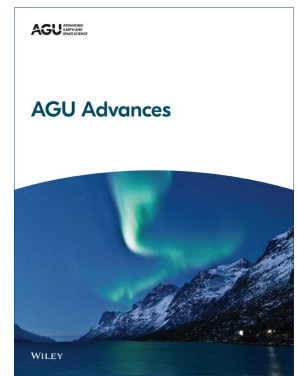


Carbon-Neutral Pathways for the United States

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- The United States can reach zero net CO₂ emissions from energy and industry in 2050 at a net cost of 0.2–1.2% of GDP, not counting climate benefits
- Multiple feasible pathways exist, all based on energy efficiency, clean electricity, electrification, and carbon capture for use or storage
- Least-cost electricity systems obtain >80% of their energy from wind and solar, with existing types of thermal generation for reliability

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Abstract The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C points to the need for carbon neutrality by mid-century. Achieving this in the United States in only 30 years will be challenging, and practical pathways detailing the technologies, infrastructure, costs, and tradeoffs involved are needed. Modeling the entire U.S. energy and industrial system with new analysis tools that capture synergies not represented in sector-specific or integrated assessment models, we created multiple pathways to net zero and net negative CO₂ emissions by 2050. They met all forecast U.S. energy needs at a net cost of 0.2–1.2% of GDP in 2050, using only commercial or near-commercial technologies, and requiring no early retirement of existing infrastructure. Pathways with constraints on consumer behavior, land use, biomass use, and technology choices (e.g., no nuclear) met the target but at higher cost. All pathways employed four basic strategies: energy efficiency, decarbonized electricity, electrification, and carbon capture. Least-cost pathways were based on >80% wind and solar electricity plus thermal generation for reliability. A 100% renewable primary energy system was feasible but had higher cost and land use. We found multiple feasible options for supplying low-carbon fuels for non-electrifiable end uses in industry, freight, and aviation, which were not required in bulk until after 2035. In the next decade, the actions required in all pathways were similar: expand renewable capacity 3.5 fold, retire coal, maintain existing gas generating capacity, and increase electric vehicle and heat pump sales to >50% of market share. This study provides a playbook for carbon neutrality policy with concrete near-term priorities.

Plain Language Summary We created multiple blueprints for the United States to reach zero or negative CO₂ emissions from the energy system by 2050 to avoid the most damaging impacts of climate change. By methodically increasing energy efficiency, switching to electric technologies, utilizing clean electricity (especially wind and solar power), and deploying a small amount of carbon capture technology, the United States can reach zero emissions without requiring changes to behavior. Cost is about \$1 per person per day, not counting climate benefits; this is significantly less than estimates from a few years ago because of recent technology progress. Models with more detail than used in the past revealed unexpected synergies, counterintuitive results, and tradeoffs. The lowest-cost electricity systems get >80% of energy from wind and solar power but need other resources to provide reliable service. Eliminating fossil fuel use altogether is possible but higher cost. Restricting biomass use and land for renewables is possible but could require nuclear power to compensate. All blueprints for the United States agree on the key tasks for the 2020s: increasing the capacity of wind and solar power by 3.5 times, retiring coal plants, and increasing electric vehicle and electric heat pump sales to >50% of market share.

1. Introduction

The Paris Agreement calls for “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015).” Moreover, avoiding the worst impacts of climate change may require not only staying below 1.5°C but a return to 1°C by 2100 (Hansen et al., 2013). Climate outcomes of 2°C, 1.5°C, and 1°C are associated with end of century atmospheric CO₂ concentrations of roughly 450, 400, and 350 ppm, respectively, entailing global net CO₂ emissions trajectories that reach zero by roughly 2070, 2055, and 2040 and are negative thereafter (Hansen et al., 2017; IPCC, 2018).

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Table 1
Summary of Scenarios Used in This Analysis

Scenario	Description
Reference	Business-as-usual case based on DOE <i>Annual Energy Outlook</i>
Central	Least-cost carbon-neutral pathway
Central, Low Fossil Fuel Price	Central case sensitivity using low fossil fuel price forecast
Central, Low Renewables Cost	Central case sensitivity using low renewable technology cost forecast
Low Land	Limited bioenergy and land for siting renewables and transmission
Delayed Electrification	Slow consumer uptake of electric technologies
Low Demand	High conservation resulting in reduced demand for energy services
100% Renewable Primary Energy	No fossil fuels or nuclear power allowed by mid-century
Net Negative	Least-cost pathway to negative emissions consistent with 1°C/350 ppm

This paper examines specific pathways by which emissions reductions consistent with these trajectories can be achieved in the United States. We focus on reductions in energy and industrial (E&I) CO₂, which constitutes more than 80% of current gross U.S. greenhouse gas (GHG) emissions (U.S. EPA, 2019a). We combined our modeled results for E&I with published values for non-CO₂ GHG emissions and the land CO₂ sink to obtain a range of economy-wide CO₂e values for comparison to global trajectories and policy targets adopted by United States and other jurisdictions, including “80% by 2050,” “net zero by 2050,” and “350 ppm by 2100” (Le Quéré et al., 2018; U.S. Climate Alliance, 2020).

Our objective in this paper was to develop realistic deep decarbonization scenarios that reach net zero or net negative E&I CO₂ emissions by 2050 while meeting all forecast demand for energy services at the lowest possible cost, using only technologies that are commercial or have been demonstrated at large pilot scale. The scope of the analysis includes all energy flows through the U.S. economy, from primary energy inputs, such as petroleum and natural gas, to energy conversion processes, such as oil refining and power generation, to end uses in buildings, transportation, and industry that consume final energy in the form of electricity and solid, liquid, and gaseous fuels. We modeled the transition pathways in all these areas in detail to answer high-level questions of interest to policy makers—technical feasibility, infrastructure requirements, cost, the implications of different assumptions and tradeoffs, and the required types and scale of policy interventions—as well as technical questions of interest to specialists, for example, how to optimally integrate high levels of variable renewable energy (VRE), produce low-carbon fuels from biomass and electricity, decarbonize challenging end uses in industry and freight transport, and incorporate carbon capture, utilization, and storage (CCUS) into the overall E&I system (Bataille, 2020; Davis et al., 2018; Dessens et al., 2016; Rogelj et al., 2015).

2. Scenarios

We modeled eight different deep decarbonization scenarios for the United States (Table 1) using a bottom-up approach similar to our previous work (Haley et al., 2018; Williams et al., 2012, 2015). The scenarios were designed to explore the effects of societal choices and resource constraints on decarbonization strategies and outcomes. A business-as-usual scenario (hereafter, *reference case*) based on the *Annual Energy Outlook (AEO)* of the U.S. Department of Energy (DOE) (U.S. EIA, 2019) was developed for comparison to the decarbonized cases in terms of CO₂ emissions, cost, energy mix, infrastructure requirements, and land use (Table 2). The scenario that achieves zero net E&I CO₂ emissions in 2050 at the lowest cost is called the (i) *central case*. The (ii) *low fossil fuel price* and (iii) *low renewables cost* scenarios test the sensitivity of the central case results to changes in cost input assumptions.

Three other scenarios also reach zero net emissions in 2050, while meeting additional constraints. The (iv) *low land case* tests the effect of limitations on land use in response to concerns about the sustainability of biomass use (Fletcher et al., 2011; IPCC, 2019; Searchinger et al., 2008; Smith et al., 2013) and the land requirements for siting renewable energy and transmission facilities (Hise et al., 2020; Kahn, 2000; McDonald et al., 2009; Wu et al., 2016, 2020). In this scenario, the land area of onshore wind and utility-scale solar was limited to 50% of the central case value, and the biomass supply was limited to 50% of its technical potential (Langholtz et al., 2016). The (v) *delayed electrification case* evaluates the impact

Table 2
Emissions, Energy, and Cost Results for Reference and Deep Decarbonization Scenarios in 2050

Indicator	Units	2020	2050 reference	Central	Delayed electrification	100% renewable	Low land	Low demand	Net negative
<i>Emissions</i>									
Gross E&I CO ₂	Mt CO ₂	5,580	4,571	840	904	147	1,204	635	489
Product and Bunker CO ₂	Mt CO ₂	390	553	524	524	524	524	395	524
Net E&I CO ₂	Mt CO ₂	5,190	4,018	0	0	-377	0	0	-500
Cumulative Net E&I CO ₂	Mt CO ₂	NA	140.5	78.9	78.9	74.8	78.9	78.8	72.9
“Low Mitigation” Total CO ₂ e	Mt CO ₂	NA	4,518	500	500	123	500	500	0
“High Mitigation” Total CO ₂ e	Gt CO ₂	NA	4,018	0	0	-377	0	0	-500
<i>Carbon Capture, Utilization, and Sequestration</i>									
E&I CO ₂ Captured	Mt CO ₂	0	1	787	1,060	664	794	640	1,063
E&I CO ₂ Utilized	Mt CO ₂	0	1	471	680	664	115	400	598
E&I CO ₂ Sequestered	Mt CO ₂	0	0	316	380	0	680	240	465
<i>Primary Energy Supply</i>									
Petroleum	EJ	39.0	37.1	4.4	5.3	0	10.3	2.4	0.6
Natural Gas	EJ	31.4	29.3	8.3	7.8	0	8.1	7.4	5.7
Coal	EJ	15.1	5.5	0	0.5	0	0	0.2	0
Biomass	EJ	3.6	3.2	12.2	17.5	16.1	10.3	10.4	17.1
Nuclear	EJ	8.9	4.3	4.3	4.4	0	13.4	4.3	4.4
Solar	EJ	0.4	3.7	12.5	12.5	18.9	11.2	9	13.7
Wind	EJ	1.3	8.2	28.3	30.4	36.3	17.2	22.8	30.6
Hydro	EJ	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Geothermal	EJ	0.05	0.05	0.05	0.05	0.11	0.06	0.05	0.05
Total	EJ	100.8	92.4	71.1	79.5	72.4	71.6	57.6	73.2
<i>Final Energy Demand</i>									
Residential	EJ	11.83	11.02	6.54	7.39	6.54	6.54	5.52	6.54
Commercial	EJ	9.08	10.92	7.34	7.85	7.34	7.34	6.30	7.34
Transportation	EJ	28.50	26.00	13.85	16.43	13.85	13.85	10.15	13.85
Industry	EJ	19.79	25.72	23.24	23.43	23.24	23.24	18.23	23.24
Total	EJ	69.20	73.66	50.97	55.10	50.97	50.97	40.20	50.97
<i>Electricity Share of Final Energy</i>									
Buildings—Residential	%	46%	56%	87%	74%	87%	87%	88%	87%
Buildings—Commercial	%	52%	51%	91%	78%	91%	91%	92%	91%
Light-Duty Vehicles	%	0%	4%	93%	54%	93%	93%	93%	93%
Transport Other	%	0%	0%	26%	18%	26%	26%	26%	26%
Industry	%	17%	18%	25%	23%	25%	25%	26%	25%
Total	%	20%	23%	49%	40%	49%	49%	50%	49%
<i>Electric Generation</i>									
Total Generation	TWh	4,170	5,430	12,040	12,420	15,190	9,570	9,550	12,840
Wind	%	9%	41%	63%	66%	64%	49%	64%	64%
Solar	%	3%	19%	28%	27%	34%	32%	26%	29%
Hydro	%	7%	6%	3%	2%	2%	3%	3%	2%
Biomass	%	1%	0%	0%	0%	0%	0%	0%	0%
Nuclear	%	19%	7%	3%	3%	0%	13%	4%	3%
Coal	%	31%	7%	0%	0%	0%	0%	0%	0%
Gas	%	31%	20%	3%	1%	1%	3%	3%	2%
Gas w/CCS	%	0%	0%	0%	0%	0%	0%	0%	0%
Thermal Capacity Factor	%	44%	33%	12%	11%	2%	27%	13%	11%
<i>Fuels</i>									
Total Production	EJ	55.5	56.7	21.9	28.1	20.2	22.1	17.5	20.9
Fossil Share	%	98%	98%	43%	41%	0%	67%	41%	23%
Biomass Share	%	2%	2%	25%	29%	41%	23%	27%	40%
Electric Fuel Share	%	0%	0%	31%	30%	59%	9%	32%	38%
Consumed as Liquid	%	66%	63%	60%	67%	65%	59%	58%	63%
Consumed as Gas	%	32%	35%	39%	31%	34%	40%	41%	36%
<i>Indicators</i>									
U.S. population	Million	334	397	397	397	397	397	397	397
Utility Wind and Solar Land Use	MHa	2.0	9.7	36.0	38.6	47.7	16.6	29.0	38.8

