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Expenditure-elasticity and income-elasticity of GHG emissions
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Abstract

The relationship between income of households and their carbon emissions is often summed up by a number, the elasticity of the carbon footprint with respect to income. I survey here the cross-sectional studies of household carbon footprints and their estimation of elasticities with respect to *income* and with respect to *expenditures*. The distinction between the two elasticities comes from the fact that the saving rate rises with income.

I compile published estimates of elasticities of carbon footprint or energy requirements, and I compute new estimates. This totals around eighty estimates (a third of which are newly computed) for over twenty countries. It shows that, generally, the carbon footprint grows less rapidly than expenditures, and confirms that the income-elasticity is lower than expenditure-elasticity. Unambiguously, the assumption of an income- elasticity equal to 1 is not supported by the published literature.

I discuss the difference between carbon inequality and carbon concentration, the ambiguity in the literature between income-elasticity and expenditures-elasticity. I present the limitations of our knowledge on the income-carbon footprint relationship, from contestable assumption in the methodology as well as measurement errors in household budget surveys. I examine how elasticity can be used in "top-down" assessment of global distribution of carbon footprint.

JEL Classification: D12, D14, D30, D31, Q56, R20

Keywords: carbon footprint, GHG emissions, inequality, household consumption, income and expenditure surveys, elasticity

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Expenditure-elasticity and income-elasticity of GHG emissions

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Concerns about equity among countries have been present from the start of the public discussions about climate change. They have further extended to equity and responsibility among households or individuals. In the context of rising concerns about inequality, the relationship between income and related carbon emissions, as well as the share of top incomes in these emissions, have become topics of public interest.

Most of what we know about the relationship between income and carbon emissions comes from the analysis of household budget surveys by so-called bottom-up studies. They compute the carbon footprint of households from micro-data on the level and pattern of household consumption. They then relate the carbon footprint, i.e. GHG emissions due to consumption, to several socio-demographic and economic explanatory variables, including income, and can sum up the relationship between income or expenditures and carbon footprint with a single number, the elasticity of carbon footprint.

The top-down method overcomes the need for high quality household budget data, which is not always available, and not for all countries. It was devised by Chakravarty et al. (2009), who also introduced the terminology bottom-up and top-down. The principle is to posit a relationship between individual income and individual carbon footprint, in the form of a constant elasticity, and then, from the distribution of income within a country, to infer the distribution of individual carbon footprint within that country. The relation between income and carbon footprint is to be calibrated from elasticities provided by bottom-up studies. The advantage of this method is that it relies on the income distribution, which is quite well known. Its disadvantage, which makes it more an expedient than a method, is that it requires the value of the elasticity, which can only be estimated from already existing bottom-up studies. This strongly diminishes the interest of a top-down assessment. But the top-down method can be applied to countries where no-such bottom-up studies exist, in which case the elasticity is inferred from bottom-up studies. This extrapolation makes it possible to apply the method to every country, and by aggregation at the global level (Oxfam, 2015; Piketty and Chancel, 2015), which was the original motivation of the method.

This article surveys what is known in the literature about the elasticity of GHG emissions, with an eye to its use in the top-down method. There are several ways to understand and thus compute the elasticity of GHG emissions with respect to income. One can use time-series of the carbon footprint of a country to relate it to its GDP (e.g. Park and Heo (2007), Markaki et al. (2017), Pachauri and Spreng (2002)) or one can rely on cross-section analysis at the country level (e.g. Reinders et al. (2003), Hertwich and Peters (2009), Ivanova et al. (2016)), or even panel estimates, still at the country level (Liddle, 2015). Given the way income-elasticity is used as an input in the top-down method, it is more appropriate here to rely on cross-sectional studies of household carbon footprint within a single country, which fortunately constitute the bulk of the literature. I therefore survey the part of the literature that analyses the relationship between income and carbon footprint at the level of households or household groups. I more specifically focus on the question of elasticity, how it is measured and which values have been found. For reviews of other aspects of household carbon footprint, see Hertwich (2005), Minx et al. (2009), Donato et al. (2015), or Druckman and Jackson (2016).

This paper is organized as follows. Section 1 sets out the methodology to compute household carbon footprint and introduces several concepts relevant for the understanding and discussion of the literature, such as the difference between expenditure-elasticity and income-elasticity. Section 2 reviews the evidence available from the literature on household carbon footprint, making place to the literature on energy requirements from which the former originates. I report published estimates and also compute new estimates from available studies. As stylized facts, carbon footprint generally grows less rapidly than expenditure (expenditure-elasticity below 1) and the income-elasticity is lower than the expenditure-elasticity. Section 3 investigates a recent implementation of the top-down method at the global level, done by a team from Oxfam and Stockholm Environmental Institute (Kartha et al., 2020), which claims that an income elasticity of carbon footprint equal to 1 is supported by the literature, contrary to my findings. A careful examination of the reasons put forward reveals a confusion in the literature between expenditure-elasticity and income-elasticity. Section 3 further speculates on the consequences of my findings for the global distribution of carbon footprint. In section 4, I discuss several limits that bear upon the whole investigation: those of comparing elasticities across different studies and countries, those of modeling the income-carbon footprint relationship with a single elasticity, those of the methodology to reconstitute carbon footprint at the household level, especially as it pertains to the carbon footprint of the wealthiest. Section 5 concludes with some recommendations for the implementation of top-down methods.

1 Carbon footprint of households and its income-elasticity

This section presents what is the carbon footprint of households, how it is computed from Household Budget Surveys and what are the expenditure-elasticity and income-elasticity. This section and the following deal only with bottom-up studies which are primary sources of information. The top-down method is derived from them and cannot compute independently carbon footprints or elasticities: it instead rely on bottom-up studies to calibrate the elasticity it uses.

1.1 Computation of carbon footprint of households

Computing the emissions of an economic actor like a country or a household is tied with a responsibility principle that attributes emissions to this economic actor. As it is well-known from the case of countries, two responsibility principles are widely used (see Tukker et al. (2020) for an overview of the major responsibility principles). With producer responsibility (or production-based accounting), emissions are attributed to those actors or activities that actually release GHG into the atmosphere. With the consumer responsibility (or consumption-based accounting), emissions are attributed to those actors who consume the goods whose supply chains have emitted GHG. One switches from a view to another with Input-Output analysis techniques, that transform, with the Leontieff inverse, emission factors of production to carbon content of final goods (Peters, 2008).

For the emissions of households, the literature has quasi-exclusively adopted the consumer responsibility principle. This way of attributing GHG emissions to an household results in its carbon footprint. This standard, if slightly improper, term refers to the cumulative mass of CO_2 or GHG emissions that the household is responsible for, either directly (when a household member releases GHG, for example by burning gasoline while driving) or indirectly (when buying goods whose production processes led to GHG emissions, the so-called embodied emissions).

The level and nature of consumption, as well as the GHG associated to this consumption, are the two building blocks of the computation of the carbon footprint of households at the micro level. If e_i is the carbon intensity of good i (including direct and embodied emissions) and S_i^h is the consumption of good i by household h, the carbon footprint of h would be:

$$CF^h = \sum_i e_i S_i^h \tag{1}$$

The consumption S_i^h is in principle the physical quantity of the good, but this is rarely available. It is then replaced by spending data generally derived from Household Budget Surveys (a.k.a. Family Expenditure Survey in the UK or Consumer Expenditure Survey in the US). These surveys ask household how much they spend per category of consumption. Sampled households are usually interviewed about their characteristics and their consumption and are asked to fill a diary of their expenditure. This allows measuring the expenditure of household h on goods of category i, which is taken as a proxy for the actual quantity consumed. Carbon intensities are mostly obtained through input-output techniques that transform emissions intensities of production activities into emissions intensities of final products (Miller and Blair, 1985). Bridging the two involves some complications (see Steen-Olsen et al. (2016); Min and Rao (2018) for a detailed account of the technical subtleties).

From a macro perspective, the carbon footprint of all households of a country is only a part, admittedly large (around 70%, Hertwich and Peters, 2009), of the carbon footprint of the country, because household (i.e. private) consumption is only a part of a country's final demand, with government (i.e. public) consumption and investment being the other main components. The carbon footprint of a country, that results in this perspective, from its final demand, can then be split according to its components, so that it decomposes, ignoring residual categories, as the sum of the carbon footprints of private consumption, public consumption and investment. Public consumption and investment are generally not attributed to households.

1.2 Income and expenditure elasticity

The literature has investigated the drivers of the carbon footprint of households (occupation, location, age, household size,...). Two variables which have been put to the fore are particularly important in our context: total expenditure and income. Total expenditure is the amount of money spent in consumption, that is with our notations, $\sum_i S_i^h$. Given the way carbon footprint is computed, it should come as no surprise that expenditures are correlated to carbon footprint. Income is not easily defined (Usher, 1987) but it is roughly speaking the money earned (with or without capital gains, before or after taxes...). How expenditure or income influences household carbon footprint has been the subject of much investigation in the past twenty years. A common way to measure the strength of the link between income (resp. expenditure) and carbon footprint is to compute the income-elasticity (resp. expenditure-elasticity) of carbon footprint, that is how much the carbon footprint grows when income (resp. expenditure) grows by 1%. If the income-elasticity is below 1, this means that the carbon footprint grows less rapidly than income, so that we have a relative decoupling between income and carbon footprint, if the elasticity equals one, this means that the carbon footprint grows as fast as income.

Income and expenditure differ because not all income is spent. Part of it is saved for various motives such as bequest, consumption smoothing, or precautionary behavior *inter alia* (Browning and Lusardi, 1996). However, were the saving rate constant across the income distribution, increasing income by 1% and increasing expenditure by 1% would be one and the same. There would be no difference between income elasticity and expenditure elasticity.

However, the saving rate is in fact not constant across the income distribution: it increases dramatically with income. This can be observed in the Household Budget Surveys where the part of income spent plummets as income increases. Table 1 collects the average propensity to consume (i.e. the expenditure to income ratio) for income groups at the bottom and at the top of the income distribution. Data suggests that high income households save much more than low income households.

Country	Year	Average propensity to consume	
		bottom of the income distribution	top of the income distribution
Belgium[a]	2018	1.36 (first quartile)	0.65 (first quartile)
Italy[b]	2016	1.2 (first quintile)	0.64 (last quintile)
Spain[c]	2000	1.43 (lowest bracket)	0.47 (highest bracket)
Sweden[d]	2012	1.37 (first quartile)	0.67 (first quartile)
USA[e]	2019	4 (first decile)	0.65 (last decile)

[a] `https://statbel.fgov.be/sites/default/files/files/documents/Huishoudens/10.1Huishoudbudget/Plus/FR/EBM_0113_2018_FR_19NOV19.XLSX`

[b] Survey on Household Income and Wealth conducted by the Bank of Italy. Data from 2016, table T4 "Mean household expenditure and income, `https://www.bancaditalia.it/statistiche/tematiche/indagini-famiglie-imprese/bilanci-famiglie/risultati-indagine/cross_sectional_tables.zip?language_id=1`

[c] Duarte et al. (2010, table 7)

[d] `https://www.scb.se/en/finding-statistics/statistics-by-subject-area/household-finances/household-expenditures/household-budget-survey-hbs/pong/tables-and-graphs/2012/disposable-income--expenditures-per-household-2012-in-sek/`

[e] Consumer Expenditure Survey: `https://www.bls.gov/cex/2019/combined/decile.xlsx`

Table 1: Propensity to consume in several countries at the bottom and the top of income distribution

This fact has been recognized for long. Conventional economic wisdom explains it by pointing to intertemporal consumption smoothing, either in the form of permanent income hypothesis (an household experiencing a transitory boost in current income would not increase its consumption) or of life cycle model (a typical household would borrow in its early, low income years, save in its high income year, and dissave in retirement years).

The correlation between high income and high rate is not disputed (Browning and Lusardi, 1996, 3.2, Dynan et al., 2004, V.A), when the measure of income is current income. There has been much debate about whether the correlation still holds for other economically meaningful measures, such as permanent income (and, if so, why). The evidence indeed points in this direction: "the picture that emerges from [the facts gathered by Browning and Lusardi (1996)] is that saving is concentrated among those with high income/wealth/education." And Dynan et al. (2004) "find a strong positive relationship between saving rates and lifetime income".

This brief overview of the literature on saving lends some insights into the difference between expenditure-elasticity and income-elasticity. As saving rate increases with income, a 1% increase in income gives raise to a lower increase in consumption expenditures. A 1% increase in income thus increases the carbon footprint by a lower amount than does a 1% increase in expenditures. Said differently, we know beforehand that estimations of income-elasticity of carbon footprint would be lower than estimations of expenditure-elasticity of carbon-footprint. There is nothing really new here. Although this contrast may have been overlooked in recent works, in an older landmark study, Vringer and Blok (1995) point out that the income elasticity is lower than the expenditure elasticity (0.63 vs. 0.83) and highlight the above mentioned reason for that (p. 698, see also Wier et al. (2001, p. 269)). The consequence is that one has to pay attention to the difference between income-elasticity and expenditure-elasticity and not mix up the two.

2 Elasticities of carbon footprint and energy requirements

This section presents the survey of elasticities of household carbon footprint, highlights some stylized facts and discusses in details the (weak) link between elasticity of carbon footprint and carbon footprint inequality.

