Inequality, (re)distribution and luxury-taxation of international household energy and carbon footprints

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Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds

Sustainability Research Institute

School of Earth and Environment

June 2022

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Primary publications

Chapter 2 of this thesis has appeared as publication: **Oswald, Y.**, Owen, A. and Steinberger, J. K. (2020) ‘Large inequality in international and intranational energy footprints between income groups and across consumption categories’, Nature Energy. Springer US, 5(3), pp. 231–239. doi: 10.1038/s41560-020-0579-8.

The research and methods were conceived by Yannick Oswald, Julia K. Steinberger and Anne Owen. The analysis was carried out by Yannick Oswald with significant contributions from Julia K. Steinberger and Anne Owen. The first draft was written by Yannick Oswald. All authors wrote the final version of the paper.

Chapter 3 of this thesis has appeared as publication: **Oswald, Y.** et al. (2021) ‘Global redistribution of income and household energy footprints: A computational thought experiment’, Global Sustainability. doi: 10.1017/sus.2021.1.

The research was conceived by Yannick Oswald and Julia K. Steinberger. Research design and methods were conceived by all authors. The first draft was written by Yannick Oswald. The analysis was carried out by Yannick Oswald. All authors contributed to the final version of the paper.

Chapter 4 of this thesis is a paper draft ready for submission.

The research was conceived by Yannick Oswald. Research design and methods were conceived by Yannick Oswald with significant contributions from all authors. The analysis was carried out by Yannick Oswald. The first draft was written by Yannick Oswald. All authors contributed to the final version of the paper.

Additional publications

Millward-Hopkins, J. and **Oswald, Y.** (2021) ‘“Fair” inequality, consumption and climate mitigation’, Environmental Research Letters, 16(3). doi: 10.1088/1748-9326/abe14f.

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D. and **Oswald, Y.** (2020) ‘Providing Decent Living with Minimum Energy: A Global Scenario’, Global Environmental Change, 65, pp. 1–10. doi: https://doi.org/10.1016/j.gloenvcha.2020.102168.

Acknowledgments

I would like to thank my supervisors Joel Millward-Hopkins, Anne Owen, Diana Ivanova and Julia Steinberger. This PhD would not have been possible without their guidance. I learned a lot from all of them and their advice and critical eye has continuously improved this work. A special thanks I want to say to Julia Steinberger who hired me for this PhD position, therefore created the opportunity for all of the present work, believed in me and my work and encouraged me to believe in myself. Thanks to Julia for being an awesome supervisor as well as a brilliant mentor. There is *always* something new to learn from her. Thanks also to Joel Millward-Hopkins for many walks and inspiring discussions around inequality, history, the future and economic modelling. In addition, I would like to mention, and say thanks to, Thomas Schmickl from the University of Graz. He was not involved with this PhD, but he was the first Professor who encouraged me to pursue science and a PhD, even inspired me to do so, through his unparalleled teaching in system science and computational modelling, and I quite possibly would not have made the leap without him.

Further, I would like to thank all the members of the LiLi project for being a great team to be part of. I would also like to thank the entire Sustainability Research Institute as well as the School of Earth and Environment, and all involved colleagues, for providing a supportive and pleasant environment for PhD students. Thanks to Marta Baltruszewicz, Jefim Vogel, Elke Pirgmaier, Lukas Hardt, Paul Brockway, Dan O’Neill, Emmanuel Aramendia, Jaime Nieto Vega and Lina Brand-Correa for making office life enjoyable.

I am deeply grateful also to my parents who have supported me during ten years of university education and are always there for us. My father had a significant intellectual influence on me. He taught me abstract thinking and to see the big-picture. Both my parents taught me that it is most important in life to be a kind person. A big thanks also to my sister for always having an open ear and her support. Finally, I am forever grateful to Mary Eliza. Thank you for accompanying me through life and in particular through all the ups and downs of this PhD. Your support is invaluable, your presence irreplaceable.

Abstract

Climate change is caused predominantly by high-income countries, and by upper economic classes within countries, through high energy demand. After decades of political and economic failure to end fossil fuel dependence and reduce emissions through innovation on the supply-side and in energy efficiency, attention is now shifting towards the reorganization of energy demand. Here we contribute to this paradigm shift by identifying levers to reduce energy inequality, recompose energy demand and ultimately mitigate emissions and the climate crisis. Going beyond established measures of energy inequality, we analyse international household final energy footprints according to consumption purposes and classify consumption in terms of energy intensity and income elasticity of demand. We find that transport-related goods and services are very energy intensive, while also being luxury goods, disproving the long-standing assumption that household consumption automatically becomes greener and less resource-intensive with increasing income. Moreover, we introduce novel scenarios of global income redistribution and its impact on household final energy footprints. We find that the energy costs of greater equity are small. An equal income distribution also recomposes energy demand towards subsistence for a majority, contrasting with an unequal income distribution, which results in luxury energy demand for a wealthy minority. Finally, we integrate information on the distribution and purpose of consumption into an innovative carbon tax design targeting household consumption by differentiated tax rates — setting higher tax rates for luxuries and lower rates for necessities. We find that this differentiated design improves the progressivity of carbon taxes, even before revenue redistribution, and with no detriment to effectiveness when compared to traditional uniform carbon taxation.

Table of Contents

List of Tables

List of Figures

Abbreviations

BP	British Petroleum
BRICS	Brazil, Russia, India, China, South Africa
CBA	Consumption-based accounting
COICOP	Classification of Individual Consumption According to Purpose
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DLE	Decent living energy
EJ	Exajoule(s)
EU	European Union
GCD	Global Consumption Database
GDP	Gross domestic product
GHG	Greenhouse gas(es)
GJ	Gigajoule(s)
Gt	Gigatonne
GTAP	Global Trade Analysis Project
IEA	International Energy Agency
ISIC	International Standard Industrial Classification of All Economic Activities
MJ	Megajoule(s)
MRIO	Multi-Regional Input-Output Model
NATO	North Atlantic Treaty Organization
OECD	Organisation for Economic Co-operation and Development
PBA	Production-based accounting
PPP	Purchasing power parity
Std.	Standard deviation
UK	United Kingdom
USA	United States of America
yr	Year
°C	Degree Celsius
€	Euro *(currency)*
$	United States dollar *(currency)*

'*The main force pushing toward reduction in inequality has always been the diffusion of knowledge and the diffusion of education*.' — Thomas Piketty

1 Introduction

1.1 Prelude and overview

Adam Smith's 'The Wealth of Nations' is one of the most influential economics books of all time, if not *the* most influential one. Smith set in motion the modern belief in markets and capitalism by introducing the 'invisible hand' of supply and demand. It may come as a surprise that Adam Smith was deeply concerned with the distribution of income and wealth. He argued that the wealth of an economy should *not* be measured through the accumulation of affluence among a minority elite but through inclusion of the poor and the allocation of adequate income to them (Rasmussen, 2016; Walraevens, 2021). And while Smith regarded the super-rich and their luxury consumption as a kind of driving force to the economy, because consumption leads to industrial manufacturing and jobs, he also worried that high inequality leads to fetishization of the rich and disdain for the poor. The pursuit of luxury possessions he viewed critically because he feared they do not contribute enough to the well-being of the wider public and must be taxed progressively (Rasmussen, 2016).

Fast forward 250 years and despite radical technological and social revolutions, Smith's worries still constitute the very core of the 21st century challenges, including climate change and ecological breakdown. We do measure the success of our economies by aggregate GDP, knowing very well that most of it accrues to the already wealthy (Alvaredo et al., 2018a) and a lot of it emerges from harmful sectors rather than beneficial ones, while several beneficial ones, such as care work within families, go entirely unnoticed (Luxton, 1997). We do consume more materials and energy than ever before in history (Schaffartzik et al., 2014), with high-income nations consuming roughly ten times more material per capita more than low-income ones (Wiedmann et al., 2015). Yet, the poor, globally and within many countries, are not provided the necessary income let alone material and energy they require in order to satisfy basic needs (Kikstra et al., 2021).

This disparity in resource and energy use has become a much-studied phenomenon. In particular, inequality in carbon emissions has taken centre stage (Hubacek, Baiocchi, Feng, Sun, et al., 2017; Chancel, 2021). Anthropogenic emissions cause global warming which is a threat to human civilization and all other life on Earth. Progress on reducing emissions and transforming the energy system, however, has remained far too slow for achieving internationally agreed climate goals (Riahi et al., 2021).

Less work has been dedicated to energy inequality compared to carbon inequality. Energy research as a whole has overwhelmingly focused on technological innovation and solving the climate crisis through cheaper emission-free energy production. Social solutions, and in particular the reorganization of energy demand, have been largely neglected and only received significant attention recently (Shove and Walker, 2014; Creutzig et al., 2018) after decades of failure to end fossil fuel dependence.

Previous work on energy and carbon inequality has focused either on single countries (Herendeen and Tanaka, 1976; Herendeen, 1978; Bossanyi, 1979; Büchs and Schnepf, 2013; Wiedenhofer et al., 2017; Wu, Zheng and Wei, 2017) or on measuring energy and carbon inequality from an aggregate perspective without decomposing it according to the purpose of energy use (Podobnik, 2002; Steinberger, Krausmann and Eisenmenger, 2010; Lawrence, Liu and Yakovenko, 2013; Ivanova et al., 2015; Hubacek, Baiocchi, Feng, Sun, et al., 2017; Semieniuk and Yakovenko, 2020; Chancel, 2021). The contribution of this thesis is to quantify energy and greenhouse gas emission inequality of households across diverse countries, while incorporating a high degree of granularity with respect to the purpose of consumption and applying the novel data to redistribution and taxation models. In chapter two, I show how global energy disparities emerge from the distribution of energy across consumption purposes and income groups – thus also revealing opportunities to recompose energy demand. Going further, in chapter three, I propose a model of global income redistribution and study its effect on energy poverty as well as structural change in the energy system. Lastly, in chapter four, I integrate distributional data and information about the purpose of consumption into a model of carbon taxation for fair and effective climate policy.

Altogether, this thesis is motivated by recent advances and insufficiencies in energy and climate research, yet it also traces an arc to the roots of economics by studying the distribution of resources and how to (re)shape this for everyone’s well-being.

1.2 Literature review

1.2.1 A modern interest in inequality

Bill Gates once said '*It is better to be born today than 20 years ago, and it will be better to be born in 20 years than today*' (McCarthy, 2019). In other words, the future will be better than past or present — for anyone, anywhere. This statement represents not only an optimist's mind-set, but the widespread believe in social and economic progress under capitalism. For a long time, economic optimism seemed warranted. Since the advent of the industrial revolution, and especially after the Second World War, extreme poverty around the globe fell rapidly. In 2015, for the first time, less than 10% of the global population lived in extreme poverty, defined as living below $1.9 purchasing power parity (PPP) consumption expenditure per person per day (Beltekian and Ortiz-Ospina, 2018). Global economic growth between 1961 and 2009 was continuously positive and mostly between 2% and 4%. Surely *a rising tide lifts all boats* and eventually results in a prosperous life for everyone? The financial crisis 2008 ended the growth run and the world economy entered a recession. As a result, the unfettered faith in neoliberal capitalism was broken and many economists started questioning the entire system, including the distribution of income and wealth.

Of course, there had been prior work on income inequality. To name just a few examples, Milanovic (1996) pointed out that income inequality increased in Eastern Europe after the fall of the Soviet Union and Nolan (1986) described changes in the distribution of income in the United Kingdom (UK). Various inequality metrics were theoretically well-understood by that time (Dorfman, 1979; Cowell, 1980, 2009). The famous Gini coefficient was already invented in 1912 (Ceriani and Verme, 2012). Despite this, inequality never really occupied centre-stage in economics, and only played minor roles in fields like optimal taxation theory (Saez, 2001). No Nobel Memorial Prize for economics has ever been awarded related to the topic (as of January 2022), contrasting with four prizes for contributions to economic growth theory. The reasons for this long-term neglect are probably manifold, ranging from the above-mentioned capitalism-optimism nexus to limited data availability. Comprehensive data on the distribution of income is cumbersome to assemble and became easier to administrate with computers. Today, economic inequality is at the forefront of public and scholarly debate, and even on covers of textbooks for teaching economics (The CORE Team, 2022). The decisive turn probably came with impactful books like 'The Price of Inequality' by Joseph Stiglitz and with the data-driven science-epos 'Capital in the 21st century' by Thomas Piketty. Piketty assembled an unprecedented amount of data on income and wealth inequality across a range of countries from historic tax records. His main insight was that income inequality always rises when capital returns (*r*) are larger than the overall economic growth rate (*g*). He also describes empirical facts in detail. For instance, he shows that the share of national income going to the top decile in the USA went down after Second World War from

45% to 35% and then up again in 1980 from 35% to nearly 50% in the 2010s (Piketty, 2014). A similar U-curve over time is observed in Europe, although the recent spike is much less pronounced and only increased from 30% to 35% (Piketty and Saez, 2014). Subsequently, this data has been significantly extended in the World Inequality Report administered by Piketty's team at the Paris School of Economics. The report portrays income and wealth inequalities for nearly every country in the world. National income ratios between the top 10% and the bottom 50% range from ~5-10 in Europe to ~20-50 in Latin America and Africa (Chancel et al., 2022). National wealth inequality is even more severe than national income inequality. In the USA, the top 1% own 35% of the wealth, the bottom 50% only ~1% (Chancel et al., 2022). Considering the global level and income inequality, the top 10% earn more than 50% of the global income, the bottom 50% less than 10% (Chancel et al., 2022). Wealth inequality at the global level is extraordinarily high. The distribution of per capita wealth spans roughly 6 orders of magnitude from ~€PPP 10 to ~€PPP 10,000,000 and this does not yet include a proper description of the heavy tail. Compared to global income inequality, measured in per adult monthly income, where it is 4 orders of magnitude from circa €PPP 3 to roughly €PPP 35,000, this is substantially larger spread (Chancel et al., 2022). Notable is also that regional wealth inequality is largest in the Global South, specifically so in Africa and Latin America. For instance, in Europe the ratio of the top 10% wealth owners to the bottom 50% is ~60. In Latin America it is ~600 (Chancel et al., 2022).

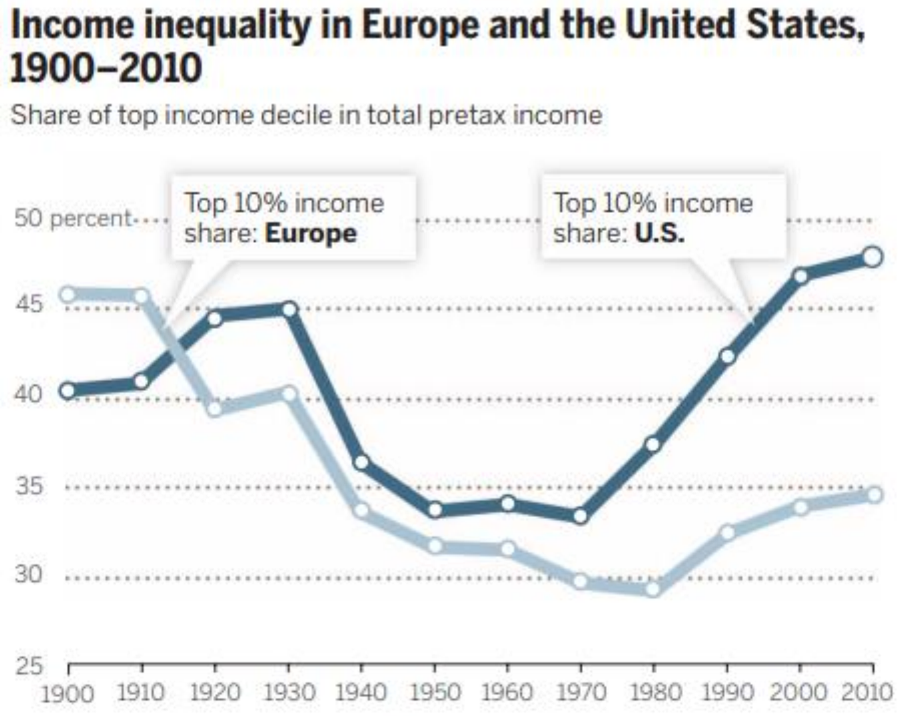


Figure 1-1: Income inequality in Europe and the United States
Notes: Adopted from Piketty and Saez (2014).

Piketty and his team rely on a ‘ratio-approach’ to measure inequality. They consider it best for revealing the true extent of inequality and highlighting the heavy tails of the distributions. However, it is useful to complement the picture by inequality data from other databases and including other metrics such as national and global Gini coefficients. There are several older (but still frequently updated) international income inequality databases and they do not fully agree on the exact degree of income inequality per country. There is, however, in more than 80% of countries a high correlation between income Gini coefficients across at least eight such databases (Ferreira, Lustig and Teles, 2015). The other databases include, for instance, the Luxembourg Income Study (LIS), which focuses primarily on high-income countries, as well as broad-coverage data-sets like the World Income Inequality Database (WIID) by the United Nations and the Standardized World Income Inequality Database (SWIID) maintained by Frederick Solt (Ferreira, Lustig and Teles, 2015). Significant differences between Piketty’s data and these databases include the primary data that they rely on (e.g. tax records vs. household surveys or secondary data and then imputation) and their method of construction (Ferreira, Lustig and Teles, 2015). For example, while Piketty’s team assembles data from tax records and constructs distributional accounts of pre-tax national income, the Luxembourg Income Study focuses on post-tax disposable income.

According to the World Bank, within-country income Gini coefficients range from ~0.25 to 0.55 in 2018 (World Bank, 2020). The Gini coefficient is lowest in Scandinavia and in high-income countries in Eastern Europe like the Czech Republic where it is 0.24. It is systematically highest across Latin America. For example, Mexico, Paraguay, Costa Rica, Colombia and Brazil all have Gini coefficients above 0.45. Its development over time varies considerably across countries and discussing drivers of inequality requires going beyond Piketty’s r>g formula. The theory is debated (Góes, 2016).

In any case, across all metrics, inequality is largest when measured internationally. The global Gini coefficient of income has been estimated to be between 0.6 and 0.7 (Anand and Segal, 2008; Milanovic, 2013). International inequality is also more persistent than often assumed in public debate (Hickel, 2019a). Apart from Asia, no Global South region is increasing its prosperity relative to the Global North. Sub-Saharan Africa is even falling further behind. For instance, the USA increased its GDP per capita by a factor of 1.6 from 1990 to 2019, Sub-Saharan Africa did so only by a factor of 1.3. In absolute numbers, the USA added another $PPP 22,000 to its GDP per capita, Sub-Saharan Africa only $PPP 880. This trend is depicted in Figure 1-2. The rapidly decreasing extreme poverty is at best an Asian success story, at worst it emphasizes a very weak notion of improvement.

Inequality makes us question how the economy distributes resources and their benefits. It is at least very questionable whether Bill Gates was right or ever will be. Will life be better for *anyone anywhere* in the future? How are improvements distributed? The distribution of income and wealth is by no means a perfect indicator for quality of life, but it does partly describe the unequal distribution of living standards. As a next step, I elaborate on the inequality in consumption which intends to measure the goods and services that people can access.

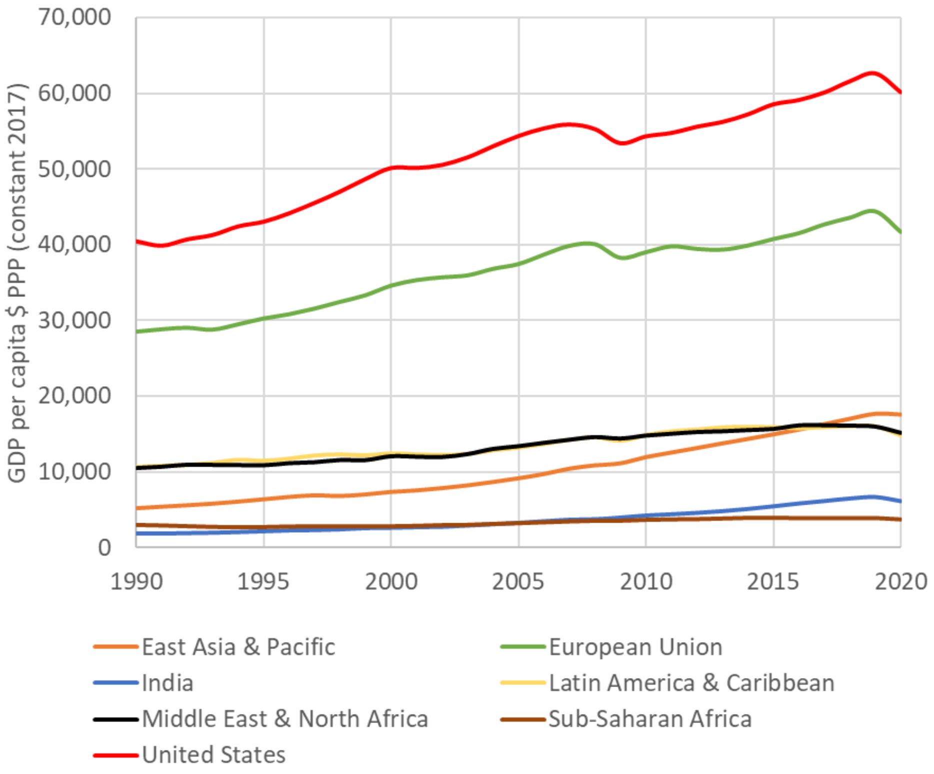


Figure 1-2: Regional evolution of GDP per capita
Notes: The underlying data is from the World Bank open repository (World Bank, 2022a).

1.2.2 Households and consumption inequality

Households do play an important role in the global economy. Within the discipline of macroeconomics, and within national accounting conventions, demand is segmented into three ‘sectors’, namely government spending, capital formation and household consumption. The fraction of a national economy these sectors constitute varies. For instance, in the USA household consumption makes up roughly 70% of GDP while in China it is less than 40% (World Bank, 2022c). In the USA, investments in infrastructure have decreased over the last decades (with the popular notion being that Americas infrastructure is crumbling, although in international comparison it is likely still in good shape (Lane, 2021)) and in China they have increased dramatically due to the Belt and Road Initiative and other massive infrastructural undertakings (World Bank, 2022b). From a global perspective, household consumption makes up ~60% of the entire economy and thus it takes a critical role in shaping ecological and social outcomes. Considering only size, it is arguably the most significant of all demand-side sectors. Another distinguishing feature of household consumption is that there is direct and high-quality evidence about its distribution based on consumer surveys. Distributional information on government spending and capital formation, on the other hand, while also clearly benefitting different populations to a different degree, is harder to obtain and requires relying on uncertain assumptions about the distribution of these resources according to income and wealth groups (Chancel, 2021).

Many national statistical offices maintain their own consumer surveys. For instance, one can readily access detailed household spending data for the USA, the UK, Japan and all countries in the European Union. The largest assembly of household consumption data however is probably maintained by the World Bank. The World Bank maintains two different types of household consumption data: On the one hand, there is data derived from national accounts, and on the other hand there is its Poverty Calculation unit (PovcalNet) based on household surveys. Both types vary in magnitude but are highly correlated. Household consumption in national accounts, as the World Bank maintains it, include the non-profit sector, consumption by institutionalized population and imputed rents (Milanovic, 2021). Consumption measured through consumer surveys on average constitutes 75% of the national accounts type (Milanovic, 2021). As a matter of fact, the data measured in PovcalNet is often referred to as disposable income. It is not entirely explicit whether the data corresponding to each country and income group represents only consumption expenditure, or also savings. This is due to the fact that the data is assembled through a mix of income statements and consumer expenditure surveys. In particular in terms of low- and middle income countries the data refers to consumption rather than income (Milanovic, 2021). Nevertheless, for the United States for instance, the average disposable income in the PovcalNet data closely matches official household expenditure data as well. So, if I refer to disposable income in the following, I am aware that this is close to consumption expenditure.

Importantly the World Bank uses purchasing power parity (PPP) to assess consumption. This is an international currency normed on the US-dollar and a specific consumption basket. The concept is meant to overcome price differences between different countries and allows comparing the *physical volume* of consumption from one place to another.

The World Bank uses this data to assess poverty, and also to quantify inequalities. Lakner and Milanovic analysed the global disposable income distribution based on PovcalNet. They first noted the global Elephant Curve of disposable income growth (Lakner and Milanovic, 2016). The Elephant Curve illustrates how incomes have grown for different percentiles of the global distribution. The lowest 10% experienced cumulative growth of less than 40% between 1988 and 2008. The lower global middle class (10th percentile to 80th percentile) experienced high cumulative growth of up to 80%. The upper middle class (80th percentile to 99th percentile) has been squeezed the most with very low growth rates ranging from barely over 0% to 30%. The top 1% global income earners experienced cumulative growth of nearly 70%. In absolute numbers, this elephant shape implies a substantial gulf between the trajectory of the global top 1% and the rest of the world (Hickel, 2019b). The pattern also has been replicated by Piketty's team employing national income data (Alvaredo et al., 2018a).

Through the PovcalNet data we can observe for instance that the lowest 70% in the USA are significantly poorer than the lowest 70% in Norway but the richest 30% are richer than in Norway. Further, we can observe that the lowest 90% of households in the Czech Republic are richer than the lowest 90% of households in Brazil. Yet the top 10% in Brazil are significantly richer than the top 10% in Czech Republic. This data is a milestone in the history of poverty and inequality assessments since it allows evaluating living standards in a distributional manner and in great comprehensibility across almost all nations on earth. A major limitation of the PovcalNet consumption data is that we do not know *what* people actually consume – and this turns out to be a decisive question.

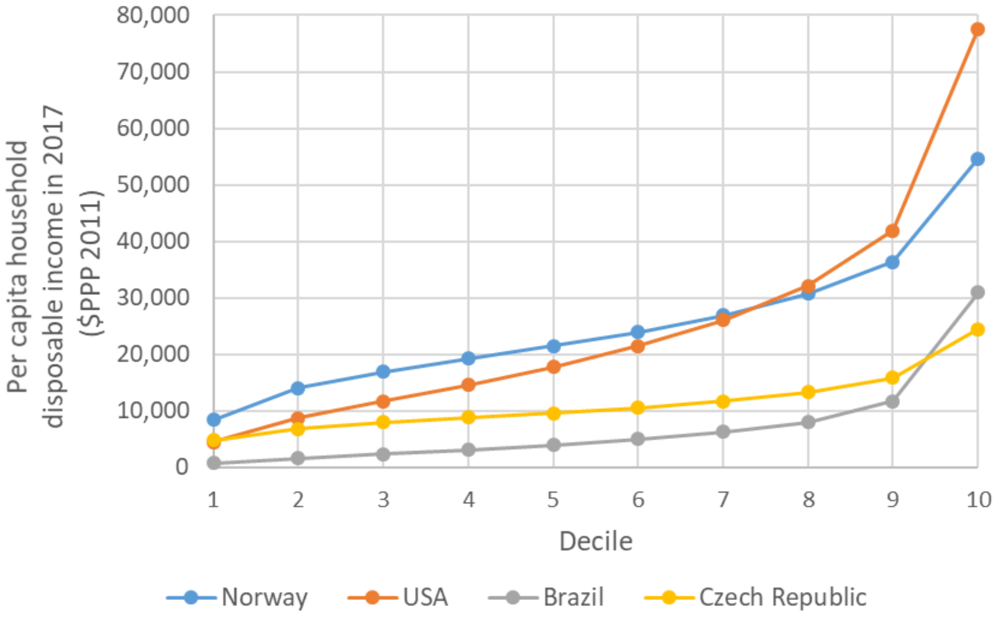


Figure 1-3: Within-country inequality in selected countries
Notes: The underlying data is from the open PovcalNet repository (PovcalNet, 2021).