Table 2
Continued

Indicator	Units	2020	2050 reference	Central	Delayed electrification	100% renewable	Low land	Low demand	Net negative
Interstate Transmission Capacity	GW-km	145	176	368	365	462	319	287	389
Per Capita Energy Use Rate	GJ/per	209	188	131	141	131	131	103	131
Per Capita Emissions	tCO ₂ /per	15.5	10.1	0.0	0.0	-0.9	0.0	0.0	-1.3
U.S. GDP	\$T	22.2	38.4	38.4	38.4	38.4	38.4	38.4	38.4
E&I Net System Cost 2050	\$B	NA	NA	145	225	340	161	NA	214
Net Cost as Share of GDP	%	NA	NA	0.38%	0.59%	0.89%	0.42%	NA	0.56%
E&I Net System Cost NPV	\$B	NA	NA	1,728	2,496	2,644	1,799	NA	2,215
Economic Energy Intensity	MJ/\$	4.5	2.4	1.9	2.1	1.9	1.9	1.5	1.9
Economic Emission Intensity	kg CO ₂ /\$	0.23	0.10	0.00	0.00	-0.01	0.00	0.00	-0.01
Electric Emission Intensity	gCO ₂ /kWh	475.6	154.1	16.2	8.8	0	14.7	16.3	9.9

on mitigation strategies if consumers are slow to adopt low-carbon technologies (McCollum et al., 2014; Sugiyama, 2012). In this scenario, full uptake of electrified end use technologies such as electric vehicles and heat pumps was delayed by 15 years relative to the central case. The (vi) *low-demand case* explores high levels of conservation (Dietz et al., 2009; Grubler et al., 2018; Van Vuuren et al., 2018). In this scenario, energy service demand in key end uses such as driving and flying was reduced 20–40% below AEO levels.

Two other scenarios resulted in negative net E&I CO₂ emissions. The (vii) *100% renewable primary energy case* was designed to test the much-debated feasibility and cost of an E&I system based entirely on renewable energy (Breyer et al., 2018; Brick & Thernstrom, 2016; Clack et al., 2017; Jacobson et al., 2015, 2017; Shaner et al., 2018). By 2050, this scenario has no nuclear power remaining, no fossil fuel remaining, even for feedstocks, and no geologic carbon sequestration. In this case only, the energy mix constraint was binding and emissions were a result rather than a constraint. The (viii) *net negative case* was designed to explore the requirements of deeper emissions reductions consistent with a trajectory that peaks below 1.5°C and returns to 1°C/350 ppm by 2100 (Hansen et al., 2013, 2017; Rogelj et al., 2015; Van Vuuren et al., 2018). We report the scenario that achieves net E&I emissions of -500 Mt CO₂ in 2050 at lowest cost.

All cases except the low-demand case were constrained to meet the same demand for energy services as the reference case and to use AEO assumptions for population, GDP, and industrial production. (See Tables S2, S7, and S9 in the Supporting Information for further details on scenario definitions and input values).

3. Modeling Approach

Energy models are designed to address specific research questions that determine which aspects of a problem can be simplified and which require greater fidelity; they typically perform better within the scope of the research questions for which they were designed and less well when extended past that scope. In U.S. public policy making, the most widely used energy models (e.g., the National Energy Modeling System (NEMS), the Integrated Planning Model (IPM), and MARKAL) were designed decades ago when the research questions (e.g., forecasting near-term oil prices or criteria air pollutants from power plants) led to decisions about model structure that while appropriate at the time, make them less useful for studying the transition to low-carbon energy systems (Pfenninger et al., 2014). A key concern is the temporal representation of electricity operations, which requires much greater fidelity when variable renewable generation is involved (Poncelet et al., 2016). Similarly, integrated assessment models, the most common type of tool used today in academic climate policy research, were designed to answer questions about global climate trajectories as a function of policy scenarios. However, because answering these questions requires representing not only the energy system but also the climate system, the economy, land use, and all GHGs, the fidelity with which the energy system is represented is not adequate for making physical infrastructure plans that can be implemented, for example, by an electric utility. Finally, sectoral models (e.g., of electricity,

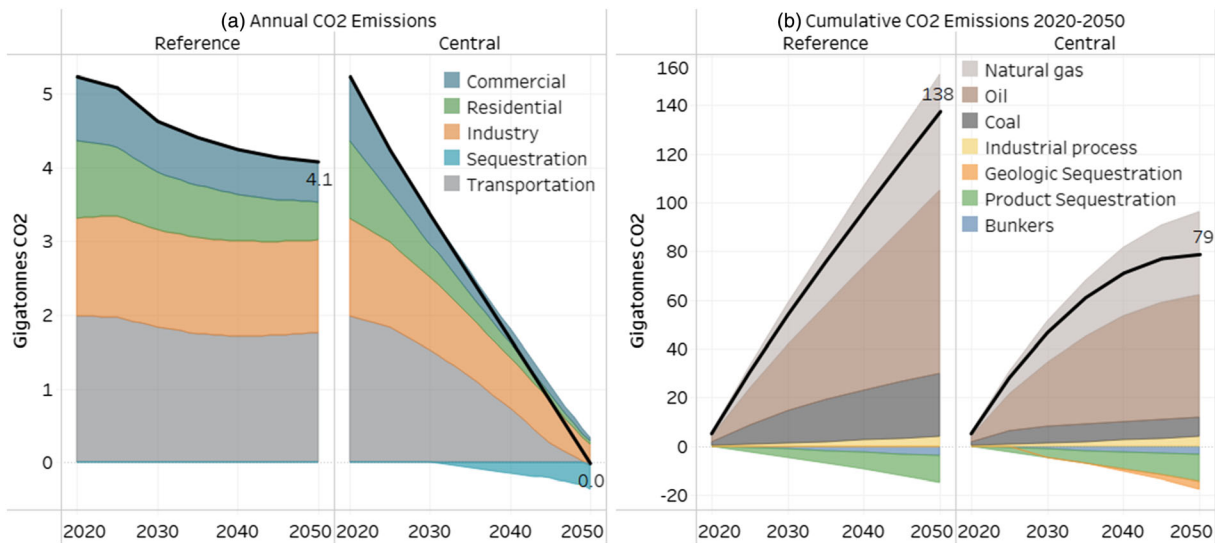


Figure 1. (a) Annual E&I CO₂ emissions for the reference and central cases. (b) Cumulative emissions. Solid black lines show net emissions. Right-hand figures show offsets from products and bunkers. Left-hand figures allocate these to end use sectors.

transportation, and buildings) used in the business and regulatory domains generally lack any representation of the whole energy system transition, which is essential for providing boundary conditions and other inputs needed to analyze sectoral decarbonization.

Recognizing these shortcomings, we built two new models, EnergyPATHWAYS (EP) and RIO, to address them. These models are run in series within a partial equilibrium framework and together analyze energy system decarbonization with sufficient accuracy to make implementable infrastructure plans. The analysis starts with bottom-up development of economy-wide final energy demand in EP, a detailed stock-rollover accounting model, with 64 different demand subsectors and 25 final energy types, for 16 geographic regions in the United States (for map, see Figure S42). In EP, the modeler makes demand-side technology choices (e.g., the rate of consumer uptake of electric vehicles) that determine the composition of the technology fleets used to meet demand for energy services (e.g., vehicle miles traveled), which are taken from the *AEO*.

Time-varying electricity and fuel demand from EP are input into RIO, a linear programming model that combines capacity expansion (planning of new facilities) with sequential hourly operations over a sampling of representative days to find the lowest-cost solution for decarbonized energy supply. RIO is unique in its high-resolution modeling of the interactions among electricity generation, fuel production, and CCUS; this allows it to determine the optimal decarbonization investment across these sectors and the optimal allocation of scarce resources, such as biomass, between them. RIO uses the same geographic regions as EP, and all infrastructure decisions are solved at 5-year time steps with perfect foresight and perfect coordination between supply sectors. The state of charge of electricity and fuels storage is tracked over an entire year, providing unique accuracy in modeling reliability and coproduction of fuels in electricity systems with very high VRE. Fuel and technology cost and performance inputs were all from public sources. The cost of producing and delivering energy from RIO is combined with the demand-side technology transition cost from EP to estimate energy system transition cost over the study period. This is done without the explicit economic feedbacks of a full-equilibrium framework, in which changes in relative prices drive consumer choices (DeCarolis et al., 2010; Pye et al., 2020). (For details of the EP and RIO methodologies, see Supporting Information sections S5 and S6.)

4. Emissions

4.1. Emissions Trajectories

Emissions trajectories for the reference and central cases are shown in Figure 1. In the reference case, net E&I CO₂ emissions decreased 22% below the 2020 level by mid-century, reflecting expected declines in

coal-fired power generation. For the central and all other carbon-neutral scenarios, net emissions were constrained to follow a straight-line path from 2020 to 2050, for the sake of comparability and to avoid trajectories that require even steeper reduction rates during some part of the period in order to achieve the same cumulative emissions. Following UNFCCC accounting rules, emissions were calculated as gross E&I CO₂ emissions minus negative E&I CO₂ emissions, which consist of geologic sequestration, sequestration in durable products such as plastics, and bunker offsets; the latter are credits for reductions in emissions from fuels used in international shipping and air travel, which do not count as national emissions. In the central case, modeled gross emissions in 2050 were 840 Mt CO₂/year, a reduction of 84% below the 2020 level (5,190 Mt/year), offset by products and bunkers of −524 Mt/year and geologic sequestration of −316 Mt/year. Cumulative emissions from 2020 to 2050 were 79 Gt CO₂, compared to 138 Gt in the reference case (Table 2).