2.1 Survey

I have reviewed works published on carbon footprint of households where households are disaggregated in income groups or expenditure groups. I have retained only works that computed total (direct and indirect) emissions from consumption, leaving aside the literature focusing either on direct or on indirect emissions only. I therefore build on works that actually compute elasticity of carbon footprint but also on works from which I was able to estimate elasticities myself[1].

The survey reported in table 2 is to my knowledge the most extensive coverage[2] of elasticities of carbon footprint to date. Other papers have made partial reviews of the literature (e.g. Wier et al. (2001), Chakravarty et al. (2009, supplementary material) or Zsuzsa Lévay et al. (2020)), including up to a dozen of studies. Here, thirty-six studies are included, delivering 55 estimates of elasticity of carbon footprint with respect to expenditure and income, out of which 25 are estimates computed for this survey. In addition, I have computed 5 upper bounds. The elasticity reported is the mean elasticity of carbon footprint for all households in a given country at a given period.

Table 3 separately reports[3] some studies about (total) energy requirements of the households (also called energy cost of living and more recently energy footprints). This represents 16 studies with 22 estimates of elasticity, as long as 3 upper bounds. The table includes prominent works that have been discussed in the literature of household carbon footprint. Indeed, although energy requirements and carbon footprint are conceptually

[1] See appendix A for details on own estimates.

[2] I do not claim this survey to be comprehensive. Some studies may have gone unnoticed, but I expect these to be few. I have consulted works in greater number than the ones reported, as for a significant number of published works, I was not able to extract information relevant for the elasticity of carbon footprint.

[3] I have not looked for energy requirements studies as extensively as I have for carbon footprint ones, so that I cannot pretend to have a coverage as good as for carbon footprint studies.

different, elasticities of energy requirements have been mobilized in the discussion about carbon footprint, especially in the context of the calibration of top-down methods (e.g. Chakravarty et al., 2009). There are two main reasons for that. The first is that the work on energy requirements predates by two decades works on household carbon footprint, with Wier et al. (2001) making a connection between the two topics. The second is that, when the energy mix available does not vary much with income, the values of elasticity of energy requirements and of elasticity of carbon footprint will be similar. To improve the comparability with previous discussions and facilitate cross-referencing, I have therefore included estimates of elasticity of energy requirements in this survey.

In the tables, I have reported whenever possible the elasticity of carbon footprint estimated without econometric control. This is consistent with the use of elasticity of carbon footprint in the top-down method, where carbon footprint is derived from a single independent variable. The bivariate association of carbon footprint and the independent variable (expenditure or income) is partly the result of other factors, that are correlated with the independent variable. Controlling for these factors (household size, urbanity,...) generally modifies the elasticity: I have indicated when they are controls in the column 'Remark' of the tables. Income refers to disposable (after-tax) income, unless otherwise stated. I have also used a log-log specification whenever possible (see discussion in section 4).

Table 2: Expenditure and income elasticities of GHG or CO_2 emissions

Country	Period	Reference	Expenditure elasticity	Income elasticity	Scope	Remarks
Australia	1993-1994	(Lenzen, 1998)	0.70	0.55	GHG	emissions from government / public consumption allocated according to taxes paid
Belgium (Flanders)	2010	own estimates from Christis et al. (2019)	0.84	0.52	GHG	
Belgium	2014	(Zsuzsa Lévay et al., 2020)	0.80	0.47	GHG	
China (urban)	2005	own estimates from Golley and Meng (2012)	0.83	0.74	CO_2	
China	2007	own estimates from	0.95	0.84	CO_2	
China	2012	Wiedenhofer et al. (2017)	0.93	0.76	CO_2	
Czech republic	2010	(Mach et al., 2018)	0.81	0.59	GHG	income-elasticity computed by Radomír Mach for this survey
Denmark	1995	(Wier et al., 2001)	0.90	0.51	CO_2	
Finland	2006	(Ala-Mantila et al., 2014)	0.80	0.61	GHG	
France	2005	own estimates from Lenglart et al. (2010)	0.82	0.62	CO_2	
France	2010	(Malliet, 2020)		0.54	GHG	
Germany (West)	1988	own estimates from Weber (1999)		$\simeq 0.8$	CO_2	
Germany	2013	(Hardadi et al., 2020) and own estimates	1.04	0.58	GHG	correct for underreporting in the consumer expenditure survey.

Table 2: Expenditure and income elasticities of GHG or CO_2 emissions (continued)

Country	Period	Reference	Expenditure elasticity	Income elasticity	Scope	Remarks
Germany	2013	(Gill and Moeller, 2018)		0.56	GHG	emissions from government expenditure distributed per capita, and emissions from capital formation distributed per expenditure, control for household size
Indonesia	2005	own estimates from Irfany and Klasen (2016)	1.13		CO_2	without emissions from LULUCF; for an econometric estimate combining data for 2005 and 2009, see Irfany and Klasen (2017)
Indonesia	2009		1.00		CO_2	
India	1989-1990	own estimates from Murthy et al. (1997a)	1.07		CO_2	
India	1989-1990	own estimates from Parikh et al. (1997)	1.10		CO_2	
India	2003-2004	own estimates from Parikh et al. (2009)	1.04	0.86	CO_2	
Netherlands	2000	(Kerkhof, Nonhebel, and Moll, 2009)	0.84		GHG	
Norway	1999-2001	(Peters et al., 2006)	0.91		CO_2	with controls
Norway	2012	(Steen-Olsen et al., 2016)	1.14	<1.04		
Norway	2007	(Isaksen and Narbel, 2017)	0.99		CO_2	

Table 2: Expenditure and income elasticities of GHG or CO_2 emissions (continued)

Country	Period	Reference	Expenditure elasticity	Income elasticity	Scope	Remarks
Philippines	2000	(Seriño and Klasen, 2015)		0.80	CO_2	excluding emissions from LULUCF, with controls
Spain	1999	(Duarte et al., 2012)	0.84		CO_2	with controls; carbon intensities are computed from a SAM,
Spain	1999	own estimates from Duarte et al. (2010)		<0.41	CO_2	
Spain	2000	(Roca and Serrano, 2007)	0.98		GHG	
Spain	2000	(Roca and Serrano, 2007)	0.99		CO_2	
Spain	2006-2013	own estimates from López et al. (2016)		<0.54	GHG	
Sweden	2006	(Nässén, 2014)	0.83		GHG	
Switzerland	2002-2005	(Girod and Haan, 2010)	1.06		CO_2	spending model (see main text in 4.2)
United Kingdom	2004	own estimates from Minx et al. (2009)		0.34		
United Kingdom	2004	(Baiocchi et al., 2010)		0.7	CO_2	analysis is carried out for household-types, grouped by lifetsyle. data obtained from a commercial company, income data have been reconstructed and are prone to errors (p. 54)

Table 2: Expenditure and income elasticities of GHG or CO_2 emissions (continued)

Country	Period	Reference	Expenditure elasticity	Income elasticity	Scope	Remarks
United Kingdom	2006	(Gough et al., 2012)		0.34	GHG	
United Kingdom	2006-2009	(Büchs and Schnepf, 2013)		0.6	CO_2	
USA	1996	own estimates from Sager (2019)	0.81	0.39	CO_2	
USA	1996	own estimates from Sager (2019)	0.80	0.38	GHG	
USA	2004	(Weber and Matthews, 2008)	0.68	0.36	GHG	with controls
USA	2005	own estimates from Jones and Kammen (2011)		<0.45	GHG	
USA	2009	own estimates from Sager (2019)	0.83	0.35	CO_2	
USA	2009	own estimates from Sager (2019)	0.82	0.34	GHG	
USA	2009	own estimates from Song et al. (2019)		<0.58	GHG	income before tax
USA	2008-2012	own estimates from Ummel (2014)		0.34	GHG	
USA	2012-2014	(Fremstad et al., 2018)	0.73		CO_2	

Table 3: Expenditure and income elasticities of energy requirements

Country	Period	Reference	Expenditure elasticity	Income elasticity	Remarks
Australia	1993-1994	(Lenzen, 1998)	0.74	0.59	
Australia (Sydney)	1998-1999	(Lenzen et al., 2004) and (Lenzen et al., 2006)	0.78	0.50	with controls
Australia	1999	(Wiedenhofer et al., 2013)		0.41	with controls
Brazil (11 cities)	1995-1996	(Cohen et al., 2005)	1.01	<0.94	
China (urban)	2005	own estimates from Golley and Meng (2012)	0.76	0.68	
Denmark	1995	(Wier et al., 2001)	0.90	0.51	
India	1993-1994	(Pachauri, 2004)	0.67		with controls
India (urban)	1997-1998	(Lenzen et al., 2006)	0.86		with controls
Japan	1999	(Lenzen et al., 2006)	0.64		with controls
Netherlands	1990	(Vringer and Blok, 1995)	0.83	0.63	
New-Zealand	1973-1980	own estimates from Peet et al. (1985)	$\simeq 0.8$		
Norway	1973	(Herendeen, 1978)	0.72		
Sweden	2006	(Nässén, 2014)	0.78		
Switzerland	2006	(Tilov et al., 2019)		<0.47	

Table 3: Expenditure and income elasticities of energy requirements (continued)

Country	Period	Reference	Expenditure elasticity	Income elasticity	Remarks
United Kingdom	1968	own estimates from Roberts (1976)	0.76	<0.69	
USA	1960-1961	own estimates from Herendeen and Tanaka (1976)	0.90	0.69	
USA	1972-1973	own estimates from Herendeen et al. (1981)	0.81		
USA	2003	(Shammin et al., 2010)	0.68		

2.2 The stylized facts

Examining the bunch of elasticities compiled in tables 2 and 3, one can denote a few stylized facts.

The first one is that expenditure-elasticity is higher than income-elasticity. This suffers no exception. It is always the case when studies reported both, but it is also the case when one compares across studies for the same country and a similar period. This confirms the insights derived from the saving behavior: Expenditure-elasticity and income-elasticity are conceptually and empirically different, and the gap between the two is quite large.

There is another qualitative difference between income and expenditure in their relation with carbon footprint. Carbon footprints are much tightly related to expenditures than they are to income. This is not visible in table 2 and 3 but can be seen in table 4 that collects the coefficient of determination R^2 in the regression of (log of) carbon footprints against (log of) income or expenditures, for the studies that report both. Given that carbon footprint is computed from expenditures by categories as is total expenditures, this should not be too much a surprise. Expenditures are then a much stronger predictor of carbon footprint than income.

Study	Coefficient of determination (R^2)	
	when independent variable is expenditures	when independent variable is income
(Zsuzsa Lévay et al., 2020)	0.66	0.37
(Mach et al., 2018)[a]	0.55	0.36
(Wier et al., 2001)	0.77	0.47
(Ala-Mantila et al., 2014)	0.74	0.45
(Weber and Matthews, 2008)[b]	0.71	0.49
own estimates from Sager (2019) (GHG 1996)	0.79	0.42
own estimates from Sager (2019) (GHG 2009)	0.76	0.38

[a] regression for income computed by Radomír Mach for this survey
[b] with controls for household size

Table 4: Coefficient of determination (R^2) of the regression of log of carbon footprint against log of independent variable (expenditures or income)

The second stylized fact is that expenditure-elasticity of carbon footprint is generally below 1, i.e. carbon footprint grows less rapidly than expenditure. The explanation is found in almost every article surveyed. Per unit of spending, buying energy for heating or gasoline for driving a car (direct emissions) releases more carbon than buying goods or services (indirect emissions). The share spent on energy decreases when total expenditure increases, reflecting that energy is an inferior good, or a necessity of modern life. As direct emissions constitute a large share of carbon footprint, the total carbon footprint also increases less rapidly than expenditure, i.e. the expenditure elasticity is below 1.

A manifestation of this phenomenon is that a rich urban household will emit more than a rural poor household, simply because it consumes more. But the rural household will spend proportionally more for transportation (relying on private cars instead of public transports) and housing (heating a detached house compared to a relatively energy efficient flat). As a consequence, carbon footprint will not grow as fast as expenditure.

It is interesting to have a closer look at the countries where expenditure elasticities are close to 1 to see how they escape the general pattern. From the discussion above, one could guess that it would be the case when spending on energy is not more carbon-intensive than other spending or when spending on energy-intensive activities increases as fast as, or faster than, expenditures. I will first discuss the four developed countries where some estimates of expenditure-elasticity is close to 1, and the four developing countries.

Let us look first at Norway, which is more sampled than others in our survey as there are active groups in industrial ecology there. Isaksen and Narbel (2017) have recently devoted themselves to explaining why carbon footprint is proportional to expenditure in this country. They found that the elasticity close to one "can be explained by the very low emissions from the Norwegian electricity production" mostly from hydropower (see also the comparison of UK and the Netherlands vs. Norway and Sweden in Kerkhof, Benders, and Moll (2009)). Actually using the EU mix for the carbon embodied in electricity lowers the expenditure-elasticity of carbon footprint to 0.64. The reason may be similar in Switzerland, for the electricity mix is dominated by nuclear and hydro power. From this observation, one can predict that, keeping spending structure constant, the expenditure-elasticity will rise as decarbonisation in electricity, housing and transport unfolds.