In some national and regional databases on household consumption, consumption is segmented according to the Classification of individual consumption by purpose (COICOP) (SCB Statistics, 2010). For example, Eurostat, a European data agency, maintains data on consumption by purpose for 28 countries in five-year intervals (so for instance 2005, 2010, 2015). This is an advantage compared to the PovcalNet data, because we can observe what things people buy at different incomes. How is consumption shaped by available income? What do people need even if they have little income, and what do they buy if they have a lot of financial leeway?

Purpose-structured consumption data is rare for the Global South. Nevertheless, also here the World Bank is one of the institutions that made efforts towards closing that gap. For instance, they assembled the publically available Global Consumption Database which is a detailed collection of household consumer surveys representing the year 2010 for 91 countries (World Bank, 2018). One exemplary insight based on this data is how spending per capita on road and air transport in India varies across four different income groups. Road transport scales modestly with income group, while for air transport the three lowest income groups consume virtually nothing and the highest income group spends ~$PPP 1600 per year on flights.

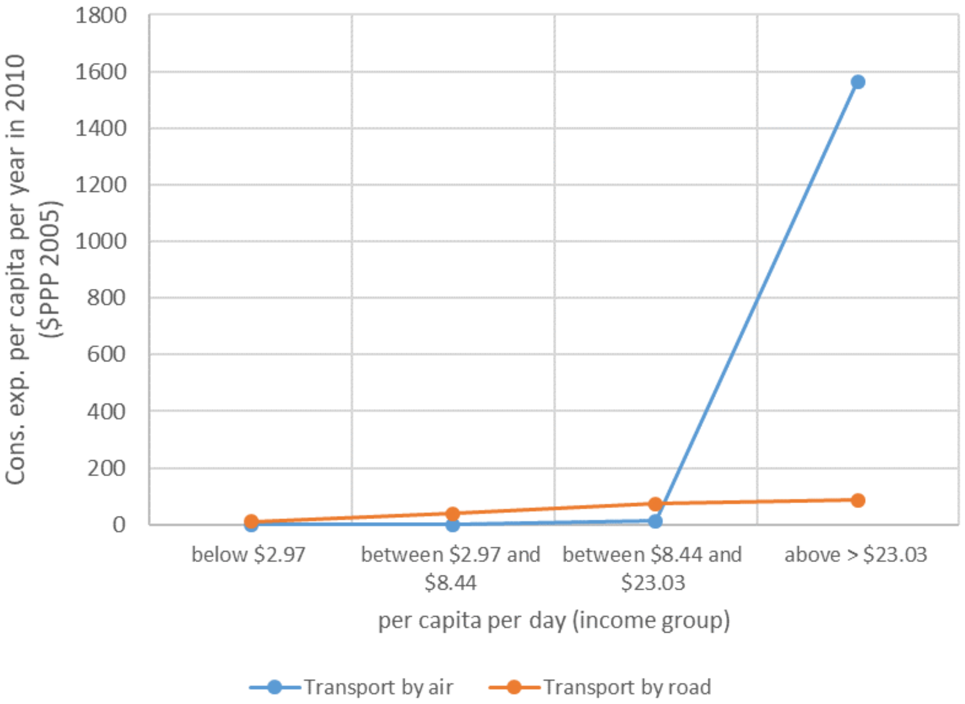


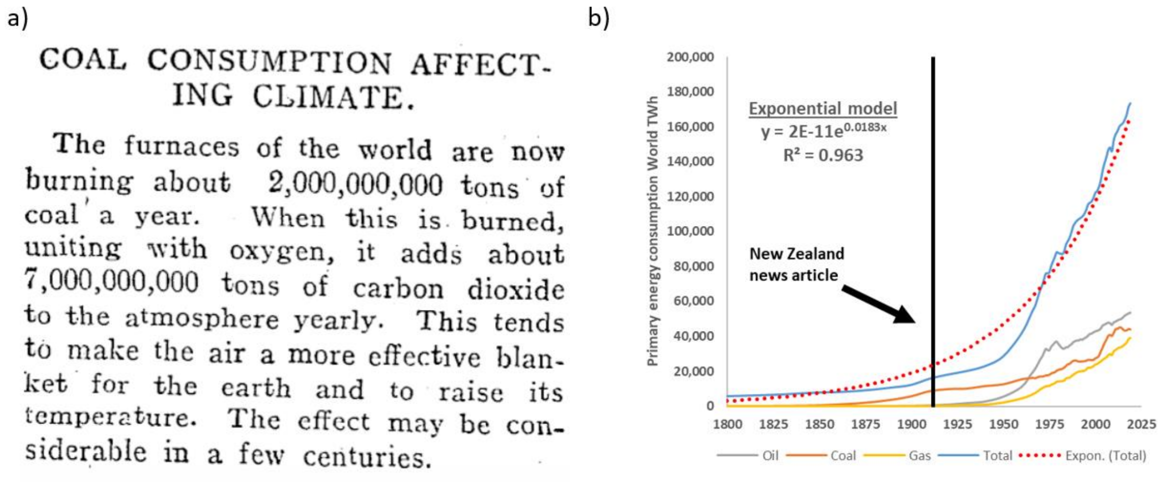
Figure 1-4: Per capita spending on road and air transport in India
Notes: The underlying data is from World Bank (2018).

This case illustrates that spending across income groups varies dramatically, and that it is not only important to know the sum of expenditure but also about the consumption purposes. Not every dollar spent is the same in terms of benefit gained nor in terms of environmental impact. Therefore, ecological economists investigate the environmental impacts of household consumption. I elaborate on this field in section 1.2.4.

1.2.3 Climate – the ultimate constraint to economics in the 21st century

Economics is the science of decision-making under constraints. Paradoxically, societal decision-making under environmental constraints receives little attention in the predominant neoclassical paradigm. The classical economists like Adam Smith and David Ricardo considered the resource of land as a factor of production, but they were little concerned with the consequences of its use. In the early 20th century, economists began to question whether unabated exploitation of the environment could continue (Gray, 1914; Hotelling, 1931). The Hotelling rule, for example, determines an optimal pathway to use resources so that resource rents are maximized across time without exploiting them too early. Clearly, this is far from the notion of sustainability brought forward by, for example, the Brundtland report, 50 years later. However, it represents one of the first instances in which elementary resource constraints to economics are acknowledged and has since been many times applied to energy resources (Loeschel et al., 2020). In the 1960s, with the advent of Ecological Economics, and in particular Nicholas Georgescu-Roegen's book on 'The Entropy Law and the Economic Process', energy and materials were recognized as the fundamental inputs to- and limits of the economy. Georgescu-Roegen emphasized that economic activity constitutes merely a transformation process of what is already present in the environment (Georgescu-Roegen, 1971). Eventually, energy availability and quality will degrade as posited by the laws of thermodynamics.

Despite these insights, environmental constraints were hardly the focus of economic research (externalities yes, but ultimate constraints not so much, Ecological Economics remained a niche) – until climate change began to receive considerable attention. The Greenhouse effect was already hypothesised in the early 19th century (Fourier, 1827), confirmed by late 19th century (Arrhenius, 1896), and by the beginning of the 20th century it was relatively clear what the use of fossil fuels implies for average temperatures. For example, there was already climate change reporting in newspapers in 1912 (Figure 1-5 (a)), yet this marked only the beginning of enormous fossil fuel expansion as Figure 1-5 Panel (b) illustrates.



a)

COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

b)

Figure 1-5: Climate news in 1912 and world energy consumption
Notes: The article in Panel (a) originally appeared in the magazine ‘Popular Mechanics’ but in less concise printing. This version is from a New Zealand newspaper (Rodney and Otamatea Times, 1912). Panel (b) shows global primary energy consumption over time and the data is from Roser and Ritchie (2022).

Today, we know that global warming is linearly proportional to carbon dioxide (Matthews et al., 2009). The contributions of other greenhouse gases continues to be an active field of research, but their radiative forcing properties are mostly well understood (Rogelj et al., 2014). Every trillion tonnes of carbon dioxide add roughly half a degree Celsius of average global surface temperature (IPCC, 2021). It is also consensus that there are severe consequences, especially in high warming scenarios (>2 °C). Already today, at ~1.2 °C warming there are frequent extreme-weather events and human catastrophes attributable to climate change. Sea-level rise is one of the widely known effects. There is also a global increase in heatwaves and heat intensity, as well as in heavy rainfall (IPCC, 2021).

Further, it remains an open question if climate tipping points could be triggered, which would cause additional devastating warming. Some climate scientists argue that these tipping cascades are ‘*too risky to bet against*’ and warming absolutely needs to be limited to below 1.5 degree (Lenton et al., 2019).

Economists have been estimating the impact of global warming on the economy since the 1970s (Nordhaus, 1977). Nordhaus estimated that controlling emissions excessively will result in large costs but little benefit. Even though since then he has updated his models and even considers climate tipping posts, he has moved little from the position that the social costs of carbon are smaller than the costs of rapidly decarbonizing the economy (Nordhaus, 2019). Other economists are more cautious about the uncertainty of climate outcomes induced by tipping points and calculate higher social costs of carbon (Dietz et al., 2021), thus urging a more rapid departure from fossil fuels. Yet again others argue that economists gravely misunderstand how the climate will impact the economy and denounce the concept of the social costs of carbon and how they are integrated in future GDP estimates (Keen, 2020).

A more pragmatic approach originated in climate science and is also more widely applied by ecological economists. Because we know the relationship between climate and emissions with respectable certainty (tipping points aside), we also know how many tonnes of emissions are left until we reach a certain amount of global warming — this is the idea of carbon budgets (Meinshausen et al., 2009). The best estimate is that 300 $GtCO_2$ are left from 2020 onwards if warming is to be limited to 1.5 °C warming with 83% probability and 900 $GtCO_2$ to 2 °C (IPCC, 2021).

The carbon budgets represent a strict constraint on global emissions. If global emissions are limited, so are emissions of countries and specific groups within. This implies direct policy relevance. I will elaborate on the following in the next section, but richer countries generally emit more than low-income countries and the same goes for high-income vs. low-income groups within countries. Given the budget constraints, this evokes a debate around equity and justice: Should certain countries or groups be allowed to consume more of the carbon budget left than others? The short answer is no. The long answer takes history into account.

Given that, historically, some countries have contributed a lot more to emissions than others, the carbon budget allocation needs to be organized accordingly (Hickel, 2020). From this perspective, large emitters like the USA or the UK are owed much less of the remaining budget than other nations. However, even if remaining historically neutral, the large inequality in emissions necessitates redistribution. For instance, it has been shown that an increase of prosperity of the poorest to $2.97-$8.44 consumption per day requires substantially faster emission mitigation to stay within the 2 degree budget than without poverty eradication (Hubacek, Baiocchi, Feng and Patwardhan, 2017). Economic development now bumps into the carbon budget constraint, even though recent studies also show that extreme poverty can be eradicated with very little additional carbon emissions (Bruckner et al., 2022). In any case, globally the top 10% income earners emit between 35% and 50% of all emissions, so reducing their emissions would set free development for the poorest (Chancel and Piketty, 2015; Hubacek, Baiocchi, Feng and Patwardhan, 2017; Chancel, 2021; Bruckner et al., 2022). Moreover, it has been shown that allocating total global emission budgets on an equal per capita basis requires redistribution from highest emitters to lowest emitters (Chakravarty et al., 2009). If we were to allocate the remaining 1.5-degree budget (from 2020), for example, on an equitable per capita basis and assume constant population, every person had a budget of 38 tonnes carbon dioxide left. For the average American this would last barely 3 years, for the average Nigerian 62 years (territorial emissions). This is obviously not a feasible solution and requires reduction of American emissions, while there is leeway to increase Nigerian emissions and improve living standards.

Therefore, climate is in a way the ultimate constraint to economic activity this century. Since carbon budgets have been introduced, it is certainly the most pressing and the energy transition is a global priority (as well as reducing emissions from other sources such as animal agriculture). Of course, there are other generic environmental constraints and problems in the world. And new economic schools build on this. For instance, Doughnut economics considers all planetary boundaries which, next to emissions, includes land use, biodiversity loss, chemical pollution and more (Raworth, 2017). But none has so far evoked as much discourse around allocation of economic resources, equity and a fair transition as climate change has.

1.2.4 Carbon and energy footprints of households and inequality

The idea that human activity leads to environmental impact is not brand new. Early during the 19th century it already gained traction, but the concern was mainly with the size of the human population (Malthus et al., 1803). In the second half of the 20th century the focus shifted to the decomposition of impact-drivers into population, economic activity and technology used (Commoner, 1971; Ehrlich and Holdren, 1971; Meadows et al., 1972; Nordhaus, 1977; Dietz and Rosa, 1997). This trend towards a more nuanced analysis and higher granularity continued. Two major methodological innovations, which unfolded over several decades, were to consider impact by different groups of people with a focus on income groups (Herendeen, 1978; Weber and Matthews, 2007), and to adjust data for international trade in order to reveal the impact of globalization and characterize the role of countries within the global economy (Leontief, 1970; Peters and Hertwich, 2006).

Adjustment for international trade is now a popular approach, known as consumption-based accounting (CBA) in input-output analysis or more colloquially as footprint accounting. The definition of 'footprint' has an intricate history and deserves some attention before diving deep into CBA. Initially the term 'ecological footprint' was conceived by Mathis Wackernagel in the 1990s for a more public-facing description of his work on the 'appropriation of ecological carrying capacity' (Wackernagel et al., 1999). Subsequently in the 2000s, a whole family of 'footprints' emerged, including energy, water, materials and carbon (Fang, Heijungs and De Snoo, 2014). For instance, the term was adopted by the oil and gas company British Petroleum (BP) to refer to the carbon footprint of individuals (Wiedmann and Minx, 2007). BP's definition includes all daily activities, so for instance how much emissions are caused by running a washing machine or taking the car to work. Today, this focus on individuals by BP is criticized and considered a marketing strategy to divert attention from the fossil fuel industry's responsibility for climate change (Solnit, 2021). In any case, the precise concept of (carbon and energy) footprint is contingent on the system boundaries chosen (Wiedmann and Minx, 2007). There are manifold contributions in terms of life-cycle analysis for specific products , for instance, exhibiting high variation of system scope (Draucker et al., 2011).

Most importantly for our purposes, the term is associated with environmentally extended input-output analysis and in particular the sub-category 'consumption-based accounting'. Input-output analysis is a Nobel-prize winning mathematical framework by Wassily Leontief (Leontief, 1936). The approach is about conceiving the economy as a comprehensive accounting table of sectors and what they exchange. Multi-Regional Input-Output analysis (MRIO analysis) is perhaps most interesting because countries are related by a complex network of trade relationships. The core idea of input-output analysis is that economic output can be modelled as a function of final demand (Owen, 2017). The consumption of households makes up a significant share of this final demand (~60% globally as mentioned above). To implement this model, one considers that the exchanges between sectors and the sales to final demand can be recorded in a 'transaction matrix'. This transaction matrix can be transformed into a so called 'technology matrix' or 'requirements matrix' by considering how much of total input of a sector is delivered by one transaction with another sector. By employing linear algebra, this technology matrix can be transformed into the so-called Leontief inverse L. The elements of L can be interpreted as a multiplier of how supply reacts to demand, or as the number of supply chain stages involved in one production process (Miller and Blair, 2009; Owen, 2017). Leontief himself also introduced the environmental extensions (Leontief, 1970). The idea of the environmental extensions is to associate a certain quantity of resource input with each production stage in the economy and compute how resource-intensive final demand is.

Input-output tables can be used to conduct CBA or the contrasting approaches production-based accounting (PBA) and territorial accounting of resource use. 'Production-based' means that resources are accounted, like the name implies, at the production stage of the economy. For example, with respect to the United Kingdom (UK) and CO_2, it accounts for all the CO_2 emitted within UK-borders regardless of whether the produced goods and services are also consumed within the UK or elsewhere. A consumption-based perspective, on the other hand, accounts for all the CO_2 that is emitted within the supply chain behind a certain type of final consumption. It does not matter whether this CO_2 is emitted within the UK or in China. As long as the end-product is consumed in the UK, it is accounted for as UK CO_2 emissions. There is a technical difference between territorial and production-based accounting too. Territorial emissions is the accounting framework required by the 'The United Nations Framework Convention on Climate Change (UNFCCC)' and refers to emissions within national jurisdictions but does not include international aviation and shipping bunkers while production-based accounting does so (Barrett et al., 2013). Clearly, the difference to consumption-based emissions is of more fundamental nature.

Consumption-based accounting has been used to assess material footprints (Wiedmann et al., 2015; Teixidó-Figueras et al., 2016), water footprints (Zhang and Anadon, 2014; Ali et al., 2018) as well as land and ecological footprints (Hubacek and Giljum, 2003) and is widely applied to calculate carbon footprints. For example, it has been shown that in Norway, where national electricity production is relatively low-carbon through a substantial fraction provided by hydropower, 60% of all CO_2 emissions are imported (Peters and Hertwich, 2006). Globally, studies demonstrated that 22-23% of all CO_2 emissions were traded in the early 2000s (Peters and Hertwich, 2008; Davis and Caldeira, 2010) but also that this share had been steadily growing from 20% in 1990 to 26% in 2008 (Peters et al., 2011). Attention soon shifted to understanding carbon footprints as a function of affluence and the distribution across consumption purposes (Hertwich and Peters, 2009; Ivanova et al., 2015). Peters and Hertwich for instance demonstrated that the cross-national expenditure elasticity of carbon footprints is ~0.8 (referring to GHG not just CO_2) (Hertwich and Peters, 2009). They also found that food accounts for 20% of GHG emissions, residences 19% and mobility 17%. The UK stands out being the subject of a large number of carbon footprint studies which also include time-series analysis. These studies reveal that the gap between CBA and PBA of emissions in the UK is widening, with the CBA footprint being 60% larger than the PBA one in 2009 (Druckman and Jackson, 2009; Barrett et al., 2013).

CBA also has been used extensively to assess *carbon inequality* that is the distribution of carbon footprints across income groups. Robust associations between emissions and income have been found for example for the UK (Büchs and Schnepf, 2013), China (Wiedenhofer et al., 2017) and the USA (Weber and Matthews, 2007). Furthermore, the literature also includes a significant number of international, regional and global assessments. Large inequality in household carbon footprints has been identified in Europe (Ivanova and Wood, 2020) and globally including many developing and emerging economies (Chancel and Piketty, 2015; Hubacek, Baiocchi, Feng, Sun, et al., 2017; Chancel, 2021). It has been shown for instance that national expenditure-carbon elasticities vary around the world from roughly 0.5 to 1.5 (Hubacek, Baiocchi, Feng, Sun, et al., 2017).

In Europe the top 1% of households have a carbon footprint of more than 40 tCO_2e/capita and the bottom 50% only 4 tCO_2e/capita (Ivanova and Wood, 2020). Globally the largest carbon footprints per capita are greater than 100 tCO_2e/capita and the smallest less than 1 tCO_2e/capita (Hubacek, Baiocchi, Feng, Sun, et al., 2017). Newest data indicates that the top 1% of emitters emit ~17% of emissions and the bottom 50% only ~12% (Chancel, 2021). However, these global estimates include capital formation and government expenditure. In short, carbon footprints extend economic inequalities to environmentally relevant dimensions.

Energy footprints received less attention in recent decades. This is probably due to the fact that climate change emerged as the predominant constraint to the economy as discussed in section 1.2.3 and scientific analysis consequently focused directly on emissions. Nonetheless, accounting of embodied energy has considerable history (Roberts, 1978; Costanza and Herendeen, 1984) also triggered by the oil crises of the 1970s and by awareness that energy supply chains are vulnerable (Heun, Owen and Brockway, 2018). For instance, in the 1970s Robert A. Herendeen calculated the embodied energy of products and services in the USA and Norway and also how this energy scales as a function of affluence (Herendeen and Tanaka, 1976; Herendeen, 1978). Lenzen (1998) calculated primary energy intensities for Australian final demand employing CBA and found that industrial sectors like steel and manufacturing are the most energy intensive sectors. Primary energy requirements of household consumption were assessed for India too, finding that energy is evenly split between direct and indirect energy use and that energy demand increased by 25% in one decade (1984 to 1994) (Pachauri and Spreng, 2002).

One critical aspect when talking about input-output analysis for energy accounting is *what type of energy consumption vector* is associated with the different production stages. Energy consumption can be measured at different stages (Duro and Padilla, 2011). There is the primary energy stage, which accounts for energy consumption before transformation and transmission, in contrast to the final and useful energy stages. Primary energy gives a larger weight to fossil fuels, especially to coal and gas in the electricity sector, because fossil fuels accumulate efficiency losses along the way from production to the end-use. When coal is burned for electricity, only 30% to 45% of the energy stored in the coal actually becomes electricity (Fu et al., 2015). Renewables, in contrast, often exhibit only marginal efficiency losses. Wind turbines and solar cells generate electricity directly, there is no combustion process and no heat to electricity transformation. Most importantly, primary renewable energy, as it is currently defined refers to the energy produced, but not to the energy available in the natural environment. For instance, it accounts for the total energy produced by solar cells, but not for the total energy that sun light delivers per square meter. Final energy accounts for the energy which the end-consumer obtains. In the case of a car, this refers to refined petroleum before combustion but in the case of electricity from coal this is after combustion and transmission. For renewable energy, primary and final energy are nearly indistinguishable and only differ by transmission losses. Final energy accounting is closer to end-use energy services (Fell, 2017) than primary energy. However, some energy economists suggest that this final energy stage is still too far from representing energy services accurately, and refer to useful energy instead (Aramendia et al., 2021). Useful energy is the amount of energy that is actually useful to the end-consumer, after *all kinds* of efficiency losses. For example, useful energy in the process of driving (in a combustion engine car) refers to the energy converted into motion, after combustion of petroleum *and* after friction losses. Useful energy is harder to estimate (Heun, Owen and Brockway, 2018; Aramendia et al., 2021) than final energy and The International Energy Agency comprises data for nearly every country in terms of final energy, but not in terms of useful energy.

When it comes to input-output analysis the choice of energy vectors depends on the research question (Owen et al., 2017). For studying extraction and upstream questions (for instance: How much coal is mined globally to satisfy energy needs in the UK?) primary energy accounting is more appropriate, while for downstream and demand-oriented questions final energy is likely the better choice (for instance: How much energy does the chemical industry in Germany use? Or how much energy do German households use?).

Final energy and input-output accounting was applied to identify 'key sectors' (or key energy consumers) in industry (Alcántara and Padilla, 2003). However, primary energy continues to be applied in some end-use studies such as the energy requirements of households (Wiedenhofer, Lenzen and Steinberger, 2013). There are several contributions that calculate national energy footprints or energy embodied in trade (Lenzen, Dey and Foran, 2004; Kok, Benders and Moll, 2006; Park and Heo, 2007) and a few global perspectives (Chen and Chen, 2011; Chen et al., 2018) but, in contrast to carbon footprints, inequality rarely has played an explicit role. If affluence was of concern it was limited to associations between energy consumption and annual expenditure or income, but did not quantify inequality (Lenzen, Dey and Foran, 2004; Cohen, Lenzen and Schaeffer, 2005). For example, Cohen, Lenzen and Schaeffer (2005) found that the energy intensity of household consumption in Brazil *increases* with rising expenditure, but they did not quantify how energy is distributed across the population.

There is a strand of literature that quantified energy inequality using territorial accounting across countries, but not CBA or the household level (Podobnik, 2002; Banerjee and Yakovenko, 2010; Lawrence, Liu and Yakovenko, 2013). For instance, Podobnik (2002) found that the global Gini coefficient of energy consumption oscillates around 0.5 over time and that the world average energy consumption is only 20% of average US energy consumption. Energy inequality also has been studied by statistical physicists seeking to explain inequality as a universal property across many scales and systems (Banerjee and Yakovenko, 2010). It has been demonstrated that energy consumption per capita is exponentially distributed in 2010 and in line with that over time the distribution of primary energy consumption across countries tends towards a Gini coefficient of 0.5 — the Gini coefficient corresponding to an exponential distribution (Lawrence, Liu and Yakovenko, 2013). The physicists hypothesized that this is a 'natural' outcome of partitioning global energy resources because it maximizes entropy. This hypothesis is however being challenged by economists who argue that this not an invariant natural law but rather a feature of accounting conventions (Semieniuk and Weber, 2020). Nevertheless, this work yielded valuable distributional insights. The top 10% energy consumers consume ~35% of the total energy, the bottom 50% only little more than 10%.

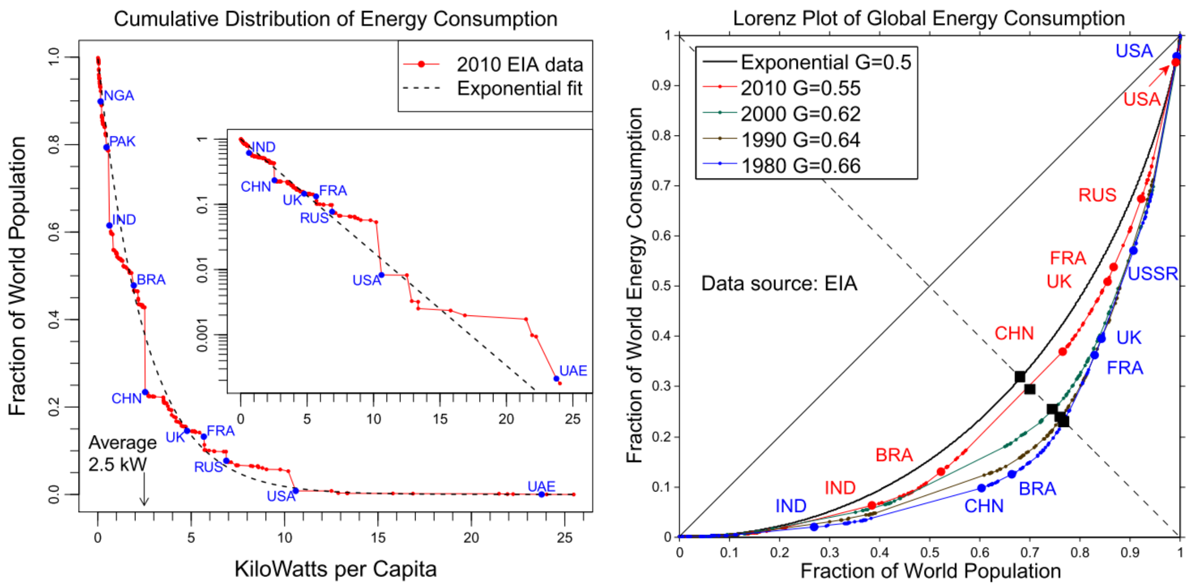


Figure 1-6: Global energy inequality from a primary energy and territorial perspective
Notes: Adopted from Lawrence, Liu and Yakovenko (2013).

Lastly, it is important to highlight a few 'meta-properties' of the consumption-based approach. As explored, CBA refers to resource accounting adjusted for international trade. While correct, this denotation understates the full substantive consequences. First, from an analytical and ontological perspective, it implies an acknowledgement of the network character of the global economy (Chen et al., 2018) and therewith falls in line with the generic and long-term shift of science towards recognizing the importance of high connectivity among elements and to view the economy as a complex adaptive system. A consumption-based perspective on energy flows and energy inequalities recognizes that what happens in one place (for instance the consumption of a good somewhere in Western Europe) has potentially large consequence somewhere far away (for instance a coalminer in India dying prematurely of pollutant-induced lung disease). This spatial interconnectivity has been termed 'telecoupling' (Fang et al., 2016). The awareness of spatial interconnectivity is related to the awareness of temporal dependencies in the wider sustainability sciences (and in intergenerational welfare economics to be fair) which aim to 'provide for current generations without sacrificing opportunity for future generations' (Brundtland, 1987). Both, space and time dependency, shine light on history and path-dependency. For instance, consumption in the Global North evidently appropriates resources from the Global South (Kanemoto, Moran and Hertwich, 2016). This hints at the unequal trade relationships between hemispheres. And trade relationships are indeed shaped by colonial path-dependencies or neo-colonial structures (Subrahmanyam, 2006; Bhambra, 2020). The take-away is that the consumption-based view allows to see how resource use is distributed around the globe for the benefits of certain groups complementing the structure-blindness of the production-based view.