4.2. Total GHG Emissions

Reaching net zero emissions for E&I CO₂ alone will not be sufficient to reach net zero in total GHG emissions. For example, if U.S. emissions of non-CO₂ GHGs and the U.S. land sink were maintained at their current values (roughly +1,250 and −750 Mt/year CO₂e, respectively), these sum to +500 Mt/year CO₂e, and total U.S. emissions would be +500 Mt CO₂e in 2050 even though E&I CO₂ was zero (U.S. EPA, 2019a). More ambitious but plausible levels of mitigation found in the literature, in which the combination of non-CO₂ and the land sink sum to zero—for example, a 10% reduction in non-CO₂ GHGs to +1,125 Mt/year and a 50% increase in the land sink to −1,125 Mt/year—are required for total CO₂e to reach net zero, consistent with a 1.5°C trajectory (Fargione et al., 2018; IPCC, 2018; Paustian et al., 2016; White House, 2016; Williams et al., 2014).

4.3. The 1°C/350 ppm Trajectory

In the net negative scenario, net E&I CO₂ emissions were constrained to follow a straight-line path to −500 Mt in 2050. The modeled result achieved this with gross emissions of 489 Mt, offset by products and bunkers of −524 Mt and geologic sequestration of −465 Mt. Cumulative E&I emissions 2020–2050 summed to 73 Gt CO₂ in the net negative scenario. If net emissions were maintained at the −500 Mt CO₂/year level over the latter half of the 21st century, cumulative E&I CO₂ emissions from 2020 to 2100 would decline to 48 Gt CO₂. This is consistent with a global trajectory peaking below 1.5°C and returning to 1°C/350 ppm CO₂ by 2100, if done in parallel with more ambitious mitigation of the land sink and non-CO₂ emissions, as described above (Haley et al., 2018; Hansen et al., 2017).

5. The Low-Carbon Transition

5.1. Four Pillars of Deep Decarbonization

The emissions objectives were reached in all scenarios, while meeting all energy needs. As in previous deep decarbonization pathways studies, the transition from a high-carbon to a low-carbon energy system was based on the strategies of (1) *using energy more efficiently*, (2) *decarbonizing electricity*, and (3) *switching* from fuel combustion in end uses to *electricity* (Bataille et al., 2016; White House, 2016; Williams et al., 2012, 2015). Since the emissions reduction impacts of these strategies are multiplicative, they must be simultaneously applied to achieve their full potential. This study further shows that reaching net zero E&I emissions, including non-energy CO₂ from industrial processes, requires an additional strategy: (4) *capturing carbon*, which can either be sequestered geologically or utilized in making carbon-neutral fuels and feedstocks (section 7.3) (Haley et al., 2018). Benchmark values for the four strategies are shown in Figure 2 (Figure S11). Per capita energy use declined 40% in 2050 compared to 2020, and energy intensity of GDP declined by two thirds. The carbon intensity of electricity was reduced 95%, while electricity's share of end use energy tripled, from 20% to 60%, including electrically derived fuels. Carbon capture reached almost 800 Mt CO₂/year, up from negligible levels today; of this, about 60% was utilized and about 40% was geologically sequestered.

The energy system transformation resulting from applying the four strategies is shown for two bookend cases in Figure 3. The 100% renewable primary energy case has no fossil fuels remaining in 2050, while the central case with low fossil fuel prices has the highest residual fossil fuel use. In both scenarios, both primary and final energy uses are lower in 2050 than in today's system, despite meeting higher energy service

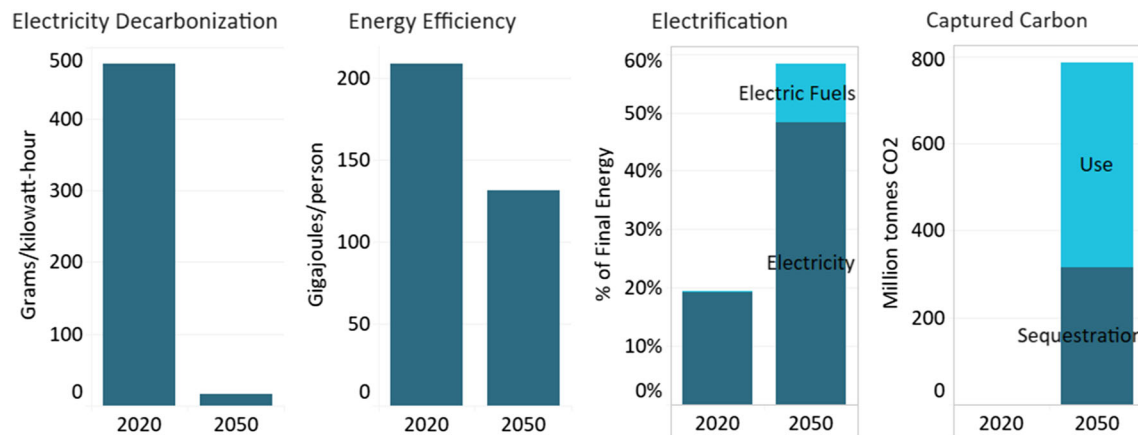


Figure 2. Metrics for the four main strategies of deep decarbonization, 2050 central case compared to current levels.

demand due to rising population and GDP. The shares of coal, oil, and natural gas in primary energy supply decrease dramatically from today's level, replaced primarily by wind, solar, and biomass. Low-carbon electricity and fuels replace fossil fuels in most final energy uses. Conversion processes that currently play a minimal role—biomass refining and production of hydrogen and synthetic fuels from electricity—become important in the decarbonized energy system, replacing most or all petroleum refining (Figures S1–S4). Contrasts between the decarbonized cases are discussed in section 5.3 (Table 2).

5.2. Infrastructure Changes

Deep decarbonization entails an infrastructure transition over the next three decades in which high-emitting, low-efficiency, and fuel-consuming technologies are replaced by low-emitting, high-efficiency, and electricity-consuming technologies, at the scale and pace necessary to reach the emission targets (Davis et al., 2010, 2018; Davis & Socolow, 2014; Shearer et al., 2020). The required scale and pace are illustrated in Figure 4 for three sectors that together comprise two thirds of current E&I CO₂ emissions: electric power generation, vehicles, and space and water heating in buildings (Figures S12–S14 and S22) (U.S. EPA, 2019a). By 2050, electric generation capacity increased by 3,200 GW; virtually all of the net increase was wind and solar (section 6.4). Coal was fully retired. Out of 296 million cars and light trucks, more than 280 million were battery electric vehicles. In residential buildings, electric heat pumps constituted 119 million out of 147 million space heating units and 88 million out of 153 million water heating units, with electric resistance heaters comprising most of the remainder. This transition was accomplished over a period of 30 years by replacement of equipment at the end of its normal lifetime, without early retirement.

5.3. Alternate Pathways

The constrained scenarios demonstrate that feasible alternate pathways to the same carbon target exist even in the face of limits on technology choices and resource availability. However, these scenarios required compensating changes in other areas, resulting in higher net cost and greater use of other resources (Table 2):

1. *Low land.* As a result of limiting the land area available for siting wind and solar, this case had the lowest renewable capacity among all scenarios and was forced to adopt higher-cost forms of electricity generation. It was the only case in which new nuclear capacity was economic and had the highest share of offshore wind generation. Electric fuel production was less than a third the level of the central case. With biomass also limited by definition, this scenario had substantially higher fossil fuel use and consequently geological carbon sequestration, than the central case. It was one of only two cases, along with the low fossil fuel price sensitivity, to require extensive direct air capture (DAC) (126 Mt CO₂/year) (Figure S30).
2. *Delayed electrification.* Delaying consumer adoption of electrified end use technologies and consequently lower economy-wide electrification resulted in the highest fuel demand, biomass use, carbon capture, and carbon utilization among the cases that met the net zero goal. Perhaps counterintuitively, this case required more electricity generation than the central case because of the need to produce fuels derived from electricity (electric fuels); accordingly, this scenario also had higher generating capacity and land requirements.

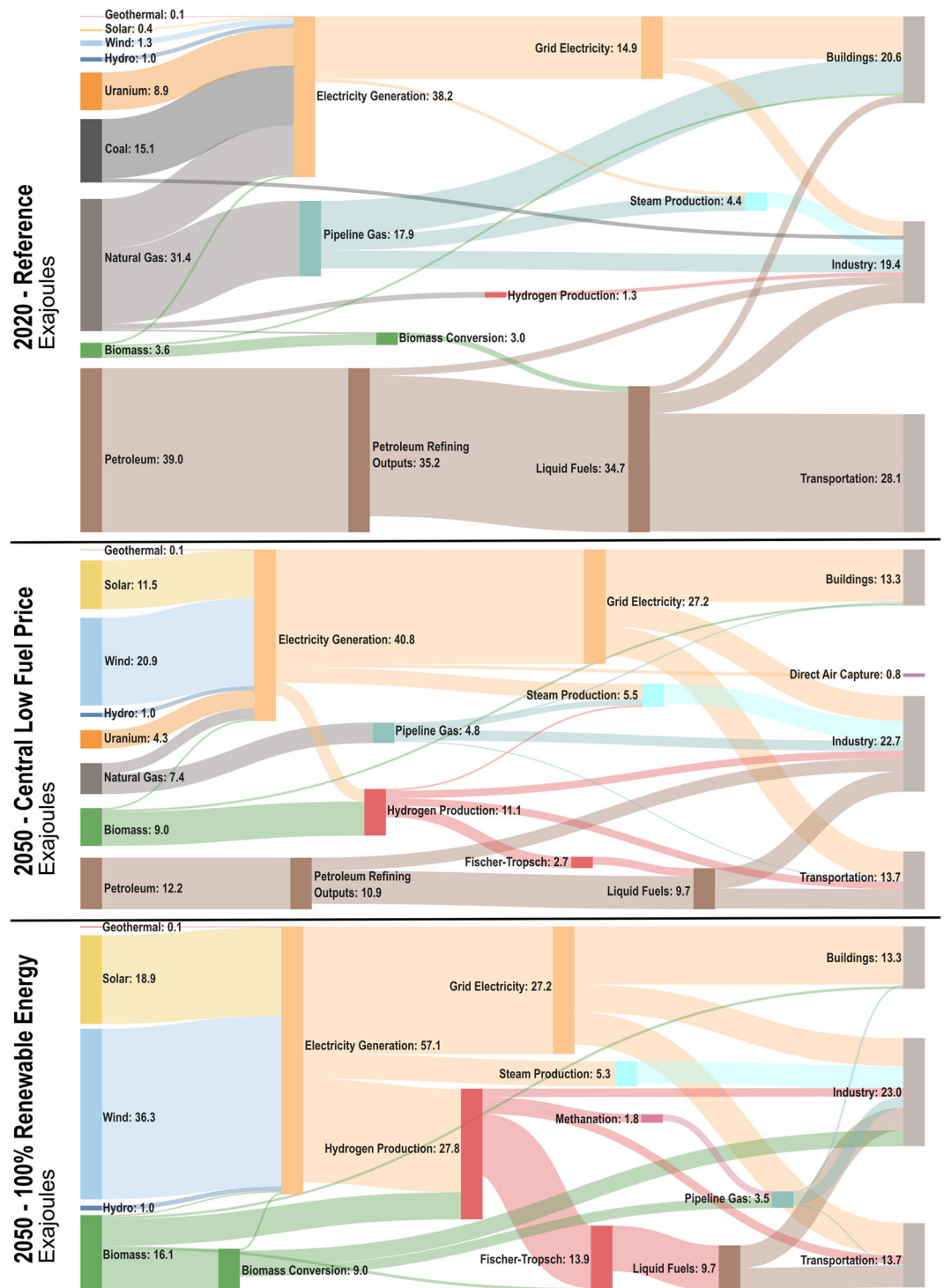


Figure 3. Sankey diagrams for (top) the current U.S. energy system, (middle) the central carbon-neutral case with low fossil fuel prices, and (bottom) the 100% renewable primary energy case. Primary energy supplies are on the left, conversion processes in the middle, and final energy consumption on the right. Line widths are proportional to magnitude of energy flows.

