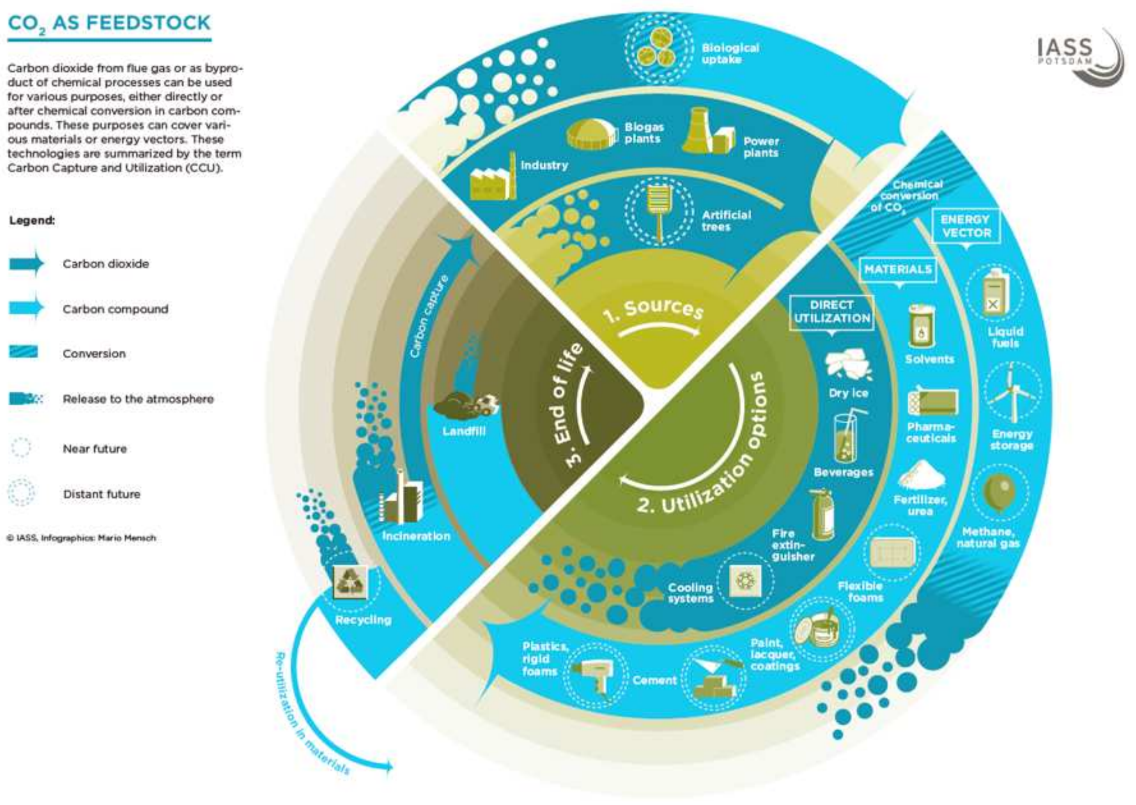
[834] CEPS (2018), The Role of Business in the Circular Economy, https://www.ceps.eu/system/files/RoleBusinessCircularEconomyTFR.pdf

of those materials and technological ease of sorting and purification. Moreover, for most of the raw materials needed in renewable energies or high tech applications, such as rare earth elements, indium, gallium or lithium, secondary production only represents a marginal contribution (often only around 1% or less) in meeting fast growing materials demand. An additional issue creating challenges to recycling is the increasing complexity in the composition of products (e.g. electronics).

### *7.6.8 CCU*

Carbon, capture and utilisation (CCU) is a technology closely linked with the circular economy. Capturing $CO_2$ emissions from waste management processes (incineration), combustion or process emissions, which would otherwise be released, represents the last chance to keep the carbon in the technical use sphere. It thus supplements the options of reuse and material recycling, and is of particular relevance for mixed organic wastes and hazardous wastes, as the chemical structure of the contained compounds is destroyed, their harmful properties thus being eliminated, as $CO_2$ is converted to other carbon-based substances. CCU could allow $CO_2$ utilisation into one or several cycles, depending the application, avoiding the use of an equal carbon amount of fossil based resources. Its applications are quite wide, ranging from fuels to chemicals and minerals, see Figure 159.