This is not to say that CBA does not have any blind spots. CBA emphasizes the end-consumer. This perspective bypasses, for instance, the responsibility of industries and in particular large, often multi-national, companies who set consumption trends with the products they offer and hence induce demand. Another critique is that CBA might be incompatible with feasible politics because politicians and laws have limited or no control over embodied resources (Afionis et al., 2017) (except of course reducing consumption).

1.2.5 Human needs, energy and emissions

Energy may not only be seen as a resource input to the economy. Social science also has studied the relationship between energy and society from different points of view. Notably, Leslie White proposed that energy is the driving force behind cultural evolution (White, 1943). He summarized that relationship in a simple equation $C = E*T$ where C is culture, E the quantity of energy used and T the technological efficiency of energy used. Cultural evolution is understood as some progression of technological, social and ideological standards. Today, this thesis is problematic from many view-points including anthropological ones and ecological ones. For instance, the idea that 'more is always better' is obviously not true from a sustainability point of view, nor are judgements about the 'progressiveness' of a society based on the amount of energy and technology used necessarily sensible. After all, industrialized Western nations use most energy at the most efficient rates yet contribute the most to environmental pressures — an arguably immoral and egoistic undertaking (Jia et al., 2017) (and this is just one of many questionable instances). Further, one can find societies with incredibly complex social and political systems, but very simple technologies (Wengrow and Graeber, 2015).

Nevertheless, energy continues to be seen as a vital input to social functions. Shove and Walker for instance argue to view energy from a social practice perspective (Shove and Walker, 2014). They argue that energy is essential to all kinds of social practices (i.e. human activities). They differentiate between different kinds of daily practices and from an energy policy point of view argue to scrutinize them for their potential to change and reduce energy demand. This contrasts with the intent of solely using new technology to support the same practice with less energy.

An extended approach has been taken by Brand-Correa and Steinberger. They build on human needs theory, specifically inspired by Manfred Max-Neef, and adopt an eudaimonic perspective on human needs (Brand-Correa and Steinberger, 2017). This means that human needs are assumed to be universal and invariant across space and time but that need satisfiers can vary. Need satisfiers are the things that one can make use of to satisfy a need, for example, take a train to work instead of driving, or engage in the neighbourhood to attain a feeling of belonging instead of going on an expensive holiday and posting pictures to Instagram for gratification. Need satisfiers have a certain energy requirement, and thus choosing specific need satisfiers is directly relevant for energy and ecological outcomes. The perspective dovetails with Shove and Walker because the focus is on changing social functions for reducing energy throughput and thereby mitigating ecological crisis (Brand-Correa et al., 2020).

Another complementary approach has been taken by Rao to estimate how much energy and emissions are required to enable 'decent living standards' (Rao and Baer, 2012; Rao and Min, 2018a). Earlier there had been similar attempts in terms of energy, usually employing top-down methods (Max-Neef, 1995; Steinberger and Roberts, 2010), demonstrating that quality of life indicators saturate as a function of energy use of nations. Rao's work is a bottom-up approach and estimates how much energy or emissions are embodied in the material foundations that people need. This approach builds on earlier work by Goldemberg et al. (1985). It utilises a CBA perspective, in that it calculates the resource inputs to certain 'goods and services' people need, but it turns the research question on its head: whereas CBA investigates given consumption patterns, Rao's decent life approach *defines* what consumption patterns *could* be and only then calculates the resource requirements (Rao and Min, 2018a).

From this line of research, it is evident that the energy threshold for decently high living standards is substantially lower than industrialized economies consume on average. Rao estimates that decent living energy significantly depends on location. For instance in India it is only between 10-15 GJ/capita/year but in Brazil it is around 25GJ/capita/year (Rao, Min and Mastrucci, 2019). When accounting for uncertainty across technological efficiency, socio-economic organization, geographical conditions, and taking several studies into account, the range of plausible decent living energy is somewhere between 10 – 50 Gigajoule per capita per year (GJ/capita/yr). For comparison, the average American consumes ~200 GJ/capita/yr (based on IEA final consumption data via territorial accounting and population for 2019 (International Energy Agency, 2022)).

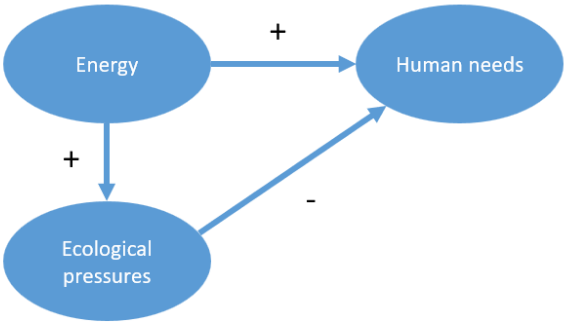


Figure 1-7: Simplified relationship between energy and human needs
Notes: The figure illustrates a key lesson from the science on energy and society. Energy is crucial in order to satisfy human needs and improve quality of life. But its overconsumption causes ecological damage which eventually impairs quality of life. Moreover, the positive relationship between energy and human needs exhibits diminishing returns. The shape and temporal evolution of the other relationships in the diagram is less clear but their existence is broadly accepted.

Our best proxy for contemporary real-world need satisfaction across a range of socio-economic groups is household consumption. Measuring household consumption of goods and services to assess standards of living has a long empirical tradition in economics (Zimmerman, 1932) and is rooted in the classical theory of the household. However, the approach is highly controversial in light of above discussed human needs theory. According to human needs theory, needs are not just a set of preferences that can be satisfied by consuming specified quantities of tangible goods, but include social intangibles like ‘participation’, ‘freedom’ and ’interacting’, which all exist in a complex interdependent web of needs (Brand-Correa and Steinberger, 2017). It remains necessary however to make the pragmatic assumption that investigating household consumption and embodied resources covers a fraction of needs large enough to explore not only the distribution of energy, but also the distribution of need satisfaction.

1.2.6 Redistribution of energy and emissions

Quantifying inequality in energy and emissions and declaring it unsustainable is not enough. With policy in mind, we need to understand how to reduce energy and emission inequalities and also what consequences different degrees of inequality have.

1.2.6.1 Scenarios of energy and emission redistribution

In section 1.2.3, I discussed that climate change and in particular carbon budgets necessitate redistribution of emissions and since emissions are 75% an energy problem (Ritchie and Roser, 2022), the same logic applies to energy. The relationship between human needs and energy strengthens this argument further. We know that quality of life indicators saturate as a function of energy and emissions (Steinberger and Roberts, 2010; Steinberger et al., 2012) and also that a minimum level of energy is a critical component of achieving good social outcomes. Consequently, if many people consume energy below the decent level and at the same time many people consume well-beyond benefit-saturation levels, energy consumption is sub-optimally distributed (not to mention unfairly distributed).

Chakravarty and Tavoni (2013) modelled the global distribution of household final energy demand. The results are not perfectly appropriate to assess thresholds, like Rao's decent living thresholds or Goldemberg's 1 Kilowatt society, because the distribution is given in discrete and coarse intervals, and not as a continuous function. Chakravarty and Tavoni projected this distribution from 2009 to 2030 (coloured areas in Figure 1-8 Panel (a) illustrate the change) and also queried what would happen if an energy floor of 10 GJ/capita/year were achieved. Total global energy requirements would only change by 7% and this can be offset by a 15% reduction of energy use by all people living above average European energy consumption levels. An eye-catching result is that if we consider a modestly higher energy floor, like Goldemberg's ~30GJ/capita, the fraction of the population not achieving decent living energy is extremely large (~5 billion people which makes ~72% in 2009). This implies that the necessary degree of redistribution is very sensitive to the floors chosen. Chakravarty et al. (2009) proposed a model estimating the implications of redistributing emissions. Here the question studied was how many people must reduce their emissions and by how much to achieve pre-Paris climate targets. The targets were not properly specified at the time, so they opted for 30 $GtCO_2$ in 2030. According to this scenario, this requires 13 $GtCO_2$ reduction in total and only the highest 15% of emitters must contribute. Their emissions must be capped at 10.8 tonnes CO_2. This change is depicted in Figure 1-8 Panel (b) (blue area). If, additionally, a global emissions floor of 1 tonne CO_2 per capita is introduced, it changes results modestly to a cap of 9.6 tonnes CO_2 and only a slightly larger fraction of the total high emitting population has to contribute. It does however also imply a significant improvement in access to material goods for the lowest 2.7 billion emitters.

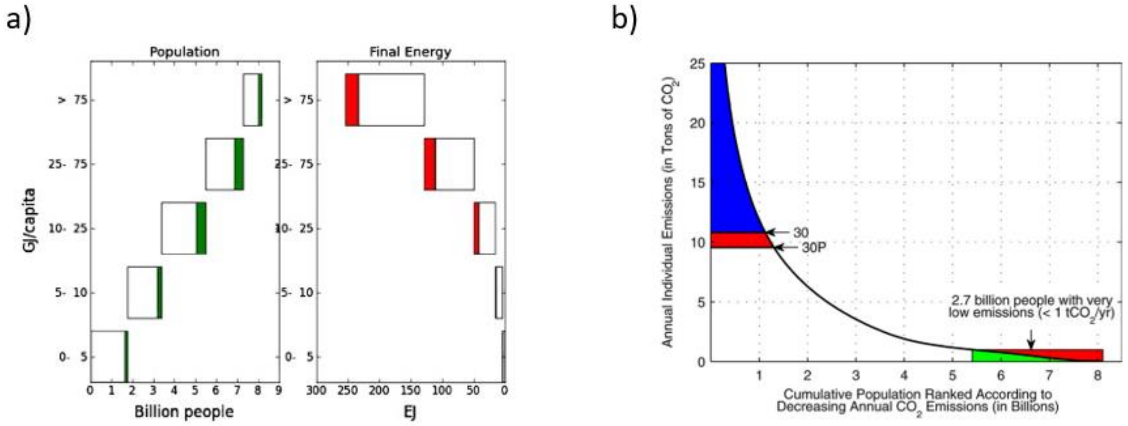


Figure 1-8: Global redistribution scenarios of energy and emissions by Chakravarty et al.
Notes: Panel (a) is adopted from Chakravarty and Tavoni (2013). Panel (b) is adopted from Chakravarty et al. (2009).

These scenarios are purposefully constructed so that inequality of emissions and total emissions reduce, but they do not necessarily represent an accurate relationship to *economic inequality*. Rao and Min in contrast elaborate on this point by probing different income elasticities of emissions and energy as well as considering distinct income inequality scenarios derived from the Shared Socio-Economic Pathways (SSPs) (Rao and Min, 2018b). They do two things: First they change economic inequality given a constant elasticity between energy and income (0.7) and observe the effects. Second, they keep economic inequality constant and change the elasticity from 0.7 to 1. In the first case, they demonstrate that decreasing inequality aggressively within countries (reducing the Gini coefficient from 0.55 to 0.30) would maximally increase energy use and emissions by 8%. The increase happens because the income-energy relationship is concave, so a saturating function. Hence low-income groups consume more energy relative to their income. In the second case, they estimate how overall global energy consumption grows over time as a function of global GDP under different elasticities. One key insight is that if the energy-income elasticity is equal to one, then in a trajectory to 2050 the world will experience massive growth in energy and emissions. If the elasticity is limited to 0.7, future energy and emissions will be substantially lower. Therefore, the relationship between energy and income (or emissions and income) is an absolutely critical parameter not just for distributional outcomes but also for future trajectories under economic growth.

With these scenarios they provide an argument complementary to previously established results. Some economists tested the relationship between income inequality and emissions econometrically and found a trade-off between inequality and total emissions – lower inequality implies higher total emissions (Ravallion, Heil and Jalan, 2000). The contribution of Rao and Min is an upper bound to this trade-off which is a 8% increase within countries and globally and as they note '*smaller than energy efficiency potential of extremely low hanging fruit like replacing light bulbs*'.

The literature on explicit redistribution scenarios of energy and emissions remains a minor niche and merits further contribution.

1.2.6.2 Policies for energy and emission redistribution

None of the above scenarios studies policies to achieve redistribution of energy and emissions. We know from section 1.2.4 that energy and emissions strongly scale with income and consumption of households. Therefore, an a priori conclusion is that reducing economic inequalities reduces energy and emission inequalities. The literature on redistribution in economics is vast, especially in terms of optimal tax design of wealth, income and consumption. For the sake of brevity, I only give a very broad outline of this literature before moving on to considerations originating from climate economics and ecological economics.

In economics there is one strand of literature studying people's preferences for redistribution (Corneo and Grüner, 2002; Bénabou and Tirole, 2006; Olivera, 2015; Starmans, Sheskin and Bloom, 2017). This literature emphasizes that there is a great diversity of beliefs about 'fairness'. For instance some studies conclude that the USA and Europe, which are often perceived as different models of capitalism due to different degrees of government intervention and redistribution, can both be fair with respect to these beliefs (Alesina, Angeletos and Cozzi, 2005). Fundamental enquiries into the nature of fairness and the corresponding formalization are also part of economics. For example, in 'Fair division and collective welfare', Moulin reviews four principles of distributive justice (compensation, reward, exogenous rights, and fitness) and demonstrates how assuming each one of them in formal models yields different conclusions for how to redistribute resources (Moulin, 2003).

Within economics, the most prominent study of redistribution is likely found within the field of optimal taxation theory, with its focus on income and consumption. Mankiw, Weinzierl and Yagan (2009) provide a comprehensive historical overview. According to them, seminal results were the taxation theory of Ramsey (1927) and that of Mirrlees (1971). Ramsey faced the problem of how to maximize consumption tax revenue without destroying functioning markets and supply, so he derived the result that the optimal tax on consumer goods is inversely proportional to the consumer elasticity of demand. The higher the elasticity, the lower the tax. The lower the elasticity, the higher the tax (Ramsey, 1927; Mankiw, Weinzierl and Yagan, 2009). This way consumers do not forego demand even when facing high tax rates and businesses do not lose revenue. Mirrlees' contribution is at the heart of the equity-efficiency trade-off. The idea is that if income taxes for high incomes are too high, people are discouraged to put in a lot of effort for earning this income and hence overall the dynamism and efficiency of the economy decreases. They also summarize stylized facts (heavily debated stylized facts) of optimal taxation theory such as that 'final goods ought to be taxed uniformly' or 'capital income ought to be untaxed'.

In ecological economics, and in the degrowth school, there are proposals for more radical redistribution policies. For instance minimum and maximum caps on income and wealth are frequently mentioned (Buch-Hansen and Koch, 2019). However, Buch-Hansen and Koch warn that while there is an argument for such measures in an ecologically constrained world, these need to be carefully considered and democratically implemented rather than top-down imposed. Otherwise resistance to- and flight from these measures (for instance through emigration to other countries) are probable outcomes (Buch-Hansen and Koch, 2019).

Turning to climate and energy economics, the most prominent policy approach is carbon taxation. It is not motivated through redistribution but through carbon abatement. Carbon taxes are essentially

Pigouvian taxes (Edenhofer, Franks and Kalkuhl, 2021). The purpose of carbon taxation is to internalize the social costs of carbon, or in other words to internalize the externalities caused by burning fossil fuels through a carbon price. While not a redistributive policy, the distributional implications of carbon taxes have been investigated a lot (Speck, 1999; Wang et al., 2016; Edenhofer, Franks and Kalkuhl, 2021; Malerba, Gaentzsch and Ward, 2021; Steckel et al., 2021). Because carbon taxes affect consumption including necessities like heating and fuel for driving, they face barriers to acceptance and their impacts have been found to be regressive in high-income countries. In scientific scenarios, as well as political plans, these barriers are overcome through different forms of revenue recycling which is an empirically proven but context-dependent approach (Beiser-McGrath and Bernauer, 2019). Revenue recycling can be conducted through, for example, lump-sum transfers which make the tax most often progressive. There are also cases where carbon taxes are found to be progressive before revenue recycling including low- and middle income countries as well as few instances in high-income countries (Beck et al., 2015; Dorband et al., 2019). Overall, carbon taxes are interesting in terms of redistribution because of their substantial and varied distributional implications.

In response to the 1992 Rio de Janeiro climate conference, the philosopher and ethicist Henry Shue fundamentally criticized comprehensive attempts at regulating and reducing emissions. He argued that considering any '*common-sense notion of justice'*, it makes no sense to apply the same carbon regulations to 1) rich countries and poor countries (a point which also has been made by Global South scholars around the same time already see for example (Agarwal and Narain, 1991)) and 2) to purposes across the board where some are more related to basic needs and others to luxuries. He suggests that choosing a least-cost rationale for carbon abatement only makes sense if you compare identical items or circumstances. To quote him literally: *'What if, to be briefly concrete, the economic costs of abandoning rice paddies are less than the economic costs of reducing miles-per-gallon in luxury cars? Does it make no difference that some people need those rice paddies in order to feed their children, but no one needs a luxury car?'* - (Shue, 1993).

This critique goes against much of the mainstream economic approach. Shue argues the mainstream has abstracted *preferences* and *utility* too much from concrete day-to-day situations. The homeless person who craves shelter for the night and the wealthy financier who would like to invest capital-returns into a boat both reveal their preferences and they both increase utility. Yet the judgement that the former is more necessary than the latter is clear under a common-sense notion – but not so often in economic models. Shue also elaborates on the question of *who must pay for what.* According to him, if wealthy individuals would pay for the carbon abatement costs incurred by the poor, then it would be fair to start with the least-cost option. However, since this not generally the case, the purpose-driven argument remains.

A related argument has been made by Ian Gough. Gough argues that the since the impact of climate policies and carbon taxation depends on the Engel Curve of a consumer good (Gough, 2017) this property needs to be central to policy. If a consumer good is luxury, that is the relative share in the consumption basket increases with income, consumption taxes are progressive. In other words, the income elasticity of demand is greater than one. If a consumer good is a necessity, that is the relative share in the consumption basket decreases with income, consumption taxes are regressive. In other words, the income elasticity of demand is smaller than one. Gough argues that this property should determine carbon taxation policies in combination with the carbon intensity of goods. There are high carbon luxuries and low carbon luxuries, high carbon necessities and low carbon necessities. Inspired by David Fell's 'smart' value-added tax to differentiate healthy and unhealthy foods (Fell, 2016), Gough suggests that the smart way to tax consumption would be to focus on high carbon luxuries. He points out that this is a necessary but not a sufficient condition to successful redistribution of emissions, because wealthier people save more. The gap between income and consumption increases with rising income, so to truly tackle ecological inequalities one also must limit the potential for future luxury consumption (Gough, 2017).

1.3 Research gaps and research questions

The literature review above provides comprehensive assessments of national and global economic inequalities (Alvaredo et al., 2018b; Chancel et al., 2022) and global carbon footprint inequalities (Hubacek, Baiocchi, Feng, Sun, et al., 2017) as well as numerous single country studies, but there is no international study on inequality and energy footprints. Energy footprint studies that take the Global South sufficiently into account are missing as well. Moreover, the room for novel redistributive scenarios for energy and carbon is large. There are a few redistributive scenarios (Chakravarty et al., 2009; Rao and Min, 2018b), none taking sectoral resolution into account. In terms of redistributive policies, there are many open questions. What are feasible policies to redistribute energy and emissions? How do these vary across countries? In particular, it could prove fruitful to rigorously test Shue's and Gough's suggestions to tackle emissions with respect to luxury and necessity consumption (Shue, 1993; Gough, 2017).

Given the discussed literature, the following research gaps are identified:

- International and global perspective on consumption-based final energy
- International and global perspective on household energy inequality
- Granularity with respect to goods and services
- Identifying opportunities to reshape and reduce energy demand (and thereby greenhouse gas emissions)

- Redistributive scenarios of energy and emissions with sectoral resolution
- Evaluate alternative income distributions and how they reshape energy demand
- Test climate and energy policies with respect to luxury and necessity consumption

These gaps can be reduced to the themes

- Internationality
- Granularity
- Policy design

and be specified with the help of the following research questions (RQs).

(RQ1): What is the final energy footprint associated with household consumption?

- How does it vary across countries, income groups and consumption purposes?
- In quantitative terms, what are the income elasticities of demand and energy intensities of different consumption categories?
- Are there systematic relationships between the income elasticity of consumption categories, their inequality and their energy intensity?

(RQ2): Can alternative distributions of income and final energy lead to improved social and ecological outcomes?

- How does redistribution of income change the distribution of energy?
- All other things being equal, would an equitable redistribution of income/expenditure change the total household energy footprint?
- Would redistribution recompose energy demand significantly?

(RQ3): What are the implications of consumption purposes and distribution for demand-oriented climate policy?

- How can the distribution and purpose of consumption inform policy design?
- What role do luxuries and necessities play for policy design?
- Can carbon taxation be improved (with respect to fairness and effectiveness) based on differentiating the purpose of consumption and the income level of countries?

In Figure 1-9 the research structure is summarized. It illustrates that internationality and granularity are addressed in every chapter of this thesis and in every publication corresponding to a chapter. Policy design is primarily approached in publication two and three. It also shows the association between research questions (RQs) and publications. Finally, it follows an overall discussion, conclusion and outlook.

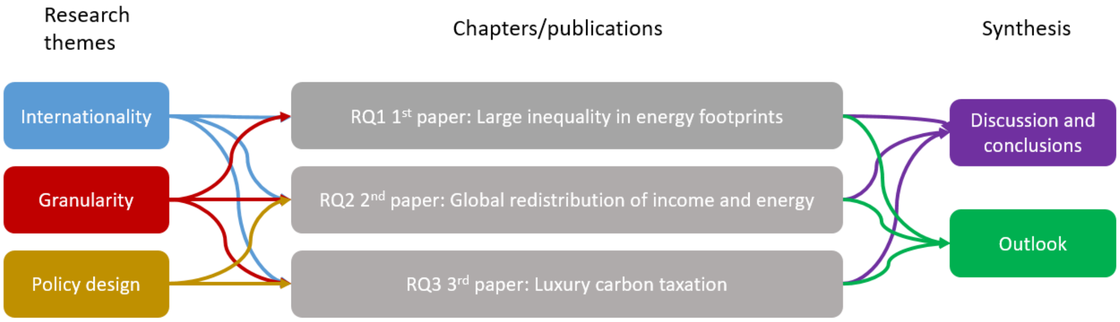


Figure 1-9: Research themes to research elements and overall research structure

1.4 Approach and methods overview

In this section, I briefly outline the approach applied to each research question and some of the most innovative methodological elements involved. Since each of the chapters two, three and four represents a published work, or a work ready for submission, detailed descriptions of the methods and quantitative concepts follow in the respective chapters.

The overall approach chosen in this thesis is to construct data-driven models of energy- and carbon inequality and the corresponding redistribution. All chapters employ quantitative modelling with a focus on distributional aspects, so the methodological overlap between chapters can be briefly pointed out, too. I describe distributions of income and energy demand employing established concepts like Lorenz curves, Gini coefficients, Pen's parade and ratio metrics (Cowell, 2009), but apply them to novel data, such as energy and carbon footprints for specific goods and services as well as energy and carbon footprints across various countries that have not been extensively considered before. Further, I *model* income and consumption expenditure distributions, specifically in chapter three and four, employing parameterized log-normal distributions. In chapter three, I vary parameters in this log-normal model to observe the impact of income distribution on household energy footprints which is an innovative modelling approach not appearing in earlier literature. Another important modelling aspect applied across chapters is to describe and model household consumption behaviour. I capture household consumption by estimating income elasticities of demand from data and price elasticities of demand through a theoretical model. As a foundational method to inform all of the research in this thesis, I employ Multi-Regional Input-Output (MRIO) modelling to ascertain the distributions of energy and carbon footprints (Miller and Blair, 2009). Input-output modelling describes the structure of the economy and informs us about the resource intensity of goods and services. Thereby, I explicitly combine distributional modelling with structural economics throughout this thesis.

1.4.1 Chapter 2 and research question 1

Research question one is about the final energy footprint associated with household consumption and its distribution across income groups within countries and across countries. For calculating the energy footprint, I employ standard Multi-Regional Input-Output (MRIO) analysis. According to Owen (2017), MRIO can be depicted with the help of Figure 1-10. The figure illustrates how economic trade data, the transaction matrix, is complemented by a final demand vector and an environmental extension vector. In final demand, I focus on household final demand because there is appropriate data informing us about its distribution across income groups, consumption categories and countries but I do not consider capital formation and government expenditure. The environmental extension is specified as a final energy vector so that I approximate the energy services that people make use of as closely as possible.

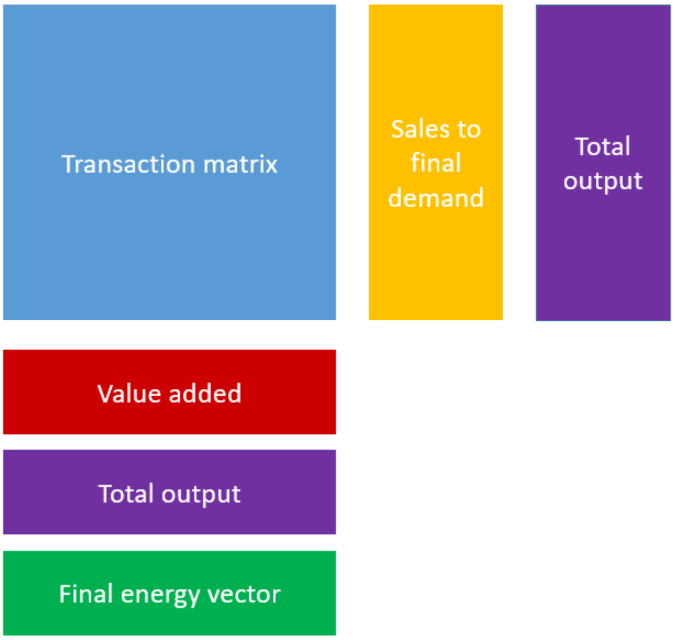


Figure 1-10: Multi-Regional Input-Output structure
Notes: Adopted from Owen (2017).

To model global trade (the transaction matrix in Figure 1-10) and national accounts I choose the Global Trade Analysis Project (GTAP 9) (Aguiar, Narayanan and McDougall, 2016) because of its wide international scope, including 140 countries and regions as well as its detailed sectoral classifications. Subsequently, I complement the trade data by distributional accounts of household consumption with granularity across consumption categories from the World Bank and Eurostat, which, in relation to final energy footprints and broad international scope, has never been done before (Eurostat, 2015; World Bank, 2018). There is one earlier study employing similar data and methods to capture international *carbon* footprints but the study did not elaborate on distributional aspects across consumption categories (Hubacek, Baiocchi, Feng, Sun, et al., 2017). Final energy data is taken from the International Energy Agency (IEA) and accessed via the UK Data Service (UK Data Service, 2018). A central part of the method applied in this chapter is bridging the multi-regional trade data with the household final demand vector and the final energy data. All three datasets come with distinct sectoral classifications, so I develop novel 'bridge matrices' (so called concordance matrixes) between the datasets and use tailored algorithms to minimize the uncertainties. The specific algorithm for this purpose applied is the 'RAS-balancing' technique (Miller and Blair, 2009).