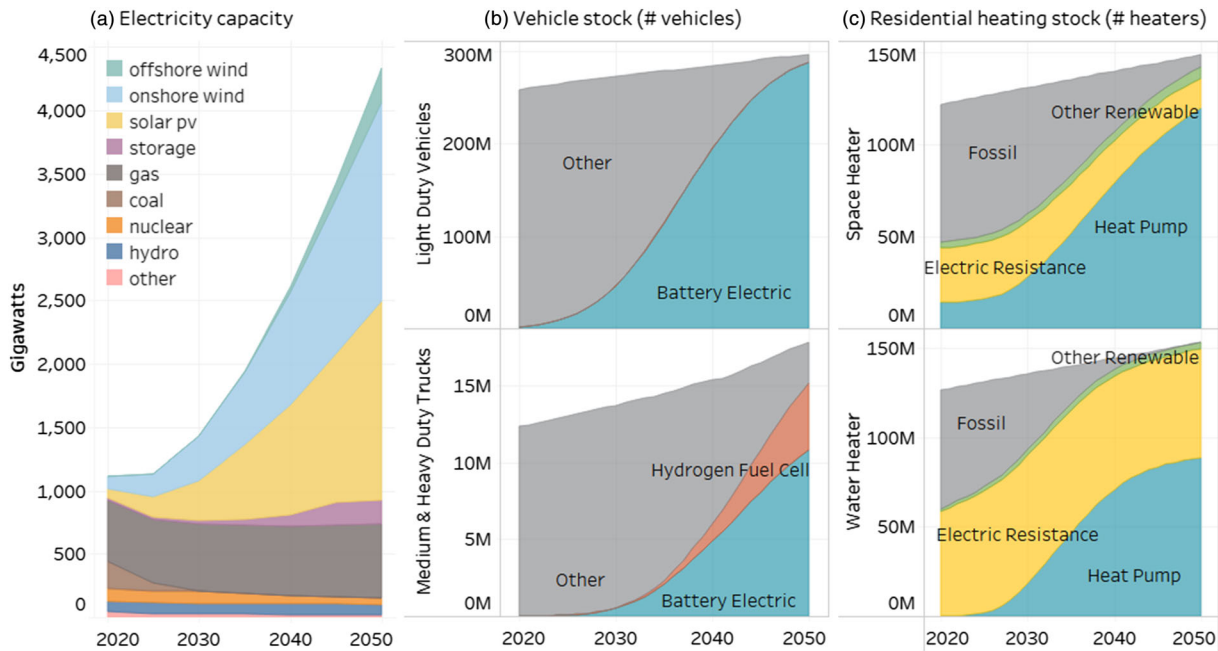


Figure 4. Infrastructure transition in central case for (a) power generating capacity, (b) vehicles, and (c) space and water heating.

3. *Low demand.* This case demonstrated that reducing consumer demand for energy services such as driving and flying lowers the infrastructure requirements of mitigation but does not eliminate the need for large-scale deployment of other decarbonization measures such as electrification and electricity decarbonization. In other words, energy efficiency and conservation alone were not sufficient to achieve the target. That said, this case had the lowest primary and final energy (both ~20% lower than the central case), along with the lowest electricity generation, fuel demand, carbon capture, interstate transmission, and overall infrastructure build. It also had lower land area and geological sequestration requirements than the central case. Net cost was not calculated for this scenario, as the cost of voluntary conservation is difficult to estimate, and there was no low-demand reference scenario to compare it to.
4. *100% renewable primary energy.* Because this case had no fossil fuels, the choices for producing fuels and feedstocks were limited to biomass and electricity. When combined with the effect of having no nuclear power, this scenario required the highest level of electricity generation, electric fuel production, wind and solar capacity, electrolysis capacity, interstate transmission, and land area across scenarios. It also had higher biomass use than the central case. Although geologic sequestration was not permitted, a relatively high level of carbon capture was required to supply the carbon needed for fuel production. Because some biogenic carbon in feedstocks was sequestered in durable products, this scenario had net negative CO₂ emissions in 2050 (−377 Mt/year).
5. *Net negative.* In order to reach net negative emissions of −500 Mt CO₂/year in 2050, this scenario had the lowest fossil fuel use of all cases except for the 100% renewable primary energy case. It compensated for this by consuming higher levels of biomass and electric fuels and, consequently, required more electricity generation, land area, and interstate transmission than the central case. It had the highest level of carbon capture across cases, with higher levels of both utilization and geologic sequestration than the central case. DAC was small (−7 Mt CO₂/year). On most measures, the requirements of this case fell within the same range as other scenarios, though toward the upper end, suggesting it is feasible if mitigation options are not limited.

5.4. Cost

The levelized net energy system cost of this transformation for the central case was \$145 billion in 2050, equivalent to 0.4% of GDP in that year (Figures 5 and S7–S10). This is the difference in the annualized capital and operating costs of supplying and using energy in the central case compared to the reference case, plus the net cost of reducing or offsetting non-energy industrial process emissions. Except where noted, cost

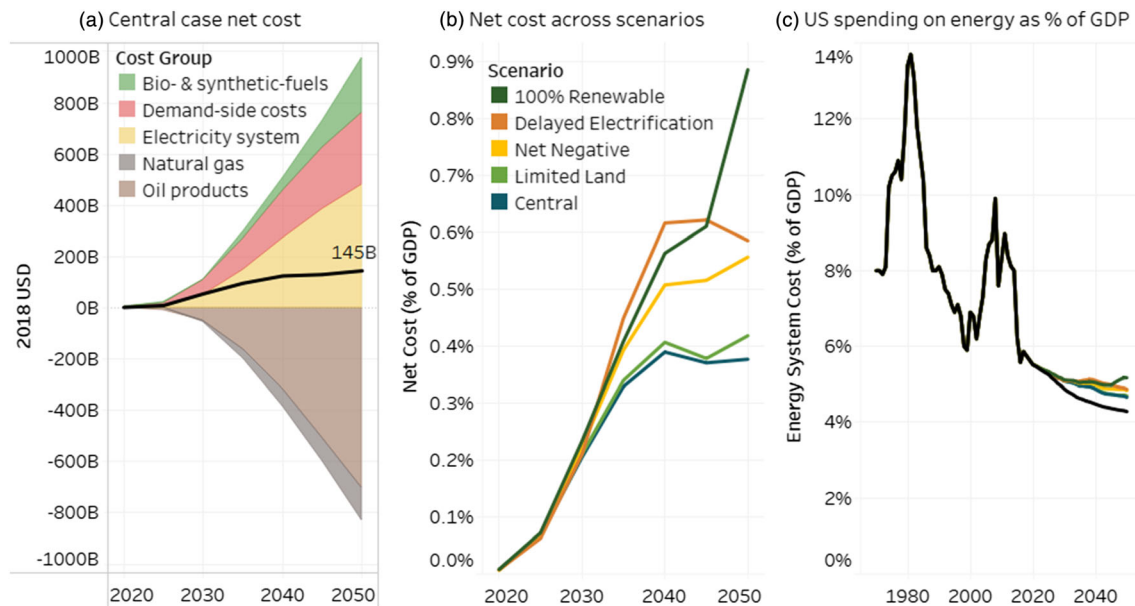


Figure 5. (a) Net annual levelized system cost of central case (black line), (b) net cost across scenarios as share of GDP, and (c) total U.S. spending on energy as share of GDP, historical and modeled for reference and decarbonized cases. Note: Forecast GDP growth average is 1.84% per year, 2020–2050, following AEO (U.S. EIA, 2019).

inputs were the reference values of DOE long-term fossil fuel price and technology cost forecasts (NREL, 2019; U.S. EIA, 2019). The net present value of net system cost was \$1.7 trillion over the 2020–2050 period, using a 2% societal discount rate. In the central case, increased spending on incremental capital costs for low-carbon, efficient, and electrified technologies (\$980 billion in 2050) was offset by reduced spending on fossil fuels and incumbent technologies (−\$835 billion in 2050). A sensitivity case using the DOE low fossil fuel price forecast raised the central case net cost to 1.2% of GDP in 2050 (net cost is higher because the counterfactual reference case cost is lower); using the low technology cost forecasts for renewables lowered it to 0.2% of GDP. The net costs of all other scenarios ranged from about 0.45% in the low land case up to 0.9% in the 100% renewable primary energy case. The net negative case consistent with a 1°C/350 ppm trajectory had a net cost of less than 0.6% of GDP in 2050.

Historical total U.S. spending on energy has ranged between 5.5% and 13% of GDP from 1970 to the present. In the reference case, this is projected to decline to 4.3% in 2050. With deep decarbonization, the spending could reach as high as 5.2% of GDP depending on the scenario but would still be well below the historical range.

6. Electricity

6.1. Electricity Generation

Until recently, it was unclear whether VRE, nuclear, or fossil fuel with CCS would become the main form of generation in a decarbonized electricity system. Analyses of U.S. economy-wide deep decarbonization (~80% GHG reductions) have generally shown roughly equal shares of generation from each of these sources, with the proportions changing depending on policy and cost assumptions (Bistline et al., 2018; Clarke et al., 2014; White House, 2016; Williams et al., 2012, 2015). The cost decline of VRE over the last few years, however, has definitively changed the situation.

Our analysis shows that electricity from VRE is the least-cost form, not only of power generation but of primary energy economy wide, even when that requires investment in complementary technologies and new operational strategies to maintain reliability. All cost-minimizing pathways to deep decarbonization are organized around using VRE to the maximum feasible extent, to supply both traditional loads and new loads such as EVs, heat pumps, and hydrogen production. As a result, electricity demand increases dramatically, to roughly three times the current level by 2050 (230% to 360% across cases; Figure 6b and Table 2). This demand is met primarily by VRE in all cases. In the central case, the generation mix was 90% wind and

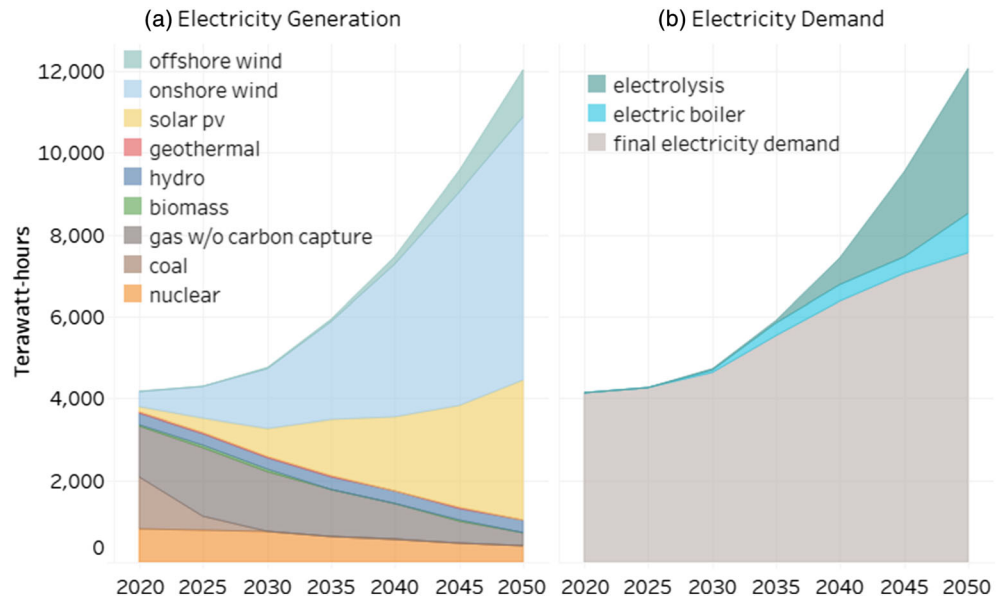


Figure 6. (a) Electricity generation by type, central case, and (b) electricity demand, central case.

solar (Figure 6a); the minimum level was 81% in the limited-land case (Figures S23–S25 and S27). It is possible that dramatic cost breakthroughs in new generating technologies such as Allam Cycle CCS and Gen IV nuclear could result in a reduced VRE share, but the breakthroughs would need to happen soon in order to deploy them at the pace and scale required in these scenarios.