**Figure 157: Overview of $CO_2$ sources, utilisation options and end of life considerations**



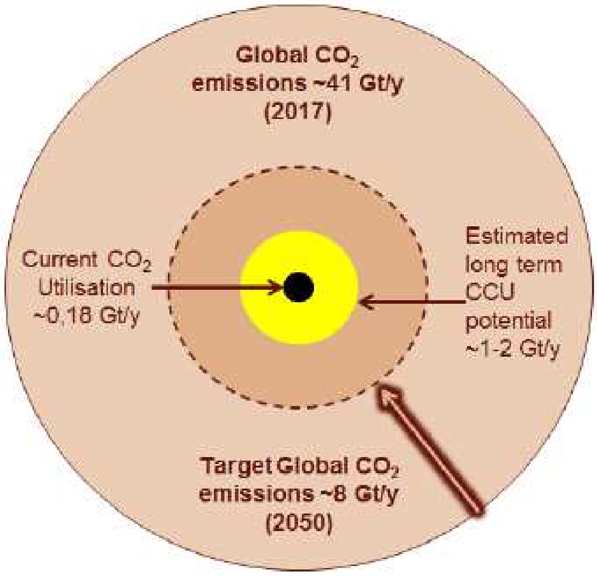

*Source: IASS Potsdam*[835].

GHG emissions reduction from CCU processes depend largely on the energy used and there is a general agreement that energy inputs in the processes need to be low carbon so the application of

[835] http://www.iass-potsdam.de/en/research/emerging-technologies/ccu

CCU technologies results in overall reduction of emissions. Large volumes of affordable renewable energy and integration in existing industrial systems would be needed for CCU technologies to deliver substantial climate benefits. The current mitigation potential is thus limited, however in the future, when the power becomes low carbon, and the overall emissions reduce, the share of $CO_2$ captured for CCU products can substantially increase, see Figure 158.

**Figure 158: Global $CO_2$ emissions and the role of CCU**




*Source: SAM HLG Opinion on CCU* [836].

CCU technologies present a number of opportunities not directly linked to climate change mitigation such as boosting European industry competitiveness, offering a technological advantage, providing an alternative carbon feedstock for the chemical industry, increasing energy security, providing energy storage options and synthetic fuels that can be used in existing infrastructure.

Some of the CCU technologies are still in various stages of technological development, their costs are high in comparison to conventional products and necessitate novel business models coupling industrial flows of different plants. In the case of CCU the specificities of each specific project may be more important than the technology as such. Detailed life-cycle and economic assessment would be needed on a project level to determine impacts of individual projects and to avoid emission shifting from one sector to another with "simply" delayed emission release, as well as gaps in coverage (e.g. exception for the waste incineration sector).