Reasons for Germany and Spain are less apparent. For Germany, Hardadi et al. (2020) find an income elasticity slightly above one. They report that the transportation share of carbon footprint roughly doubles from the bottom to the top of the income distribution, the combination of a strong increase in share spent on transportation and a declining carbon intensity of transportation expenditure. For Spain in Roca and Serrano (2007), there is little information on sources of emissions that could be used to explain the high expenditure-elasticity found. The expenditure-elasticity close to 1 is hard to reconcile with declining intensities of GHG plotted there. It may be an artifact of the way household size is taken into account as Roca and Serrano (2007) also report an elasticity of 0.91 (for CO_2) and 0.89 (for all GHG).

In developing countries, the situation is different from that of Norway. Closer-to-unity elasticities seem to derive from the fact that fossil energy is a normal or superior good. Consider the case of Brazil[4]. For Brazilian cities in 1995-1996, the elasticity around 1 is driven by an increase in mobility from lower income (that use public transportation) to higher incomes (that use private car) (Cohen et al., 2005, p. 559). In Indonesia, Irfany and Klasen (2016, 2017) give little sociological context, but the share spent on transportation increases across expenditure quintiles, making it a superior goods, whereas the share spent on fuel and light diminishes, resulting in an expenditure-elasticity close to or above one (Irfany and Klasen, 2017, supplementary appendix). In India, (Murthy et al., 1997b) report that emissions per unit of expenditure are typically 20-30% higher in urban (richer) areas compared to rural ones. This can be explained by increasing share spent on transportation as well as a difference in energy mix between biomass energy for poor rural households and commercial, fossil energy for richer, urban households (Murthy et al., 1997b; Pachauri, 2004). In the Philippines, Seriño and Klasen (2015) also point to the increasing use of transportation and fossil energy in cities compared to poorer rural areas. This suggests that developing countries show a different pattern than developed countries. Poor (and especially rural) households rely on biomass energy and do not own private cars whereas low-income households in developed countries do not differ significantly from the national

[4] One has to recall that Cohen et al. (2005) report data for urban Brazil only, so that the elasticity is in a way controlled for the location of households. Including rural households would change the estimates.

average in their access to the energy mix and are generally car-dependent. This drives the expenditure-elasticity closer to or even above 1 in developing countries.

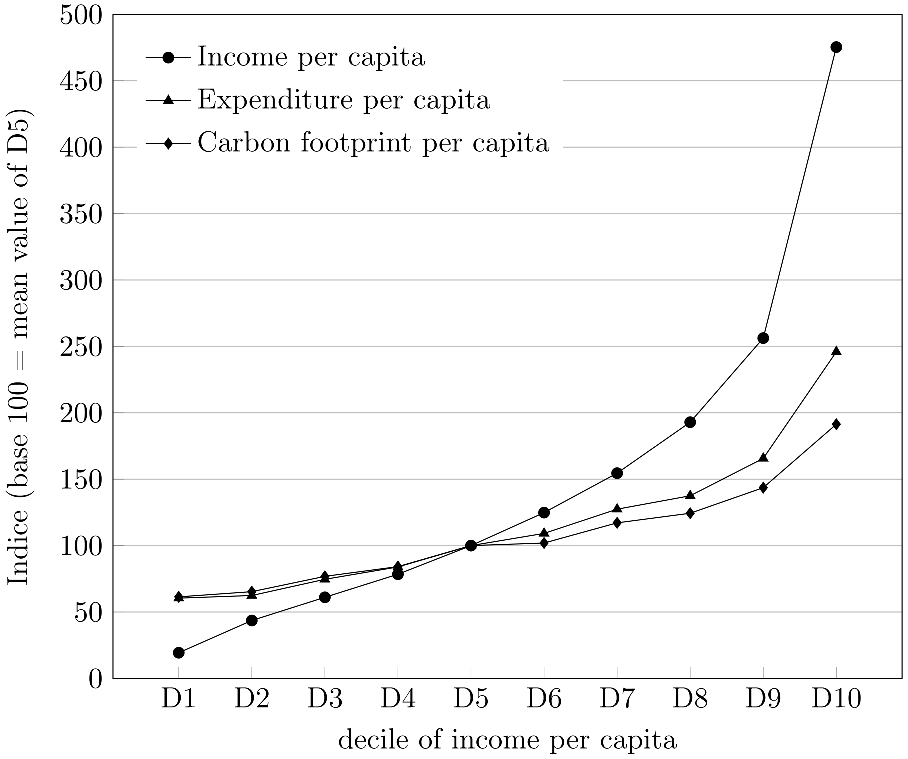

Figure 1: Income per capita, expenditure per capita, and carbon footprint per capita by income per capita level, (US, 2009)

Notes: data of US households in 2009 from supplementary appendix of Sager (2019)

These stylized facts mean that carbon footprint will grow less rapidly than expenditure, which itself grows less rapidly than income. This is shown in Fig. 1 for US households in 2009, from the carbon footprint computed by Sager (2019) from data of CEX, WIOD, EPA and EIA. To put it differently, the share of carbon footprint due to top incomes is less than their share of expenditures, itself less than their share of incomes. The situation is reversed at the other end of the distribution: the share of carbon footprint of bottom incomes is more than their share of expenditures, which is more than their share of incomes. To contrast, an income-elasticity of carbon footprint equal to 1 would mean than the carbon footprints of income classes are as unequal as their income. To sum up, across income classes, expenditures are more equally distributed than income and carbon emissions are more equally distributed than expenditures. The lessons that can be drawn from elasticity of energy requirements do not differ significantly from those from elasticity of carbon footprint.

2.3 Carbon inequality and concentration by income

The last statement concerns the relative inequality of carbon footprint, expenditures and income when one moves along the income distribution and it should not be confused with any assessment of the carbon inequality per se. Some studies have indeed investigated the inequality of carbon footprint or energy requirements, measured by the Gini coefficient. For example, Oswald et al. (2020, p. 232) found that "the energy footprint inequality is generally larger than expenditure inequality"[5]. This is not contradictory with my statement as the two concern different phenomena.

I will dwell on the difference between carbon inequality and the relationship between carbon footprint and income, because it helps to understand more accurately what the top-down method does or does not. The discussion is most easily conducted in terms of Lorenz curves, on which the Gini measure is based. In the Lorenz curve for income, the cumulative share of population ranked by increasing income is plotted against their cumulative share of income[6]. It depicts income inequality. Similarly, the Lorenz curve for carbon footprint plots the cumulative share of population ranked by increasing carbon footprint against the cumulative share of carbon footprint[7]. It depicts carbon inequality and synthesizes answers to questions such as: how much emit the bottom emitters? or how much emit the top emitters?

In investigating the relation between income and emissions, others questions are asked: how much emit those who earn the less? How much emit those who earn the most? The Lorenz curve for carbon footprint is not relevant to answer them. Instead, one would look at what I would name after Kakwani (1977) the *concentration curve* of carbon footprint. The concentration curve of carbon footprint plots the cumulative share of population *ranked by increasing income* against their cumulative share of carbon footprint[8] whereas the Lorenz curve for carbon footprint plots the cumulative share of population *ranked by increasing carbon footprint* against their cumulative share of carbon footprint. The concentration curve depicts what can be named the concentration of carbon footprint with income, or, in short, carbon concentration.

The position of the concentration curve of carbon footprint relative to the Lorenz curve for income is related to the income-elasticity of carbon footprint (Kakwani, 1977): when it is below 1, the concentration curve of carbon footprint will lie above the Lorenz curve for income, and when it is above 1, it will lie below. On the contrary, the relative position of the Lorenz curves for income and for carbon footprint bears no relation with income-elasticity of carbon footprint. A comparison between the income Gini and the carbon footprint Gini has nothing to do with the relationship between income and carbon footprint. In other words, a carbon inequality higher than the income (resp. expenditure) inequality is no indication than the income (resp. expenditure) elasticity of carbon footprint is above 1.

The difference between the Lorenz curve for carbon footprint and the concentration

[5]In the studies surveyed here, Irfany and Klasen (2016, p.472) in Indonesia and Mach et al. (2018, p. 66) in Czech Republic both find expenditures Gini to be lower than carbon footprint Gini. In China, expenditure Gini and carbon footprint Gini are similar (Wiedenhofer et al., 2017, p. 78) whereas Sager (2019, p. 5) finds an income Gini higher than expenditure Gini, itself higher than carbon footprint Gini for the USA. Income Gini is found to higher than energy requirements Gini in Brazil (Cohen et al., 2005, p. 260) and higher than carbon footprint Gini again in the USA (Ummel, 2014, p. 13). In Germany, Hardadi et al. (2020) also report an income Gini higher than carbon footprint Gini, but their carbon footprint Gini seems to be actually a concentration index. Ivanova and Wood (2020) also compute carbon footprint Gini but do not relate it to expenditure nor income Gini.

[6]Mathematically speaking, if f is the probability density function of income and μ the mean income, the Lorenz curve for income is the relationship between the cumulative distribution function $F(z) = \int_0^z f(x)dx$ and the cumulative share of the first moment $\frac{1}{\mu}\int_0^z xf(x)dx$, or the graph of the function $p \mapsto \frac{1}{\mu}\int_0^p F^{[-1]}(u)du$.

[7]If g is the probability density function of carbon footprint and ν the mean carbon footprint, the Lorenz curve for carbon footprint is the relationship between $G(t) = \int_0^t g(s)ds$ and $\frac{1}{\nu}\int_0^t sg(s)ds$, or the graph of the function $p \mapsto \frac{1}{\nu}\int_0^p G^{[-1]}(u)du$.

[8]If one notes $E(x)$ the mean carbon footprint conditional on income being x, the concentration curve of carbon footprint is the relationship between $F(z)$ and $\frac{1}{\nu}\int_0^z E(x)f(x)dx$, or the graph of the function $p \mapsto \frac{1}{\nu}\int_0^p E(F^{[-1]}(u))du$. Strictly speaking, this should be named the concentration curve of function E, that is the concentration curve of carbon footprint conditional on income.

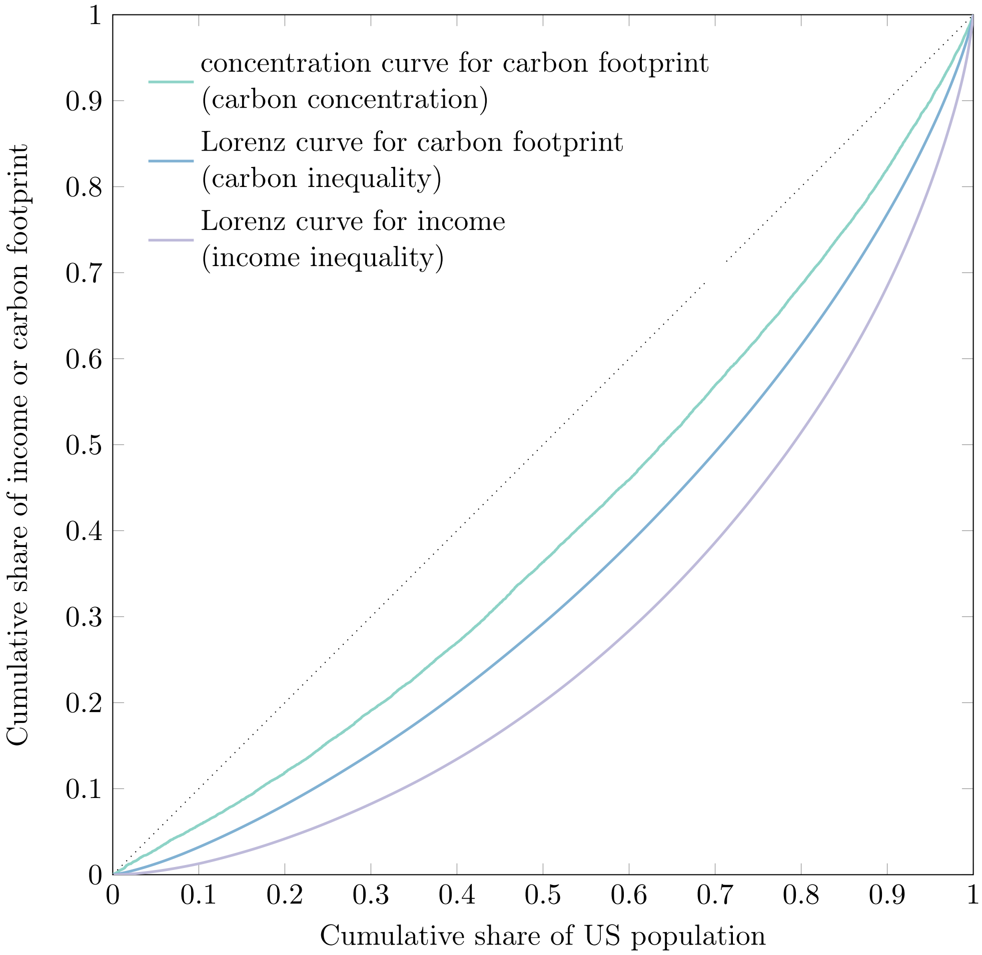

Figure 2: Lorenz and concentration curves
Notes: data for carbon footprint (CO_2 only) of US households in 2009 from supplementary appendix of Sager (2019)

curve of carbon footprint may look mathematically subtle but it is empirically significant. In Fig. 2, I plot the empirical Lorenz curves for income and for carbon footprint, as well as the concentration curve for carbon footprint, still for US households in 2019. The concentration curve of carbon footprint is well above the Lorenz curve for income, reflecting an income-elasticity well below 1. Furthermore, and this is the new information, the Lorenz curve for carbon footprint is below the concentration curve of carbon footprint.