In terms of quantitative metrics applied in this study, I rely on standard approaches: I employ the Gini coefficient to quantify inequality and the Lorenz Curve to depict it and furthermore I calculate the income elasticity of demand and energy intensities to classify consumption categories.

1.4.2 Chapter 3 and research question 2

Research question two studies alternative distributions of global income and their implications for household final energy footprints. First, I model the relationship between income and household energy footprints on a global level but with granularity across consumption categories. For this purpose, we employ international cross-country and population-weighted regressions to estimate the relationship between income and total household expenditure as well as to estimate the relationships between total household expenditure and expenditure per consumption category. Second, I parameterize the distribution of global income and apply a sensitivity analysis which increases or decreases the inequality of the distribution. For instance, the parameter controlling the inequality of a log-normal distribution is the log-transformed standard deviation. Figure 1-11 illustrates the idea with the help of some generic log-normal distributions exhibiting different spread but constant mean. Putting both steps together allows 'controlling' the global income distribution and observing the household energy demand outcomes. This approach has, to the best of my knowledge, never been applied before in the literature. The energy intensity data for knowing about the environmental implications of different income distributions is the same as in the previous chapter (chapter two) on household energy footprints but extended by data on the USA and Japan. For modelling the global income distribution, in terms of GDP per capita, I fit a log-normal model to data provided by the World Inequality Lab which is acknowledged to be of high quality due to its extensive use of national tax records across a wide range of countries (Alvaredo et al., 2018b). To verify robustness of the log-normal assumption, however, I also cross-check with data provided by Lakner and Milanovic (2016).

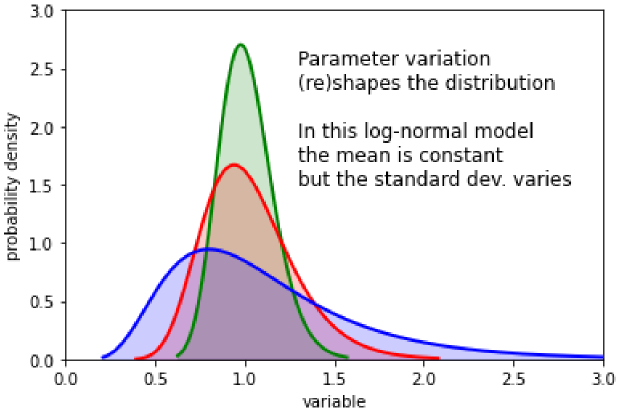


Figure 1-11: Schematic illustration of reshaped distributions

1.4.3 Chapter 4 and research question 3

Research question 3 is concerned with how the purpose and distribution of consumption can inform climate policy. To be pragmatic, I restrict my research to a particular case of climate policy, namely carbon taxation. Carbon taxation is a well-defined and established policy approach in which tax rates can be controlled by setting specific carbon prices. A novel element I introduce, however, is to differentiate carbon tax rates for luxuries and necessities on top of the implicit distinction made by the carbon-intensity of consumption. In particular, I differentiate carbon prices per product by employing the respective income elasticity of demand as a weighting-factor, because it informs us about the distribution and purpose of the consumption. All other things being equal (that is the carbon intensity), I set the carbon price per product linearly proportional to the income elasticity of demand. Figure 1-12 summarizes this idea. The MRIO model informing this work is the same as in chapters two and three but using the GTAP 9 greenhouse gas emissions vector instead of a final energy vector and covers 88 nations including most of Europe, the USA and the largest emerging economies such as Brazil, Russia, India, China and South Africa (BRICS). The wide international scope has been chosen specifically to uncover systematic patterns of distributional impacts (which are due to the carbon tax) across the global income distribution and geographic spectrum of countries. Further elements of this chapter include a simple generic model of revenue recycling, also addressing retrofit investments, as well as a dynamic analysis of emission trajectories.

$$carbon\ price\ per\ product \propto income\ elasticity\ of\ demand\ per\ product$$

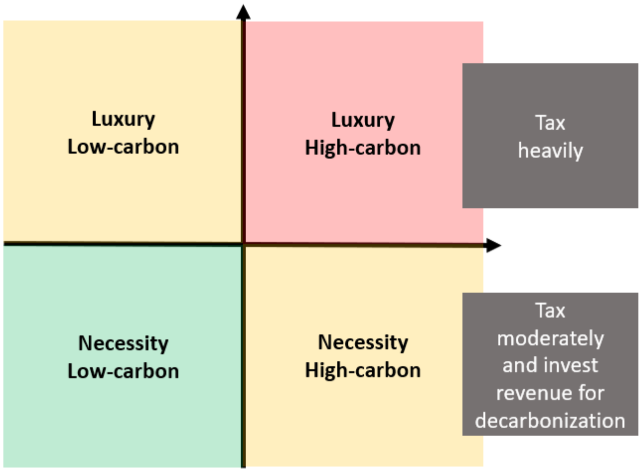


Figure 1-12: Schematic illustration of differentiated carbon taxation

1.5 Structure of the thesis

This thesis consists of five chapters including this introduction. Here we laid out the rationale and introduced the overall research approach. Chapter two and three correspond to peer-reviewed publications and chapter four is a draft ready for submission. Chapter two is a Multi-Regional Input-Output (MRIO) model of household final energy footprints for 86 countries. Chapter three is a (re)distributional model of global income and household final energy footprints. Chapter four comprises a static-distributional as well as a dynamic model of luxury carbon taxation of household consumption. Chapter five discusses the results in depth, interprets results considering current debates and provides an outlook on future research.

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2 Large inequality in international and intranational energy footprints between income groups and across consumption categories

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Abstract

Inequality in energy consumption, both direct and indirect, affects the distribution of benefits resulting from energy use. Detailed measures of this inequality are required to ensure an equitable and just energy transition. Here, we calculate final energy footprints: the energy embodied in goods and services across income classes in 86 countries, both highly industrialised and developing. We analyse the energy intensity of goods and services used by different income groups, as well as their income elasticity of demand. We find that inequality in the distribution of energy footprints varies across different goods and services. Energy intensive goods tend to be more elastic, leading to higher energy footprints of high-income individuals. Our results consequently expose large inequality in international energy footprints: the consumption share of the bottom half of the population is less than 20% of final energy footprints, which in turn is less than what the top 5% consume.

2.1 Introduction

Income and wealth inequality have been increasing within most major economies since the 1980s. The top 1% of global income earners benefit the most from economic growth, having increased their income share substantially, from 15% to more than 20% (Alvaredo et al., 2018b). Oxfam adds that in 2017, *'82% of all wealth created went to the top 1%'* (Oxfam, 2018). Inequality is now recognized as a decisive force of our time and has been linked to issues ranging from the environmental performance of nations to domestic terrorism (Hubacek, Baiocchi, Feng, Sun, et al., 2017; Krieger and Meierrieks, 2019). Climate change is likewise high on the global agenda and so is energy's role in decarbonizing the economy (Rockström et al., 2017; Steffen and et al., 2018). Numerous studies have shown that economic inequality translates to inequality in energy consumption as well as in emissions (Steinberger, Krausmann and Eisenmenger, 2010; Ivanova et al., 2015; Teixidó-Figueras et al., 2016). This is largely because people with different purchasing power make use of different goods and services (Galvin and Sunikka-blank, 2018) and different goods and services are sustained by different energy quantities and carriers.

Most studies considering energy footprints and inequality focus on single countries. International and consumption-granular comparisons remain restricted to carbon inequality instead of energy (Ivanova et al., 2015; Hubacek, Baiocchi, Feng, Sun, et al., 2017). Moreover, in energy transition research, the production and supply side have been the dominant focus. The demand side has received much less attention – and when it is considered, it is usually from a technological perspective (Baker, 2018; Creutzig et al., 2018). Recent scenario work demonstrates that reorganizing and reducing energy demand can ease the shift to a low-carbon energy system (Grubler et al., 2018) but it is largely projected to happen through techno-economic means. A starting point for change can be to understand how people's everyday practices constitute the foundations for the energy system. What do people need energy for? And how much? Shove and Walker (2014) argue that different social practices entail different patterns of energy consumption. Whatever a person does in their life affects the *energy footprint* left behind. Going to work by internal-combustion-engine car instead of electric bicycle reinforces distinct supply chains building their products upon distinct amounts of energy and upon distinct fuels, oil in the first case, electricity in the latter. Consequently, energy system design is not just an engineering issue but a social one too. Energy is not purchased or used for its own sake, but for the end-use services it delivers (Fell, 2017). Some end-use services are essential to people's life while others are 'luxuries' that people enjoy (Shue, 1993). For example, cooking, heating, and access to health or education infrastructure are fundamental to individual well-being and even to survival. In contrast, travel holidays and plasma TVs may be desirable, but are not essential. Not all people on earth benefit from essential energy services. Roughly one billion people still do not have access to electricity (World Bank, 2019a). Some studies highlight that if we increase living standards of the poor we jeopardize achieving climate goals (Lamb and Rao, 2015; Hubacek, Baiocchi, Feng and Patwardhan, 2017; Scherer et al., 2018). Various authors, however, have raised the question of whether providing the poor with a 'decent living standard' requires curbing 'luxury' elsewhere (Shue, 1993; Rao and Min, 2018). Some have suggested limiting per capita energy consumption and emissions of high-consumers to create space to provide essential energy services to those left behind (Goldemberg et al., 1985; Chakravarty et al., 2009; Jess, 2010). Indeed, international climate goals are threatened by the emissions of high-income countries and individuals. Chakravarty et al. (2009), for instance, have shown that the potential for climate change mitigation through the reduction in emissions of one billion high emitters is far greater than the threat of granting the poorest 2.7 billion a basic level of emissions that comes with decent living standards. Thinking in terms of emissions is crucial to climate change mitigation but it is secondary in thinking about living standards. Energy enables living standards, not emissions (Rao, Min and Mastrucci, 2019). This is why we have to consider the distribution of energy in the first place. In this context, it is important to consider both the global distribution and the purpose-specific consumption of energy by income classes.

We built an energy and expenditure extended input-output model that distinguishes between income groups of households. Input-output models draw on a long tradition of calculating the environmental impacts related to the production, flows and consumption of goods including their emissions, water, land, material and energy footprints (Steinberger et al., 2012; Wiedmann et al., 2015; Moran et al., 2018; Owen, Scott and Barrett, 2018; Wu et al., 2019). We employ a Global Trade Analysis Project (GTAP 9) based Multi-Regional Input-Output Model (MRIO) for the year 2011 (Peters, Andrew and Lennox, 2011). This model is then extended via household expenditure patterns from two different sources: the Global Consumption Database (GCD) of the World Bank, which comprises developing and emerging economies including the BRICS states (World Bank, 2018) (Brazil, Russia, India, China, South Africa), and Eurostat Household Budget Surveys, which includes all 28 economies of the European Union (EU) plus Norway and Turkey (Eurostat, 2015). We find that international and intranational inequality both are large, to the extent that the bottom half consumes less than the top 5%.

2.2 Results

2.2.1 Energy footprints and expenditure

Energy footprints per capita generally grow as a function of income or expenditure (Wiedenhofer, Lenzen and Steinberger, 2013; Wu et al., 2019). We now test this hypothesis across a significant sample of 86 countries and 4-5 income groups resulting into 374 population segments, shown in Figure 2-1. We fit a power law and find that energy footprints scale sublinearly with expenditure. Expenditure at higher levels becomes mildly less energy intense, corresponding to weak relative decoupling. However, this result does not differentiate between different consumption categories. It is notable that the European income quintiles and their corresponding energy footprints per capita exhibit low variation with the respective expenditure amounts. On the other hand, the data for developing countries reveals four, clearly distinct, clusters with considerable vertical variation, both above and below the EU range of energy intensities. This is caused by the structure of the Global Consumption database and its four invariant income thresholds (*<\$2.97, <\$8.44, <\$23.03 and >\$23.03 per capita a day)*. They comprise technological, geographical and consumption differences. For example, in Belarus there is much more heating gas used than in Thailand, at a similar expenditure level, resulting in very different energy footprints.

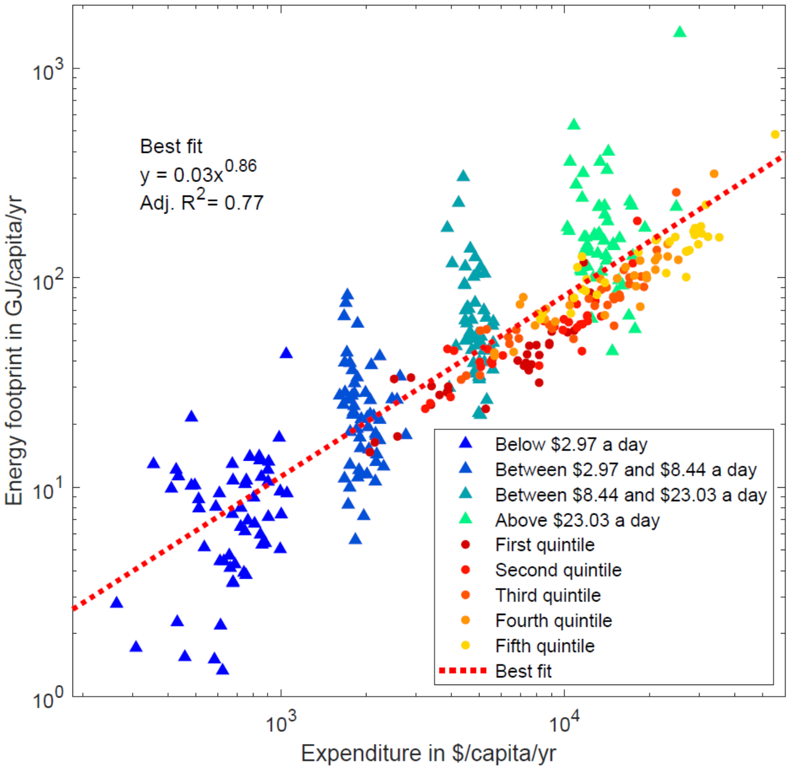

Figure 2-1: Energy footprints versus expenditure
Notes: Energy footprints scale sublinearly with expenditure (Adj. R-squared 0.77). Triangles represent GCD data and dots Eurostat data.

2.2.2 Intranational inequality

In terms of intranational inequality, the Gini coefficients of expenditure have a slightly narrower range than the Gini coefficients of energy footprints, as shown in Figure 2-2, implying that energy footprints differ more widely in their inequality than expenditure does. When expenditure is highly unequal within a country, i.e. has a high Gini coefficient, the corresponding inequality in energy footprints will tend to be even larger. This is particularly the case for Sub-Saharan and Latin American economies (e.g. Gini coefficients in Namibia are 0.7 for expenditure vs. 0.8 for energy, Paraguay: 0.64 for expenditure vs. 0.77 for energy). At lower expenditure inequality, metrics are more likely to be similar. This is the case for many of the European countries considered. The pattern is even more pronounced when comparing income inequality and energy inequality, see Supplementary Note 9. South Africa, for example, is consistently reported to be one of the most unequal societies in the world, with high unemployment and with substantial energy poverty (Isreal-Akinbo, Snowball and Gavin, 2018). Failure in economic inclusion causes exclusion from energy provision. Most people cannot afford electricity and thus retreat to consuming dirty fuels or very little energy.

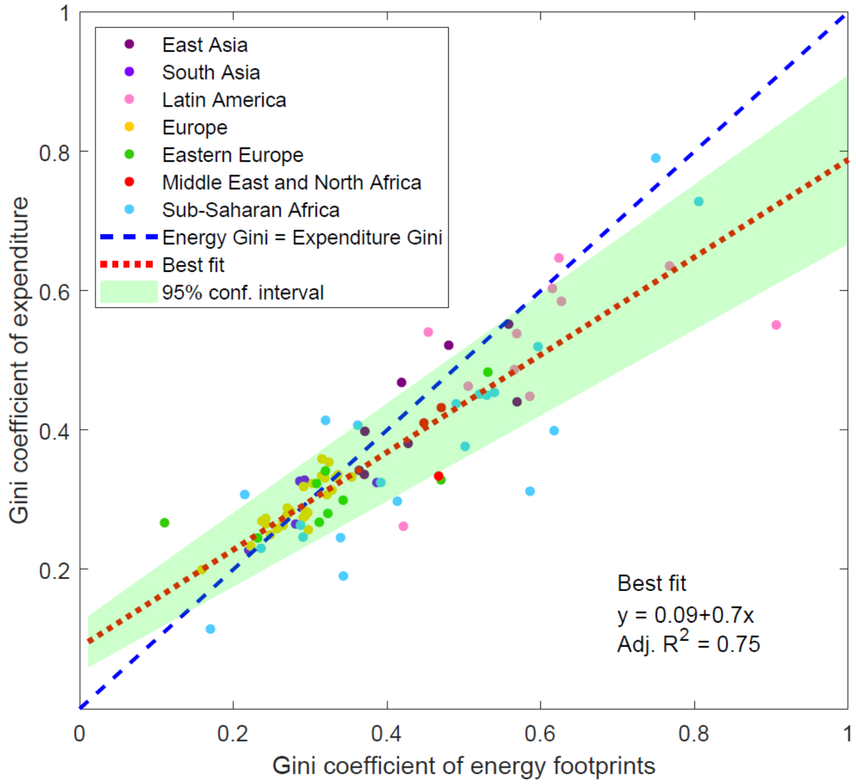

Figure 2-2: Energy footprint inequality versus expenditure inequality for 2011
Notes: Energy footprint inequality scales in a superlinear way with expenditure inequality (Adj. R-squared 0.75). The energy footprint inequality is generally larger than expenditure inequality. Therefore, the best fit (red line) has a lower slope than the line of linear scaling (blue line).

2.2.3 Income elasticity of demand and energy intensity

We measured the energy intensity and income elasticity of demand of different consumption categories over all countries in the sample. We defined energy intensity as the energy footprint intensity, which is the energy footprint of a consumption category divided by the money spent by the end-consumer. Income elasticity of demand measures how much more % of a good is consumed if income rises by 1%. If it increases by exactly 1%, then the elasticity is 1. If it is less, the elasticity is less than 1 (basic good), and if it is more the elasticity is above 1 (luxury good) (Steinberger, Krausmann and Eisenmenger, 2010).

We observe wide variations in energy intensities and elasticities across consumption categories. Package Holidays, for instance, comprises all sorts of transport services, including flights, and thus exhibits large energy intensities and large variation. Food products and 'Dwelling Maintenance and Water supply' (denoted here as 'Other Housing') feature lower energy intensities around the world. This is depicted in Figure 2-3 (a) and (c) using probability density functions. The upper row, with (a) and (b), depicts the indirect energy use categories Food, Package Holiday or Other Housing. The lower row, with (c) and (d), shows the direct energy use categories Heat and Electricity as well as Vehicle Fuel and Operation (for simplicity summarised as Vehicle Fuel). The averages of the distributions are shown as dashed lines. The average energy intensities of Food and Other Housing are similar whereas that of Package Holidays is clearly distinct (at 22.5MJ/$). The corresponding elasticities of Package Holidays, in Figure 2-3 (b) are high too, with an average elasticity ~2. The elasticity of Food is on average ~0.6 and of Other Housing ~1.

In Figure 2-3 (c) we show the spectrum of energy intensities in the direct energy use categories Heat and Electricity as well as Vehicle Fuel. Besides gas, heat often includes bio-based cooking fuels, particularly in developing countries. We see that the energy intensity distributions of both are similar, long tailed to the right, with the bulk of their measurements in the wide interval 25 – 150 MJ/$. The wide range in these categories is a result of both technological and price differences. Figure 2-3 (d), in contrast, demonstrates that the elasticity spectra of both categories are distinct, with Heat and Electricity elasticities mostly below 1, and 'Vehicle Fuel' mostly above. Consumption categories that feature higher energy intensities and higher elasticities, such as Vehicle Fuel, concentrate energy use among high income individuals. A category that exhibits high energy intensity but lower elasticities, like for example Heat and Electricity, distributes energy more uniformly in society.

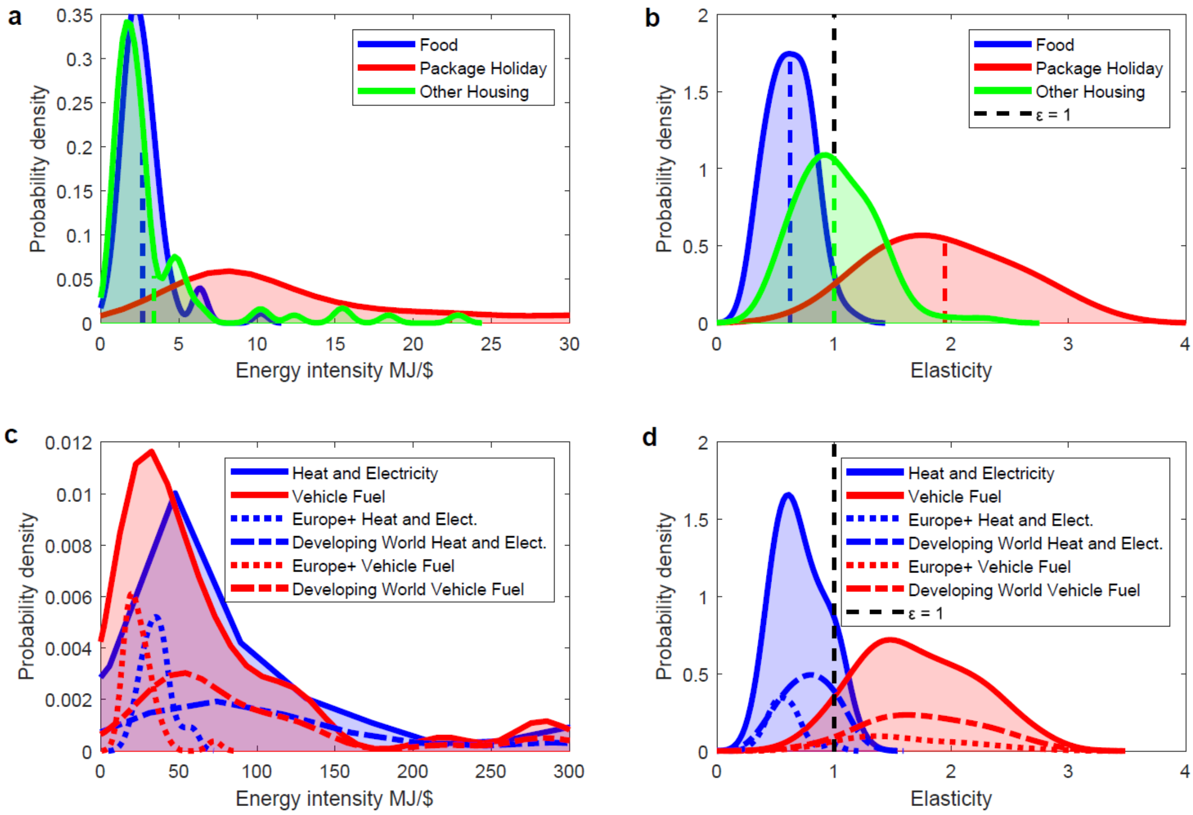

Figure 2-3: Energy intensity and elasticity spectra
Notes: The figure displays the probability density function of the energy intensities (a-c) and income elasticities (b-d) of consumption categories. Panels (a) and (b) refer to indirect, and panels (c) and (d) to direct, energy use categories. The vertical dashed lines in (a) and (b) depict the mean of the distributions. The vertical dashed black line in (b) and (d) represents an income elasticity of 1. For direct energy use, one clearly can distinguish between the distributions in European countries and developing economies, which are the dashed and dotted curves below the continuous lines in (c) and (d) (downscaled in size to make them visible and comparable). The energy intensities and elasticities in Europe are on average lower, reflecting differences in technology, and lower economic inequality, respectively.

Is there a general relationship between energy intensity and elasticities of consumption categories? In order to investigate that question, we take the population weighted mean of energy intensities and elasticities across all sample countries. The population weighted mean guarantees that the energy intensities and elasticities which are 'in use' most are represented effectively. If both attributes are low we label a consumption category 'Basic and low intensity'. If both are high we label them 'Luxury and high intensity'. The terms 'Basic' and 'Luxury' are to be understood as the usual economic characterizations of consumption categories, with luxury indicating consumption associated with higher incomes, and basic associated with lower ones.

Figure 2-4 shows the result with a resolution of 14 consumption categories. The figure is segmented into four quadrants defined by an elasticity of 1 in the y-dimension and the median of the non-population weighted distribution in the x-dimension (red dashed lines). The size of the circles indicates the relative contribution of each category to the total energy footprint. We observe a moderate rank-correlation between the two variables if Heat and Electricity is excluded (ρ = 0.52, p-value=0.04). This means that for indirect/embodied energy footprints as well as for private vehicle fuel consumption, there is a significant tendency of energy intensive categories to be elastic. Note that all education and health expenditure considered is private expenditure and not state-provided, explaining elasticities close to 1 and above.

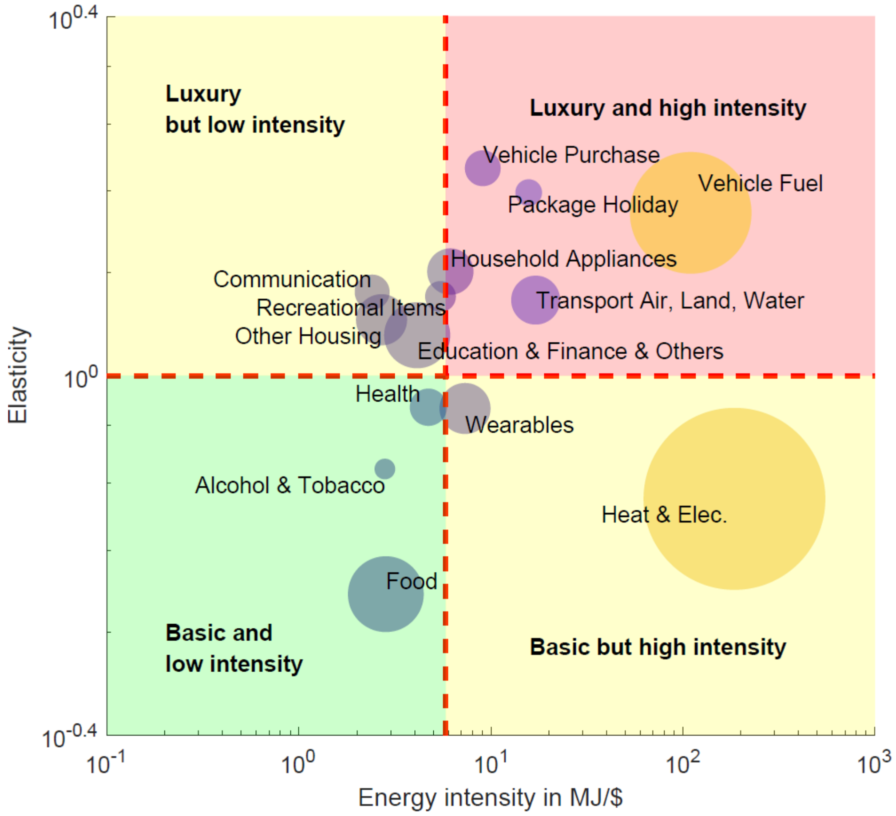

Figure 2-4: Elasticity versus energy intensity

The energy intensity of MJ/€ for Eurostat-based data was converted via the 2011 average exchange to MJ/$. For indirect energy consumption (dark circles), the income elasticity of demand correlates with the given energy intensity (rank correlation: ρ = 0.52, p-value=0.04). The direct energy consumption (light circles) through Vehicle Fuel fits well into this relationship. The only category behaving fundamentally differently is Heating and Electricity, exhibiting a low elasticity but the highest energy intensity.