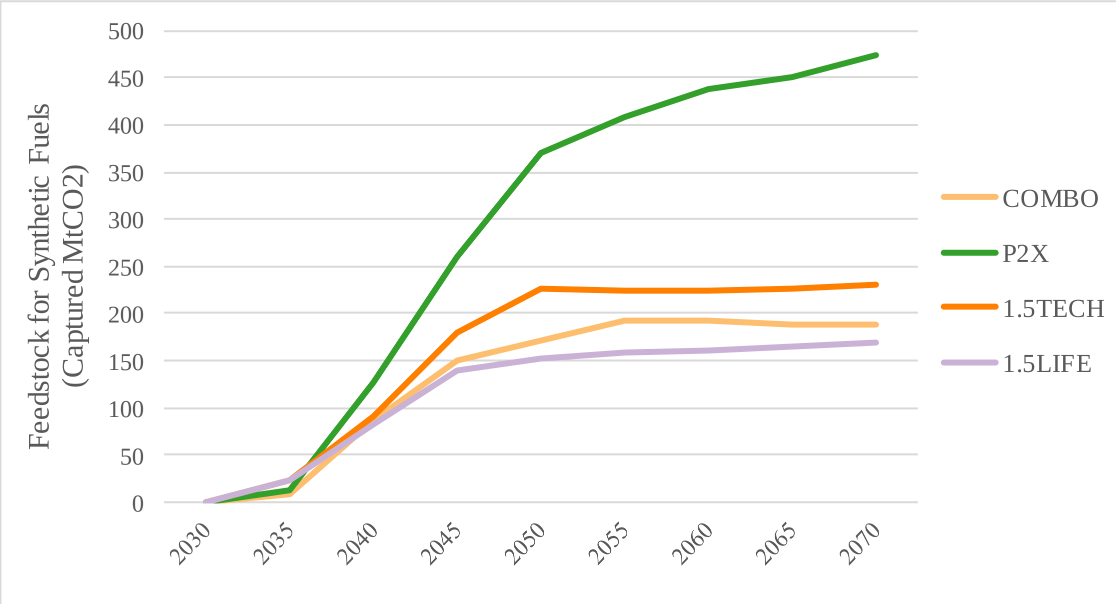
A possible commercial application of CCU is for the production of synthetic fuels, providing an alternative low carbon carrier to biofuels in transport, and thus reducing the need for importing biomass in the EU and allowing reallocation of domestic production for use in other harder to abate sectors or for the production of negative emissions. Their large $CO_2$ binding volume and its higher price than methane could make this option attractive in the future, when their price is competitive with the price of fossil fuels.[837] On the negative side, such liquid fuel applications of CCU means that the $CO_2$ is relatively quickly released to the air again after use. This is why their

[836] Scientific Opinion of the SAM HLG (2018), Novel Carbon Capture and Utilisation Technologies, https://ec.europa.eu/research/sam/index.cfm?pg=ccu

[837] Currently the price of Sunfire's synthetic fuels derived from $CO_2$ for example, is twice as high as the benchmark price.[781]

production is often considered together with $CO_2$ captured from Direct Air capture plants.[838] PRIMES runs indicated that such an option could deliver the desired ambition, but at a higher cost than other options. The $CO_2$ feedstock used for synthetic fuels can be seen in Figure 159 (mainly coming from DACs).

**Figure 159: $CO_2$ Feedstock used for the production of Synthetic Fuels (in $MtCO_2$)**




*Source: PRIMES.*

CCU can be developed along CCS in CCS/CCU clusters. There are a few of these CCS or CCU clusters under development around major industrial sites in Europe such as the Ports of Rotterdam, Antwerp and Marseilles, Tees Valley.[839] A high density of industrial sites could make economically viable the development of a common $CO_2$ infrastructure for capturing and using $CO_2$ even from installations with low emissions. The $CO_2$ that cannot be used economically can be piped to geological storage sites.

In the context the circular economy the focus of the final use of CCU would be in materials. CCU based materials, in contrast to CCU fuels, have the further advantage that they can be used several times and feed into material recycling. Materials can be plastics, building material substitutes or other materials that will be derived from CCU processes. Their lifespan depends on the end use of the CCU product. Examples would be the application in the automotive sector (e.g. polyurethane car seat cushions) or in the construction sector (e.g. concrete building blocks). Materials in general are suited for integration to the circular economy, as the overall lifespan can be elongated via material recycling.[840]

### *7.6.9 Industrial Symbiosis*

In industrial symbiosis, traditionally separated industries are brought together in partnerships, optimizing the use of resources and minimizing waste and associated costs. The physical

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[838] One such innovative approach is considered by Carbon Engineering (http://carbonengineering.com/), claiming that this technology can become economic in the near future.