This difference reflects a variability of carbon footprint that stems from other sources than income (for an early depiction of the phenomena, see Vringer and Blok (1995, Fig. 5)). This variability is the consequence of heterogeneity of households at a given income level. Because households with the same income do not also have in common size, transportation needs, heating system, consumption habits, etc., they will have different spending patterns and saving behavior and thus not the same carbon footprint. This is "horizontal" heterogeneity as opposed to vertical, i.e. attached to position on the income ladder. This variability has been linked to household size, location (countryside vs. city), local climate, occupation (employed vs. retired), access to different technologies and energies... Some of it may be spurious as it directly relates to the method of estimating carbon footprint from household budget surveys (infrequent purchases, seasonal variability).

Because of horizontal heterogeneity in carbon footprint, ranking population according to income and according to carbon footprint are not the same. The cumulative share of carbon footprint is therefore not computed across the same subpopulation for the Lorenz curve and for the concentration curve, and the two curves will differ. The difference is all the more significant as the carbon footprint exhibits a lot of horizontal heterogeneity. This is the reason why carbon inequality, which includes horizontal heterogeneity, is no indication of the carbon concentration, which abstract from it and is the joint result of only income inequality and the shape of the income - carbon footprint relationship.

This discussion bears consequence for a proper understanding of the top-down method. As said in the introduction, from the distribution of income, it reconstructs carbon footprints of households by assuming a deterministic relationship between carbon footprint and income. Thus, the carbon footprint of an household is purely determined by its income. At a given level of income, it actually assumes that there is no variability of carbon footprint. The distribution of the carbon footprint reconstructed by the top-down method lacks the horizontal variability. It is therefore much closer to the distribution of mean carbon footprint conditional on income than to the full-fledged distribution of carbon-footprint, that still exhibits variability when conditioned on income.

The distribution of carbon footprint obtained by the top-down method is therefore suited to investigate the concentration of carbon footprint, but not the carbon footprint inequality per se. The top-down method could actually be supplemented by adding heterogeneity not related to income. Instead of simply positing that $CF = A.I^{\varepsilon}$ with ε the income-elasticity of carbon footprint, one could introduce variability in this deterministic equation by assuming that $CF = A.I^{\varepsilon}\mathrm{e}^{u}$ where u is a stochastic disturbance term, independent from income, chosen so that $\mathbb{E}[\mathrm{e}^{u}] = 1$. This patch would enable the top-down method to represent both carbon concentration and carbon inequality, with a proper calibration of the income-elasticity and of the disturbance term that catches the horizontal heterogeneity[9]. When this, or something equivalent in spirit, is not done, the top-down method can reproduce only concentration of carbon footprint.

3 Misuse of a constant income-elasticity to compute global distribution of carbon footprint

The evidence gathered in this survey is overwhelming. Expenditure-elasticity may be found to be around 1 or even above for some countries but it is by no means a general rule, and income-elasticity is systematically below the expenditure-elasticity. No study supports an income-elasticity of carbon footprint equal to one. On the contrary, there is vast amount of evidence showing that, in every country, the income-elasticity is below one, and most of the time far below.

The top-down method has been recently implemented at the global level, by a team from Oxfam and the Stockholm Environmental Institute (Kartha et al., 2020). They use income distributions in 117 countries, taken from the World Inequality Database and the World Income Inequality Database to derive in each country the concentration of carbon footprint[10]. Aggregating these distributions delivers the concentration curve of

[9]For example, one has with the given assumption: $\sigma^2_{\log CF} = \varepsilon^2\sigma^2_{\log I} + \sigma^2_u$. Furthermore the coefficient of determination in the log-log regression is $R^2 = \varepsilon^2\sigma^2_{\log I}/\sigma^2_{\log CF}$. So that one can calibrate the variance of u as $\sigma^2_u = \frac{1-R^2}{R^2}\varepsilon^2\sigma^2_{\log I}$, with $R^2 \simeq 0.4$ from table 4.

[10]Mathematically speaking, the top-down method assumes that, within in a country, the distribution of carbon footprint is the pushforward of the distribution of income by the income-carbon footprint relationship. With notation as in above footnotes, $g = E_*(f)$, or, in terms of pdf, $g(E(x)) = f(x)/E'(x)$. The two

carbon footprint at the global level. Following a trend set by Chakravarty et al. (2009), and as in a previous report (Oxfam, 2015), Kartha et al. (2020) assume that, in each country, the elasticity of carbon footprint with respect to income equals one. They state that "this assumption is grounded in the findings of numerous studies relating income, consumption, energy use and/or emissions". This reading of the literature cannot be more different than the one proposed here. It is worth examining how they justify it as it uncovers some ambiguities in the literature (section 3.1). As this assumption eventually cannot be substantiated, I discuss the plausible consequences for the global concentration of carbon footprint of calibrating the income-elasticity closer to the values found in this survey (section 3.2).

3.1 Alleged justifications of an income-elasticity equal to 1

Kartha et al. (2020) cite works in support of a unitary income-elasticity of carbon footprint. Let us examine them one by one and see whether the works provide evidence for this disputed assumption.

First, Kartha et al. (2020) point to some studies that actually deal with distributional impacts of a carbon tax scheme. This is a point related to carbon footprint of households, but still different as many effects are embarked in the impact of a carbon tax, which thus does not derive simply from how carbon footprint varies with income. I do not delve further into these works as they provide at best only indirect indications on the income-carbon footprint relationship. Second, they quote a work that deals only with the indirect part of carbon footprint, and work by Ivanova and Wood (2020) that is not concerned with the income-carbon footprint relationship but only carbon inequality per se, as we have seen.

Third, they refer to works (Wiedenhofer et al., 2013; Ummel, 2014; Wiedenhofer et al., 2017; Song et al., 2019) included in this survey, although none of them support their assumption, as can be seen from the corresponding entries in tables 2 or 3. Strangely enough, they compute the income-elasticity from Ummel (2014) and found it to be 0.65[11], only to dismiss this value because it "is much lower than the typical range of 0.9–1.1 for estimated emissions elasticities", – which begs the question. They also express reservations on the ground that the data used "experience underreporting at high incomes". It is inconsistent to disregard this particular study. Almost all studies share the same methodology and rely on household budget surveys to reconstruct the carbon footprint of household and then to estimate the income or expenditure elasticity of carbon footprint. So if one study must be rejected on this ground, all must be. I will discuss more precisely measurement problems in 4.3, with the conclusion that they should not really impinge on the elasticity. But again were this conclusion to be invalidated, all the literature would have to be revised, with the consequence that the top-down studies, which are bound to rely on bottom-up estimates to calibrate the expenditure/income-carbon footprint relationship, would have an even less firm basis than nowadays to do so.

Finally, they point to Hubacek et al. (2017) and Oswald et al. (2020) which investigate the relationship between carbon footprint or energy requirements and income groups for many countries thanks to global databases. Let us discuss these last two in more details.

A cursory look at Hubacek et al. (2017) may give the impression that they compute the income-elasticity of household carbon footprint. They indeed plot in Figure 4 the "Household carbon elasticity of income" for 120 countries, a figure reproduced in Kartha

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data of this method are thus the pdf of income f and the income-to-carbon-footprint map E. Bottom-up studies give empirical estimates of g, f and E from observations of household budget surveys.

[11] It is actually much lower at 0.34. This error is linked to the discussion of 2.3, see appendix A.

et al. (2020). The devil however lies in the details. As the commentary p.365 makes it clear, income is "proxied by expenditures per consumption segment", an expedient one could have guessed, since the databases (the Global consumption database from World Bank and the Eurostat structure of consumption expenditure) do not report income. What they actually computed is thus the *expenditure* elasticity of carbon footprint. In this respect, scientific papers are no different from advertisements: one has to read the small print.

Oswald et al. (2020) use the same datasets to compute a power law at the global level relating energy requirements and expenditure. They conclude that "energy footprints scale sublinearily with expenditure", finding an elasticity[12] of 0.86. Kartha et al. (2020) mistook what is unambiguously an *expenditure*-elasticity for an "average *income* elasticity of energy demand" (p.35, my emphasis). Oswald et al. (2020) do not report any income elasticity of total energy requirements. As a matter of fact, they do compute elasticities of consumption categories, some of which are (probably) above 1. However, although they are named "income elasticities", these elasticities are truly *expenditures elasticities* as, again, "total expenditure per capita [...] functions as an approximation to income per capita, which itself is not available" (p. 237).

This confusion between expenditure-elasticity and income-elasticity has been present somehow since the start of the top-down method. Chakravarty et al. (2009) do not distinguish the two kinds of elasticities and the reply by Grubler and Pachauri (2009) did not help either. Although they seemingly report "income elasticity" of CO_2 emissions for India per quintile and localisation (urban / rural), a careful examination may have led to realizing these were expenditure elasticity[13]. The opportunity was missed to clear up the confusion at an early stage.

To conclude, there is thus no doubt that the income-elasticity of carbon footprint has been miscalibrated by Kartha et al. (2020), for reasons that partly point to a confusion in some of the literature between expenditure-elasticity and income-elasticity. This put the calibrated elasticity outside the range of the observed income-elasticities in bottom-up studies.

3.2 Consequences for the global concentration of carbon footprint

How does the overestimation of the income-elasticity impact the global concentration of carbon footprint computed by Kartha et al. (2020)? This is unclear. The excel sheet[14] that compiles the data underlying the analysis of Kartha et al. (2020) is protected, not commented and I was therefore not able to explore the impacts of changing the income-elasticity to come closer to observed levels. As it is reconstructed by the top-down method, the global concentration of carbon footprint is at the interplay of two distributions: the distribution of carbon footprint across countries, with richer countries having, generally speaking, increased carbon footprint per capita, and the concentration of carbon footprint within each country. Correcting the income-elasticity affects only the second distribution, but not the first.

Thus, exact consequences for the cumulative shares of carbon footprint for global income groups (such as bottom 50%, middle 40% and top 10% used by Kartha et al. (2020)) remain to be investigated. If a country falls entirely into a global income group, changing

[12] I have not reported it in table 2 as it is a cross-country pool estimate, not a cross-section estimate within a single country.

[13] Income micro data is not available in the Indian survey used and previous works only talked about expenditure elasticity (Pachauri, 2004, 2007). Asked in private correspondence, Dr. Pachauri has confirmed that elasticities in the reply are expenditure elasticities.

[14] Available at `https://www.sei.org/projects-and-tools/tools/emissions-inequality-dashboard/`.

the concentration of carbon footprint within this country will have no effect on the cumulative share of carbon footprint for this income group. The cumulative share of an income group will only change in so far as population of countries falls partially in this income group. Although correcting income-elasticity will certainly reduce the global concentration of carbon footprint, it may only moderately affect the cumulative share of carbon footprint of large global income groups in so far as those include whole countries. It will however strongly affect small global income groups (like the top 1% and top 0.1%) that are made up of small groups of population from many countries.

At a national level, the consequence of the over-estimation of income-elasticity is simply a gross overestimation of the concentration of carbon footprint with income. In the US, data from Sager (2019) indicate that the interdecile ratio D9/D1 of mean carbon footprint per capita conditional on income per capita is 2.5 whereas the assumption of Kartha et al. (2020) will put it at the same level of the interdecile ratio of income per capita, that is 9.5 in this dataset. Piketty (2014, p.267-269) has warned against the sole use of indicators like the interdecile ratio to represent income inequality. As he explains, they may overlook what happens in the tail of the distribution and give no information on the share of national income captured by top incomes. Applied to the concentration of carbon footprint, this points to looking at the cumulative share of carbon footprint due to top incomes as a relevant indicator. Estimating directly this share with data derived from household budget surveys may lead to underestimate it as these surveys experience some underreporting of expenditure and inadequate representation of very high incomes (see discussion in 4.3). This is where the top-down method has an advantage. Because it can use a more precise distribution of income, generally derived from fiscal data, it could give a better view on cumulative shares – with the proviso that it posits a correct income-carbon footprint relationship. Using an income-elasticity of 1 distorts the income-carbon footprint relationship as the gross overestimate of the interdecile ratio makes clear. Applying this distorted relation on a more accurate distribution of income cannot give a reliable estimate of cumulative shares of carbon footprint.

The key point is that for a given income distribution, the way Kartha et al. (2020) reconstruct the carbon footprint from income overestimates the share of top income and underestimates the share of bottom income. To see that clearly, I have plotted in Fig. 3 the concentration curve of carbon footprint[15] for US households, reconstructed by Sager (2019) with the standard bottom-up method, and the concentration curve of carbon footprint, reconstructed with the top-down method[16] of Kartha et al. (2020) with an income-elasticity equal to 1.