We also observe that the result of Figure 2-4 is not determined by geographical particularities. One might think that the population weighted mean emphasizes energy intensities in India or China so much that the results in other countries are overwritten. This not the case. Scrutinizing the non-population-weighted version of the measurements yields that 90% of Package Holiday, 92% Vehicle Fuel are found in the red quadrant 'Luxury and High intensity' while 94% of Food is found in the green quadrant 'Basic and low intensity'.

2.2.4 International energy footprint inequality

Considering all countries and income classes together, we obtain international distributions and inequality metrics. The ensuing total international energy footprint inequality is large, with a Gini coefficient of 0.52. The different consumption categories exhibit high variation, with Gini coefficients ranging from 0.45 in Heat and Electricity to 0.82 in Package Holidays. Extreme inequality is also observed when comparing how much energy the bottom 10% of the distributions consume compared to the top 10%. There are ~550 Million people in each decile, so roughly the equivalent of today's European Union. The top 10% consume ~39% of total final energy (nearly equivalent to the consumption of the bottom 80%), while the lowest 10% consume almost 20x less, ~2%. There are three categories where the bottom 10% are entirely excluded from energy consumption so far: Recreational Items, Package Holiday, Vehicle Purchases. Recreational Items comprise goods like boats, vans or musical instruments. In terms of Vehicle Fuel, currently 187 times more energy is used by the top 10% consumers relative to the bottom 10%. The energy inequality is thus not just of quantity but also of quality, where energy services like 'individual mobility', are out of range for the poorest populations. Table 2-1 provides an overview of inequality in international energy footprints distinguished by consumption category.

Table 2-1: Overview international energy footprint inequality over 86 countries

Consumption category	**Gini coefficient**	**Top 10% to Bottom 10% ratio**	**Top 10% share**	**Bottom 10% share**
Indirect energy	0.58	30	45%	1.5%
Food	0.45	13	32.5%	2.5%
Alcohol and Tobacco	0.60	40	40%	1%
Wearables	0.54	21	42%	2%
Other Housing	0.70	110	55%	0.5%
Appliances and Services	0.66	53	53%	1%
Health	0.56	84	42%	0.5%
Vehicle Purchase	0.79	/	70%	0%
Other Transport	0.60	92	46%	0.5%
Communication	0.73	580	58%	0.1%
Recreational Items	0.77	/	66%	0%
Package Holiday	0.82	/	76%	0%
Education & Finance & Other Luxury	0.66	102	51%	0.5%
Direct energy	0.5	18	36%	2%
Heat and Electricity	0.45	13	32%	2.5%
Vehicle Fuel and Operation	0.70	187	56%	0.3%
Total	0.52	20	39%	2%

The distribution (Lorenz curves) of different consumption categories are shown in Figure 2-5. Figure 2-5 (a) depicts the Lorenz curves for the entire sample while (b) emphasizes the difference between land- and air transport in developing and emerging economies (56 countries). In Land Transport, the bottom 50% receive a bit more than 10% of the energy used and in Air Transport they make use of less than 5%. On the other hand, the top 10% use ~45% of the energy for Land Transport and around 75% for Air Transport. Air Transport is a hugely unequal domain when considered across developing countries, and over all countries the results are similar. Air Transport related activities, like Package Holiday have the 'steepest' Lorenz curves. Vehicle Fuel and Other Transport are likewise very unequal. Food and Residential energy use, in contrast, are a little less unequal than the total average.

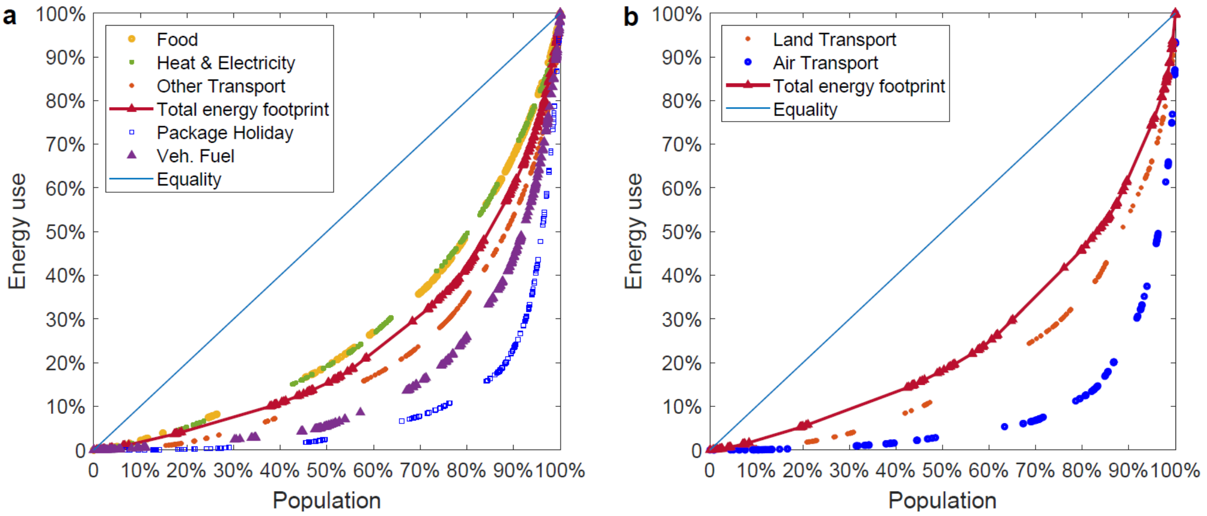

Figure 2-5: International Lorenz curves
Notes: Panel (a) shows the international inequality of energy footprints across all income classes within the 86 countries taken together, for different consumption categories. The overall energy footprint inequality is the red continuous line. Embodied energy in food and direct residential energy consumption, in the form of electricity and heat, exhibit the least inequality but with Gini coefficients of 0.45 still can be described as highly unequal. The highest inequality occurs in transport-related energy consumption: Vehicle Fuel as well as Package Holidays, the latter relying often on flights. Panel (b) accentuates the difference in energy inequality for Land Transport and Air Transport in the developing world (56 countries), with Air Transport being clearly more unequal.

2.2.5 Implications of energy inequality

Energy provision is considered a fundamental and integral development challenge (Brand-Correa and Steinberger, 2017; Rao and Pachauri, 2017). A minimum level of energy consumption is required to enable decent well-being. Our results demonstrate that energy consumption is far from equitable and varies to extreme degrees across countries and income groups. This suggests that the inequality in the distribution of final energy is impeding the Sustainable Development Goals, rather than enabling them. Many people suffer from energy deprivation, and quite a few are consuming far too much.

By combining intra country and inter country results, we obtain a higher granularity and wider range of energy footprints than comparable international studies that only operate at the national average level (Wu et al., 2019). At high incomes, final energy footprints per capita are frequently greater than 200 GJ/yr or occasionally even greater than 300GJ/yr (see Figure 2-1). This is one order of magnitude greater than what has been identified as necessary for a decent quality of life (Goldemberg et al., 1985). We also find that 77% of people consume less than 30GJ/yr/capita and 38% consume less than 10GJ/yr/capita – this lower end is almost certainly insufficient for a decent quality of life (Steinberger and Roberts, 2010). Based on national averages we would measure, for example, that only 8% of the population consume less than 10GJ/yr/capita. This is a dramatic difference, enabled by considering intra-national inequality. Despite the improvement in resolution, our results are constrained by the income granularity present in the data. In Europe, the richest people we can observe are the top 20% of the population. What energy do the top 1%, 0.1% or 0.01% use? In the data for developing countries we occasionally attain a more fine-grained picture of the narrow top segments in a country because few people fall beyond the income threshold of >24$ a day. We find that the top 0.01% (~300 people) in Armenia for example have a final energy footprint of ~1000GJ/capita/yr. If everyone would use that much, we would require ~7600EJ (Exajoule) of final energy on this planet, ~27 times more than we currently use (UK Data Service, 2018).

Transport has been identified as a problematic sector before, encountering difficulties transitioning to low-carbon alternatives (Davis et al., 2018). We show that transport-related consumption categories are among the most unequal ones. Moreover, we measure larger inequality in Air Transport compared to public Land Transport in Figure 2-5 (b). Large parts of the population are almost or entirely excluded from aviation. A similar trend can be observed surrounding the private vehicle. The top 10% consume ~55% of mobility related energy, equivalent to 13.5% of total final energy demand, the vast majority of it fossil fuel based. It is then questionable whether systems that serve only global minorities and are highly dependent on fossil fuels are favourable in facilitating mobility. The mobility of a few locks the entire energy and transport systems in to fossil-fuel dependency. It has previously been suggested that many of the engineering challenges to 'net-zero emissions energy systems' could be overcome or moderated by rethinking demand (Davis et al., 2018). There are concrete policy proposals that address transport demand such as a frequent flyer levy (Devlin and Bernick, 2015) or reducing car dependency through urban planning as well as committing to alternative vehicle technologies, including electric and hydrogen (Shepherd, 2017).

We find that that no consumption category is free from energy inequality and benefits equal populations to an equal degree. We even observe energy inequality in health and education for example. Clearly, we only observe the footprints of private expenditure and not of public provision, but both are privatized to large degrees in many countries. Moreover, public and legally binding health provision, as for instance in Germany, is debited from people's private income and thus is captured by the underlying data. Energy footprint inequality is a general phenomenon and not confined to specific domains. On the contrary, it is enforced by economic inequality across domains.

2.2.6 Future energy inequality

Our analysis delivers key insights into the relationship of socio-economic- and technological systems. We observe that high income elasticities of demand most often coincide with high consumption-based energy intensities. Their international spectra superpose. This superposition inevitably leads to unequal distribution of energy footprints. With economic growth as a core goal of political and economic processes, it is likely that this pattern will proceed and even aggravate in the future. Particularly so, if economic growth is distributed mostly to high-income people as is suggested by recent evidence (Alvaredo et al., 2018a). High-income individuals will then further expand their demand of high energy intensity goods and their footprint will increase. The energy footprint of low-income individuals will remain low. Ultimately, energy footprints will sheer further away from each other. From Figure 2-2, we can anticipate that increasing expenditure inequality will be translated into even larger energy inequality.

In order to test this reasoning, we projected expenditure and population levels into the future for the two years 2030 and 2050. We did so by making use of long-term GDP projections by the OECD and long-term population projections by the United Nations. According to this simple projection (which does not take into account energy efficiency improvements, for instance), energy footprints would double by 2030, and more than triple by 2050, with half of the increase occurring in India and China. Overall energy inequality remains quite stable, going from a Gini coefficient of 0.52 in 2011 to one of 0.50 in 2050. Considering consumption categories, 31% of the energy increase can be attributed to 'Vehicle Fuel' alone, another 33% to 'Heat and Electricity', and another 12% together to 'Other transport' and 'Education & Finance & Other Luxury'. Other subsistence like 'Food' and 'Wearables', together contribute only 7% to the increase. By 2050, we see increased inequality in some categories with income elasticity of demand above 1. For instance, the inequality of 'Other Transport' first decreases, going from a Gini coefficient of 0.60 to 0.57, but then increases to 0.63. 'Package Holiday' remains highly unequal and its Gini coefficient increases slightly to 0.82 in 2050. Figure 2-6 displays major trends in household energy footprints by aggregated consumption categories. Transport related energy footprints are increasing their share of total while subsistence, including 'Food' and 'Housing', and 'Heating and Electricity' decrease their share. The increase in transport energy is a disastrous development for a favourable climate, if transport continues to rely on fossil fuels. One crucial limitation of our projection is that we assume economic growth is uniformly distributed across income groups within countries, when we know that it tends to accrue to the wealthiest (Alvaredo et al., 2018a). Despite this limitation, we find that energy inequality is not likely to reduce significantly, and even increases by 2050 in several crucial consumption categories.

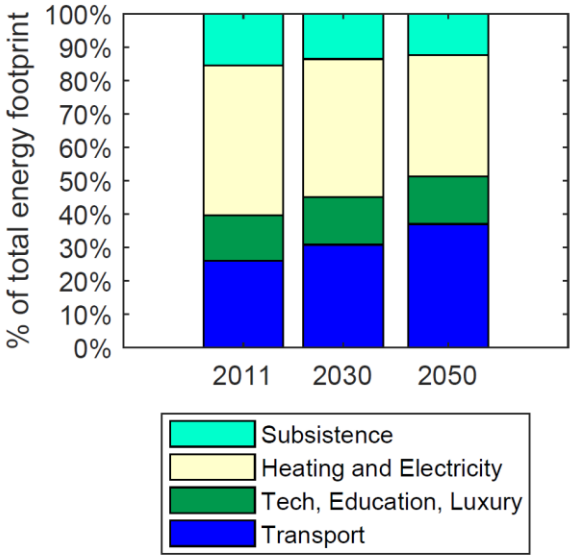

Figure 2-6: Business as usual trends for household energy footprints
Notes: The business as usual scenario (BAU) is a simple computational experiment extrapolating expenditure patterns and energy consumption on the basis of projected economic growth and population trends. More money is spent on high elasticity goods, particularly if income was already high to start with in 2011. Therefore, the amount of additional energy required in transport dominates. This is why, according to our model, transport will become the most energy consuming household activity by 2050.

However, persisting inequality can be prevented through appropriate intervention. We can classify four types of consumption categories as illustrated through the four quadrants in Figure 2-4. Based on their distinct nature, the four types require type-specific policy and action. The upper right-hand quadrant (high intensity, high elasticity) is dominated by transport and hard to decarbonise. Therefore, we recommend to move towards significant taxation, curtailment and replacement with collective and low carbon alternatives including electrified trains, buses, bicycles and small bespoke vehicles at the individual level (depending on disability, age and professional requirements). Going counter-clockwise to the upper left-hand quadrant (low intensity, high elasticity), we should consider redistributive efforts, and move away from profit-based provision models, particularly if essential in the case of education and health, while maintaining an agenda of full decarbonisation. For the lower left-hand quadrant (low intensity, low elasticity), the public investment agenda of decarbonisation should be maintained, while avoiding regressive measures such as taxation. Finally, the lower right-hand quadrant (high intensity, low elasticity) is dominated by electricity and heating in buildings and therefore requires large-scale public programmes that retrofit buildings, since such measures will not be affordable or accessible to all.

It is certainly worth probing how changing the distribution of final energy consumption can cope with the dilemma of providing a decent life for everyone while protecting climate and ecosystems. Therefore, we suggest that the next step in this research should be the exploration of energy demand distribution scenarios, testing the here suggested measures. Identifying a feasible alternative demand architecture could hugely benefit energy and climate policy.

2.3 Methods

2.3.1 Model overview

We compute household energy footprints but not the footprints of government expenditure and business-related capital formation. Household energy footprints cover 70% of all energy footprints. A full description of the data and its constituents is provided in the Supplementary Table 2. The two expenditure databases are constructed with respect to the Classification of Individual Consumption according to Purpose (COICOP Version 1999) (United Nations, 1999). Therefore, the two databases can be aligned with the GTAP sectors. The Global Consumption Database (GCD) distinguishes between four different household income groups defined by the World Bank. The Eurostat Household Budget surveys distinguish between quintiles. In terms of energy data, we use final energy consumption provided by the International Energy Agency (IEA) for 2011 and aligned with GTAP sectors. Final energy is closer to the energy that people actually make use of compared to primary energy. It approximates the amount of energy that 'operates on site' to provide a certain service. It also better represents the energy capacity required to replace fossil fuels by low-carbon alternatives. Low-carbon alternatives, for instance solar or wind, often do not exhibit big differences between primary production and final use. Our database consists of the 86 countries within the intersection of the IEA, GTAP and expenditure data, representing 78% of global population, 56% of global GDP and 64% of all final energy in 2011.

Based on the MRIO we then calculate energy footprints per consumption category, per nation, per income group and per capita. We also compute income elasticities of demand and consumption-based energy intensities per consumption category. For representing inequality, we show the distributional Lorenz Curves and the corresponding Gini Coefficient. Both are comparable across a wide range of studies (Lawrence, Liu and Yakovenko, 2013; Milanovic, 2013; Liberati, 2015) and are relatively robust against outliers (Duro, 2012).

2.3.2 Data and data treatment

The energy extended Multi-Regional Input-Output model (MRIO) is based on the Global Trade Analysis Project (GTAP) 2011 and the IEA – Energy Balances of 2011. GTAP has been chosen because of its wide scope (140 regions) and its availability for the year 2011, which match both with the scope of the IEA data and the expenditure data. For differentiating between consumer groups according to income, we make use of the Global Consumption Database (GCD) by the World Bank and the Eurostat data tables on household expenditure patterns. The Eurostat expenditure data is given per quintile. The GCD is given per four invariant income segments: '*Lowest—below $2.97 per capita a day, Low—between $2.97 and $8.44 per capita a day, Middle—between $8.44 and $23.03 per capita a day, Higher—above $23.03 per capita a day*'. The Eurostat expenditure data per consumption category comes in parts per mille (ppm). This is equivalent to the percentage, of total expenditure, a household spends a year on a given category. Therefore, the mean total expenditure of households has to be distributed across the different categories according to these percentages. Subsequently, both expenditure databases have to be scaled to national level. In the Eurostat case, the expenditure is given per household, so we used the number of households as in the 2011 census to attain national expenditure volumes. The Global Consumption Database data is given per capita as well as total population is provided. The Supplementary Figure 1 demonstrates that the scaled-up national expenditure volumes fit to the national expenditure volumes of households in the GTAP (correlations with Adj. $R^2 = 0.99$ for Eurostat and Adj. $R^2 = 0.91$ for GCD). Even though we start from household units in the case of Eurostat and the GTAP, we generate per capita volumes in both cases, dividing the national level volumes by population.

The final energy balance for each country has to be amended twofold. First international aviation and shipping bunkers have to be included too. This has been done by splitting up the world total of international aviation and shipping bunkers according to the 'economic volumes' of the corresponding sectors within the GTAP. Second, one has to treat direct energy footprints of households separately. This concerns private vehicle fuel use and residential energy use in the form of heat and electricity. Residential energy use can simply be taken to be a separate vector whereas distinguishing private road fuel use from commercial fuel use requires making estimates. We did so by considering that the GTAP sector Transport n.e.c. comprises commercial vehicle use as well as supporting transport activities (e.g. for an Amazon delivery) and the Trade sector includes private fuel purchases. Then we simply took the ratio of both sectors with respect to their common total. For instance, if both sectors together are worth 10 million \$ and Trade constitutes 6 million \$ of that total, then 60% of the road energy goes to private direct use and 40% to commercial and indirect private use. Formally stated, let N_i equal the monetary volume of Transport n.e.c. (in \$) in country *i*, M_i the Trade sector volume (in \$) in country *i*, $F_i$the total road energy in TJ for country i, K_i is the commercial road energy use in TJ and P_i the private road energy in TJ in country *i*, then we define

$$K_i = \frac{N_i}{N_i + M_i} * F_i \tag{2-1}$$

$$P_i = F_i - K_i \tag{2-2}$$

K_i (commercial) is between 20% and 50% of the total road energy for around 70% of the countries. P_i (private) is then between 50% and 80% for 70% of the countries. This is a first order heuristic that does not correct for the sectoral heterogeneity within Transport n.e.c. and the Trade sector. Considering the large sample size and non-existent international data for this purpose, however, it is an efficient way of distinguishing between direct and indirect energy in road transport. A comparison with GHG gas emissions by source data from Eurostat yields that the attained ratios for European countries are maximally of 20% of difference. For developing countries, the difference is sometimes higher. Nevertheless, our mean ratios of private to commercial road fuel are 65% private and 35% commercial. On the basis of the Eurostat emissions data they are 58% and 42% respectively. This is not unreasonably far off.

Additional data for the income Gini coefficient has been acquired from the World Bank (World Bank, 2020). Currency transformations from Euro to Dollar have been conducted via the yearly average exchange rate of 2011, 1.39$=1€.

2.3.3 Input-output modelling of energy footprints

The GTAP is a quadratic input-output table and hence we can apply the standard environmentally extended input-output computation.

We need the production-based energy intensity of each industry which is

$$e = f * \hat{x}^{-1} \tag{2-3}$$

where *f* is the energy extension and $\hat{x}$ the diagonalized output of each industry. The $\widehat{\ }$ denotes matrix diagonalization. The Leontief multiplier is given by

$$L = (I - A)^{-1} \tag{2-4}$$

where *I* is the identity matrix and *A* the technology matrix of the economy. The total energy footprint of a country's (*i*) households (*h*) can then be computed by

$$q_i = e * L * Y_{h,i} \tag{2-5}$$

We want to access footprints per consumption category in the format of the household surveys, the Classification of Individual Consumption According to Purpose (COICOP). Thus, we compute

$$Q_i = \widehat{eL} * C_i \tag{2-6}$$

where Q_i is a matrix that if summed up along the columns provides the energy footprint per category in COICOP and if summed along the rows the one within GTAP. C_i is a balanced concordance matrix that translates between the two datasets. Now if we take the sum of each column j in Q_i and divide it by the total original spends for the respective category we attain the energy intensity of a consumption category j, as for example used in Figure 2-3 and Figure 2-4. Then we use the energy intensities and multiply them with the income- and consumption-granular expenditures in the household budget surveys to arrive at the energy footprint per consumption category and per income group.

2.3.4 Transformations between databases and RAS balancing

The expenditure data comes with a different product and service classification than the GTAP does as well as the IEA energy balances do. This is why one has to transform the expenditure data and the IEA energy balances into GTAP format. Transforming the IEA energy balances into GTAP format is based on the fact that both formats maintain correspondence to the International Standard Industrial Classification of Economic Activities Revision 3.1 (ISIC Rev. 3.1). Thus, equivalent sectors have been determined and mapped accordingly. If one of the 26 IEA sectors has several correspondences in the GTAP format, the split between them has been determined by the economic size of the GTAP sectors. A second version of splitting has been tested where the splits have been computed based on the 'spends on energy' by each sector but we found that the total difference in consumption-based-accounts is marginal, particularly for large and significant sectors (~5% on average). The two versions correlate to 99%.

Mapping from Eurostat and GCD expenditure data to the GTAP is also based on the ISIC Rev. 3.1 as reference. However, the national household expenditure volumes in total and per consumption category are not 100% equal to the ones within GTAP. Moreover, when mapping one COICOP consumption category to two or more GTAP sectors, it is unclear how much of the COICOP version belongs where. For overcoming this 'blackbox' an iterative proportional balancing technique has been applied, mathematically equivalent to RAS balancing (Miller and Blair, 2009). As a first step the COICOP version is scaled so that its volume exhibits the exact size of national GTAP household expenditures. This also overcomes currency differences as for example between Euro PPS and Dollar PPP. Afterwards, let C^1 be the initially distributed concordance matrix between the COICOP system and the GTAP system. In C^1 the column sum represents the expenditures per category in COICOP and the row sum the expenditures per sector in GTAP format. C^1 will be subject to significant error with respect to at least one of the sides. The goal is to minimize this error by iteration with respect to both sides. The next version of C, that is C^2, is determined by calculating the row sum of C^1, and then setting it into relation to the actual GTAP expenditures. The resulting ratio is denoted r^1. Then C^1 will be multiplied by this ratio across its rows. From the resulting matrix one proceeds in a similar way with the column sum and compares it against the scaled COICOP expenditures. This ratio is denoted s^1. Similarly C^1will be adjusted by multiplying across columns. One iteration is formalized by

$$C^{i+1} = \hat{r}^i C^i \hat{s}^i \tag{2-7}$$

where $\widehat{}$ denotes matrix diagonalization. This procedure is repeated 500 times. r and s saturate often after a few dozens of iterations, meaning the system is in equilibrium already and the error minimized with respect to both sides.

2.3.5 Income elasticities of demand

To obtain the income elasticity of demand per consumption category we employ a log-log regression of *expenditure per consumption category (Y)* on *total expenditure per capita (X),* along the different income classes and over all countries as follows:

$$log(Y_{ij}) = a + b * log(X_i) \tag{2-8}$$

where *i* is the country index and *j* is the consumption category index. The coefficient *b* is directly interpretable as an elasticity (see supplementary information section 8). *Total expenditure per capita (X*) functions as an approximation to income per capita, which itself is not available. Only the thresholds separating the income segments are known. We validate the statistical significance of the elasticities by the students T-test which is given by *b* over its standard error (Steinberger, Krausmann and Eisenmenger, 2010). If an elasticity is not significant it is not considered for the analysis in the section 'Income elasticity of demand and energy intensity'.

2.3.6 Inequality metrics

For assessing the distribution of energy footprints we rely on the Lorenz curve as a visual tool and on the Gini coefficient to quantify it.

The Lorenz curve can be described by

$$y_n = L(x_n) \tag{2-9}$$

where

$$x_n = \sum_1^n P_n / P_{global} \tag{2-10}$$

x_n is the population share of country *n*, ranked by per capita energy in y_n, and

$$y_n = \sum_{1}^{n} E_n / E_{global} \tag{2-11}$$

where y_n is the energy consumption of country *n*. The energy Gini coefficient then is (Dorfman, 1979; Steinberger, Krausmann and Eisenmenger, 2010)

$$G = 1 - 2 \int L(x) dx \tag{2-12}$$

We want to compute Gini coefficients of individual countries. Then our sample size is reduced to 4 or 5 data points on the Lorenz curve because we only have information on quintiles or four income segments. However, we can apply a well-defined small sample bias correction (Deltas, 2003)

$$G_{corrected} = G * \frac{n}{n-1} \tag{2-13}$$

where *n* is the sample size.

2.3.7 Business as usual scenario

The income per capita growth rates are based on the long-term GDP forecast by the OECD which maintains granular projections for each OECD member plus several other important economies including the BRIC nations (OECD, 2014). For countries where no long-term forecasts are available, we applied the projected world average. We applied income growth rates to our proxy for income: total expenditure. Based on the projected total expenditure, we distributed consumption shares by our empirically determined income elasticities. We projected population based on the United Nations long-term population prospects where data is available for all countries in our sample (United Nations, 2019). There are two important features for a distributional scenario that we did consider but did not implement yet: first, varied growth rates across income groups and, second, evolving technology. We kept energy intensities the same, a choice that greatly simplifies the modelling exercise but contributes to converging energy footprints across income segments because developing countries tend to have high energy intensities in direct energy use and consequently higher projected energy demand. Both of these simplifications should be revised in more sophisticated scenario work.

We also did test a variation of this scenario applying the average historical final energy intensity decline but it does not affect the distributional results at all. Since global GDP grew on average by 3.1%/year from 1971 – 2015 (based on World Bank data) (World Bank, 2019b) and final energy on average by 1.8%/year during the same period (based on IEA data), the average energy intensity (in final energy) declined by ~-1.3%/year. We applied this rate uniformly to the here measured energy intensities. In this version, by 2030 household energy footprints rise to ~216EJ, i.e. they increase by ~50%, and by 2050 to ~285EJ, i.e. they roughly double. This may be a more realistic forecast of household energy demand under business as usual. Inequality and share by consumption category, however, remain completely unaffected by this modification since it does not account for region-specific or sector-specific technology improvement. Our scenario should be understood as a simple computational experiment extrapolating the observed expenditure and energy footprints of households with the purpose of understanding energy inequality trends, not as an accurate prediction of energy demand.