6.2. Reliability in High Renewables Systems

There has been a vigorous debate over the feasibility of electricity systems with very high levels of VRE generation (Brown, Bischof-Niemz, et al., 2018; Clack et al., 2017; Diesendorf & Elliston, 2018; Heard et al., 2017; Jacobson et al., 2015, 2017; Jenkins et al., 2018). In our view, this debate’s focus on “100% wind-water-sunlight” electricity systems per se is less useful than what electricity system configuration is most cost effective in reliably meeting the overall energy needs of a carbon-neutral or carbon-negative economy. In other words, the economics and reliable operation of a high VRE electricity system boil down to what technologies are deployed to balance supply and demand in all hours of the year. The technologies required depend on the time scale of the imbalance and whether there is an energy deficit or surplus (Figure S18). Analyzing across multiple time scales and geographies, we found that balancing was most cost effectively addressed through a combination of thermal generation to provide reliable capacity during times of deficit, along with transmission, energy storage, and flexible loads to move surplus energy in time or space, plus renewable curtailment.

The provision of reliable capacity (MW) in a decarbonized electricity system is fundamentally separate from the provision of energy (MWh). The capacity resource that pairs best with a high VRE system is one with very low capital cost, because its role is to provide reliability for a limited number of hours per year (average capacity factors ~10%; Figures 7b and S17), rather than zero-carbon energy in bulk. In this analysis, reliable capacity came mostly from thermal generation using gas without carbon capture (Figure S28). The much higher initial capital cost of CCS and nuclear plants as currently forecast could not be justified for such low utilization rates, and at the same time, they were uncompetitive with VRE for the bulk of operating hours unless VRE buildout was constrained. The gas generation fleet in the central case was 590 GW and ranged between 470 and 675 GW across scenarios, compared to 480 GW today (Figure 7a). To remain within carbon constraints, gas-fired plants without carbon capture either burned carbon-neutral fuels or natural gas for which emissions were offset elsewhere, depending on the carbon budget, resource constraints, and relative costs (see section 7.2).

The reason gas generating capacity comparable to today’s is needed in a carbon-neutral energy system is illustrated in Figure 8, which shows hourly balancing in a high renewables system in a northeastern state that

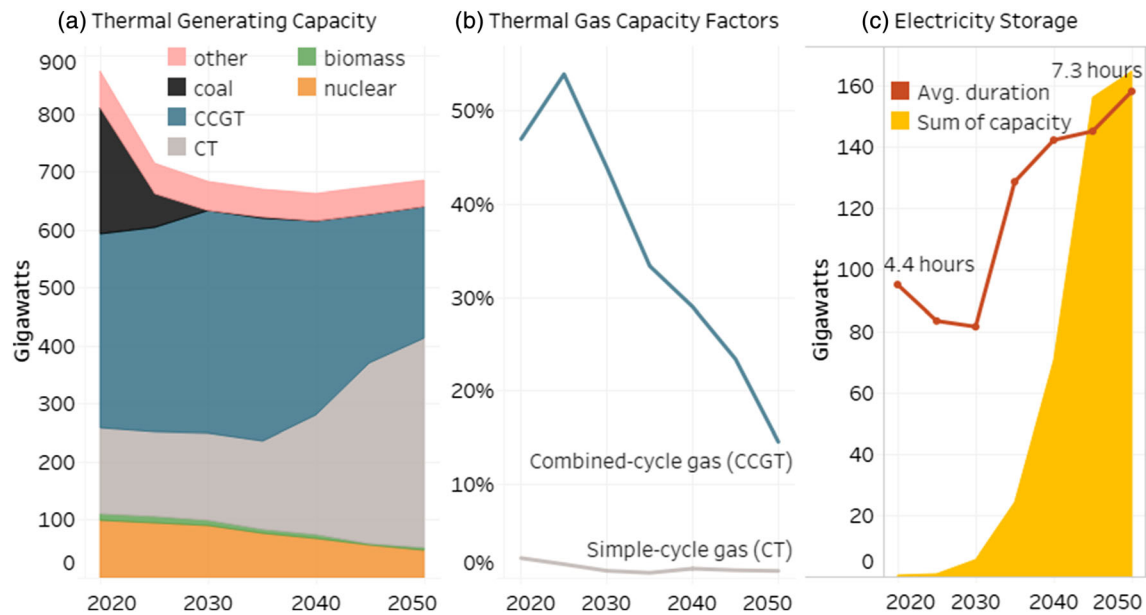


Figure 7. Central case (a) thermal generating capacity, (b) thermal capacity factors for gas, and (c) energy storage.

relies primarily on offshore wind for decarbonized electricity. On a high-wind, low-load day, wind and solar production exceed load in most hours of the day, with excess generation being partly curtailed, partly exported, partly converted to hydrogen by means of electrolysis, partly used to heat water in industrial boilers, and partly shifted in time with storage and flexible loads. No gas generation was required. On a

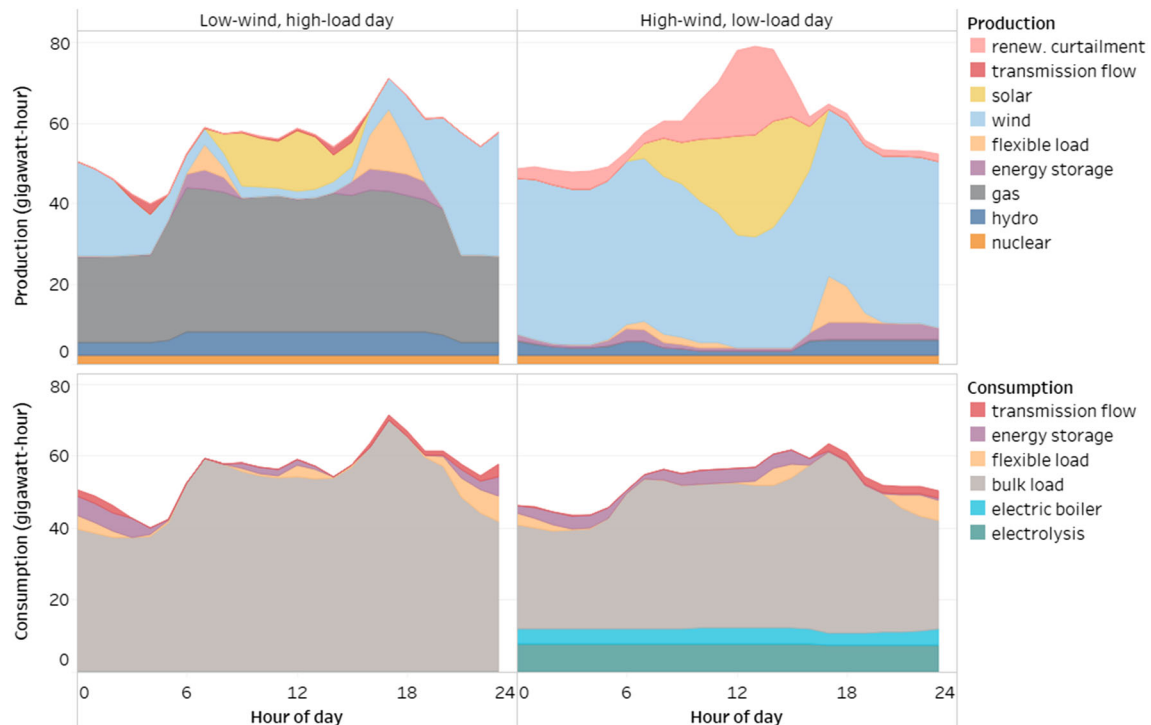


Figure 8. Balancing in a northeastern state in 2050, central case, with production (top) and consumption (bottom) for a low-wind, high-load day (left) and a high-wind, low-load day (right).

low-wind, high-load day, by contrast, significant gas generation was required during every hour of the day. In general, extended periods of low renewables output combined with high loads determine the amount of thermal capacity required for reliably meeting demand in each electricity region (Figures S16 and S28). Energy storage was not competitive in meeting sustained energy deficits because the large quantity of energy needed required a large investment in storage, while the infrequent occurrence of such events resulted in very low storage utilization. These results illustrate why proposals for rapid retirement of gas-fired capacity are ill advised.

6.3. Additional Balancing Resources

Transmission enables VRE systems to take advantage of geographically diverse load and generation profiles. Interregional transmission capacity increased 168% in the central case (85–217% across scenarios; Figure S32). Most transmission was built between wind-rich and wind-poor regions, generally from the wind belt in the center of the United States toward the Southeast and Mid-Atlantic (Figure S33). This is because wind resource quality and potential in the United States has much higher disparity between regions than does solar, which in nearly all of the United States is more economic to develop locally than import from another region.

Batteries can economically time-shift renewable generation from surplus to deficit periods over the course of a day; battery capacity ranged 80–217 GW across scenarios (Figures 7c and S29). As noted above, batteries were not cost effective for long duration balancing. Moreover, flexible consumer loads (e.g., EVs and water heaters) were cost competitive with batteries in providing peak-load reduction, with 74–116 GW across scenarios (Sepulveda et al., 2018).

High-VRE systems designed to provide sufficient energy in high-demand months will over-generate in other months. Large-scale industrial loads that can operate flexibly while producing a useful product from electricity allow energy demand to change to match available VRE supply across a wide range of conditions. For example, electrolysis of water was used to balance the system and produce fuels for applications that were hard to electrify (Figures 8, S15, S31, and S34). This allows for the economic overbuilding of renewables to reduce the need for other balancing resources on energy-constrained days, increasing the competitiveness of VRE against other low-carbon generation. Flex-fuel boilers were also built economically and dispatched flexibly. Many other large industrial loads, such as desalination, could play a similar role but were not analyzed here. As a result of the balancing measures employed, renewable curtailment was only 2–5% across scenarios (Figure S21).