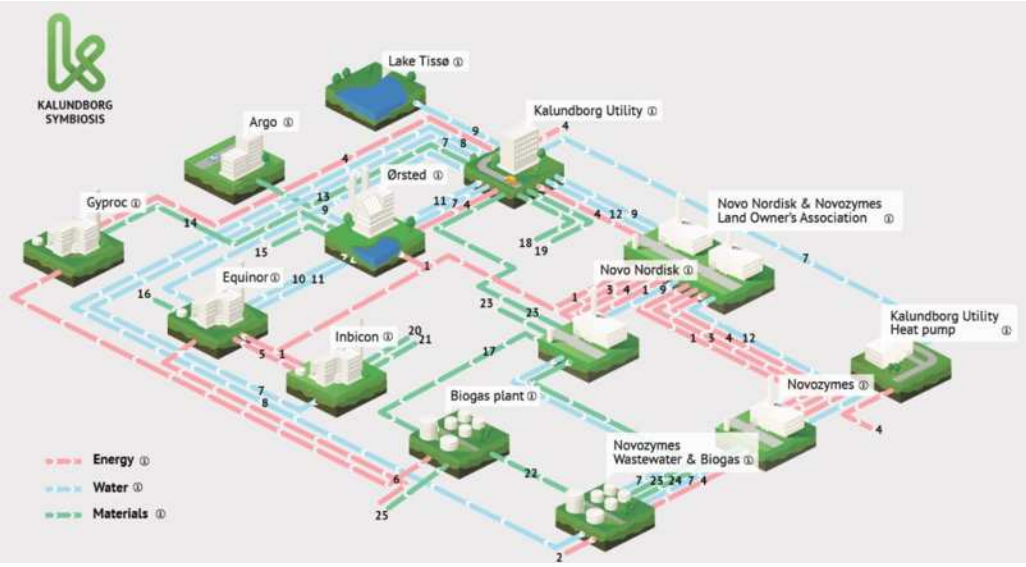
[839] European Commission (2017), SET-Plan Action 9 on CCS and CCU Implementation plan, https://setis.ec.europa.eu/system/files/set_plan_ccus_implementation_plan.pdf.

[840] Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects. [781]

exchanges between industries may include materials, energy, water and by-products. As a result, industries enjoy economic gains, while reducing environmental impacts and costs.

The typical model that has been applied in several regions of the world is where an "anchor-tenant" organisation with energy and by-product linkages is connected to companies physically located nearby.[841] This is usually a result of the so-called unplanned symbiosis, like the Kalundborg industrial site located in Denmark[842]. Kalundborg Symbiosis started more than 40 years ago and is one of the most well-known and well-described industrial symbiosis in the world. Kalundborg Symbiosis includes world-leading as well as smaller companies, with clear benefits for all of its participants (Figure 160).

**Figure 160: The Kalundborg Symbiose**




*Source: Kalundborg Symbiose.*

An alternative model is the so called managed network, where a third part can work as a facilitator for existing companies or even centrally plan the site and attract new businesses.[843] Prime examples of this model are ports, like the Ports of Rotterdam[844], Amsterdam[845] and Antwerp[846]. Such cases may be further supported with the increasing digitisation of industry, allowing to more easily monitor the available input and output resources, as well as waste, and identify opportunities for collaboration.

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841 Baas (2011), Planning and Uncovering Industrial Symbiosis, https://doi.org/10.1002/bse.735.
842 http://www.symbiosis.dk/en/
843 Trinomics (2018), Cooperation fostering industrial symbiosis: market potential, good practice and policy actions, https://publications.europa.eu/en/publication-detail/-/publication/174996c9-3947-11e8-b5fe-01aa75ed71a1/language-en
844 Wuppertal Institut for the Port of Rotterdam (2016), Decarbonisation Pathways for the Industrial Cluster of the Port of Rotterdam, https://www.portofrotterdam.com/sites/default/files/rapport-decarbonization-pathways-for-the-industrial-cluster-of-the-port-of-rotterdam.pdf?token=4Ri58reM.
845 Port of Amsterdam (2017), The Sustainable Port, https://www.portofamsterdam.com/sites/poa/files/media/havenbedrijf/duurzaamheidsplan_en_digitaal_2017.pdf
846 Vansteenbrugge, J. (2012), Industriële symbiose in havengebied - taakstelling voor de ruimtelijke planning? https://lib.ugent.be/fulltxt/RUG01/001/887/236/RUG01-001887236_2012_0001_AC.pdf