2.3.8 Limitations

We assume that the amount of expenditure represents physical quantity consumed and thus directly translates to energy quantity consumed. For example, we are blind to whether somebody bought ten Ford cars or one Ferrari. Analysis has shown that footprints can be overestimated for high-income earners who spend on quality products that are priced high but do not use up more resources (Girod and de Haan, 2010). However, the authors note that differences between monetary based and physical unit based models is limited, particularly for energy intensive and direct energy use categories such as fuel use and aviation. Crucially, there is little physical consumption data available and the monetary data used here is all in Purchasing Power Parities designed to capture and compare physical consumption baskets. Nevertheless, in the future efforts should be undertaken to build up actual physical data. There are further uncertainties arising from a variety of sources. For example, the underlying input-output model is harmonized with respect to currencies and the individual national supply and use tables which reduces detail and accuracy. The consumption expenditure surveys come with several caveats including, survey design, non-response bias, sampling bias and so forth. The Global Consumption Database is a compilation of diverse household budget surveys that have been harmonized and extrapolated. On top of that, the transformations aligning the different databases cannot fully overcome differences in sector and product classifications. Discussing all uncertainties in detail however is not within the scope of this work. Here we highlighted some of the crucial ones when interpreting our results and evaluating our approach. A comprehensive list of uncertainties in household energy-footprint modelling can be found in Min and Rao (2018).

Data availability

The expenditure data used is available at http://datatopics.worldbank.org/consumption/ and https://ec.europa.eu/eurostat/data/database. The IEA data can be downloaded under institutional license from the UK data service at https://stats2.digitalresources.jisc.ac.uk/ and https://doi.org/10.5257/iea/web/2018-10. The underlying GTAP 9 database can be purchased from https://www.gtap.agecon.purdue.edu/databases/v9/default.asp. The concordance matrices used in the footprint calculations are depicted in the Supplementary Tables 3 and 4. The final energy footprint data per consumption category, nation and income group as well as energy intensities, elasticities and scenario parameters are available from the corresponding author upon reasonable request.

Code availability

MATLAB code for obtaining final energy footprints from the MRIO and calculating elasticities and the Gini coefficient is available at https://github.com/eeyouol.

Acknowledgements

Y.O. is supported by the Leverhulme Trust's Research Leadership Award 'Living Well Within Limits' project awarded to J.K.S. J.K.S was partly supported by an International Academic Fellowship of the Leverhulme Trust. The contributions of A.O. were supported by EPSRC Fellowship award EP/R005052/1. We also would like to thank Marta Baltruszewicz, Jefim Vogel, Joel Millward-Hopkins, Paul Brockway and Lukas Hardt for helpful discussions.

Author contributions

Y.O., J.K.S. and A.O. jointly designed the study, sourced the data, designed the analysis and wrote the paper. Y.O. conducted the analysis.

Competing interests

The authors declare no competing interests.

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3 Global redistribution of income and household energy footprints: A computational thought experiment

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Abstract

Despite a rapidly growing number of studies on the relationship between inequality and energy, there is little research estimating the effect of income redistribution on energy demand. We contribute to this debate by proposing a simple but granular and data-driven model of the global income distribution and of global household energy consumption. We isolate the effect of income distribution on household energy consumption and move beyond the assumption of aggregate income-energy elasticities. First, we model expenditure as a function of income. Second, we determine budget shares of expenditure for a variety of products and services by employing product-granular income elasticities of demand. Subsequently, we apply consumption-based final energy intensities to product and services to obtain energy footprint accounts. Testing variants of the global income distribution, we find that the 'energy costs' of equity are small. Equitable and inequitable distributions of income, however, entail distinct structural change in energy system terms. In an equitable world fewer people live in energy poverty and more energy is consumed for subsistence and necessities, instead of luxury and transport.

3.1 Introduction

3.1.1 Global inequalities

'The rich get richer' is an expression dating back to the early 19th century poet Percy Bysshe Shelly (Shelley, 2009). Two hundred years later, Thomas Piketty demonstrated that this is not only poetic wordplay but a working principle of the capitalist system as it stands today (Piketty and Saez, 2014). The return on capital that the very wealthy profit from is much higher than aggregate economic growth and the wage growth of the general public. As a consequence the gap between rich and poor is widening (Alvaredo et al., 2018).

There is no country where income inequality has a Gini coefficient below 0.25: most are above 0.3 and a large number of countries exists with Gini coefficients above 0.4 (World Bank, 2020c). Even at the lowest Gini coefficients of around 0.25, as for example in the case of Sweden, the top 10% income earners of the population may hold ~23% of total income and the bottom 10% only ~3% (World Bank, 2020d). National income inequality is also correlated to various other inequality dimensions, for instance the rural-urban divide, gender inequality and racial inequality (Ma et al., 2018; Ortiz-Ospina and Roser, 2018).

Nevertheless, income inequality is largest when measured at the international level, despite at least one decade of global income convergence between countries (Milanovic, 2013). The global Gini coefficient of income is estimated to be between 0.6 and 0.7 (Anand and Segal, 2008; Milanovic, 2013). This is more than in any single country.

The global divide does not end with prosperity and affluence. It also has been repeatedly shown that environmental footprints scale with income level (Wiedenhofer, Lenzen and Steinberger, 2013; Ivanova et al., 2015; Wiedenhofer et al., 2017; Moran et al., 2018). Energy consumption is coupled to income and so are carbon emissions (Teixidó-Figueras et al., 2016; Oswald, Owen and Steinberger, 2020). Affluence is now widely considered the largest driver of resource use and environmental degradation (Wiedmann et al., 2020). This is why the global income distribution is directly linked to the climate emergency and other ecological crises. High-income countries contribute by far the most to emissions, as do high-income individuals within countries. Conversely, low-income households and communities often struggle to afford basics such as clean cooking fuel, lighting and food storage (Rao and Pachauri, 2017). Low income countries in the Global South are also those most affected by climate change (Byers et al., 2018). Southern island states and coastal mega-cities are vulnerable to sea level rise, and extreme heat in Sub-Saharan Africa is already discussed as a cause for armed conflicts (O'Loughlin et al., 2012; Sen Roy, 2018). On top of that, developing countries often lack the economic resources to adapt to climate change (Mertz et al., 2009).

The distribution of economic wealth around the globe emerges as a key not only to the biggest problems of our time, but also to their solutions. If wealthy countries were to reduce their affluence, they would lessen the burden on the environment. As of today, no country is actively pursuing such a degrowth strategy (Hickel, 2019c). This is despite evidence demonstrating that well-being is only coupled to affluence up to a certain level, beyond which no significant gains in well-being are made (Easterlin, 1974; Fanning and Neill, 2019; Steinberger, Lamb and Sakai, 2020). Expressed in terms of Gross Domestic Product (GDP) and allowing for simplification, the gain in well-being indicators (life expectancy, life satisfaction etc.) is relatively small after roughly 15,000 $ Purchasing Power Parity

(PPP) per capita – a level only modestly larger than the global average (although maxima are achieved at higher levels (Jebb et al., 2018)). If poor countries were to increase their prosperity, however, they would likely see a rapid increase in well-being, including an across-the-board surge in health indicators and adoption of clean technologies such as electric cooking stoves (Vigolo, Sallaku and Testa, 2018).

Besides the ambivalent relationships between income, the environment and well-being, there are also studies that point to the degree of inequality itself as a critical social parameter. Arguments have been made that inequality affects the very fabric of society: the mental health of people. Evidence points to relationships between inequality and crime, obesity, educational outcomes and so forth (Wilkinson and Pickett, 2009). More equal nations consistently perform best across indicators.

Despite continually growing evidence of the critical importance of inequality in shaping environmental and social outcomes, there is little research quantifying the potential consequences of alternative distributions (Melamed and Smithyes, 2009). What would be the consequences of altering the distribution of income across the globe? How would this impact poverty and ecology? How would it reshape international relations? Is it even possible to keep the global economy the same size, redistribute and achieve better social outcomes and less environmental impact? These are big questions that can be addressed in many ways. Here we want to make a simple but novel contribution: simple in its approach, but novel in its quantification of radically different income distributions and their consequences. We model alternative distributions of global income (GDP per capita) and study the effect on final energy consumption of households.

3.1.2 Energy and human life

Why final energy consumption of households? Energy is a universal quantity pervading physical, biological, economic and social processes. It is the services that energy provides that people make use of to meet their needs (Fell, 2017; Kalt et al., 2019). Final energy is closer to these end-use services than primary energy. Between energy and well-being exists a similar saturating relationship as between income and well-being, with high levels of energy consumption not contributing much to well-being (Brand-Correa and Steinberger, 2017). Nevertheless, a minimum quantity applied in the right way is absolutely crucial in achieving a high quality of life: This minimum has recently been referred to as ‘Decent living energy’ (DLE)(Narasimha D Rao and Min, 2018). The DLE level has been quantified with estimates pointing to somewhere between 10 and 40 Gigajoule per capita per year (GJ/capita/yr) depending on what kind of technology is assumed, the location dealt with and what is assumed to be essential for well-being (Goldemberg et al., 1985; Steinberger and Roberts, 2010; Rao, Min and Mastrucci, 2019).

A recently estimated global average for Decent Living Energy is around 15 GJ/capita/yr when very advanced technologies are deployed worldwide (Millward-Hopkins et al., 2020), rising to 26 GJ/capita/yr when somewhat less advanced technologies are assumed (but still significantly more efficient than currently prevailing ones). Indeed, energy consumption at any level in no way guarantees a decent living standard, since it is the quality and composition of energy services achieved which ultimately matter. Energy consumption can be inefficient and misapplied. However, for the purposes of this study, we will use 26 GJ/capita/yr as a reasonable threshold for energy poverty. It is important to note that we focus purely on household consumption related energy footprints: we do not include energy used for government expenditure or capital formation. In DLE estimates, however, this collective form of energy actually plays a substantial role. It sometimes constitutes up to a third of DLE estimates. As a consequence, 26 GJ/capita/yr for DLE is a conservative estimate for household energy alone and a good first order approximation. A major advantage of household energy is that we can clearly associate it with different income groups. This is not so straightforward with government and capital formation related energy.

Real-world energy consumption of course is much more varied, with a large amount of people living below this threshold and an affluent, largely western, economic elite consuming drastically more energy. The global range of final energy consumption spans roughly 1-300 GJ/capita/yr (Oswald, Owen and Steinberger, 2020), but this is without considering the super-rich who likely attain energy footprints in excess of 1,000 GJ/capita/yr (Otto et al., 2019; Oswald, Owen and Steinberger, 2020). In short, there is both extreme energy poverty and severe energy excess on the same planet. Although far from perfect, final energy consumed by households is one of the best indicators for living standards and for the biophysical impact of people, encompassing what is necessary to achieve a decent life and pure luxury. This makes final energy consumed by households an attractive consequential indicator. We use it to observe and judge re-distributional outcomes.

3.1.3 Energy, inequality and scenarios

Models of energy systems have for a long time not been considerate of income distribution but worked on the basis of a single representative household (Rao et al., 2017; van Soest et al., 2019). Recently there have been various efforts to integrate income distribution into general equilibrium models and in particular energy system scenarios (van Ruijven et al., 2011; van Ruijven, O'Neill and Chateau, 2015). Yet, they mostly project change to happen on the basis of large-scale diffusion of innovation or efficiency gains (Grubler et al., 2018; Rogelj et al., 2019) and energy demand is often only made income-granular after the simulations. Most importantly, if income distributions are integrated in models they remain close to the empirically observable and plausible under current or planned policies (van Ruijven, O'Neill and Chateau, 2015; Trutnevyte et al., 2019) and at times even assume constant distributions for future projections. Studies more explicitly addressing the implications of radically alternative income or wealth distributions for energy demand are so far missing. There are now projections of income inequality into the future (Rao et al., 2019) but whenever inequalities in energy and emissions decline in future scenarios, it is a by-product of catch-up economic growth in developing countries and efficiency gains in developed ones. It often is an extrapolation of past technological trends and growth trajectories (Bauer et al., 2017; Riahi et al., 2017), not a consequence of economic redistribution. This approach to solving international energy inequality is very slow (Semieniuk and Yakovenko, 2020), and given the scale and the urgency of transforming the economy and the energy system, it is arguably not adequate. Going beyond these studies, our purpose is to test the potentially large leverage of alternative income distributions to address energy development and climate.

Previous distribution-focused research includes several important studies. One is a scenario by Rao and Min 2018 (Narasimha D. Rao and Min, 2018), who simulate income distributions jointly with other scenario parameters drawn from the Shared Socio-Economic Pathways (SSPs) (Bauer et al., 2017). They concluded that a reduction in inequality, if associated with growth in low-income countries and low growth in high-income regions, yields lower global carbon emissions. The result depends on assumptions about energy efficiency improvements in large economies such as India and China. Instead of further dwelling on technical aspects, they suggest examining the mechanisms of consumption for different income groups: Who consumes what, and why? In other recent work equity policies have been implemented in a national-scale integrated assessment model (D'Alessandro et al., 2020). The model focuses on the interactions of redistributive policies with other policies in several scenarios; most notably testing a green growth policy agenda and a degrowth one. The study concludes, that under degrowth policies, greater equity and lower carbon emissions are compatible objectives, whereas under green growth, lower emissions are only possible at the cost of higher inequality. Two rare contributions that solely focus on the distribution of energy and carbon emissions have been made by Chakravarty et al. The first concluded that allowing a minimum floor of 3.7 tons/capita/yr CO2 emissions for the poor can be off-set by capping emissions of the one billion highest emitters (Chakravarty et al., 2009). The second modelled the global distribution of energy consumption and tested the implications of implementing a floor of 10 GJ/capita as well as projecting energy demand over time but did not consider redistribution itself (Chakravarty and Tavoni, 2013).

These studies report important findings but none of them has attempted what we do here: changing the global income distribution and studying the outcomes in energy terms. The goal of this study is not to propagate a naive or overly simplified political narrative. We do however believe that the case for a global income and energy redistribution is compelling enough in order to be taken seriously and studied accordingly.

3.1.4 On terminology: Income, wealth, affluence or which one?

The term income can refer to several things. For example, it can refer to the income of a person or the income of a household subsuming different incomes sources, such as wages and return on capital. In an international context, when comparing countries, the term income is often equated with gross domestic product (GDP) per capita. There is also Gross National Income (GNI) which, in addition to the territorial measure of GDP accounts for value added by citizens abroad. GNI is less commonly used and the relationships between GDP, household expenditure and energy consumption are well established in the literature. In this work, we model the global distribution of GDP per capita per year, and thus we use the term income interchangeably with GDP per capita per year. From this, we derive expenditure of households (via the relationship depicted in Supplementary Figure 1) which is the money people spend on different goods and services. Wealth, on the other hand, is the sum of physical and financial assets somebody owns. The general terms affluence and prosperity combine income, expenditure and wealth. Affluence generally denotes excess, whereas prosperity has a more positive connotation referring to decent levels of well-being.

3.2 Methods

3.2.1 Methods and model overview

We model the global income per capita distribution in a simple but data-driven way by building on data by the World Inequality Lab and the World Bank. We elaborate on this in section 2.2. After modelling income, we estimate expenditure as a power law function of income, based on a log-log regression between the two. We then allocate expenditure between 14 different consumption categories, taken from Oswald, Owen and Steinberger (2020). The budget share of consumption categories, i.e. the share of total expenditure that is allocated to a certain good or service, is determined by income elasticities of demand. These elasticities can also be interpreted as power law exponents and are derived from log-log regressions of expenditure per category on total expenditure (Steinberger, Krausmann and Eisenmenger, 2010). The regressions are population-weighted cross-country models which avoids bias from very small countries or small population segments within countries (Steinberger and Roberts, 2010). The regressions cover 88 countries with each country including 4 to 5 income groups (~85% of the global population and ~85% of global GDP) resulting in a sample size generally around 350 or larger and spanning roughly 4 orders of magnitude of household expenditure groups, from roughly 100$ to 100,000$ PPP per year. The income elasticity of demand represents how much percentage the demand in a certain consumption category increases, when income increases by one percent. Each consumption category corresponds to an energy intensity (MJ/$) that is based on final energy footprint accounts in Oswald, Owen and Steinberger (2020). The energy intensity either represents the direct final energy used at home (as in the category 'heating or electricity'), or the indirect final energy that is embodied in the entire supply chain of a good (as in the case of the category 'food'). Energy intensities are the aggregate global final energy intensities of household consumption, so global final energy per category over global household expenditure per category, and thus constant and homogenous across the income distribution. The average energy intensity per income group varies because of differences in the composition of expenditure across income, see Supplementary Figure 2 for details. Of course, in reality, energy intensities are dynamic and evolve over time, particularly so during the ongoing global energy transition and efforts in efficiency and decarbonisation. This means that in the future energy intensities across consumption categories may change incrementally or drastically, and thus the technological conditions underlying redistribution scenarios may be altered. Our static model reproduces the fundamentals of technology as observed in 2011, with high energy intensities occurring mostly in direct energy consumption such as residential energy or fuel and lower energy intensities of indirect energy consumption – a pattern that is very likely to be persistent.

The consumption elasticities are held constant as well, which is a simplifying assumption, since income elasticities of demand have been shown to vary across income levels (Harold, Cullinan and Lyons, 2017). Yet, at the minimum, the power laws employed capture the average global trend of consumption and, since the equations are non-linear, they account for variation in budget allocation. We tested for non-constant elasticities (evolving with income levels) but did not find trends that are sufficiently significant, see Supplementary Table 4. The constant elasticities are based on the most reliable regression models we tested and are consistent with constant energy intensities.

A full list of consumption categories, energy intensities and elasticities can be found in the Supplementary Table 2. Figure 3-1 illustrates the basic flow of the model; from income distribution to final energy footprint accounts. It also depicts at what stages of the model we 'intervene' and explore its behaviour: In section 3.3.1 and 3.3.2 we redistribute income by varying the parameters of the income distribution (first we vary the standard deviation and then we set floors and ceilings) and in section 3.3.3 we evaluate the uncertainty inherent to the model, by employing a simple Monte Carlo simulation on the elasticities and energy intensities.

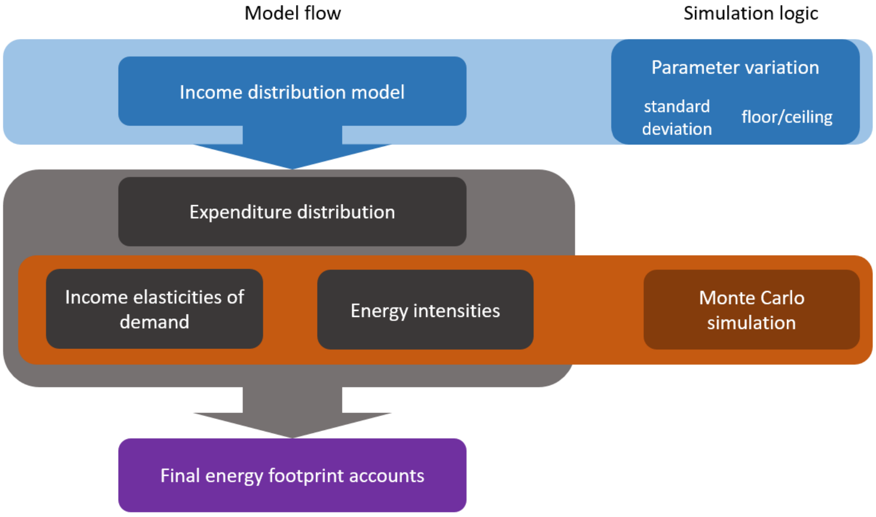

Figure 3-1: Model flowchart

A crucial feature of our model is that global gross domestic product (GDP) is constant before and after redistribution. Another fixed parameter is population. The expenditure and energy demand resulting from changes in the income distribution, however, are not preserved and change with the model parameters. The model is static; we consider the year 2011 only. This is deliberate as we wish to isolate the effect of distribution from the influence of other variables, which would inevitably change over time. The simulations should be considered 'computational experiments' that test the effect of redistribution under certain experimental conditions and holding everything else constant. The model is implemented in Python Anaconda and all code and data can be accessed on https://github.com/eeyouol. Table 3-1 summarizes all major assumptions of the model.

Table 3-1: Major assumptions of the model

Number	**Assumption**
1	Constant world GDP
2	Constant population
3	GDP per capita is distributed as income per adult equivalent
4	GDP per capita and expenditure per capita are correlated by a power law
5	Household expenditure is distributed over 14 consumption categories
6	The budget share per consumption category is determined by constant income elasticities of demand
7	Constant and homogenous technology

3.2.2 Modelling the global income distribution

The global income distribution has been estimated many times (Anand and Segal, 2008; Liberati, 2015; Lakner and Milanovic, 2016) and recent data is from Alvaredo et al. (Alvaredo et al., 2018). They estimate the income distribution in terms of per adult equivalent national income and EURO purchasing power parity (PPP). We converted this distribution into dollar GDP PPP per capita, via a coefficient representing the currency exchange rate and a 'working-age population' factor for the translation of the adult equivalent scale to the per capita one (World Bank, 2020a). In addition, we estimated the global distribution of GDP per capita ourselves based on household expenditure data in Oswald, Owen and Steinberger (2020). We also consulted another estimate made by Lakner and Milanovic (Lakner and Milanovic, 2013). We compare the cumulative distribution function of all estimates in Figure 3-2, finding their shapes to be similar, resembling an 'S-curve' when the x-axis is log-scale. The Lakner and Milanovic data displays visibly lower incomes, but their data is for 2008 rather than 2011 and concerns disposable household income, not GDP or pre-tax national income.

We fit a log-normal distribution to the adjusted data by Alvaredo et al. (2018) and fix its mean to the average global GDP per capita in 2011 (=13592 USD PPP constant 2011) (World Bank, 2020b). This way we cover two essential properties of the distribution: 1) the shape of the distribution provided by Alvaredo et al. and 2) the global mean income provided by the World Bank. The log-normal fit to the adjusted data is almost perfect (R-Squared of predicted cumulative population values >0.99) even though it does not exhibit the same long tails as the original data. It is missing out on the super-rich and people with nearly zero income. Nevertheless, the tails we are missing make up less than 0.1% of the population, and we cover a vast range of income groups from around 50 $PPP to 500,000 $PPP per capita. The log-normal model has advantages besides being a good fit to the data. For instance, it is defined via an easy-to-interpret set of parameters, the mean and the standard deviation of the logged GDP values (Cowell, 2009). There are other distributions suggested to better represent global income data such as Pareto-log-normal curves (Hajargasht and Griffiths, 2013) or generalized Pareto curves, particularly so in the heavy tails to the right (Blanchet, Fournier and Piketty, 2017). Here we do not attempt to model the income distribution perfectly but to develop a simple and useful model to investigate the relationship between income inequality and household energy consumption. Apart from our study focusing on the income-energy relationship, not the nature of the income distribution itself, there is no reliable data for income elasticities of demand or energy intensities among extremely high income groups (>> 1 million $/capita/year). For our purposes, it is thus reasonable to restrict the model to the lognormal distribution without Pareto tails.

After determining the appropriate model, we solve the cumulative distribution function of the log-normal model for 1,000 different groups, for the lowest 0.1%, the next 0.2%, and so forth until reaching 100% of the population. Therefore, we obtain income data for 1,000 distinct income groups globally. Each income group represents 0.1% of the global population or ~7 million people. We do not consider individual nations, and treat the whole distribution as one. The corresponding equations are standard and can be found in the Supplementary Note 1.

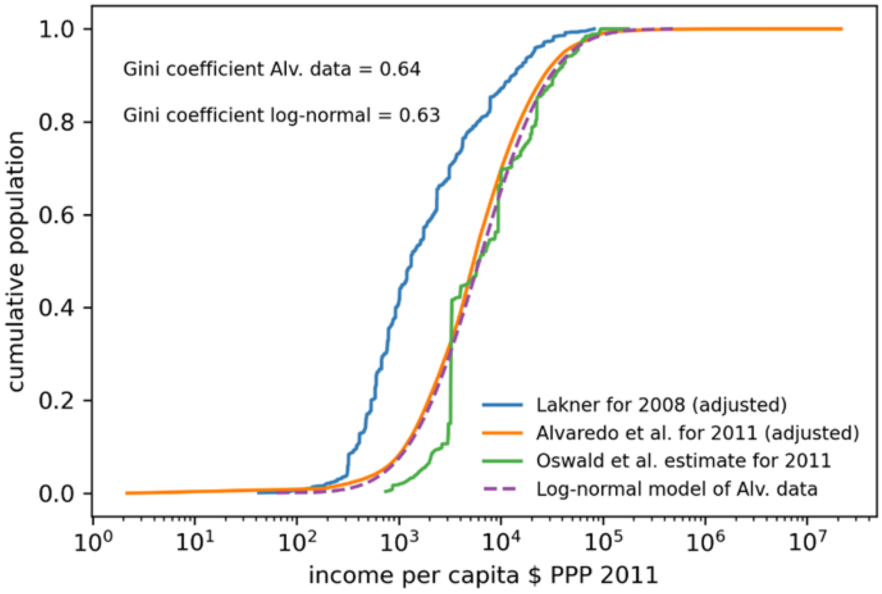

Figure 3-2: Modelling the global income distribution
Notes: Lakner and Milanovic data has been adjusted from $PPP 2005 to $PPP 2011. Alvaredo et al. data has been adjusted from national income per adult equivalent €PPP to GDP per capita $PPP.

3.3 Results

3.3.1 Simulation #1: Varying the global income distribution

The first simulation varies the spread of the global income distribution but holds the global average income constant, at ~13 600 $PPP. In other words, the total size of the world economy is preserved at 95 trillion $PPP but redistributed. The standard deviation (σ_X) of the global income distribution is ~26,800 $PPP. We decrease this in linear steps down to a tenth of the original value (2,680 $PPP) and up to twice the original (53,600 $PPP). This corresponds to global income Gini coefficients of 0.11 and 0.77 respectively. With these changes in income inequality (Figure 3-3a) come changes in total energy inequality, whereas total global energy demand changes only modestly. Global demand decreases from 209 Exajoules to 201 Exajoules (-3.8%), when increasing inequality, and increases up to 223 Exajoule (+6.7%) when decreasing inequality (Figure 3-3b). This is for two reasons: First, if inequality is decreased, the population approaches the mean value of the income distribution around ~13,600 $PPP. At this level of income, people generally spend a higher share of their total income than at higher levels. Second, there is a change in the composition of consumption. Figure 3-3 illustrates the considered ensemble of distributions in panel (a) and the implications for global energy demand in panel (b).

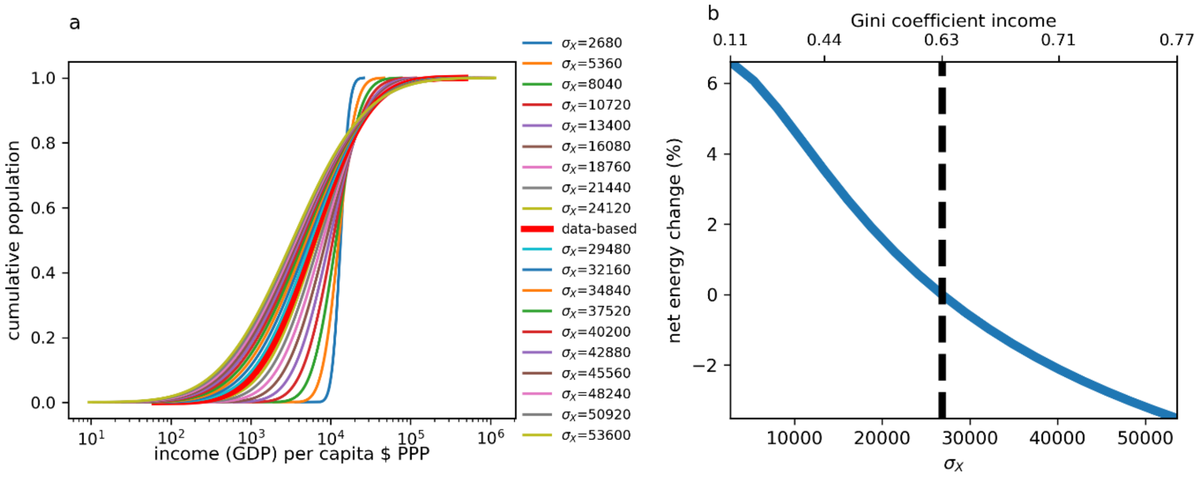

Figure 3-3: Varying the global income distribution aggregate view
Notes: Panel (a) shows the ensemble of income distributions. The red thick line represents the current income distribution. Panel (b) illustrates the implications for aggregate global energy demand. It plots total energy demand on the y-axis against total income inequality on the x-axis (expressed as the standard deviation of global income). The secondary x-axis on top displays the corresponding income Gini coefficients. The relationship between these two axes is non-linear and can be found in Supplementary Figure 10. Total energy demand increases by more than six percent when inequality is lowered and decreases by nearly four percent if inequality is increased. The black dashed line represents the situation as of 2011.