6.4. Electricity Infrastructure Buildout

The greatest challenge for a very high VRE electricity system is probably neither cost nor reliability but achieving the scale and rate of infrastructure construction required. In the central case, the average build rate of wind and solar in the 2040s was more than 160 GW per year; in the 100% renewable primary energy case, it was almost 260 GW per year; in the low land case, it was still nearly 90 GW per year (Figure 9b). For comparison, the total current U.S. wind and solar capacity is less than 150 GW (U.S. EIA, 2020). Using rule of thumb metrics for wind and solar land requirements (Miller & Keith, 2018, 2019; Ong et al., 2013; Wu et al., 2016, 2020), the total land used was 36 MHa in the central case, 17 MHa in the low land case, and 48 MHa in the 100% renewable primary energy case (Table 2), equivalent to 2–6% of contiguous U.S. land area.

In this light, we found that the 100% renewable primary energy case, employing the balancing measures described above, was technically reliable but entailed a larger infrastructure buildout and higher cost, driven in part by increasing the VRE share of generation from 90% to nearly 100% (Table 2) and in part by demand for electrically-produced fuels.

7. Fuels and CCUS

7.1. Fuel Demand

In the central case, about 50% of final energy demand was met with electricity (Table 2 and Figure S1). The remaining 50% was met with fuels (hydrocarbons and hydrogen), primarily in applications where volumetric or gravimetric energy-density requirements make electrification difficult (e.g., aviation), in industries where high process temperatures are needed, in thermal power generation, and in industrial feedstocks

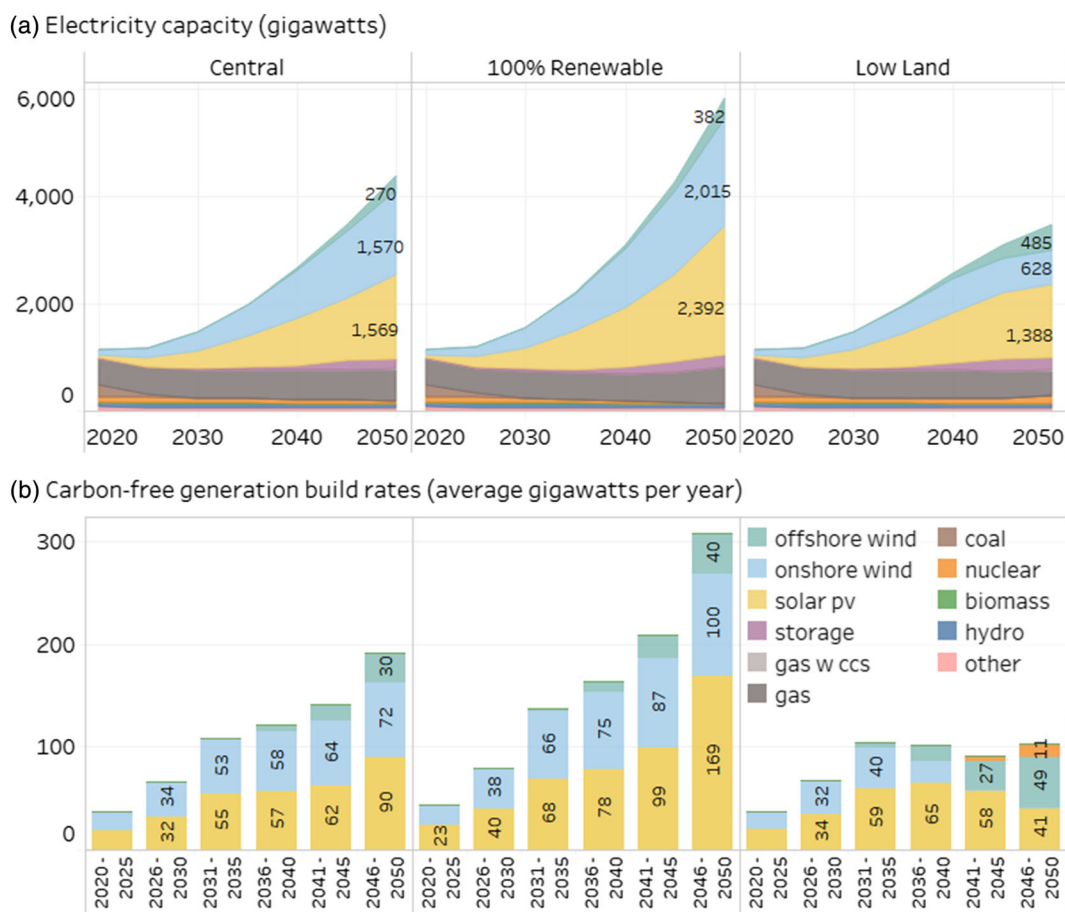


Figure 9. (a) Total electric generating capacity and (b) build rates for carbon-free generating capacity in the central, 100% renewable primary energy, and low land cases.

where hydrocarbons are required (e.g., petrochemicals). Since electricity was almost completely decarbonized, the production and use of fuels was the main source of gross CO₂ emissions economy wide, which were either captured in situ or offset by negative emissions elsewhere to achieve carbon neutrality within the E&I system as a whole.

While the share of fuels in final energy demand remained significant, the absolute quantity decreased dramatically. In the central case, total fuel demand declined >60% below today's level due to the combined effects of increased energy efficiency and increased electrification. Conservation in the low-demand scenario decreased both final energy and fuel demand an additional 20% below the central case but did not eliminate the need for industrial-scale fuel production (Table 2). Lower electrification had the opposite effect. Slow consumer uptake of EVs and heat pumps in the delayed electrification scenario reduced the electricity share of final energy to 40%, increasing fuel demand more than 25% relative to the central case (Table 2). This substantially raised the net cost and increased fossil fuel use, biomass use, electricity generation for fuel production, land requirements, and carbon sequestration.

An electrification share greater than 50% and proportionally lower fuel use may be possible but will require further research and market development. Since a large share of final energy demand in the central case was for feedstocks that cannot use electricity as a substitute, the effective electrification rate of the other end uses is already high (about 70%). How much additional electrification could occur likely depends on how industry changes its products and processes in response to increases in the price of fuel relative to electricity (Bataille, 2020; Jadun et al., 2017).

The main fuels for meeting residual fuel demand after electrification are hydrocarbons and hydrogen. Hydrocarbons have intrinsic advantages as a fuel including high energy density, high boiling point, high

combustion temperature, ease of storage, and ability to be synthesized into products such as plastics. Hydrocarbons in these scenarios were either fossil fuels or synthetic carbon-neutral “drop-in” fuels that required minimal retooling of the current end use technology; all required some form of carbon management to be consistent with net zero or net negative E&I CO₂ emissions. Hydrogen was limited by low density and difficulty of storage to 2–3 EJ of direct end use across scenarios; it had a much larger role as an intermediate product in hydrocarbon production. Ammonia, a possible alternative to hydrocarbon fuels, has less attractive technical properties and its own array of environmental concerns (Galloway et al., 2003); it was not included in our scenarios but could play an important role in end uses such as shipping (Kobayashi et al., 2019).

7.2. Fuel Supply

Drop-in fuels in our scenarios were derived from three main energy sources: (1) biomass, mainly by gasification and synthesis using the Fischer-Tropsch process; (2) electricity, by electrolysis to produce hydrogen and subsequent chemical synthesis; and (3) natural gas, by steam methane reforming (SMR) with carbon capture to produce hydrogen and subsequent chemical synthesis (Figure S34). The specific conversion technologies adopted for fuel production depend on uncertain cost and performance assumptions, but the technological details are relatively unimportant from an energy system perspective because well-established alternative conversion pathways exist. More important is that the three energy sources all have resource constraints that form upper limits to the amount of fuel that can be sustainably produced with that resource, including annual production of biomass feedstocks, overall land requirements for electricity generation and transmission, and carbon sequestration rates, respectively.

For biomass, the main constraint is the quantity of feedstocks that can be sustainably produced (IPCC, 2019; Searchinger et al., 2008; Smith et al., 2013). For this study, potentially available biomass primary energy was capped at the technical potential of the DOE *Billion Ton Study* (21.6 EJ/year) in all cases except the low land scenario, which was capped at 50% of that level (10.8 EJ/year) (Langholtz et al., 2016). The biomass used in our scenarios included all identified waste streams plus purpose-grown feedstocks that were assumed to shift to more sustainable crops (e.g., switchgrass and miscanthus) grown within the existing land footprint currently used for corn ethanol (Robertson et al., 2017; Williams et al., 2014). The central case used only about 60% (12.2 EJ) of the biomass technical potential; the maximum usage across scenarios was 80% (17.5 EJ) in the delayed electrification case (Table 2 and Figures S34 and S36).

The maximum annual CO₂ injection rate into belowground storage was capped at 1.2 Gt CO₂/year based on a Department of Energy study and CO₂ transport across regions (e.g., from the Midwest to the Gulf Coast) was not allowed (National Energy Technology Laboratory, 2017). In the central case, the sequestration rate reached 30% of the injection limit (360 Mt CO₂/year) in 2050; the low land scenario was highest across cases at 680 Mt CO₂/year (Figure 10b and Table 2). As described earlier, the land requirements for wind and solar electricity based on rules of thumb in the literature ranged from 17 to 48 MHa (Table 2). For comparison, a recent study by The Nature Conservancy found an area of 36 MHa to be suitable for wind development with low environmental impacts in the 17-state wind belt in the central United States (Hise et al., 2020).

While the shares of electricity generation by technology were broadly similar across scenarios, the shares of biomass-, electricity-, and fossil-derived fuels in the fuel mix differed widely as a function of resource constraints, price assumptions, and the quantity and type of end use fuel required (e.g., jet fuel and diesel) (Figures S34–S36). Each type of fuel supply had a cost curve that increased with production volume as a function of primary energy cost, processing cost, transport cost, end use efficiency, and carbon content. As a result, the least-cost mix of fuels in each scenario was a different blend of carbon-neutral drop-in fuels plus direct combustion of fossil fuel with carbon capture or offsetting (Figures 10a and S37 and Table 2).