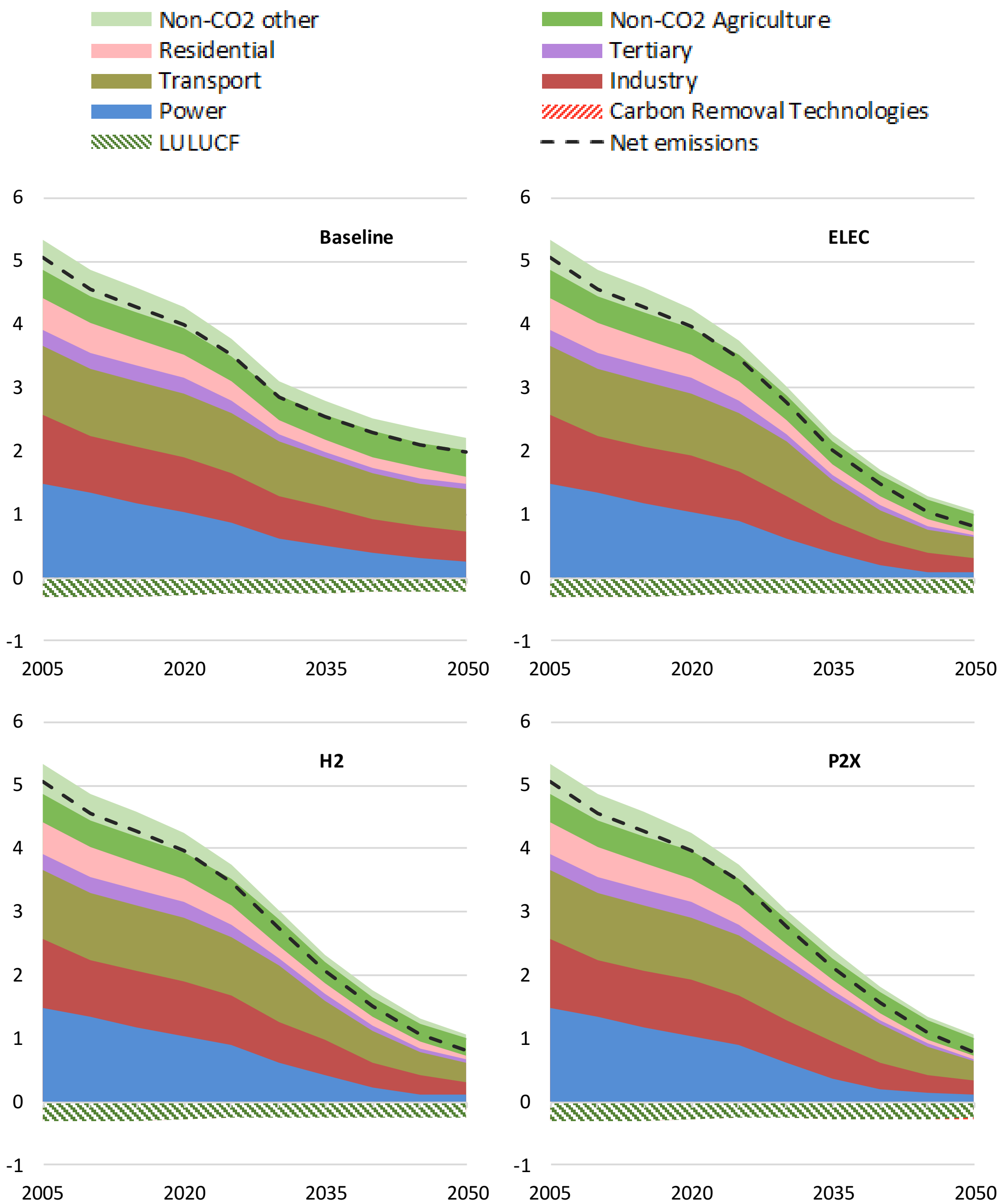
Although the existing quantitative evidence supporting the case of industrial symbiosis are limited, mainly due to the complexity of such an exercise, the cases of potential win-wins are clear. Industrial symbiosis is expected to become more prominent as sectors seek to reduce GHG emissions.[847] A broad and EU wide assessment of the future of industrial symbiosis was undertaken in EPOS, SPIRE project in 2016.[848] Nevertheless, for these benefits to be realised a number of barriers need to be removed and coordination of interested parties needs to be facilitated.[849]