The sectoral composition of energy demand also changes as a function of inequality. If income inequality is decreased, the overall energy demand shifts more to residential energy use, particularly towards heat and electricity. For the purpose of illustration, we aggregate the 14 consumption categories down to six categories in Figure 3-4. Food, wearables and other housing (which includes housing repairs etc.) are for example put into one category called subsistence. Subsistence experiences a slight increase with more equality. Transportation related energy, including fuel for vehicles, flights and public transport, is almost halved in a more equal world compared to a very unequal one (~37.5EJ vs. 66EJ respectively). The equal world consumes more domestic energy (~107 EJ) than the unequal one (~85 EJ). There is a symmetric trade-off between 'at home' and mobility. The sectoral shifts are rooted in redistributed income at a person level and expenditure moving from high-income individuals to lower income individuals.

Furthermore, with decreasing income inequality, we also see people being lifted out of energy poverty (estimated with respect to the previously discussed threshold of 26 GJ/cap/yr). The reduction in inequality must be drastic: to ensure less than 20% of population are living below 26 GJ/capita/yr, we need to decrease the spread of the distribution to a tenth of the current spread, corresponding to a Gini coefficient of 0.11. At the lowest tested inequality, the range of energy consumption is 10 GJ/capita/yr to 56 GJ/capita/yr – corresponding roughly to low income groups in Eastern Europe, and the second quintile in the U.K. or Germany, respectively. In this world, ~80% of the population falls between 26 GJ/capita/yr and 40 GJ/capita/yr. A broader 'energy middle class' emerges. At the highest tested inequality, on the contrary, the range is 1 GJ/capita/yr to 2,000 GJ/capita/yr, with nearly 80% of the population falling below 26 GJ/capita/yr. For the sake of simple comparison, we define a 'low consumer' as someone who barely meets DLE (consumes 26-30 GJ/capita/yr) and define 'mega consumer' as people with a consumption of 270 GJ/capita/yr or more, which is equivalent to the amount the top 20% Americans consumed in 2011. With increasing inequality, there are more mega-consumers and more people who do not meet DLE. At the highest inequality, for example, there are twice as many mega-consumers, constituting 1.2% of the global population compared to only 0.6% estimated to exist in the real-world of 2011. On the other hand, at the lowest inequality only around 10% live below DLE standards and there are no mega-consumers at all. Figure 3-4 illustrates the process with panel (a) showing the overall sectoral composition of demand as a function of inequality. Panel (b) displays the percentage of low consumers and mega consumers as a function of inequality, and panel (c) illustrates the 'typical' energy profile of a low consumer and a mega consumer.

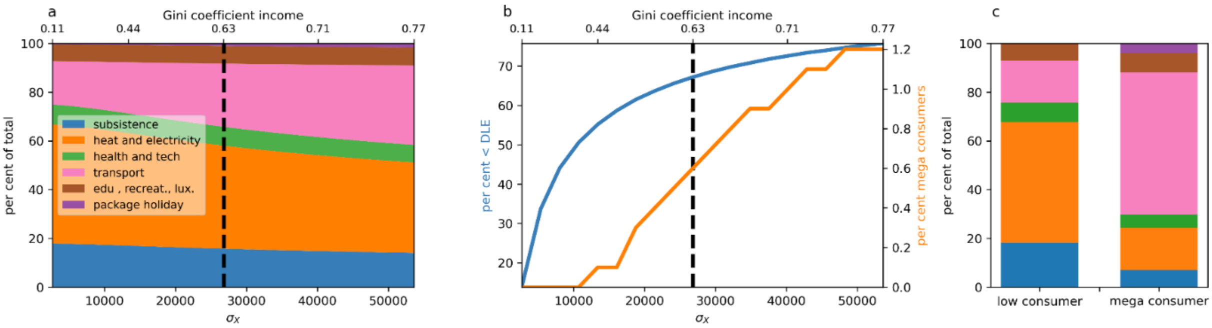

Figure 3-4: Varying the global income distribution detailed view

Notes: Panel (a) shows the composition of total global household energy demand as function of the income standard deviation. Panel (b) shows the percentage amount of low-consumer population (orange line) and the percentage amount of energy mega-consumers (blue line) as a function of the standard deviation. Panel (c) shows the typical energy consumption profile of a person barely meeting the DLE threshold and an energy mega-consumer. All three panels are connected: The composition in panel (a) changes because of the structural shifts illustrated in panel (b) and (c). The black dashed lines represent the situation as of 2011.

Oswald, Owen and Steinberger (2020) demonstrated that it is crucial to go beyond total energy inequality, and to differentiate between consumption categories. For example, energy embodied in food and residential energy use are more equally distributed than energy for the purposes of mobility or for going on holidays. This is a critical consideration in the discourse around climate justice and climate change mitigation. Energy is related to emissions and other environmental hazards, such as resource extraction and pollution, for instance during oil or gas leaks. It is thus no surprise that the inequality in emissions is very similar to the one in energy (Ivanova and Wood, 2020; Oswald, Owen and Steinberger, 2020). Consequentially, when a few people use a lot of energy and many people do not, the responsibility for environmental damage concentrates among a few. This pattern is tragic because most of the energy used by mega-consumers, is not essential. It is 'luxury energy' and 'luxury emissions' which could, in many cases, be avoided without harming anyone (Shue, 1993). The result is that some people use vast amounts of energy for luxury purposes, and others reap the negative externalities.

We investigate the correlation between income inequality and energy inequality differentiated by category. There are some categories that exhibit systematically higher energy inequality than income inequality, such as vehicle fuel, vehicle purchases and package holidays. Others such as food, heat and electricity are systematically more equal than income. As we increase income inequality, the inequality in luxury categories grows faster than the inequality in subsistence basics. When reducing income inequality to a Gini coefficient below 0.4, the energy metrics converge until they approach the level of income inequality. From a justice perspective, this means that only then do people bear more or less the same responsibility for energy externalities. Figure 3-5 plots the Gini coefficients in energy consumption (y-axis) vs. the Gini coefficient in income (x-axis). Supplementary Figure 5 depicts the corresponding absolute energy figures and the shares of the top 1% global income earners within the total energy consumption of a category. As an illustrative example of the scale of luxury externalities: among the top 1% income earners, we can be certain that most of the energy they use is luxury energy because they consume drastically more than decent living levels, particularly so in high elasticity categories. For instance, total vehicle fuel demand is large with ~48 EJ when the Gini coefficient is 0.63 (as it is in 2011) and then increases further to ~66 EJ when the Gini coefficient is 0.77. The share of the top 1% income earners within vehicle fuel is ~25% which is around ~12EJ as of 2011 (Gini = 0.63) and 45% or ~30 EJ in absolute terms in the extreme inequality scenario (Gini = 0.77). So in today's world, vehicle fuel of the global 1% accounts for nearly 6% of total household final energy, in an extreme inequality scenario this more than doubles.

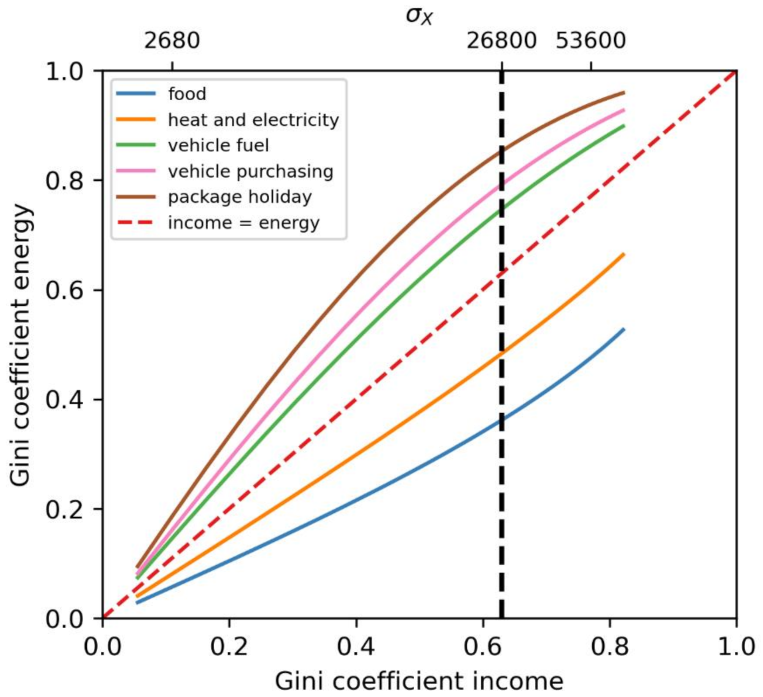

Figure 3-5: Income inequality versus energy inequality in selected consumption categories
Notes: The top axis represents the standard deviation of the income distribution.

3.3.2 Simulation #2: Paying for the poor

The second simulation shifts income from the top of the distribution to the bottom of distribution. Again, we do not consider policy or mechanisms that would initiate this change, but are only concerned with the broad outcomes. The principal question is to ask ‘How much money must be redistributed to eliminate (extreme) poverty?’ and ‘What degree of redistribution is necessary to achieve more equitable energy consumption?’ We set income floors inspired by real-world poverty lines. Then we compute a corresponding income ceiling that suffices for financing that floor via a bisection algorithm. Who is considered poor in our simulation and where do we set the poverty lines? There are many poverty lines in discussion, and income is not a sole measure of someone’s life experience. This is why there are many different concepts of poverty, including multi-dimensional ones (Isreal-Akinbo, Snowball and Gavin, 2018; Alkire and Conceição, 2019). The World Bank argues however that currently 1.9 $PPP per day are necessary to meet rudimentary needs such as nutrition and shelter. Living below that threshold is known as extreme poverty. Other authors disagree and proposed higher poverty lines to define the state of being ‘extremely poor’ (Edward, 2006). Some argue that the entire concept of extreme poverty is misleading, and propose poverty lines of up to 15 $PPP per day (Pogge and Reddy, 2005; Hickel, 2016, 2019a). This debate is mainly fuelled by disagreement on whether there has been progress made against poverty or not. The one fact that all parties seem to agree on is that it is helpful to measure poverty in such a way so that different strata of the population are taken into account (Beltekian and Ortiz-Ospina, 2018).

Here we build on that consensus and test various poverty lines, measured in consumption expenditure per day. The ones we consider are extreme poverty by the World Bank (1.9 $PPP), three more poverty thresholds by the World Bank associated with lower- and middle income countries (Beltekian and Ortiz-Ospina, 2018) (3.2 $PPP, 5.5 $PPP, 10 $PPP) and two brought forward by the scholar Jason Hickel (Hickel, 2019a) (7.4 $PPP and 15 $PPP). The logic for the latter two is that they correspond to a an updated version of Peter Edward's ethical poverty line which is necessary to achieve a life-expectancy of around 75 years and bottom U.S. living standards respectively.

Our simple model confirms findings that paying for the poor could be done within the size of the current economy (Hickel, 2019b). Even paying for half of the global population, which corresponds in our model to everyone being lifted to 10 $PPP, only requires taking money from the top 3% of the world population. The required ceiling would be relatively low, at 66,000 $PPP, but is still more than average GDP per capita in the U.S. or the U.K. today. Figure 3-6 panel (a) illustrates how we floored and capped the income distribution. Lifting fewer people would correspondingly require much less effort. For instance, lifting ~14% of the global population to roughly 3.2 $PPP requires money only from the top 0.1% of the global population. In the real-world, 14% of the population are estimated to live in extreme poverty in 2011 (Beltekian and Ortiz-Ospina, 2018). Therefore, eradicating extreme poverty is theoretically doable by means of modest redistribution, without growing the overall global economy and without severe policy intervention to the general population. Only an affluent minority would need to contribute to the redistribution, and still would be very well off. The amount of money generated from that top 0.1% would be an enormous figure at ~600 billion GDP. It would thus be roughly 4 times bigger than the annual development aid issued by OECD countries. Of course, eradicating poverty is only easy in theory. In practice, such a redistribution is much more intricate and complex. The annual OECD development aid of around 150 billion is already 10 times bigger than what is estimated to be required to eradicate world hunger (Fan et al., 2018). Yet hunger persists. The amount of money applied is not necessarily proportional to the outcome but depends on manifold institutional, political and socio-economic factors.

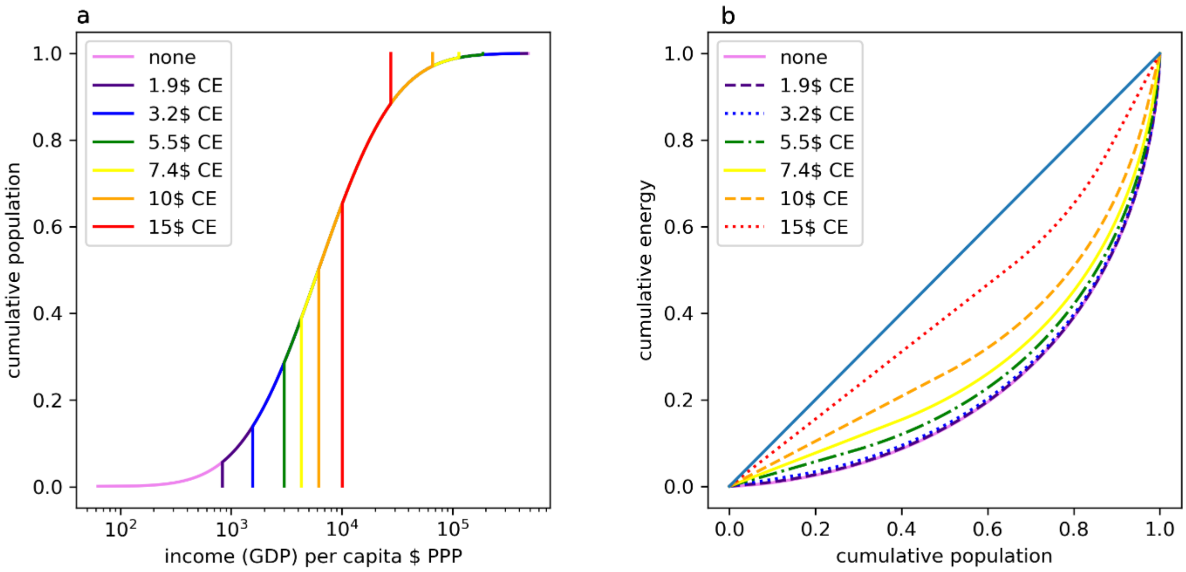

Figure 3-6: Flooring and capping the income distribution

The most important insight of simulation #2 is that getting rid of energy inequality and energy poverty requires more drastic interventions. Only with the highest floor of 15 $PPP do we bring global energy inequality down to below Scandinavian levels (Gini coefficient income = 0.2, Gini coefficient energy = 0.17) and lift everyone into the proximity of DLE standards (to ~26 GJ/capita/yr). On the contrary, if we only tackle extreme poverty, the world remains basically at the same level of energy inequality. Figure 3-6 panel (b) illustrates how the different floors and ceilings impact the energy Lorenz Curve. The Lorenz Curves displays the global population cumulatively on the x-axis vs. the global cumulative energy demand on the y-axis. It is a very common depiction of inequality and is directly related to the Gini coefficient. Table 3-2 provides an overview of the consumption floors applied (most left column) and then lists notable metrics of income and energy for comparison.

Table 3-2: Floor and ceiling of income and energy metrics

Consumption threshold $/day	**Income floor $/year**	**Income ceiling $/year**	**Poor paid for, % of pop**	**Rich taken from, % of pop**	**Min. GJ/capita**	**Max. GJ/capita**	**Average GJ/capita**	**Gini income**	**Gini energy**
none	none	none	0	0	0.2	864	30	0.63	0.57
1.9	0.9k	467k	5.7%	0.1%	2.8	834	30	0.63	0.57
3.2	1.6k	395k	13.9%	0.1%	4.8	709	30	0.62	0.56
5.5	3k	188k	28.6%	0.3%	8.6	345	30	0.57	0.51
7.4	4.3k	114k	38.9%	1.0%	11.7	215	31	0.52	0.46
10	6.2k	66k	50.2%	3.0%	16.1	130	32	0.43	0.37
15	10k	28k	65.3%	11.6%	24.5	60	32	0.20	0.17

3.3.3 Simulation #3: Estimating uncertainty

Our model carefully builds on empirical analysis. All parameter estimates employed have a robust empirical and statistical foundation. Nonetheless, the parameters are fixed, and thus we still have to account for uncertainty. Loosely speaking, our model is a set of nested equations, starting from a value of income and then solving for expenditure and energy footprints. The essential parameters are the energy intensities and the income elasticities of demand.

In the following, we test the uncertainty in the model through a simple Monte Carlo simulation. This just means we introduce a stochastic term to the parameters and repeat the simulation until we have a sample of N = 100. For the income elasticities of demand, we are provided with an uncertainty range by the regression models (the 95% confidence intervals). For attaining an uncertainty range of energy intensities, we conduct simple bootstrapping by omitting countries or regions from the underlying global energy and expenditure accounts. This way we are provided with various sub-samples of the original country sample and see how sensitive the global average energy intensities are to the sample composition. Afterwards, we measure the variation across the different sub-samples and use this as our uncertainty estimate. We measure the respective standard-deviations and feed them into a normal-distribution centred around the mean estimators. The parameters are then sampled from these normal distributions. This process provides us with an overall sense of robustness. It also allows us to cover a vast range of model configurations because with around 30 equations and 50 parameters of which the model consists of, there are many parameter combinations possible.

For the sake of efficiency, we focus on two simulation runs. In one, we set the income standard deviation to the minimum inequality tested (Std. = 2680 $PPP, Gini coefficient income = 0.11) and in the other to the maximum inequality tested (Std. = 53 600 $PPP, Gini coefficient income = 0.77). From here on they are just called ‘equal’ vs. ‘unequal’. We then measure four key metrics and their variation resulting from the Monte Carlo simulation: 1) the Gini coefficient of energy inequality, 2) total household energy consumption, 3) the share of transport energy among total household energy and 4) the share of residential energy among total household energy. We find that the results corresponding to an equal world prove particularly robust with energy inequality decreasing drastically and overall energy demand likely increasing between 2-15%, with the best estimate at ~7%. Well-designed policy, including employment of the right technology and adequate configuration of socio-technical provisioning systems (Vogel et al., 2021), thus could keep energy demand at nearly constant levels. Additionally, it is certain that in an equal world the amount of energy needed for transport decreases relative to the status quo, whereas residential energy demand increases relative to the status quo. In alignment with the results for equality, we find that a world unequal in income is always similarly unequal in energy consumption. How the energy is distributed over consumption categories bears more uncertainty, and the differences from status quo are smaller to begin with. Yet the overall trend seems stable – total household energy demand decreases marginally while transport energy requirements increase significantly and residential energy requirements tend to be lower. In an unequal world, energy consumption is to a large extent dependent on a few rich mega consumers. Their consumption preferences make up the lion's share of energy demand. Small deviations to these preferences can result into considerably different findings. The distributions over all four variables and both simulation runs are depicted in Figure 3-7.

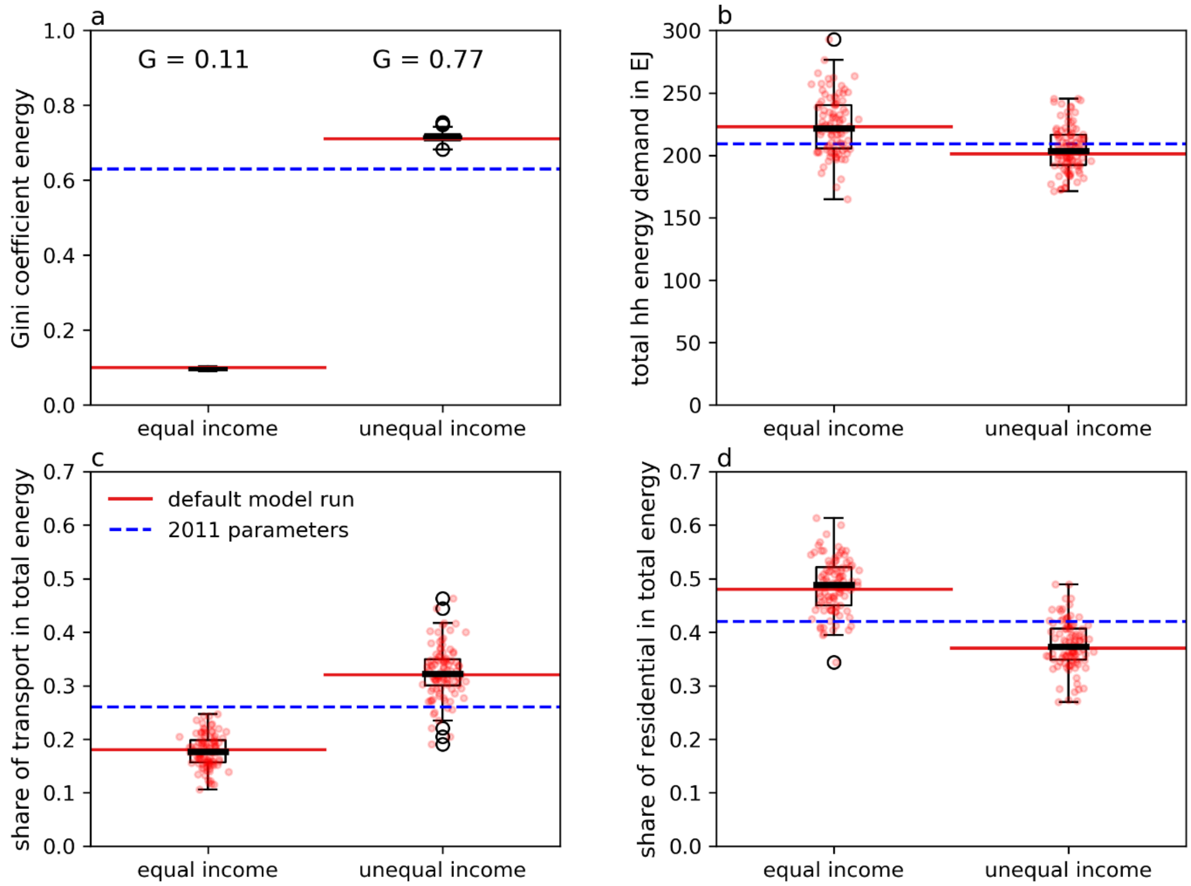

Figure 3-7: Monte Carlo simulation results

Notes: Panel (a) obviously displays a significant difference between the two income distributions and the resulting energy inequality. Panel (b) depicts the impact on total global household energy demand and the finding that total demand rises in an equal world about ~7% and most likely falls around 3-4% in an unequal world. Panel (c) and (d) depict the impact of redistribution on the sectoral composition of household energy demand, particularly on transport energy and residential energy demand. The differences in panel (c) and (d) are significant based on t-tests and a two-tailed p-value: for instance amounting to $p < 8e-57$ for panel (c). The black lines in the centre of the boxplots display the Monte Carlo simulation median. The red lines show the values attained in the default model run and the dashed blue lines running across the panels represents the parameter estimates for 2011.

3.4 Discussion and conclusions

The theme redistribution might be quickly associated with political economy. This work, however, treats redistribution rather as a structural transformation than a political one. We can conclude little about political economy from this study. Strong redistributive measures, as for instance the 90% wealth tax on billionaires that Thomas Piketty proposes or Universal Basic Income, naturally require a certain degree of intervention by the state. Redistribution on an international scale requires genuine international cooperation. In principle, however, redistribution is compatible with various forms of political economy, more centralized or more decentralized ones. To this end, we have to refer the reader to other work that elaborates on contemporary political economy, its shortcomings and ways forward (Pirgmaier and Steinberger, 2019; Creutzig, 2020; Wiedmann et al., 2020). It is also a misconception to associate redistribution only with explicitly re-distributional policies. This is not what we have studied. Simulation number one for example is completely agnostic about how lower inequality comes to be. If, let us say, OECD countries would decide to pursue degrowth and the African economy further grows, but there is no direct re-distributional link between the two processes, the end result still is a redistribution of global economic wealth.

Exact numbers are to be taken with a large grain of salt and should not be considered empirical data. For example, the model does not adequately represent the number of extremely poor in the world, and rather underestimates it. This is because we used a constant factor to convert a ‘per adult equivalent’ distribution to a ‘per capita’ one. This overlooks the fact that household size in developing countries is often larger than in high-income countries. The results are also in parts dependent on the choice of the distributional model. For instance, varying parameters of a Weibull distribution or of a Pareto distribution shifts the population in different ways as compared to the log-normal model and allocates other quantities of population to specific income levels. However, we tested several such alternative distributions and found that the overall energy demand trends, as a function of the inequality, are stable, even under entirely different income distributions (for details refer to Supplementary Note 5). Another simplification is that the model operates with homogenous energy intensities across the entire distribution. This is clearly not a fully accurate description of reality but it proved useful in answering our questions. The contribution of the model lies in illuminating qualitative characteristics of global income redistribution and its relationship to household energy demand.

Based on our results, marginal and drastic income redistribution prove to be levers for change. This naturally is the case when it comes to inequality. Lower inequality in energy could have manifold benefits, particularly to the people increasing their energy consumption from insufficient levels to a sufficient one. People being lifted out of energy poverty would gain access to a vast range of additional energy services beyond rudimentary nutrition; such as health, residential energy use and necessary mobility. Yet the ‘energy costs’ of greater equity are small (and may not be significant, as per the simulation in section 3.3.3). In the simple inequality reduction simulation (section 3.3.1), the difference between the most equal world (~220 Exajoule) and the most unequal one (~200 Exajoule) is 20 Exajoule which is about 10% of current household energy demand, and ~5% of total global final energy consumption. This is good news for the climate and the feasibility of energy development. It supports previous results demonstrating that climate protection and energy development do not have to be trade-offs, if we allow for diffusion of the right technologies (Wilson et al., 2020) and take sufficiency into account as a mitigation strategy for the affluent (Chakravarty et al., 2009; Narasimha D. Rao and Min, 2018; Scherer et al., 2018). In addition, if we were to relax the assumption of constant energy intensities, by for example, redistributing to less energy-intensive public spending, the overall energy costs of equity could shrink further.