The coupling of the electricity and fuel sectors in electric fuel production plays an important role in limiting the cost of deep decarbonization (Brown, Schlachtberger, et al., 2018; Buttler & Spliethoff, 2018). In the central case, electrolysis consumed 3,500 TWh in 2050, similar in scale to all U.S. electricity sales today, at an average capacity factor of 52%. These results show that sector coupling is not simply absorbing marginal amounts of renewable generation that might otherwise be curtailed, nor is it simply building dedicated renewables to serve fuel demand (Figures S18 and S19). Rather, sector coupling has elements of both, in which optimized integration of fuel production with electricity increased transmission-connected

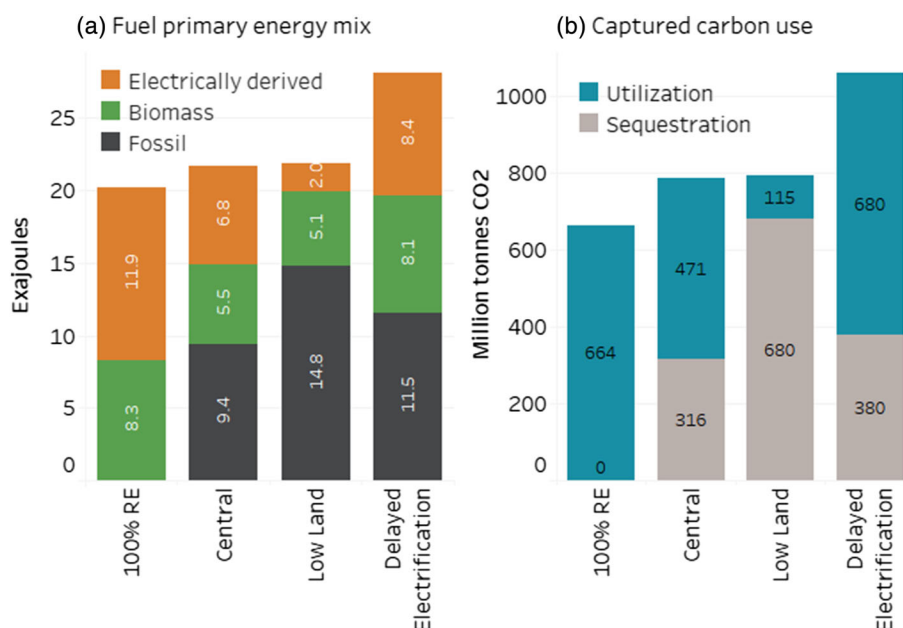


Figure 10. (a) Fuel primary energy mixes in 2050 and (b) carbon captured, utilized, and sequestered in 2050, in the central, delayed electrification, 100% renewable, and low land scenarios.

renewables to serve larger fuel production loads, but these loads were turned off about half of the time, during energy-constrained periods, to reduce the need for other balancing resources. In the central case, 9 EJ of H₂ was produced by electrolysis, with a range of 2 EJ (low fossil fuel price) to 17 EJ (100% renewable primary energy) across scenarios (Figure S34). Electrolysis capacity (electricity input) was 777 GW in the central case and ranged from 304 to 1,352 GW across scenarios (Figure S31).

Among fossil fuels, natural gas was the last to be replaced in a least-cost system because it is the least expensive per unit of energy and has the lowest carbon content. With higher renewables costs, SMR with carbon capture using natural gas displaced electrolysis for production of hydrogen. For petroleum, with higher prices oil products were replaced by drop-in carbon-neutral fuels and with lower prices, it was more economic to use fossil fuels with emissions offsetting for some applications, such as feedstocks. Our results demonstrate that there are many possible fuel pathways consistent with carbon neutrality; the optimal pathway will depend on future fossil fuel price trajectories, the cost and potential of biomass and geologic sequestration, the cost of producing fuels from electricity, and the societal and environmental constraints. However, the scenarios in this study did not require low-carbon fuels and CCUS in bulk until the 2030s to reach their emissions targets, indicating that there is still time for discovery and refinement of these strategies.

7.3. CCUS

All carbon-neutral scenarios required technological (i.e., nonbiological) carbon capture (Table 2 and Figure S38) (Keith et al., 2018; Socolow et al., 2011). Carbon capture can occur at three points in the fuel lifecycle: in making the fuel, in the exhaust stream from combusting the fuel, or from the air once CO₂ is released to the atmosphere. Post-combustion “end-of-pipe” capture was applied to concentrated, high-volume CO₂ streams from sources like cement and biofuel refineries. Once captured, the CO₂ was either *sequestered* geologically or *utilized* to make carbon-neutral drop-in fuels and feedstocks.

We found that carbon capture is a “fourth pillar” of deep decarbonization because a net zero or net negative E&I CO₂ target could not be met without it. The general relationship between fuels, emissions, and carbon capture is illustrated in Figure 11. If fossil fuels are used without carbon capture at some point in the system (end of pipe or offsetting), emissions by definition will exceed net zero. If synthetic hydrocarbon fuels are used, without carbon capture it is infeasible to supply the carbon required to produce them without

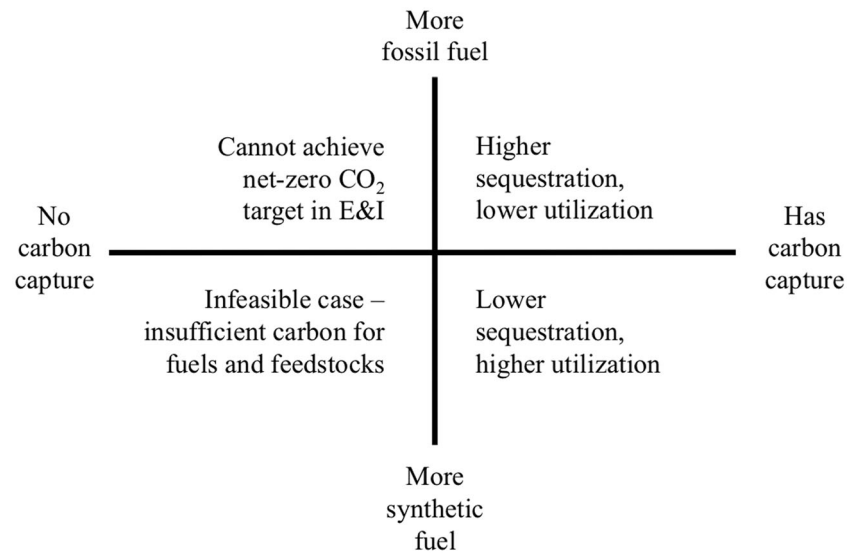


Figure 11. The relationship between fuels and carbon capture, utilization, and storage.

exceeding the biomass sustainability limit. With carbon capture, the more fossil fuel is used, the greater the share of captured carbon that must also be sequestered. Conversely, the more synthetic fuel is used, the more the captured carbon is utilized.

For these reasons, the amount of carbon capture and the split between utilization and sequestration varied dramatically across cases (Figure 10b). Even the 100% renewable primary energy case, which uses no fossil fuels, required 664 Mt/year of carbon capture in 2050 to provide the carbon for renewable fuel and feedstock production; all captured carbon in this case was utilized, and none was stored geologically. In the central case, 787 Mt/year was captured from industrial processes, biofuel refining, and hydrogen production from natural gas. Of this, 60% was used to make fuels, and 40% was geologically sequestered. The highest level of carbon capture was in the net negative case, with 1,063 Mt/year in 2050, of which 465 Mt/year was geologically sequestered (Table 2).

7.4. Negative Emissions Technologies

Offsetting of small or widely dispersed CO₂ sources for which CCS or drop-in fuels were not economic was done with negative emissions technologies (NETs), specifically bioenergy with CCS (BECCS) and DAC (Breyer et al., 2019; Clarke et al., 2014; Keith et al., 2018; McQueen et al., 2020; Sanz-Perez et al., 2016). NETs were most economic when tightly coupled to the E&I system, where the captured carbon could be flexibly used for fuels and products (e.g., plastics) or sequestered as needed. We found that the most economic form of BECCS was not in power plants, in contrast to many integrated assessment modeling studies (Clarke et al., 2014; IPCC, 2014; Smith et al., 2016; Van Vuuren et al., 2013) but in biorefineries. This is because BECCS power plants have both higher capital cost and higher operating cost than VRE, competing on the margin for a limited biomass resource that has higher value uses in making fuel and feedstocks (Figure S36). DAC costs were minimized by deployment in locations with low-cost complementary renewable generation (e.g., solar by day and wind by night) allowing DAC installations, which have high capital costs, to have utilization rates up to 85%. Overall, the use of NETs is limited by cost (DAC), sustainable biomass availability (BECCS), and sequestration injection rates (both). While NETs are necessary components of a least-cost decarbonization strategy, it is uneconomic to achieve carbon neutrality through a strategy of continuing high levels of gross fossil fuel CO₂ emissions offset by NETs.

8. Demand Sectors

In the transition to a carbon-neutral E&I system, the decarbonization of energy supplies was accompanied by parallel changes in demand-side infrastructure, for example, electrification of vehicles (Figure 4). The composition of final energy demand in the buildings, transportation, and industrial sectors (Figure 12)

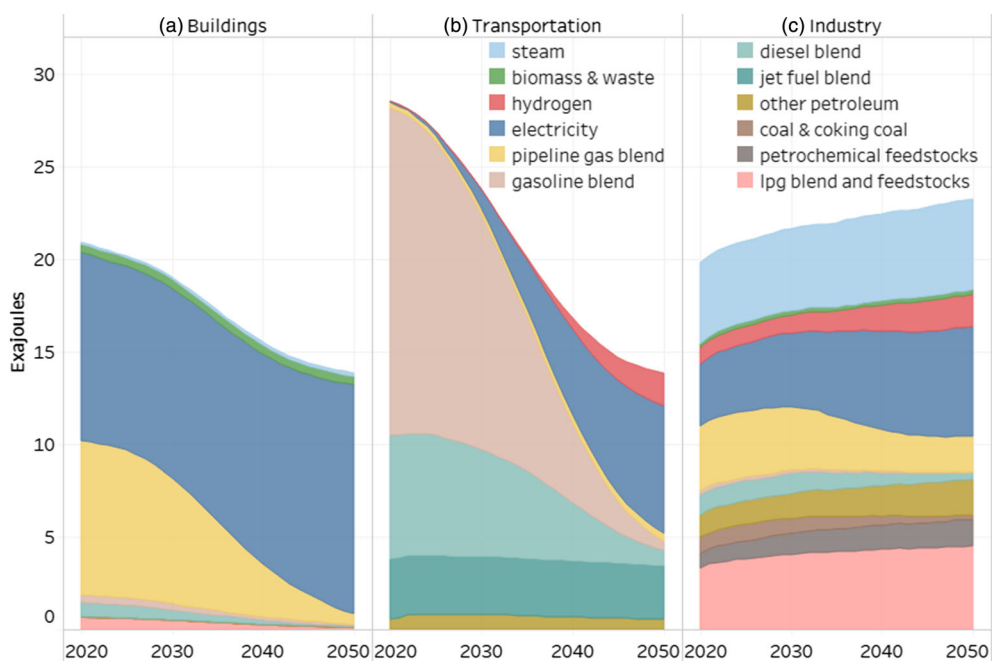


Figure 12. Composition of final energy demand in the central case in (a) buildings, (b) transportation, and (c) industry. Fuels that change composition over time, for example, when carbon-neutral fuels are mixed with fossil fuels to reduce their overall carbon intensity, are called “blends.” The legend applies to all parts of the figure.

reflects these changes, differing in the extent of electrification, type of fuels used, and change in energy demand over time. The transition strategies within each subsector were based on expert judgment that took into account the types of final energy that can be used in a given application; the relative cost of different forms of decarbonized energy; the capital cost of end use technologies; infrastructure inertia; and the cost of energy delivery.

As decarbonization proceeds, final energy costs tend to drive a transition from fuel-using to electric technologies. This is because, in general, electricity is less costly to provide in decarbonized form than are fuels. In 2019, the average marginal costs of electricity, gaseous fuels, and liquid fuels were \$9/MMBtu, \$3/MMBtu, and \$18/MMBtu, respectively, ignoring delivery charges (\$1/MMBtu = \$0.95/GJ). In 2050, the average marginal costs of the decarbonized versions of these same fuels were \$11/MMBtu, \$11/MMBtu, and \$26/MMBtu, respectively. The competitiveness of electricity vis-a-vis natural gas improved dramatically, from a 3:1 cost ratio today to 1:1 under deep decarbonization. Electrification's advantage was magnified by an intrinsic energy efficiency improvement due to thermodynamics, as is the case with electric drivetrains versus internal combustion engines; equal per-unit energy prices combined with a threefold improvement in energy efficiency to give EVs a much lower operating cost. Additionally, electricity-using technologies with flexibility in time of use were able to take advantage of electricity costs that were significantly lower than average at certain times of the day or year. Together, these advantages account for why virtually complete adoption of electric technologies in buildings and light-duty vehicles by mid-century was assumed.