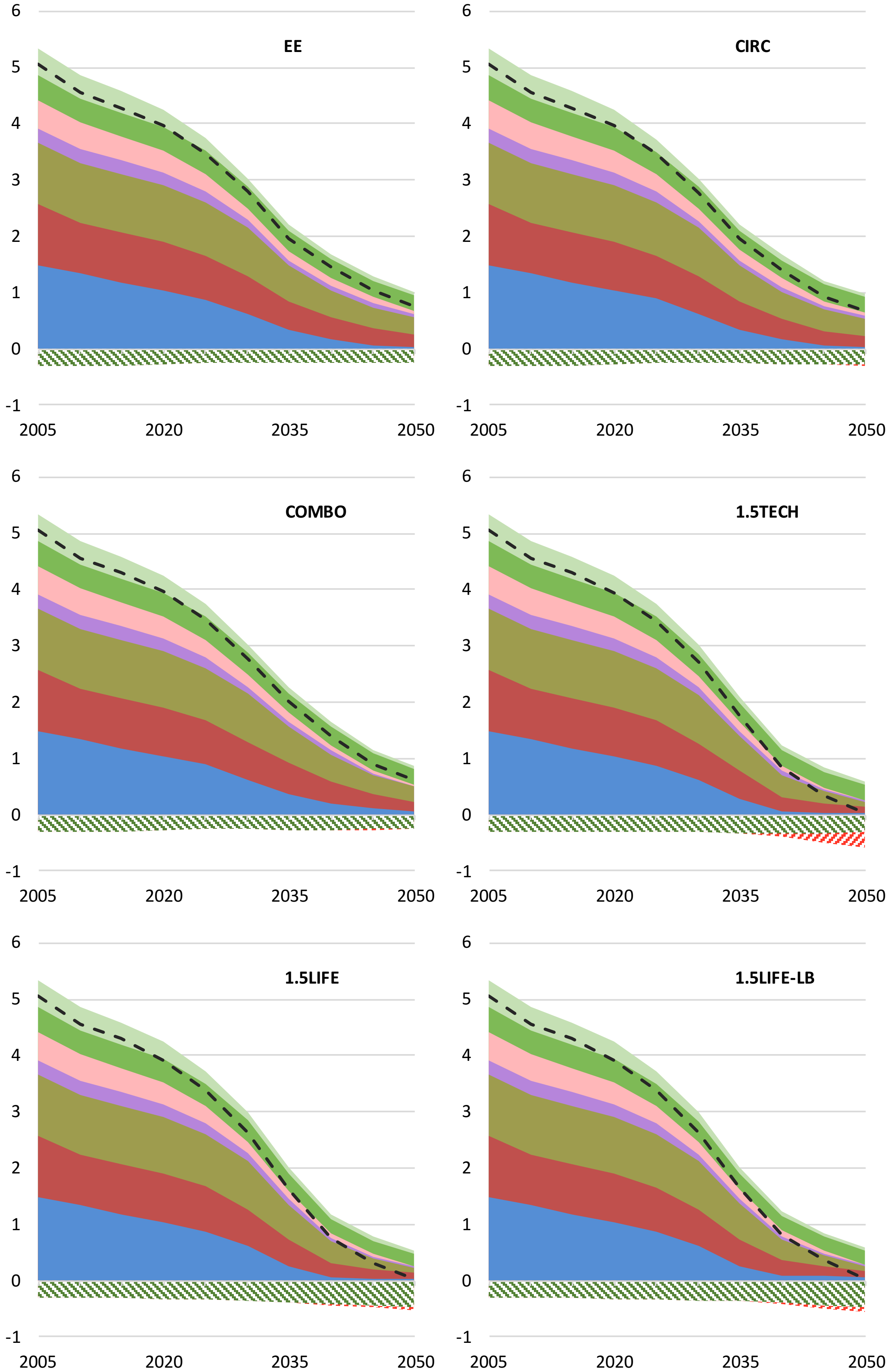
[847] VUB-IES (2018), Industrial Value Chain. A bridge towards a carbon neutral Europe, https://www.ies.be/files/Industrial_Value_Chain_25sept_0.pdf.