We can clearly see that, although the underlying income distribution is the same, their reconstruction overestimates the global concentration, underestimates the cumulative share of bottom incomes, and overestimates the cumulative share of top incomes. Indeed, with the hypothesis that income-elasticity is one, which is tantamount to say that carbon footprint is proportional to income, the concentration curve of reconstructed carbon footprint closely follows the Lorenz curve for income, and we already know, from Fig. 1 and 2, that income is much more concentrated than carbon footprint.

Choosing an income-elasticity of one is thus a gross misrepresentation of the carbon

[15]It is the same as fig. 2.

[16]Their implementation is not entirely transparent. From their explanations p.33-34, I assume that carbon footprint of household i with income I_i is $CF^i = \max(\min(a(0.3 * I_m)^\varepsilon, aI_i^\varepsilon), 300\text{tCO}_2)$, with I_m is the median income, $\varepsilon = 1$ the income-elasticity and a is chosen so that the mean of reconstructed carbon footprint matches the mean US carbon footprint. Kartha et al. (2020) are silent as whether they deal with total income or income per capita – I have assumed that it is income per capita.

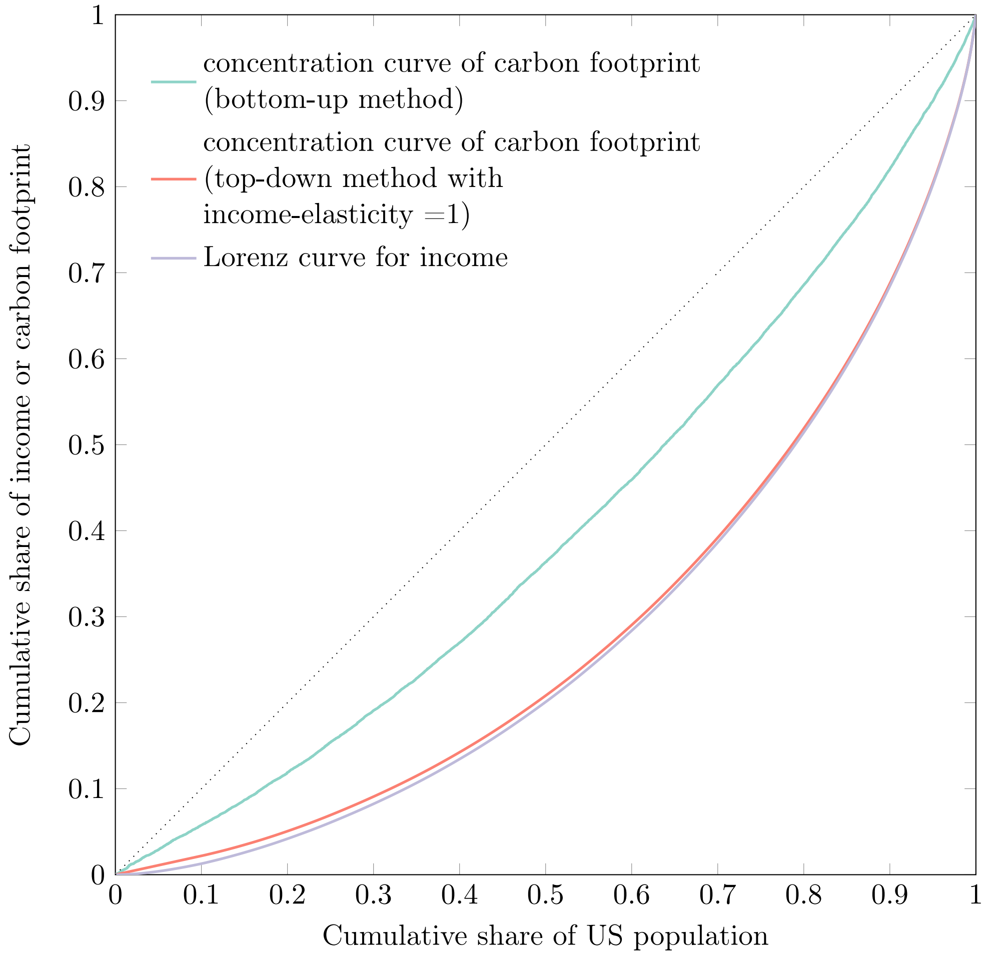

Figure 3: Concentration curves of carbon footprint, reconstructed by bottom-up and top-down methods

Notes: data for carbon footprint (CO_2 only) of US households in 2009 from supplementary appendix of Sager (2019)

footprint-income relationship. It introduces large errors in the estimation of cumulative shares of various national income groups. This should not be taken as a critique of the top-down method per se, only of the way it has been miscalibrated. Using an elasticity closer to the estimated value does deliver a very good fit between the two concentration curves.

4 Discussion

This section discusses various limitations and qualifications of this survey in particular and of studies about the income-carbon footprint relationship in general. First, it discusses whether different studies are comparable. Second, it addresses limitations of the our knowledge of the income-carbon footprint relationship. Finally, it takes seriously the problem of measurement in household budget surveys and assesses whether this could reverse the main finding of the survey.

4.1 Can we compare estimations across different studies?

Gathering and computing the numerous elasticities of carbon footprint of table 2 and 3 has shown that the assumption of an income-elasticity equals to one is not supported by the literature. It was not aimed at proposing a better value thanks to a meta-analysis of the elasticities compiled. If its outcome could not be that income-elasticity of carbon footprint is around 1, it is first and foremost dubious that such a meta-analysis would make sense.

It is problematic to lump together several studies to compare elasticities of carbon footprint across time-periods, countries and methodologies because there are so many variations that affect the results. These variations pertain to how data is organised and collected, how carbon footprint are reconstructed and how elasticities are estimated.

Structural differences on consumption may render the comparison problematic (e.g. Druckman and Jackson, 2009, p. 2072-2073, cf. also Reinders et al., 2003, p. 140). In some countries, the government supplies services (e.g. health services in the UK) that will be paid from private consumption in others (like the USA). Hence the carbon footprint of households would not reflect the same basket of services. Although there is some harmonisation, national surveys of household budgets still differ in their timing and frequency, their sample design, their structure and content, and even their definition of what is an household. This affects the various measures of the distribution of carbon footprint and of the carbon footprint-income relationship in ways that have not been looked after.

There are also considerable variations in how the methodology for computing the carbon footprint of individual households is implemented. Here are some of the choices to be made:

- which emissions are included in the carbon footprint? The scope varies: either CO_2 only or GHG (generally computed as tCO_{2e}), sometimes with industrial gases (e.g. Roca and Serrano, 2007; Mach et al., 2018), sometimes without (e.g. Nässén, 2014). An aviation impacts multiplier can be used (e.g. Gill and Moeller, 2018). One could note that all studies in developing countries have dealt with CO_2 only. Including emissions from methane and nitrous oxide, mainly related to food products, may lower the elasticity in these countries as is the case in cross-sectional analysis of countries (Hertwich and Peters, 2009).

- how the carbon intensities are computed? Studies are mostly computed thanks to environmentally extended Input-Output Analysis (EE-IOA), but some rely on hybrid approaches combining process analysis and input-output analysis (e.g. Vringer and Blok, 1995; Kerkhof, Benders, and Moll, 2009) or life-cycle assessment (e.g. Jones and Kammen, 2011). Duarte et al. (2012) are unique in using accounting multipliers from a Social Accounting Matrix instead of an IO table, so that their emissions are not a carbon footprint in the standard sense (consumption-based accounting of household emissions). Girod and Haan (2010) estimate carbon intensities for goods and services measured in functional units and then derive carbon intensities for expenditure thanks to a spending model.

- when the standard EE-IO approach is carried out, how is it implemented? Various assumptions for the IO are applied, to say nothing of the choice of dataset: full multi-regional input output (MRIO) tables as in Steen-Olsen et al. (2016), simplified MRIO as in Lenglart et al. (2010), MRIO with further regional disaggregation (e.g. Christis et al., 2019), MRIO supplemented with national data (e.g. Mach et al., 2018), single-region input-output table as in Wier et al. (2001), domestic technology assumption as in Kerkhof, Nonhebel, and Moll (2009), or domestic technology assumption with ex-post correction of carbon intensities for import (e.g. Baiocchi et al., 2010).

- how are spending data from micro survey and input-output coefficients from macro-modelling bridged? As noted by Steen-Olsen et al. (2016), this is rather opaque.

- which emissions are allocated to households? Generally, only the private consumption is allocated and other parts of final demand are not allocated. Thus public consumption (final demand of public administration) is most often not accounted for. But sometimes it is attributed to household through various hypotheses: proportional to the size of household (e.g. Gill and Moeller, 2018), proportional to the use of public services (e.g. (Gough et al., 2012)), proportional to taxes (e.g. (Lenzen, 1998)). Final demand of investment is even more rarely dealt with. Herendeen (1978) allocate consumption of fixed capital to households, whereas Lenzen et al. (2004) uses an IO model with capital formation as an input instead of more commonly considering it an output. Gill and Moeller (2018) allocated emissions from investment proportionally to expenditures. Of course these choices bear consequences on the estimated value of elasticity.

Once the carbon footprint have been computed for each surveyed household, there are other sources of variations from the way the elasticity is estimated, that is from how the income - carbon footprint relationship is summed up:

- the elasticities of carbon footprint are sometimes estimated at the micro-data level (e.g. Weber and Matthews (2008)), sometimes on aggregates on income classes (e.g. (Steen-Olsen et al., 2016)) or other socio-economic groups (e.g. Minx et al. (2009))

- the variable of interest (expenditure or income) may be the only regressor but may also be accompanied by other regressors, controlling for household size, urbanity, car possession, ages, etc. In Büchs and Schnepf (2013), income-elasticity is estimated at 0.6 without controls, but drops at 0.43 when controls are introduced.

- the elasticity is estimated with various econometric specifications. If I have chosen when possible a log-log specification, changing it dramatically alters the value estimated. Weber and Matthews (2008) test four functional forms with an expenditure elasticity ranging from 0.60 to 0.7 and an income-elasticity from 0.35 to 0.52: the log-log specification gives the highest estimate. Zsuzsa Lévay et al. (2020, table 2) have similar findings (among five specifications). Isaksen and Narbel (2017) also test several specifications of the relationship between carbon footprint and expenditures. Peters et al. (2006) discuss at length the link between specifications of Engel functions and of the carbon footprint-expenditures relationship. For theoretical and empirical reasons, they favor a linear model, which may be the consequence that carbon footprint are almost proportional to expenditure in the case of Norway.

- if definition of income and expenditure may slightly change across studies, a more confusing factor is the use of per capita or total values. Household size is sometimes directly controlled for, as seen above, but it also enters the very definition of which kind of elasticity is computed. One can use total emissions or emissions per capita on the dependent side, and total, per capita or equivalised (with various scales) on the independent side. Büchs and Schnepf (2013) regress total carbon footprint on equivalised income, Peters et al. (2006) total carbon footprint on total expenditures, Ala-Mantila et al. (2014) carbon footprint per capita on expenditure per capita... Duarte et al. (2010) even use emission per consumption units ("equivalised emissions" so to speak).

> All these seemingly innocuous variations make a great difference. For Roca and Serrano (2007), elasticity for GHG with respect to total expenditure is 0.98 in Spain in 2000 but elasticity with respect to equivalent expenditure is lower at 0.89 (note that it is unclear whether emissions are also equivalised). Similarly, Girod and Haan (2010) found that the elasticity with respect to total expenditure is 1.06 in Switzerland in 2002-2005 but elasticity with respect to equivalised expenditure drops to 0.94. This is because larger households tends to have higher incomes and thus higher emissions.

In light of the abundant discrepancies, it may be wise to recall the opinion of Peters et al. (2006, p. 149). After presenting the numerous factors changing between two studies done in two countries, they conclude that "these factors may make country comparisons of the relationship between HEI [household environmental impact, e.g. carbon footprint] and household characteristics futile."

4.2 Limitations on the income-carbon footprint relationship

When one restricts oneself to a specific country and time period, one also faces several limitations to grasp the income-carbon footprint relationship or the expenditure-carbon footprint relationship. The first is the reliance on the very number I have focused on so far, the elasticity, the second is the consequence of the methodology followed to compute carbon footprint.

The income-carbon footprint relationship has largely been summed up with a single number: the income-elasticity and similarly for expenditure. This is however regularly questioned. To a certain extent, the studies discussed above, that use specifications other than a log-log, investigate how the income-elasticity varies with income, because with these specifications, elasticity at a given point is not constantly equal to its mean.

Several papers have dealt more explicitly with a varying elasticity. In the first discussion of the top-down method, Grubler and Pachauri (2009) signal that expenditure-elasticity is highly variable, depending on expenditure quintile and location (urban vs. rural), to the point that it undermines, in their opinion, the reliability of the top-down method. Duarte et al. (2012) compute expenditure elasticity within household groups segmented by different characteristics. Segmenting by income introduces the most variability: expenditure-elasticity increases from 0.8 at the bottom of the income distribution to 0.9 at the top. Baiocchi et al. (2010, p. 63) found that in United Kingdom, income-elasticity as a function of income is U-shaped: 1.6 at the lowest household-type income, 0.6 at the national average income, 1.2 at the highest household-type income. On the contrary, in Brazil (Cohen et al., 2005, p. 560), expenditure-elasticity is bell-shaped, with a maximum at mid-income slightly under 1 (note that it is difficult to reconcile this piece of evidence with the overall expenditure-elasticity of 1.01 given by the same article). Much remains to be done in this area.