In some applications, electrification was not attractive, for example, in cases where the cost or weight of battery storage was too high, as in aviation; in high temperature process heat, where there was no thermodynamic advantage and no assumed flexibility in time of use, and in feedstock chemistry that allowed no practical alternative to a hydrocarbon fuel. Fuel cell technologies using hydrogen were adopted in some transportation applications, and hydrogen was also added to combustion fuels to reduce their carbon intensity, for example, hydrogen-methane blends used in thermal power plants (Figure S20). In applications where electrification and hydrogen were not feasible or were less competitive, end use technologies that burn hydrocarbon fuels or use them as feedstocks, with improved efficiency when possible, continued to be used. This is reflected in the amount and composition of industrial energy demand (Figures 12 and S2) (Bataille, 2020; Jadun et al., 2017).

The rate of the demand-side transition was constrained by infrastructure inertia, meaning that we modeled end use equipment with a vintage and an economic lifetime, only after which it was retired and replaced by more energy efficient equipment using lower carbon energy supplies. On the demand side, all replacement was at the “natural retirement” time; on the supply side, coal and oil power plants, most long past their anticipated lifetimes, were allowed to retire economically. The time required for fleet turnover under the inertia constraint means that the process of electrification—for example, consumer adoption of EVs and heat pumps—must begin many years before a fully electrified fleet is required to meet the net zero target (Figure 4).

The delivery infrastructure that links energy supply and end uses, today and in the future, forms a large share of energy costs. A major shift toward one form of final energy and away from another entails the expansion of one delivery infrastructure and the contraction of another, with positive and negative impacts on the net cost of the transition. Building electrification, for example, entails both the expansion of the electricity distribution system and the contraction of the natural gas distribution system. The departure of gas customers leaves a shrinking customer base to pay the fixed costs of the system; at some point, gas rates can become prohibitive. Planning an orderly transition to electricity, with due attention to equity, can ameliorate this effect (Aas et al., 2020). Planning can also limit the impact of electrification on electricity distribution costs, controlling increases in peak demand through measures such as building shell improvements and flexible vehicle charging. In our modeling, load management of this kind improved distribution infrastructure utilization, lowering the delivery cost component of electricity rates.

9. Conclusions

9.1. Carbon Neutrality Is Affordable

We have shown that achieving net zero and net negative CO₂ emissions from energy and industry in the U.S. by mid-century can be done at low net cost. Recent declines in solar, wind, and vehicle battery prices have made decarbonizing the U.S. economy increasingly affordable on its own terms, without counting the economic benefits of avoided climate change and air pollution (Garcia-Menendez et al., 2015; Hsiang et al., 2017; Nemet et al., 2010; West et al., 2013; Risky Business Project, 2016). The net cost of deep decarbonization, even to meet a 1°C/350 ppm trajectory, is substantially lower than estimates for less ambitious 80% by 2050 scenarios a few years ago (Clarke et al., 2014; Williams et al., 2015); even with decarbonization, future energy costs as a share of GDP are expected to be lower than today's.

9.2. Renewable Electricity Is the Foundation of an Affordable Transition

The least-cost decarbonized electricity system combines high VRE generation (>80% share) with low-cost reliable capacity such as natural gas without carbon capture operating infrequently. If renewables and transmission cannot be built at the scale required, for example, due to difficulty in siting, nuclear and fossil CCS generation become important. Implementing high VRE systems may require changes in wholesale electricity markets to allow cost recovery for thermal generation needed for reliability but operated <15% of the time and to provide incentives for industrial loads such as electrolysis and electric boilers to operate flexibly on renewable over-generation (Jones et al., 2018).

9.3. The Social Effects of Changes in the Energy Economy Need to Be Managed

Deep decarbonization entails a major shift in the U.S. energy economy. The variable costs of fossil fuels will be replaced by the capital cost of low-carbon technologies. Incremental capital investment averaging \$600B per year represents about 10% of current U.S. annual capital investment of \$6 T in all sectors, indicating that finance per se is not a barrier if policies that limit risk and allow cost recovery are in place (Federal Reserve Bank of St. Louis, 2019). A greater challenge is likely to be the political economy of effectively redirecting > \$800B/year from fossil fuels into low-carbon technologies. The distributional impacts of such a transition could be ameliorated through policies that support communities and sectors dependent on fossil fuel extraction, while new jobs emerge under policies that ensure a significant domestic share of the manufacturing-based low-carbon economy (Busch et al., 2018).

9.4. Consumer Incentives Are Needed to Support Timely Electrification

Carbon neutrality is aided by complete consumer adoption of electric end use technologies in light-duty transportation and buildings. Slow adoption that leads to delayed or incomplete electrification will result in greater cost and resource use. Direct mandates and/or carbon prices can drive decarbonization of electricity and fuels production, since utilities and industrial enterprises are responsive to such signals. Different policies may be required to influence consumers who are sensitive only to upfront cost. As demonstrated historically with solar PV, one option is customer incentives such as rebates that effectively lower the purchase price of EVs and heat pumps. These have the potential to dramatically increase sales, drive innovation, reduce manufacturing costs, and lower purchase prices in a self-sustaining market transformation (Nemet, 2019).

9.5. Recognizing Tradeoffs Between Decarbonization Strategies Is Essential

The scale and pace of infrastructure buildout and demands on the land in a low-carbon transition imply competition among social, environmental, and economic priorities. Our scenarios illustrate the kinds of tradeoffs that can be anticipated and their impacts. The use of biomass and of land for renewable siting are indispensable for all net zero pathways, but the amount required can differ by a factor of 2 or more. It needs to be understood that reducing biomass and land for siting implies increasing fossil fuels, nuclear power, and negative emissions. In addition to siting and biomass, increasing the land carbon sink is another element of the competing priorities among climate mitigation, food production, and other land uses (Griscom et al., 2017).

Given the regional character of energy use and resources and the U.S. system of government, many of the tradeoffs faced will need be resolved at the state and local level (Betsill & Rabe, 2009; Williams et al., 2015). Rigid positions on tradeoffs will not be helpful for informed decision-making as they may lead to over-constrained problems and policy paralysis; better public participation, analysis, and data are more likely to improve outcomes. Recent work in California, where conflicts between renewables siting, biodiversity conservation, and agriculture have emerged, points to the potential of incorporating geospatial analysis into energy planning to help reconcile competing land uses in large-scale wind, solar, and transmission buildouts (Wu et al., 2016, 2020).

9.6. The Actions Required in the Next 10 Years Are Known With High Confidence

Carbon-neutral pathways diverge in energy strategy, resource use, and cost primarily after 2035. The highest-priority near-term actions are similar across pathways and have clear quantitative benchmarks for policy: renewables build-out (>500 GW total wind and solar capacity by 2030); coal retirement (<1% of total generation by 2030); maintaining current nuclear and natural gas capacity; and electrification of light-duty vehicles (EVs > 50% of LDV sales by 2030) and buildings (heat pumps >50% of residential HVAC sales by 2030). Longer-term uncertainties are related mainly to fuels and CCUS, areas in which technical potential, costs, and environmental impacts at large scale need to be better known before specific strategies are adopted. There is time for society to explore different approaches to these questions and learn from the results before solutions are needed in bulk in the 2030s, but the solutions will only be ready if the preparatory work—R&D, demonstrations, early commercial subsidies—is begun now. In other words, taking decisive near-term action in the areas that are well understood, combined with laying the necessary groundwork in the areas of uncertainty, puts the United States on a carbon-neutral pathway right away while allowing the most difficult decisions and tradeoffs to be made with better information in the future.

Conflict of Interest

The author declares no conflicts of interest relevant to this study.

Data Availability Statement

The input data used in this research were drawn from publicly accessible published sources. These are described and referenced with in-text citations in the supporting information section S4, with full citations in the reference section of the main text. The sources are listed below by broad input data category. Individual subcategories within these broad categories are mapped to the specific sources in the supporting information tables cited.

1. The data sources for demand-side equipment stocks in the residential, commercial, and transportation sectors (Table S13) were Brooker et al. (2015), U.S. Energy Information Administration (2012), U.S. Energy Information Administration (2013), and U.S. Energy Information Administration (2019).
2. The data sources for energy service demand in the residential, commercial, and transportation sectors (Tables S14–S16) were Ashe et al. (2012), U.S. Energy Information Administration (2013), U.S. Energy Information Administration (2017), and U.S. Energy Information Administration (2019).
3. The data sources for demand-side technology characteristics including efficiency and cost in the residential, commercial, and transportation sectors (Table S17) were Bloomberg New Energy Finance (2019), Brooker et al. (2015), Den Boer et al., Dentz et al. (2014), Fulton and Miller (2015), Jadun et al. (2017), Lutsey and Nicholas (2019), TA Engineering (2017), U.S. Energy Information Administration (2015), U.S. Energy Information Administration (2017), and U.S. Energy Information Administration (2019).
4. The data source for service efficiency of carbon capture in the industrial sector (Table S19) was Kuramochi et al. (2012).
5. The data sources for energy demand in the residential, commercial, transportation, and productive (industry and agriculture) sectors (Table S20) were U.S. Energy Information Administration (2017) and U.S. Energy Information Administration (2019).
6. The data sources for demand drivers for the overall economy, industrial production, and the residential, commercial, transportation, and industrial sectors (Table S21) were National Weather Service (2019), U.S. Bureau of Economic Analysis (2012), U.S. Census Bureau (2018), U.S. Census Bureau and U.S. Bureau of Transportation Statistics (2015), U.S. Energy Information Administration (2019), U.S. Environmental Protection Agency (2019b) and U.S. Federal Highway Administration (2018).
7. The data sources for load shapes in the residential, commercial, transportation, and productive (industry and agriculture) sectors (Table S22) were De Vita et al. (2018) and secondary analyses performed by the authors, as described in Table S22.
8. The data sources for supply-side resource potential, product costs, delivery infrastructure costs, and technology cost and performance (Table S23) were Del Alamo et al. (2015), IEAGHG (2017), Eureka et al. (2016), Federal Energy Regulatory Commission (2019), Johnson et al. (2006), Keith et al. (2018), Langholtz et al. (2016), National Energy Technology Laboratory (2017), National Renewable Energy Laboratory (2015), and National Renewable Energy Laboratory (2019), U.S. Energy Information Administration (2017), U.S. Energy Information Administration (2018), U.S. Energy Information Administration (2019), U.S. Environmental Protection Agency (2018), and Wiser et al. (2015).

The summary model output data for results discussed in this paper are shown in Table 2 in the main text and in the supporting information section S1. Additional model results have been submitted to the IPCC Working Group III data compilation for AR6. Extended model results and input data, including cost data, are registered in a GitHub repository with an open access license (https://github.com/EvolvedEnergyResearch/AGU_carbon_neutral_pathways). The primary data for this research comes from model simulations. Supporting information section S5 contains the governing equations for EnergyPATHWAYS and a detailed description of the model. EnergyPATHWAYS is registered in a GitHub repository (<https://github.com/energyPATHWAYS/EnergyPATHWAYS/tree/agu>). Supporting information section S6 contains a detailed description of the RIO model.

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