[848] https://www.spire2030.eu/epos

[849] Öko-Institut, ECORYS, IDEA, Acteon, Copenhagen Resource institute (2016), Study on the energy savings potential of increasing resource efficiency, study for the European Commission, Directorate-General for Environment, http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/final_report.pdf

## 7.7 GHG Pathways towards 2050 ($GtCO_2eq$)






*Source: PRIMES/GAINS/GLOBIOM*

# 8 LIST OF ACRONYMS

| | |
|---|---|
| ACER | Agency for the Cooperation of Energy Regulators |
| ASEAN | Association of Southeast Asian Nations |
| ATM | Air Traffic Management |
| BACS | Buildings Automation, Control and Smart systems |
| BAT | Best Available Techniques |
| BAU | Business as Usual |
| BF | Blast Furnace |
| BECCS | Bio-Energy With Carbon Capture And Storage |
| BEMIP | Baltic Energy Market Interconnection Plan |
| BEV | Battery Electric Vehicle |
| CAP | Common Agricultural Policy |
| CBA | Consumption-Based Accounting |
| CCS | Carbon Capture and Storage |
| CCU | Carbon Capture and Utilisation |
| CDR | Carbon Dioxide Removal (technologies) |
| CE4AE | Clean Energy for All Europeans legislative package |
| CEF | Connecting Europe Facility |
| CEM | Clean Energy Ministerial |
| CESEC | Central and South-Eastern Europe Connectivity |
| CHP | Combined Heat and Power |
| C-ITS | Cooperative Intelligent Transport Systems |
| CNG | Compressed Natural Gas |
| COP | Conference Of the Parties |
| CSP | Concentrating Solar Power (plant) |
| CWREM | Central-West Regional Energy Market |
| DAC | Direct Air Capture |
| DACCS | Direct Air $CO_2$ Capture and Storage |

| | |
|---|---|
| DRI | Direct Reduced Iron |
| EAF | Electric Arc Furnace |
| EASA | European Aviation Safety Agency |
| ECAC | European Civil Aviation Conference |
| EEA | European Environmental Agency |
| EE | Energy Efficiency |
| EED | Energy Efficiency Directive |
| EEDI | Energy Efficiency Design Index |
| EFSI | European Fund for Strategic Investments |
| EGA | Environmental Goods Agreement |
| EII | Energy Intensive Industry |
| ENISA | European Union Agency for Network and Information Security |
| EPBD | Energy Performance in Buildings Directive |
| EPI | European Processor Initiative |
| EPRI | Electric Power Research Institute |
| ERA | European (Union) Railway Agency |
| ERDF | European Regional Development Fund |
| ERMTS | European Railway Traffic Management System |
| ESG | Environmental, Social and Governance |
| ESR | (European Union) Effort Sharing Regulation |
| EU | European Union |
| EU ETS | European Union Emissions Trading System |
| EUROCONTROL | European Organisation for the Safety of Air Navigation |
| EV | Electric Vehicle |
| FAO | Food and Agriculture Organization |
| FCEV | Fuel Cell Electric Vehicle |
| FDI | Foreign Direct Investments |
| FEC | Final Energy Consumption |
| F-gas | Fluorinated gases |

| | |
|---|---|
| FORECAST (model) | FORecasting Energy Consumption Analysis and Simulation Tool |
| FTA | Free Trade Agreement |
| G20 | Group of 20[850] |
| G4M (model) | Global forest model |
| GAINS (model) | Greenhouse gas and Air Pollution Information and Simulation |
| GCC | Gulf Cooperation Council |
| GCCA | Global Climate Change Alliance |
| GDP | Gross Domestic Product |
| GEEREF | Global Energy Efficiency and Renewable Energy Fund |
| GEM-E3 (model) | General Equilibrium Model for Economy-Energy-Environment |
| GHG | Greenhouse Gas |
| GIS | Geographical Information System |
| GIC | Gross Inland Consumption |
| GLOBIOM (model) | Global Biosphere Management Model |
| GMST | Global Mean Surface Temperature |
| HDV | Heavy-Duty Vehicles |
| HFC | HydroFluoroCarbon |
| HPC | High Performance Computing |
| HVDC | High Voltage Direct Current |
| IAEA | International Atomic Energy Agency |
| ICAO | International Civil Aviation Organisation |
| ICE | Internal Combustion Engine |
| ICT | Information and Communication Technology |
| IEA | International Energy Agency |
| IGA | Intergovernmental Agreement |