There is another limitation on our knowledge of the income-carbon footprint relationship. What can be termed the quality effect is the fact that the carbon footprint of a category may not be proportional to expenditure on this category. Going back to equation (1), the emissions (or more generally the environmental impacts) from product category i are assumed to be proportional to spending on it. If spending 30\$ on 4 shirts at 7.5\$ should emit 4 times as much as buying a 7.5\$ shirt, assuming that a 30\$ shirt emits 4 times as much as the 7.5\$ shirt is a limitation of the method, as noted early by Herendeen et al. (1981, p. 1441).

This assumption is acceptable when dealing with aggregate data, as the average spending on a category has the average carbon content of the category, but it is much more questionable when applied to specific consumers that may systematically differ from the average, as is the case when using household budget data to estimate the carbon footprint. When people spend more on a given category, they usually do not buy more of the same good, they also buy differently, changing to goods of a different quality. The general presumption is that higher quality, more expensive products have the potential to embody more labor and less energy, so that the carbon emitted per unit of expenditure in the same product category would actually decreases with the amount spent or the income of the consumer (Vringer and Blok, 1995, p. 901). The case of organic food is also telling (Hertwich, 2005, p. 4681): it is precisely because it has less environmental impact that it is more expensive. Today, with the expansion of "green consumption", consumers usually pay a premium for goods that (allegedly) have less embodied emissions.

There are few studies that go beyond anecdotal evidence. Vringer and Blok (1997) found that the quality effect is positive for some consumption categories, and that this could lower the elasticity of energy requirements with respect to net income from 0.63 to something between 0.56 and 0.60. Girod and Haan (2010) made a thorough attempt to tackle the problem. They first estimate consumption in functional units, and they compute the emissions of the functional units thanks to a LCA database. They use the mean intensity of expenditure delivered by this first estimate to estimate emissions according to spending. Hence, their method based on expenditure is not based on EE-IO analysis, so that we could not tell the difference between a standard IO method and their method based on functional units. However they found that taking into account the quality effect has a major impact on elasticities: the (total) expenditure elasticity drops from 1.06 to 0.82 whereas the (equivalised) expenditure elasticity drops from 0.94 to 0.53. This is a much larger correction than the one found by Vringer and Blok (1997).

The research has only scratched the surface of the phenomenon and these results need to be confirmed by other studies, with different and similar methodologies. As it comes from the very methodology that computes carbon footprint and not from the way the relationship is summed up with numbers, this limitation is in my opinion much more serious than the previous one.

4.3 Measurement errors in household budget surveys

Estimating the distribution of carbon footprint among households relies significantly on Household Budget Surveys (HBS). They are prone to measurement errors that contaminate the statistics derived from them. Apart from the errors coming from inappropriate execution and supervision of the survey, the measurement errors are mainly revealed by discrepancy with other statistics, and especially with estimates from national accounts. It cannot be taken from granted that the latter is correct as national accounts are subject to errors too, and there must be no general presumption in favor of one estimate over the other. I discuss here the measurement errors following Deaton (2005) and Attanasio and Pistaferri (2016), insofar as they impact computing the carbon footprint and the income-carbon footprint relationship.

First, not every household agrees to participate in HBS, and the response rate is known to vary with socio-economic status: in particular, it roughly declines with income (rich people tend to comply less when asked to participate in such a survey). This unit non-response means that there will be less rich household in the survey sample than in the actual population. If the relationship between income or expenditure and carbon footprint were truly one with constant elasticity, selective undersampling of richer households would have no effect at all. If, compared to constant elasticity, the relationship bent upward, undersampling of high income would underestimate the elasticity; if the relationship bent downwards, it would overestimate it. We have little information on how income elasticity varies with income (see previous paragraph 4.2), so that the sign of the bias is a priori unknown but we can suspect that undersampling of top income would not strongly impinge on the income-carbon footprint relationship and specifically on estimates of elasticities. Unit non-response also poses problem for estimating the share of income (or expenditures, or carbon footprint) due to top incomes. A survey with a unit response rate that decreases with income, would underestimate the income accruing to top incomes (let's say the top 5%), but as it would also underestimate aggregate income, the effect on the income share of top incomes is ambiguous[17]. In the illustrative examples of Deaton (2005), the share of the top 5% can be underestimated or overerestimated depending on whether the observed variance is lower or higher than the true variance. Numerical tests show that introducing a cutoff for response (so that the support is truncated at the top) biases downward the share of top incomes. Under-representation of high incomes due to non-response seems not so much an issue for computing income-elasticity of carbon footprint, as it is for computing the cumulative share of carbon footprint of top-incomes.

Compared to private consumption from national accounts, HBS under-report expenditures. There is also differential underreporting of goods, as HBS capture more of the estimates from national accounts for some good categories than others. It can be explained by different scopes and methodologies in national accounts and HBS as well as measurement errors. For HBS, these may come from recall bias of surveyed households, as for infrequent and small purchases, but also deliberate underestimates (item non-response) for socially undesirable goods.

The discrepancy in the statistics impinges here mostly on the level of carbon footprint. Because of relative underreporting, the mean carbon footprint estimated from HBS will indeed generally be lower than the national mean estimated from national accounts. The consequence for the expenditure-elasticity is however not clear-cut. Because the carbon footprint is endogenously computed from expenditure data (recall equation (1)), measurement errors alters both sides of the equation estimating the expenditure-elasticity of carbon footprint. Underreporting diminishes both the estimated expenditures and the estimated carbon footprint and correcting for this should change the expenditure-elasticity only marginally. Isaksen and Narbel (2017, p. 160) found that the carbon footprint from HBS is on average 7% lower, nevertheless correcting for this does not change the expenditure-elasticity. Hardadi et al. (2020) introduce a correction for under-reporting but do not compare the elasticity with and without the correction.

Finally, there is also evidence that HBS under-report income, both at bottom (Meyer and Sullivan, 2017, 5.A) and at the top of the income distribution (Bee et al., 2015). These measurement errors found in the US, and that likely extend to other developed countries, are potentially more serious for estimations of the income-elasticity than the previous measurement errors were for expenditure-elasticity. No work has been done on this subject to my knowledge. Further investigations are however unlikely to reverse the main message of this survey and particularly that, in a given country and at a given time, income-elasticity of carbon footprint is lower than expenditure-elasticity of carbon footprint. There have indeed been recently considerable works on how measurement errors

[17]Fundamentally, as shown by Mistiaen and Ravallion (2003), assuming that non-response does not affect the support of the income distribution, this is because the Lorenz curve with non-response is steeper than the true Lorenz curve at origin and at unity, so that the Lorenz curves intersect at least once.

may change the picture of consumption inequality and income inequality (Attanasio and Pistaferri, 2016). Whereas early works suggest that consumption inequality was not rising in parallel with income inequality (e.g. Krueger and Perri, 2006), some works that try to correct the measurement errors have come to the conclusion that increase in consumption inequality have tracked increase in income inequality (e.g. Aguiar and Bils, 2015). This is still an active area of research and one cannot deemed the evidence settled. For our purpose, it is sufficient to notice that, whatever the stance taken, consumption inequality is always lower than income inequality[18]. So, even when contested corrections for measurement errors are introduced, consumption is still below income inequality. Given that there is consumption variability at a given income level, it means that consumption concentration is consequently further below income inequality. This is a strong indication that measurement errors do not change the fact that income-elasticity of expenditures is well below one, so that income-elasticity of carbon footprint stays below expenditure-elasticity.

5 Conclusion

The take-away messages of this survey have been repeated at multiple times: there is a large difference between expenditure-elasticity and income-elasticity of carbon footprint; our knowledge of carbon footprint, from cross-sectional analysis of carbon footprint of households within a country, shows that the expenditure-elasticity is generally below 1 but can be around 1; it does not support that the income-elasticity is equal to 1.

I have not attempted to give an estimate of income-elasticity supported by the data as this would require further specifications. Because of the differing and changing national circumstances, "the" income-elasticity of carbon footprint is always tied to a place and a period. It makes little sense to look for the "true" or "correct" income-elasticity without specifying these. Even then, the varieties of the methods and estimates preclude that research settles on a single value in the foreseeable future. The consequence for the top-down method is that it will continue to rely on shaky evidence.

Our journey has led to a recommendation and a suggestion. The obvious recommendation for those who implement the top-down method is to pay attention to the difference between expenditure-elasticity and income-elasticity. The suggestion is to add a variability unrelated to income to recover the full distribution of carbon footprint. One can stick to the standard top-down method while keeping in mind that, in this case, one deals with concentration of carbon footprint.

To conclude, I would like to add another two recommendations. The first one is to calibrate the elasticity of carbon footprint against data with similar national contexts. The elasticity of carbon footprint, whether relative to expenditure or income, is country-dependent and this should be reflected in the methodology as far as possible. I hope that the data gathered in this survey will make easier to do it.

The second one is to proceed in two steps to reconstruct the distribution of carbon footprint from the distribution of income. Instead of using an income-elasticity of carbon footprint, one could first derive the distribution of expenditure by using an income-dependent propensity to consume, and then derive the distribution of carbon footprint using an expenditure elasticity. The advantages of this two-step method are twofold. Regarding data accuracy, expenditure is more reliable as a determinant of carbon footprint, so that it makes more sense to have expenditure as the independent variable instead of income. This method would also disentangle the spending patterns of households and the

[18] See Figure 1. of Krueger and Perri (2006), and figure 1 in conjunction with table 3 in Aguiar and Bils (2015). See also appendix table A.1 to A.4 in Meyer and Sullivan (2017).

related carbon emissions on the one hand and the saving behavior on the other. Both are currently lumped together in the single parameter of income-elasticity although they can be investigated with different pieces of evidence and empirical data.

Income and expenditure play a different role in the responsibility of household for the GHG emissions due to their consumption. Whereas expenditure is tied to consumption and thus emissions, income not spent does not emit GHG in the perspective of the consumer responsibility. The stark difference between income-elasticity and expenditure-elasticity of carbon footprint, on which the article focuses, stems from the *fact* that saving rate increases with income and from the *premise* that emissions are accounted based on consumption. True, saving is related to investment (building a factory, opening a mine...) and investing emits, like all activities, but through the lenses of the consumer responsibility, the ultimate purpose of these emissions is the production of goods that will be consumed. These emissions should be put on the shoulder of those who consume the final goods, not to these who invest. Putting a zero-emission on saving is thus not an omission, it is the logical consequence of the responsibility principle chosen at the start, that attributed GHG emissions to the households because they benefit from them through their consumption. Adding emissions from saving, whatever they be, to the carbon footprint of households would be inconsistent under consumer responsibility.

Even if the literature has not followed this path so far, one is still free to explore other responsibility principles. The emissions thus allocated to households would not be so tied to expenditures. This would put the responsibility of households for GHG emissions into a completely different light and one could wonder how the relationship between income and responsibility for GHG emissions would look like under accounting principles different from consumption-based.

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A Estimation of elasticities from previous works

Some studies do not themselves report elasticity but data in them can be used to compute it. Generally speaking, I use a simple linear regression with a log-log specification to compute the elasticity, so that I do not control for household size. I review here the methods and the data for each study, going from the more precise to the less.

For Mach et al. (2018), Radomír Mach kindly computed the income-elasticity from micro-data at the household level, specifically for this survey. The dependent variable is total emissions of the household per person, and the independent variable is net monthly income per person, available from the Czech Consumer Expenditure Survey of 2010.

Only for Sager (2019), I was able to compute the elasticity from micro-data at the household level, thanks to the data set provided in the supplementary materials. I use expenditure (variable *cost*), after-tax income (*INC_ atax*, CO_2emissions (*CO2_f_ALL*) and GHG emissions for both year 1996 and 2009. I weight observations by the CEX analytical weights (variable *finlwt21*).

When possible, I use aggregate data at the level of household groups (usually income or expenditure deciles):

- For Herendeen and Tanaka (1976), I have used data in table 3 (a). My reanalysis of expenditure elasticity differs from the one of Wier et al. (2001), which report 0.85, and of Pachauri (2004), which reports 0.87. I have not been able to reproduce the former, the latter seems to be based on data disaggregated by household size (table 3 (c) - (f)). None reports income elasticity.

- For Roberts (1976), I use energy data from table 1 and reconstitute expenditure from energy intensity. I weight data points by the number of household.

- For Herendeen (1978), I use data from table 3 (p. 622). My estimates is the same as Wier et al. (2001) and Pachauri (2004).

- For Herendeen et al. (1981), I use data from table 3 (p. 1439, column average). I assume all data points have the same weight. This yields the same estimate as Pachauri (2004), while Wier et al. (2001) reports 0.78. With several controls, Herendeen et al. (1981) found 0.73.

- For Murthy et al. (1997a), per capita expenditure and emissions are from table 4 (p. 340). Data points are weighted by population from table 6, p. 342. Data from Murthy et al. (1997b) are similar but less precise and thus have not been used.