[850] The Group of Twenty (G20) is a forum made up of the European Union and 19 countries: Argentina, Australia, Brazil, Canada, China, Germany, France, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, the United Kingdom and the United States.

| | |
|---|---|
| IMAGE (model) | Integrated Model to Assess the Global Environment |
| IMO | International Maritime Organization |
| INDC | Intended Nationally Determined Contribution |
| IPCC | Intergovernmental Panel on Climate Change |
| IRENA | International Renewable Energy Agency |
| IT | Information Technology |
| ITER | International Thermonuclear Experimental Reactor |
| JRC | Joint Research Centre |
| LDV | Light-Duty Vehicles |
| LED | Light-Emitting Diode |
| LLCP | Long-Lived Climate Pollutants |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| LULUCF | Land Use, Land-Use Change, and Forestry |
| MAC | Mobile Air Conditioning |
| MAGICC (model) | Model for the Assessment of Greenhouse Gas Induced Climate Change |
| MARPOL | Marine Pollution |
| MBM | Market-based Measure |
| MFF | Multiannual Financial Framework |
| MRV | Monitoring, Reporting and Verification |
| MS | (EU) Member State |
| MSR | Market Stability Reserve |
| NACE | Nomenclature statistique des Activités économiques dans la Communauté Européenne |
| NDC | Nationally Determined Contribution |
| NEA | Nuclear Energy Agency |
| NECPs | National Energy And Climate Plan |
| NEEAP | National Energy Efficiency Action Plan |
| NGO | Non-Governmental Organisation |

| | |
|---|---|
| NPP | Net Primary Productivity |
| NREAP | National Renewable Energy Action Plan |
| NSCOGI | North Seas Countries' Offshore Grid Initiative |
| NUTS | Nomenclature des Unités Territoriales Statistiques |
| NZEB | Nearly Zero-Energy Building |
| OECD | Organisation for Economic Co-operation and Development |
| OPC | Open Public Consultation |
| OPEC | Organization of the Petroleum Exporting Countries |
| PACE | Property Assessed Clean Energy |
| PBA | Production-Based Accounting |
| PCI | Projects of Common Interest |
| PEC | Primary Energy Consumption |
| PFC | PerFluoroCarbon |
| PHEV | Plugin Hybrid Electric Vehicle |
| PINC | Programme Indicatif Nucléaire de la Commission européenne (Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty) |
| POLES-JRC (model) | Prospective Outlook on Long-term Energy System, model version developed and operated by JRC |
| PRIMES (model) | Price-Induced Market Equilibrium System |
| PV | Photovoltaic (energy) |
| QUEST (model) | QUarterly Economic Simulation Tool |
| R&D | Research and Development |
| R&I | Research and Innovation |
| RDI | Research, Development and Innovation |
| RES | Renewable Energy Sources |
| RFC | Rail Freight Corridor |
| SAT | Surface Air Temperature |

| | |
|---|---|
| SDG | (United Nations) Sustainable Development Goal |
| SET (Plan) | Strategic Energy Technology Plan |
| SLCP | Short-Lived Climate Pollutants |
| SME | Small and Medium-sized Enterprise |
| SOC | Soil Organic Carbon |
| SPIPA | Strategic Partnerships for the Implementation of the Paris Agreement |
| SWD | Staff Working Document |
| TCBA | Technologically-Adjusted Consumption-Based Accounting |
| TEN-E | Trans-European Networks for Energy |
| TEN-T | Trans-European Networks for Transport |
| TRL | Technology Readiness Level |
| TSD | Trade and Sustainable Development |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VAT | Value Added Tax |
| VRT | Variable Rate Technology |
| WLTP | Worldwide harmonized Light vehicles Test Procedure |
| WMO | World Meteorological Organization |
| WTO | World Trade Organization |