- For Parikh et al. (1997), per capita emissions data are from table 8 (p. 251) and per capita expenditure data from p.253. Data are weighted by population weights from Fig. 1 (p.240). I have been unable to understand where the differences from the two previous studies (done by the same people) come from.

- For Minx et al. (2009), I have used datapoints from Fig. 8. I was able to find only 60 datapoints out of 61, probably because of overlaps. I assume all datapoints carry the same weight.

- For Parikh et al. (2009), carbon footprints are from Fig. 3. Population weight are from Fig. 1. I have reconstructed expenditure per capita and disposable income per capita for each expenditure class and location from the SAM provided by Saluja and Bhupesh (2006), on which Parikh et al. (2009) rely.

- For Lenglart et al. (2010), I use GHG emissions per household per quintile of standard of living (equivalised income) from table 8, p. 114. They refer to (Accardo et al., 2009) for data on income and expenditure, where I found p. 83, table 1.a, data for disposable income per consumption units. Expenditures are available p.89-90 (text and figure 6).
- For Golley and Meng (2012), I use energy requirements and carbon footprints per income decile from table 2, income per income decile from table 4. I combine data about energy requirement with total energy intensity of expenditure from table 4 to recover the expenditure of each income class.
- For Gough et al. (2012), I use emissions per capita from table 11 and mean equivalised gross household income from table 14.
- For Ummel (2014), I use the mean carbon footprint per capita by income quintile (and top 2%) provided by Fig. 1. Unfortunately the mean income within income quintile are not reported. However, from the Lorenz curve for income drawn in Fig 2, I can read the share in total income of each quintile (as well as top 2%), which is proportional to the mean income of the quintile. This allows me to compute the elasticity from data at quintile level. Kartha et al. (2020) compute the income-elasticity from the Lorenz curves of both income and carbon footprint and found 0.65, a much higher value than my estimates (that are in line with other estimates for the United States). It is interesting to understand their error and where it comes from. While estimating the income-elasticity from the Lorenz curve for carbon footprint, they are mistaken it for the concentration curve of carbon footprint, actually assuming that there is no other sources of variability in the carbon footprint than income. This overestimates how much carbon footprint grows with income and thus overestimate the income-elasticity, which is what we observe.
- For Irfany and Klasen (2016), I use table 6 at the quintile level to regress emissions on total expenditure. Using per capita variables leads to slightly lower estimates of expenditure-elasticity.
- For Wiedenhofer et al. (2017), I use table S2 for carbon footprints and expenditure, as well as population for weighting data points. I have found 2007 income data in China Statistical yearbook 2008 (table 9-6 for urban households, table 9-23 for rural households), and 2012 income data in China Statistical yearbook 2013 (table 11-6 for urban households, table 11-22 for rural households).
- For Christis et al. (2019), I use carbon footprints from Fig 2(b), supplemented by expenditure and income from StatBel[19], as indicated by the authors.
- For Hardadi et al. (2020), I use data of emissions and income available in supporting information S3. Each data point represents an income group and is weighted by population. For the elasticity with respect to expenditures, this gives 1.06 when the estimate of the authors is 1.04.

For two studies, I does not have enough information to extract data points and run a proper extraction. I therefore provide a temptative estimate (indicated by $\simeq$ in Table 2) from two data points (this is equivalent to computing the slope of the line joining the two

[19]File “Dépenses moyennes par ménages selon les déciles de revenu 1999-2010”, available at `https://statbel.fgov.be/fr/themes/menages/budget-des-menages/plus`

points in log-log diagram) as the logarithm of the ratio of emissions values divided by the logarithm of the ratio of income (or expenditures) values.

- For Peet et al. (1985), I use Figure 2 to estimate the expenditure elasticity from the extreme points of the distribution of energy consumption per household. Peet et al. (1985, p.1199) considers that elasticity is close to 0.6, whereas (Wier et al., 2001) reports 0.4 – both in my opinion underestimate the elasticity.

- For Weber (1999), I use data points at 20 and 120 TDM /(HH.a) in Figure 9-14.

Some studies do not report mean income inside household classes so that even proposing a rough estimate is not possible. I was however able to derive an upper bound for the income elasticity:

- For López et al. (2016), I use data in figure 4 that reports carbon footprints per consumption unit per income classes from 2006 to 2013. Mean income is not reported, only the bracket of income classes. The first income class is income below 499 €, whereas the last is income above 5000 € (monthly). Assuming that all income in the first class are set at 499 € and all in the last class are at 5000 € will give an (admittedly large) upper bound for the income elasticity. Income-elasticity is here computed as the logarithm of ratios of carbon footprints divided by the logarithms (e.g. 5000/499 for the (underestimated) interdecile ratio of incomes). Depending on the year, values are in the range $[0.47, 0.54]$. I report 0.54 to be conservative.

- For Jones and Kammen (2011), I use data of Figure 2(a), which reports carbon footprints per income classes and household size. I use data from one person household as these deliver the steepest increase as a function of income. Mean income is not reported, only the bracket of income classes. I disregard data above $70,000 as expenditures for these income classes have been interpolated (using the last income class delivers a lower elasticity, hence it is a conservative choice). The first income class is income below $10,000, whereas the last is between $50,000 and $60,000. Assuming that all income in the first class are set at 499 and all in the last class are at $50,000 will give an (admittedly large) upper bound for the income elasticity. Income-elasticity is here computed as the ratio of the logarithm of interdecile ratios (e.g. 50000/10000 for the (underestimated) interdecile ratio of incomes).

- For Roberts (1976), I compute an upper bound on income elasticity by using first and last income reported as an upper bound and lower bound of the income of the first and last expenditure classes.

- For Duarte et al. (2010), I use emissions per consumption units from table 4. Using last and first income bracket delivers a low upper bound of 0.28. I use the income bracket 4650-4950, which has the lowest emissions per consumption units, to obtain a comfortable upper bound of 0.41. Note that the distribution of emissions per capita or per consumption unit is almost flat, suggesting that the elasticity is much lower.

- For Song et al. (2019), I use household carbon footprint from fig. 3a, with second and last income brackets. Using the first income bracket would have lowered the upper bound, so the number reported is conservative. Upper bound for elasticity of carbon footprint per capita is even lower (cf. fig 3b).

Tilov et al. (2019) estimate separately income-elasticity for direct energy (at 0.11) and embodied energy (at 0.47). The latter thus provides an upper bound on the income-elasticity of total (direct and embodied) energy requirements.

Kerkhof, Benders, and Moll (2009) and Wadeskog and Larsson (2003) report some data by income classes but there is not enough information to derive any elasticity.

References

Accardo, Jérôme, Vanessa Bellamy, Georges Consalès, Maryse Fesseau, Sylvie Le Laidier, and Émilie Raynaud (2009) — Les inégalités entre ménages dans les comptes nationaux, une décomposition du compte des ménages, in *L'économie française, comptes et dossiers, édition 2009*, pp. 77–101. Paris: INSEE.

Aguiar, Mark and Mark Bils (2015, September) — Has Consumption Inequality Mirrored Income Inequality?, *American Economic Review* ***105***(9), pp. 2725–2756.

Ala-Mantila, Sanna, Jukka Heinonen, and Seppo Junnila (2014, August) — Relationship between urbanization, direct and indirect greenhouse gas emissions, and expenditures: A multivariate analysis, *Ecological Economics* ***104***, pp. 129–139.

Attanasio, Orazio P. and Luigi Pistaferri (2016, May) — Consumption Inequality, *Journal of Economic Perspectives* ***30***(2), pp. 3–28.

Baiocchi, Giovanni, Jan Minx, and Klaus Hubacek (2010) — The Impact of Social Factors and Consumer Behavior on Carbon Dioxide Emissions in the United Kingdom, *Journal of Industrial Ecology* ***14***(1), pp. 50–72.

Bee, Adam, Bruce D. Meyer, and James X. Sullivan (2015) — The Validity of Consumption Data: Are the Consumer Expenditure Interview and Diary Surveys Informative?, in C. D. Carroll, T. F. Crossley, and J. Sabelhaus (Eds.), *Improving the Measurement of Consumer Expenditures*, Volume 74 of *National Bureau of Economic Research Studies in Income and Wealth*, pp. 204–240. Chicago: University of Chicago Press.

Browning, Martin and Annamaria Lusardi (1996) — Household Saving: Micro Theories and Micro Facts, *Journal of Economic Literature* ***34***(4), pp. 1797–1855.

Büchs, Milena and Sylke V. Schnepf (2013, June) — Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO2 emissions, *Ecological Economics* ***90***, pp. 114–123.

Chakravarty, Shoibal, Ananth Chikkatur, Heleen de Coninck, Stephen Pacala, Robert Socolow, and Massimo Tavoni (2009) — Sharing global CO2 emission reductions among one billion high emitters, *Proceedings of the National Academy of Sciences* ***106***(29), pp. 11884–11888.

Christis, Maarten, Koen Breemersch, An Vercalsteren, and Evelien Dils (2019, August) — A detailed household carbon footprint analysis using expenditure accounts - Case of Flanders (Belgium), *Journal of Cleaner Production* ***228***, pp. 1167–1175.

Cohen, Claude, Manfred Lenzen, and Roberto Schaeffer (2005, March) — Energy requirements of households in Brazil, *Energy Policy* ***33***(4), pp. 555–562.

Deaton, Angus (2005, February) — Measuring Poverty in a Growing World (or Measuring Growth in a Poor World), *The Review of Economics and Statistics* ***87***(1), pp. 1–19.

Donato, Monica Di, Pedro L. Lomas, and Óscar Carpintero (2015) — Metabolism and Environmental Impacts of Household Consumption: A Review on the Assessment, Methodology, and Drivers, *Journal of Industrial Ecology* ***19***(5), pp. 904–916.

Druckman, Angela and Tim Jackson (2009, May) — The carbon footprint of UK households 1990-2004: A socio-economically disaggregated, quasi-multi-regional input-output model, *Ecological Economics* ***68***(7), pp. 2066–2077.

Druckman, Angela and Tim Jackson (2016) — Understanding Households as Drivers of Carbon Emissions, in R. Clift and A. Druckman (Eds.), *Taking Stock of Industrial Ecology*, pp. 181–203. Cham: Springer International Publishing.

Duarte, Rosa, Alfredo Mainar, and Julio Sánchez-Chóliz (2010, January) — The impact of household consumption patterns on emissions in Spain, *Energy Economics* ***32***(1), pp. 176–185.

Duarte, Rosa, Alfredo Mainar, and Julio Sánchez-Chóliz (2012, May) — Social groups and CO2 emissions in Spanish households, *Energy Policy* ***44***, pp. 441–450.

Dynan, Karen E., Jonathan Skinner, and Stephen P. Zeldes (2004, April) — Do the Rich Save More?, *Journal of Political Economy* ***112***(2), pp. 397–444.

Fremstad, Anders, Anthony Underwood, and Sammy Zahran (2018, March) — The Environmental Impact of Sharing: Household and Urban Economies in CO2 Emissions, *Ecological Economics* ***145***, pp. 137–147.

Gill, Bernhard and Simon Moeller (2018, March) — GHG Emissions and the Rural-Urban Divide. A Carbon Footprint Analysis Based on the German Official Income and Expenditure Survey, *Ecological Economics* ***145***, pp. 160–169.

Girod, Bastien and Peter De Haan (2010) — More or Better? A Model for Changes in Household Greenhouse Gas Emissions due to Higher Income, *Journal of Industrial Ecology* ***14***(1), pp. 31–49.

Golley, Jane and Xin Meng (2012, November) — Income inequality and carbon dioxide emissions: The case of Chinese urban households, *Energy Economics* ***34***(6), pp. 1864–1872.

Gough, Ian, Saamah Abdallah, Victoria Johnson, Josh Ryan-Collins, and Cindy Smith (2012, March) — The Distribution of Total Greenhouse Gas Emissions by Households in the UK, and Some Implications for Social Policy, Working Paper CASE/152, London School of Economics, London.

Grubler, A. and S. Pachauri (2009, October) — Problems with burden-sharing proposal among one billion high emitters, *Proceedings of the National Academy of Sciences* ***106***(43), pp. E122–E123.

Hardadi, Gilang, Alexander Buchholz, and Stefan Pauliuk (2020) — Implications of the distribution of German household environmental footprints across income groups for integrating environmental and social policy design, *Journal of Industrial Ecology* ***n/a***(n/a).

Herendeen, Robert (1978, October) — Total energy cost of household consumption in Norway, 1973, *Energy* ***3***(5), pp. 615–630.

Herendeen, Robert and Jerry Tanaka (1976, June) — Energy cost of living, *Energy* ***1***(2), pp. 165–178.

Herendeen, Robert A., Charlotte Ford, and Bruce Hannon (1981, December) — Energy cost of living, 1972-1973, *Energy* ***6***(12), pp. 1433–1450.

Hertwich, Edgar G. (2005, July) — Life Cycle Approaches to Sustainable Consumption: A Critical Review, *Environmental Science & Technology* ***39***(13), pp. 4673–4684.

Hertwich, Edgar G. and Glen P. Peters (2009, August) — Carbon Footprint of Nations: A Global, Trade-Linked Analysis, *Environmental Science & Technology* ***43***(16), pp. 6414–6420.

Hubacek, Klaus, Giovanni Baiocchi, Kuishuang Feng, Raúl Muñoz Castillo, Laixiang Sun, and Jinjun Xue (2017, December) — Global carbon inequality, *Energy, Ecology and Environment* ***2***(6), pp. 361–369.

Irfany, Mohammad Iqbal and Stephan Klasen (2016, October) — Inequality in emissions: evidence from Indonesian household, *Environmental Economics and Policy Studies* ***18***(4), pp. 459–483.

Irfany, Mohammad Iqbal and Stephan Klasen (2017, October) — Affluence and emission tradeoffs: evidence from Indonesian households' carbon footprint, *Environment and Development Economics* ***22***(5), pp. 546–570.

Isaksen, Elisabeth T. and Patrick A. Narbel (2017, January) — A carbon footprint proportional to expenditure - A case for Norway?, *Ecological Economics* ***131***, pp. 152–165.

Ivanova, Diana, Konstantin Stadler, Kjartan Steen-Olsen, Richard Wood, Gibran Vita, Arnold Tukker, et al. (2016) — Environmental Impact Assessment of Household Consumption, *Journal of Industrial Ecology* ***20***(3), pp. 526–536.

Ivanova, Diana and Richard Wood (2020) — The unequal distribution of household carbon footprints in Europe and its link to sustainability, *Global Sustainability* ***3***, pp. e18.

Jones, Christopher M. and Daniel M. Kammen (2011, May) — Quantifying Carbon Footprint Reduction Opportunities for U.S. Households and Communities, *Environmental Science & Technology* ***45***(9), pp. 4088–4095.

Kakwani, N. C. (1977) — Applications of Lorenz Curves in Economic Analysis, *Econometrica* ***45***(3), pp. 719–727.

Kartha, Sivan, Eric Kemp-Benedict, Emily Ghosh, Anisha Nazareth, and Tim Gore (2020, September) — The Carbon Inequality Era: An assessment of the global distribution of consumption emissions among individuals from 1990 to 2015 and beyond, Joint Research Report, Stockholm Environment Institute / Oxfam.

Kerkhof, Annemarie C., René M. J. Benders, and Henri C. Moll (2009, April) — Determinants of variation in household CO2 emissions between and within countries, *Energy Policy* ***37***(4), pp. 1509–1517.

Kerkhof, Annemarie C., Sanderine Nonhebel, and Henri C. Moll (2009, February) — Relating the environmental impact of consumption to household expenditures: An input-output analysis, *Ecological Economics* ***68***(4), pp. 1160–1170.

Krueger, Dirk and Fabrizio Perri (2006) — Does Income Inequality Lead to Consumption Inequality? Evidence and Theory, *The Review of Economic Studies* ***73***(1), pp. 163–193.

Lenglart, Fabrice, Christophe Lesieur, and Jean-Louis Pasquier (2010) — Les émissions de CO2 du circuit économique en France, in *L'économie française, comptes et dossiers, édition 201.* INSEE.

Lenzen, Manfred (1998, June) — Energy and greenhouse gas cost of living for Australia during 1993/94, *Energy* ***23***(6), pp. 497–516.

Lenzen, Manfred, Christopher Dey, and Barney Foran (2004, July) — Energy requirements of Sydney households, *Ecological Economics* ***49***(3), pp. 375–399.

Lenzen, Manfred, Mette Wier, Claude Cohen, Hitoshi Hayami, Shonali Pachauri, and Roberto Schaeffer (2006, February) — A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan, *Energy* ***31***(2), pp. 181–207.

Liddle, Brantley (2015, March) — What are the carbon emissions elasticities for income and population? Bridging STIRPAT and EKC via robust heterogeneous panel estimates, *Global Environmental Change* ***31***, pp. 62–73.

López, Luis Antonio, Guadalupe Arce, Manuel Morenate, and Fabio Monsalve (2016) — Assessing the Inequality of Spanish Households through the Carbon Footprint: The 21st Century Great Recession Effect, *Journal of Industrial Ecology* ***20***(3), pp. 571–581.

Mach, Radomír, Jan Weinzettel, and Milan Ščasný (2018, July) — Environmental Impact of Consumption by Czech Households: Hybrid Input-Output Analysis Linked to Household Consumption Data, *Ecological Economics* ***149***, pp. 62–73.

Malliet, Paul (2020, January) — L'empreinte carbone des ménages français et les effets redistributifs d'une fiscalité carbone aux frontières, OFCE policy brief 62, OFCE, Paris.

Markaki, M., A. Belegri-Roboli, Y. Sarafidis, and S. Mirasgedis (2017, January) — The carbon footprint of Greek households (1995-2012), *Energy Policy* ***100***, pp. 206–215.

Meyer, Bruce D. and James X. Sullivan (2017, August) — Consumption and Income Inequality in the U.S. Since the 1960s, Technical Report w23655, National Bureau of Economic Research.

Miller, Ronald E and Peter D Blair (1985) — *Input-output analysis: foundations and extensions*, Englewood Cliffs: Prentice-Hall.

Min, Jihoon and Narasimha D. Rao (2018, December) — Estimating Uncertainty in Household Energy Footprints, *Journal of Industrial Ecology* ***22***(6), pp. 1307–1317.

Minx, J. C., T. Wiedmann, R. Wood, G. P. Peters, M. Lenzen, A. Owen, et al. (2009, September) — Input-Output Analysis and Carbon Footprinting: An Overview of Applications, *Economic Systems Research* ***21***(3), pp. 187–216.

Mistiaen, Johan A. and Martin Ravallion (2003) — Survey Compliance and the Distribution of Income, Technical Report Policy Research Working Paper 2956, World Bank, Development Research Group, Washington.

Murthy, N. S., Manoj Panda, and Jyoti Parikh (1997a, July) — Economic development, poverty reduction and carbon emissions in India, *Energy Economics* ***19***(3), pp. 327–354.

Murthy, N. S., Manoj Panda, and Jyoti K. Parikh (1997b) — Economic growth, energy demand and carbon dioxide emissions in India: 1990-2020, *Environment and Development Economics* ***2***(2), pp. 173–193.

Nässén, Jonas (2014, March) — Determinants of greenhouse gas emissions from Swedish private consumption: Time-series and cross-sectional analyses, *Energy* ***66***, pp. 98–106.

Oswald, Yannick, Anne Owen, and Julia K. Steinberger (2020, March) — Large inequality in international and intranational energy footprints between income groups and across consumption categories, *Nature Energy* ***5***(3), pp. 231–239.

Oxfam (2015, December) — Carbon emissions and income inequality, Technical briefing, Oxfam.

Pachauri, Shonali (2004, October) — An analysis of cross-sectional variations in total household energy requirements in India using micro survey data, *Energy Policy* ***32***(15), pp. 1723–1735.

Pachauri, Shonali (2007) — *An energy analysis of household consumption: changing patterns of direct and indirect use in India*, Dordrecht: Springer.

Pachauri, Shonali and Daniel Spreng (2002, May) — Direct and indirect energy requirements of households in India, *Energy Policy* ***30***(6), pp. 511–523.

Parikh, Jyoti, Manoj Panda, A. Ganesh-Kumar, and Vinay Singh (2009, August) — CO2 emissions structure of Indian economy, *Energy* ***34***(8), pp. 1024–1031.

Parikh, Jyoti K., Manoj K. Panda, and N.s. Murthy (1997, January) — Consumption patterns by income groups and carbon-dioxide implications for India: 1990-2010, *International Journal of Global Energy Issues* ***9***(4-6), pp. 237–255.

Park, Hi-Chun and Eunnyeong Heo (2007, May) — The direct and indirect household energy requirements in the Republic of Korea from 1980 to 2000–An input-output analysis, *Energy Policy* ***35***(5), pp. 2839–2851.

Peet, N. J., A. J. Carter, and J. T. Baines (1985, November) — Energy in the New Zealand household, 1974-1980, *Energy* ***10***(11), pp. 1197–1208.

Peters, Glen P. (2008, March) — From production-based to consumption-based national emission inventories, *Ecological Economics* ***65***(1), pp. 13–23.

Peters, Glen P., Jørgen Aasness, Nina Holck-Steen, and Edgar G. Hertwich (2006, November) — Environmental Impacts and Household Characteristics: An econometric analysis of Norway 1999-2001, in M. Charter and A. Tukker (Eds.), *Sustainable Consumption and Production: Opportunities and Challenges*, Wuppertal, Germany, pp. 137–150.

Piketty, Thomas (2014) — *Capital in the Twenty-First Century*, Cambridge, London: Belknap Press.

Piketty, Thomas and Lucas Chancel (2015, November) — Carbon and inequality: from Kyoto to Paris Trends in the global inegality of carbon emissions (1998-2013) & prospects for an equitable adaptation fund.

Reinders, A. H. M. E., K. Vringer, and K. Blok (2003, January) — The direct and indirect energy requirement of households in the European Union, *Energy Policy* ***31***(2), pp. 139–153.

Roberts, P. C. (1976) — Energy analysis in modelling, in I. M. Blair, B. D. Jones, and A. J. V. Horn (Eds.), *Aspects of energy conversion: proceedings of a summer school held at Lincoln College, Oxford, 14-25 July, 1975*, pp. 759–771. Oxford [u.a.]: Pergamon Pr.

Roca, Jordi and Monica Serrano (2007, June) — Income growth and atmospheric pollution in Spain: An input-output approach, *Ecological Economics* ***63***(1), pp. 230–242.

Sager, Lutz (2019, October) — Income inequality and carbon consumption: Evidence from Environmental Engel curves, *Energy Economics* ***84***, pp. 104507.

Saluja, M. R. and Yadav Bhupesh (2006, June) — Social accounting matrix for 2003-04, Technical report, Indian Development Foundation, New Delhi.

Seriño, Moises Neil V. and Stephan Klasen (2015) — Estimation and Determinants of the Philippines' Household Carbon Footprint, *The Developing Economies* ***53***(1), pp. 44–62.

Shammin, Md. R., Robert A. Herendeen, Michelle J. Hanson, and Eric J. H. Wilson (2010, October) — A multivariate analysis of the energy intensity of sprawl versus compact living in the U.S. for 2003, *Ecological Economics* ***69***(12), pp. 2363–2373.

Song, Kaihui, Shen Qu, Morteza Taiebat, Sai Liang, and Ming Xu (2019, December) — Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households, *Environment International* ***133***, pp. 105137.

Steen-Olsen, Kjartan, Richard Wood, and Edgar G. Hertwich (2016) — The Carbon Footprint of Norwegian Household Consumption 1999-2012, *Journal of Industrial Ecology* ***20***(3), pp. 582–592.

Tilov, Ivan, Mehdi Farsi, and Benjamin Volland (2019, May) — Interactions in Swiss households' energy demand: A holistic approach, *Energy Policy* ***128***, pp. 136–149.

Tukker, Arnold, Hector Pollitt, and Maurits Henkemans (2020, April) — Consumption-based carbon accounting: sense and sensibility, *Climate Policy* ***20***(sup1), pp. S1–S13.

Ummel, Kevin (2014, October) — Who Pollutes? A Household-Level Database of America's Greenhouse Gas Footprint, Working Paper 381, Center for Global Development, Rochester, NY.

Usher, D. (1987) — Income, in Palgrave Macmillan (Ed.), *The New Palgrave Dictionary of Economics*. London: Palgrave Macmillan UK.

Vringer, Kees and Kornelis Blok (1995, October) — The direct and indirect energy requirements of households in the Netherlands, *Energy Policy* ***23***(10), pp. 893–910.

Vringer, Kees and Kornelis Blok (1997) — Do Higher Incomes Pay More?: The Effect of Price-income Relations on the Direct and Indirect Energy Requirement of Households in the Netherlands, Technical Report NWS-97004, Department of Science, Technology and Society, Utrecht University, Utrecht.

Wadeskog, Anders and Maja Larsson (2003, December) — Households in the environmental accounts, Technical report, DG Environment and Eurostat.

Weber, Christoph (1999) — *Konsumentenverhalten und Umwelt: Eine empirische Untersuchung am Beispiel von Energienutzung und Emissionen*, Frankfurt am Main: Peter Lang.

Weber, Christopher L. and H. Scott Matthews (2008, June) — Quantifying the global and distributional aspects of American household carbon footprint, *Ecological Economics* ***66***(2), pp. 379–391.

Wiedenhofer, Dominik, Dabo Guan, Zhu Liu, Jing Meng, Ning Zhang, and Yi-Ming Wei (2017, January) — Unequal household carbon footprints in China, *Nature Climate Change* ***7***(1), pp. 75–80.

Wiedenhofer, Dominik, Manfred Lenzen, and Julia K. Steinberger (2013, December) — Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications, *Energy Policy* ***63***, pp. 696–707.

Wier, Mette, Manfred Lenzen, Jesper Munksgaard, and Sinne Smed (2001, September) — Effects of Household Consumption Patterns on CO2 Requirements, *Economic Systems Research* ***13***(3), pp. 259–274.

Zsuzsa Lévay, Petra, Josefine Vanhille, Tim Goedemé, and Gerlinde Verbist (2020, April) — The association between the carbon footprint and the socio-economic characteristics of Belgian households, Working paper 20.05, Universiteit Antwerpen, Herman Deleeck Centre for Social Policy, Antwerp.