Despite having built a very simple model with obvious limitations, we show in the floor/ceiling simulation (section 3.3.2) that by redistributing the existing ‘economic pie’ on the planet, we could lift billions of people out of severe energy poverty without pushing anyone else into it. As little as 1% of the global population could benefit the bottom 40%, with the former retaining yearly incomes above 100,000 $PPP and an energy consumption of up to 200 GJ/capita/yr, and the latter all lifted up to at least ~12 GJ/capita/yr. These findings might particularly be relevant to degrowth scholars as they point to a more precise quantification of degrowth: How much does the economy have to degrow? Which levels of income and energy consumption are desirable and feasible? Yet, further specifics, besides household energy levels, of non-growing, degrowing, or redistributive economies are beyond the scope of this paper, despite their interest. This ‘transfer’ could also be interpreted as making significant strides towards at least three of the Sustainable Development Goals (SDGs): Firstly, ‘#7 Affordable and clean energy for everyone’ (in parts, clean is not guaranteed based on our model), secondly ‘#10 Reduced inequalities’ and thirdly ‘#1 No poverty’. This is not at all obvious considering that global economic growth is often portrayed as something we must rely upon in order to eradicate poverty, even in high-income countries. In all likelihood, the potential of redistribution as a lever for the Agenda 2030 is still underestimated. There is a vast amount of proven synergies between the SDGs (Fuso Nerini et al., 2018).

From an energy system point of view, we address a previously understudied relationship. The composition of household energy demand and the degree of income inequality are related. People at different levels of the income spectrum have different energy consumption profiles. In sum, this influences the overall composition of demand. For example, in the simple inequality change scenario (section 3.3.1), we clearly observe that an unequal world allocates a higher energy share to transport while an equal one allocates more to residential energy use. The difference comes mostly from high demand for private vehicles and fuel among a minority elite. Consequently, with increasing income inequality, there is increasing polarization between rich and poor in terms of mobility. We do not distinguish between flying and public transport as they are taken together in one consumption category, which is a constraint due to the underlying consumption surveys. If we would do so, it would further amplify the observed polarization. In fact, the mobility polarization already is a real-world phenomenon. There are now studies that show that the super-rich have disproportionally large carbon footprints due to flying (Gössling, 2019; Otto et al., 2019) and typical hobbies of super rich individuals include collecting transport items, such as expensive cars and yachts (Featherstone, 2014). In contrast, it has been estimated that 80% of people world-wide never have taken a flight (Negroni, 2016). While somewhat speculative, the result suggests that an equal world might even be more compatible with climate constraints, not less (Hubacek et al., 2017). Technologies for reducing energy demand in buildings are manifold and often already effective at a low cost (Harvey, 2009), while transport is the one sector that is intertwined with the fossil fuel industry. There are of course many efforts to electrify transport on land, in the air and on water, but the diffusion of electric cars is projected to remain slow and they are resource-intensive to produce. Electrifying long-distance air transport remains unsolved and water-cargo remains challenging (Davis et al., 2018). A limit to these conclusions is they rest on the assumption that there is no fundamental change to consumer preferences. If income elasticities of demand were to change drastically, as it might happen in the face of profound cultural change, the relationship between inequality and energy demand could exhibit different traits. An example for such profound change is the potential shift away from globalization, including a reversal of the decade long trend of increasing international tourism, towards local forms of production, consumption and leisure.

Obvious continuations of the present study would be to elaborate on the role of specific countries, on policies for redistribution and the acceptance of redistribution of income or energy among the population (as for example studied in Europe (Olivera, 2015)). Redistribution within countries might be easier to achieve than redistribution internationally, thus we recommend to further explore redistributive pathways for nations in particular. There are also many technical aspects of this study which future research can build upon. For instance, the granularity and segmentation of consumption categories could have been different. Alternative survey data might provide new opportunities to adjust the model with respect to consumer preferences and elasticities of demand. We purposefully isolated redistribution from other variables for this study, but it might prove useful to integrate income redistribution into larger structural models, such as for instance input-output models and general equilibrium models. The systemic ramifications of income redistribution deserve further attention.

Acknowledgements

We would like to thank the editors and two anonymous reviewers for their constructive comments.

Data availability

All data and Python code is available on https://github.com/eeyouol.

Author contributions

Y.O., J.K.S., J.M.H., D.I. conceived and designed the study. Y.O. conducted data gathering and analysis. Y.O., J.K.S., J.M.H., D.I. wrote the article.

Financial support

Y.O., J.K.S. and J.M.H. are supported by the Leverhulme Trust's Research Leadership Award 'Living Well Within Limits' (RL2016–048) project awarded to J.K.S. Y.O. was partly supported through a fee contract by the International Institute for Applied System Sciences (IIASA) in order to explore demand-side concepts, options and policies which could lead to a low energy demand future. D.I. received funding from the UK Research and Innovation (UKRI) Energy Programme under the Centre for Research into Energy Demand Solutions (Engineering and Physical Sciences Research Council (EPSRC) award EP/R035288/1).

Conflicts of interest declarations

The authors declare no competing interests.

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4 Luxury carbon taxes on household consumption across 88 countries

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Abstract

Equitable climate policies are required for a just and rapid energy transition. Here we model a novel carbon tax design accounting for the distribution of household consumption and carbon footprints across 88 countries covering the global north and south. The policy distinguishes luxury and basic consumption and sets higher carbon prices for luxury. Luxury carbon taxes are progressive by design, even before redistributing revenue, and reduce emissions as effectively as a uniform carbon tax. The policy reduces yearly global household emissions by 6% compared to no policy and inequalities are reduced compared to no policy as well as compared to a uniform carbon tax. By 2050, the policy saves around 100 gigatonnes carbon-equivalents which is nearly one third of what is needed for households to remain within a 1.5 degree consistent climate pathway and 75% of what is needed to remain 2 degree consistent.

Key words: carbon taxes, differentiated carbon pricing, carbon footprints, luxury consumption, inequality, equitable climate policy

4.1 Introduction

Proposed and implemented carbon taxes are uniform across sectors or limited to a few specific carbon-intensive ones like fuel, industry or residential heat (World Bank, 2021c). In developed economies, this design is proven to affect low-income households the most (Feng et al., 2010; Wang et al., 2016) and is not extensive enough to have a profound impact on emissions (Green, 2021). In contrast, what if there was carbon taxation of all household consumption, but with carbon prices varied according to the purpose of consumption? Could this help achieve the Paris climate goals in a fair way? Some emissions are produced while contributing to decent living standards (Rao and Baer, 2012) – they cover essential needs such as housing, cooking or accessing healthcare. Others are generated during the pursuit of luxury – for example when flying long-distance on holiday or driving the convertible Porsche during summer. Affluence drives those emissions, not basic human needs (Wiedmann et al., 2020). The differentiated nature of consumption has been acknowledged for more than a century (Veblen, 1899), with respect to energy and carbon footprints for decades (Shue, 1993), and recently has become a focal point in the analysis of carbon- and energy inequality (Ivanova et al., 2015; Otto et al., 2019; Ivanova and Wood, 2020; Oswald, Owen and Steinberger, 2020; Oswald et al., 2021). It has not been translated into climate policy however let alone into socially acceptable carbon pricing.

Economists traditionally have argued to keep the carbon price uniform across sectors (Hoel, 1996; Bye and Nyborg, 2003). One idea is that uniform carbon prices are optimal because they do not distort marginal abatement curves. A uniform price motivates exactly those abatements that cost less than the price of carbon (Burke, Byrnes and Fankhauser, 2019). Another argument is that since a tonne of carbon emitted has the same impact on the climate irrespective of the source, the carbon price should be fixed (Stiglitz, 2019) and moreover there is concern about cross-border carbon leakage if carbon prices across countries varied (Keppo et al., 2021). These perspectives are production oriented. While it is true that every tonne of carbon emitted is the same to the climate, this is far from accurate from the perspective of demand or social justice, since the same tonne of carbon delivers different benefits depending on who consumes for what purpose and consequentially not every tonne of carbon is equally avoidable (Benoit, 2020). Despite this, in carbon taxation design, social equity is primarily addressed through revenue recycling (World Bank, 2019b; Budolfson et al., 2021), but rarely through differentiating consumption purposes of rich and poor.

Recent studies explore differentiated carbon prices among countries. High-income countries should pay higher prices than low-income ones (Bauer et al., 2020), consistent with the fact that they are historically, and continue to be, the main cause of global warming (Hickel, 2020). Others demonstrate that prices applied to specific sectors, for instance electricity or fuel, vary in distributional impact depending on household spending and energy profiles within countries (Dorband et al., 2019; Steckel et al., 2021). Here we model a policy that takes the distinct consumption purposes of different income classes into account across 88 countries covering the global north and south. The tax distinguishes between luxury and basic consumption purpose. Tax revenue is recycled for retrofitting homes and redistributing to low-income households. We find that luxury carbon taxes are more progressive with respect to emission reductions and financial burden than uniform ones while reducing total emissions to similar extent. By 2050, in a medium scenario, the policy saves around 100 gigatonnes carbon-equivalents which is 75% of what is needed for households to stay within a 2 degree consistent climate pathway but less than a third than what is needed for 1.5 degree consistency and therefore not enough to align household consumption with the Paris climate goals alone by means of carbon taxation.

4.2 Tax design and model

The core idea of the proposed tax is very simple: Differentiate the carbon price according to consumption purpose. In other words, increase the taxes on luxury goods relative to necessities. But distinguishing these seems like a highly contentious task. Who is to judge this categorisation? However, a standard economic approach makes the decision-process straightforward. Luxury goods are defined as having an income elasticity of demand > 1, necessities those with an income elasticity < 1.

Carbon tax rates can be derived via simple multiplication – carbon price multiplied by carbon intensity. Carbon intensity refers to the amount of emissions embodied in a good or service per unit of money spent. If *p* equals price and *c* equals carbon intensity, then the tax rate τ for a good is defined as:

$$\tau = c * p \tag{4-1}$$

Indices distinguishing each good are omitted from equation (4-1). The twist is multiplying by the respective income elasticity of demand ϵ_d.

$$\tau_{luxury} = c * A * p * \epsilon_d \tag{4-2}$$

We weight the carbon prices linearly employing the elasticities ϵ_d of each good and use a normalisation factor *A* to preserve the average carbon price.

The logic behind this procedure is twofold: By integrating the elasticity we integrate distributional information and create non-arbitrary price differentials and by keeping the average costs of carbon constant, we ensure that the information of how strong the price signal has to be in order to achieve a certain goal (e.g. net-zero emissions or internalizing social costs of carbon) is preserved. From here on we name this tax design ‘luxury tax’.

Another critical component of the tax design is how the revenue is recycled. We invest revenue into retrofitting homes and redistribution. Residential energy makes up 45% of household energy consumption (Oswald, Owen and Steinberger, 2020) and 31% of emissions (in carbon dioxide equivalents, relative to energy, emissions are more skewed to other sectors e.g. food). Most people’s wellbeing relies on residential energy, yet low-income households often struggle to afford sufficient quantities. Instead of levying a heavy tax on emissions in this sector, as a uniform carbon tax would, we explore a public investment program to reduce energy demand and therewith emissions.

We model a data-driven proof-of-concept employing a dual strategy. First, we build a static-comparative model of carbon taxes on household consumption for 88 countries in 2019 (covering more than 90% of the global population and GDP). We explore the distributional implications with respect to emission reductions (and with respect to financial burden in Supplementary Figure 5 for comparison) and apply the terms progressive and regressive accordingly. The focus on emissions emphasizes individual contributions to climate targets. For comprehensive policy appraisal, we quantify impact on total emissions over time employing a dynamic model and therewith contribution to the Paris climate goals. Figure 4-1 displays the structure of our study.

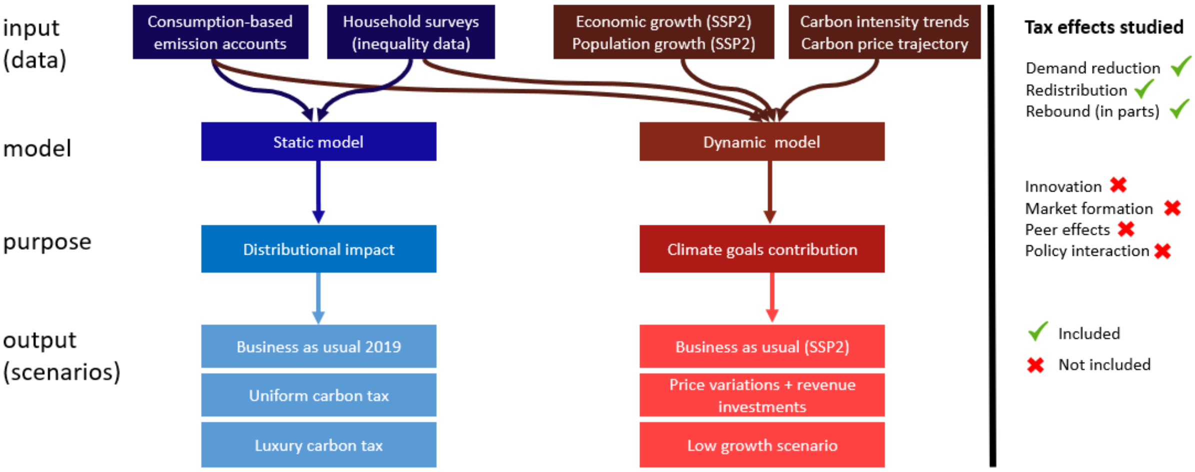

Figure 4-1: Study overview

Notes: This figure illustrates the overall structure of the study. We employ two modelling approaches for complementary purposes – static for distributional impact and dynamic for climate goals contribution. The figure is segmented into four levels vertically and two sections horizontally. The vertical levels refer to the model flow. The left section (blue shades) displays the static model. The right section (red shades) depicts the dynamic model. The right of Figure 4-1 depicts the scope of effects studied.

4.3 Results

4.3.1 Inequalities in emissions and consumption

Carbon inequality has previously been demonstrated to be large between and within countries, with the global top 10% being responsible for almost half of all emissions (Chancel, 2021). We test this finding based on our model of household emissions. We find the international Gini coefficient of household emissions is 0.56 and the global top 1% are responsible for ~10%, the top 10% for 45% and the bottom 50% for less than 15% of emissions. The USA alone accounts for 25% of household emissions, China for 18 % and India for 9%. Top and bottom percentiles for the USA, China and India are indicated in Figure 4-2 Panel (a) confirming large international and national disparities. We show the modelled distribution for 2019 (blue line) plotted against the empirical distribution for 2011, the latter is directly based on household surveys and a Multi-Regional Input-Output model (orange-dashed). Moreover, we estimate income elasticities of demand for 14 consumption categories across all countries and plot them against the corresponding national Gini coefficient for that consumption category in Figure 4-2 Panel (b). There is a substantive correlation supporting our use of elasticities to infer about the distribution of consumption. Figure 4-2 Panel (c) illustrates an example of carbon prices in the luxury tax scenario compared to the uniform tax scenario for the USA across all 14 consumption categories. Given our tax design, the price differences are explicitly determined by the relevant inequalities of consumption. In both cases, the average carbon price is set at $150 per tonne (blue bars).

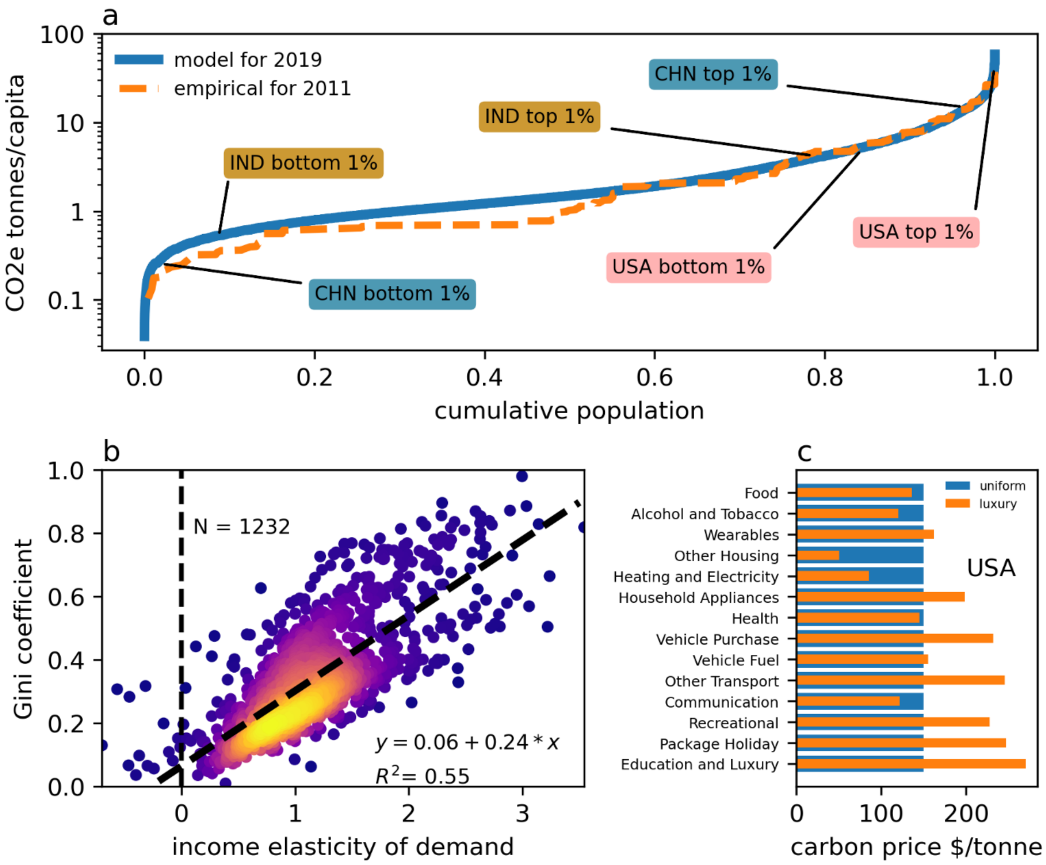

Figure 4-2: Data and model features

Notes: Panel (a) depicts the modelled international distribution of consumption-based emissions per capita in 2019 (blue line). It indicates the position of American, Indian and Chinese top and bottom percentiles. It also plots the original data for 2011 which is not interpolated or updated to 2019. Panel (b) illustrates the correlation of income elasticity of demand (ϵ_d) and Gini coefficient across all 88 countries and all 14 consumption categories. It demonstrates that most consumption categories considered are 'normal goods' (i.e. $\epsilon_d > 0$). The data exhibits heteroscedasticity but we plot a linear least squares regression simply to demonstrate the correlation trend. Panel (c) illustrates the 14 consumption categories we consider plus carbon prices for the USA under a uniform and luxury tax scenario.

4.3.2 Distributional implications: Uniform tax vs. luxury tax.

Traditional carbon taxes are financially regressive because they apply the highest rates to energy necessities like heating or fuel (Dorband et al., 2019). Here we test how regressive or progressive a carbon tax is with respect to emissions per capita if applied to all of household consumption and how this depends on the tax design: uniform vs. luxury. In both scenarios, the tax reduces global household emissions by 6% and international Gini coefficients are reduced only marginally from 0.56 to 0.55. National Gini coefficients are reduced marginally but consistently across countries by up to 6% relative to the uniform tax scenario. Panel (a) in Figure 4-3 plots national emission reductions against the tax revenue as a proportion of GDP. In high-income countries, tax revenue constitutes ~1-4% of total GDP. For the remaining country types this is substantially less at ~0.1% to ~1%. National tax revenue as a share of GDP ranges roughly over two orders of magnitude and so do national emission reductions from ~0.1% to ~10%. The relationship between the two variables is linear. There is a tendency to generate less revenue under the luxury tax but to reduce emissions more. Average national emission reductions are 4.4% in the uniform scenario and 4.8% in the luxury scenario. This is because the luxury design shifts taxes to price-responsive goods, i.e. elastic demand. Households are more likely to forego this consumption when a tax is applied resulting in more emission reductions but also less tax revenue. For instance, a wealthy city-dweller might only use their car for weekend leisure but not for commuting or shopping and thus is not reliant on the car for elementary needs satisfaction. This is an overlooked property of demand in climate mitigation strategies. Panel (a) in Figure 4-3 highlights the USA and South Africa as both important representatives of the global north and the global south respectively. US household emissions reduce by ~8%, which is a ~6% reduction with respect to total emissions (including government and capital formation). This reduction is roughly the same in the luxury and uniform scenarios (~0.4 GT) and is almost twice as much as total annual household emissions in South Africa. South African household emissions reduce by ~6.5% percent in both scenarios, equivalent to ~3% of total emissions.

Panel (b) in Figure 4-3 plots the distributional implications for USA and in South Africa. The black line represents the national distribution of emissions per capita. The lowest US household percentile emits about 5 tonnes/capita/yr, the highest around 50 tonnes/capita/yr. The distribution in South Africa covers a wider range with 50% of the population emitting less than 4 tonnes/capita/yr, the lowest percentile ~0.2 tonnes/capita/yr and the highest ~40 tonnes/capita/yr. The blue lines represent the reductions in emissions per capita in a uniform tax scenario. In the USA, the uniform tax is regressive, as expected because high carbon intensity consumption like transport fuel is high even among low-income households. In South Africa, in contrast, even the uniform tax is progressive. The lowest 20% abate far less emissions than the upper 80%. This is because the lowest 20% spend a much larger fraction of their income on food than is common in high-income countries (40% on average compared to 15% on average in the USA). In both countries, the luxury tax is progressive.

Panel (c) in Figure 4-3 generalizes the results from Panel (b) across all countries. It shows a simplified measure of how progressive the tax policy is. We measure the difference in percentage points of emission reductions between the bottom and top percentile for each country (1st percentile – 100th percentile). If the 1st percentile reduces emissions more than the 100th percentile, then the difference is positive and the tax is regressive. If the 1st percentile reduces emissions less than the 100th percentile, the difference is negative and the tax is progressive. We calculated these differences for both tax designs. The difference for the uniform one is plotted on the x-axis and the difference for the luxury one on the y-axis. If both policies are progressive the difference between bottom and top percentile is negative for both (lower-left quadrant). South Africa is a typical representative of this quadrant. The majority of countries end up in this quadrant which is evidence against the common narrative that carbon taxes are generally regressive. If applied to all consumer goods, and when considering impact on emissions per capita, they are more often progressive than regressive. However, there are also important cases where the uniform tax is indeed regressive and only the luxury one progressive as for instance the USA, UK, Germany and other industrialised economies (lower-right quadrant). The cases where both are regressive or only the luxury one is regressive do not occur. Only China exhibits very slightly regressive but nearly flat behaviour under both policies. The Chinese indifference to tax design originates from high spends on residential energy use across all income groups, but relatively low spending on private transport and other luxury consumer goods. Income elasticities in China are also all relatively close to 1, thus price differentials in the luxury scenario are not so pronounced (see Supplementary Figure 3). Panel (d) illustrates emission reductions across sectors in the USA and South Africa. The uniform tax reduces residential emissions substantially in both countries while the luxury tax design affects other consumption categories more strongly.

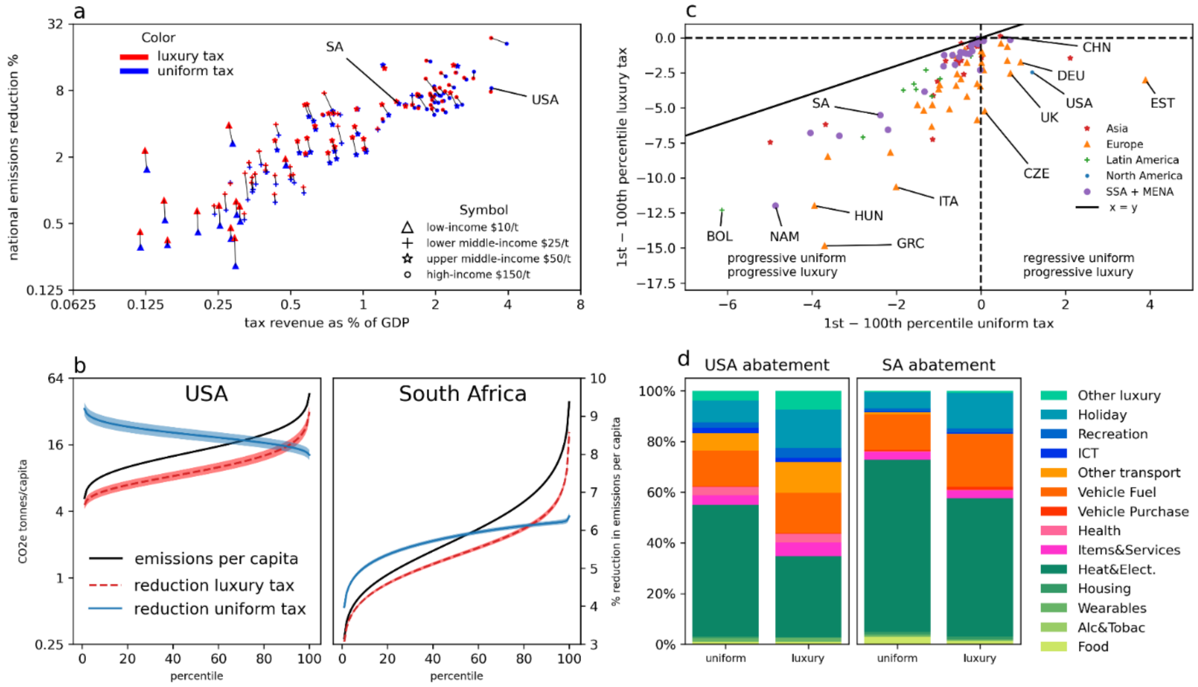

Figure 4-3: Distributional implications uniform tax and luxury tax

Notes: All results in this figure are averages over 100 simulation runs. The stochastic component is in the price elasticities of demand. Panel (a) plots national emission reductions vs. revenue as percentage of GDP. Red markers denote the luxury tax scenario and blue ones the uniform tax scenario. Panel (b) plots the emission distribution per capita for the USA and South Africa (left y-axis and black line) on a log-scale as well as the reduction in emission per capita under the uniform (right y-axis and blue line) and the luxury tax (right y-axis and red line) scenario on a linear scale. The range indicates the 99% confidence interval demonstrating that uncertainty in tax responsiveness is low. Panel (c) classifies progressivity of the uniform tax and luxury tax into two quadrants: regressive uniform and progressive luxury (lower right), progressive uniform and progressive luxury (lower left). The x-axis measures the difference in percentage emission reductions between top and bottom percentile in the uniform scenario. The y-axis does the same for the luxury scenario. The plot shows that in most countries both policies are progressive but the luxury scenario even more so. Nearly all points fall below the x = y line.

Overall, the luxury tax design improves the progressivity of carbon taxation across all countries. The degree to which it does so depends on various factors. For one, it depends on how large the variance of elasticities is. If the variance of elasticities is large, it amplifies the price difference between the uniform and the luxury scenario and consequently the difference in impact. The composition of consumption across categories plays a role too. Concentration of consumption in a specific category constrains the difference between uniform and luxury tax. For instance, in several low-income countries in Sub-Saharan Africa, food is a dominating category and here the difference between uniform and luxury tax is not very large. Another decisive factor is the average income of a country. The wealthier a country is, the lower are income elasticities of carbon intensive transport (Budolfson et al., 2021) and low carbon intensity luxuries (e.g. financial services) are consumed extensively by high-income households. Hence uniform carbon taxes tend to be regressive and switching to a luxury-focused design makes a great difference. For example, in North America and Europe driving a car is common even among low-income households yet spending a lot on financial services remains concentrated in high-income segments. In contrast, in Egypt even driving a car is predominantly concentrated in high-income segments and hence a uniform carbon tax is progressive already. Therefore, all countries benefit from a luxury tax in terms of fairness but the greatest 'fairness' gains are made in high-income countries. This finding holds in terms of individual emissions as considered above but also in terms of financial burden expressed as the share of disposable income spent on the tax. Figure 4-4 illustrates the relationship between GDP per capita and the additional 'fairness' (progressivity) gained by implementing a luxury carbon tax design compared to a uniform one.

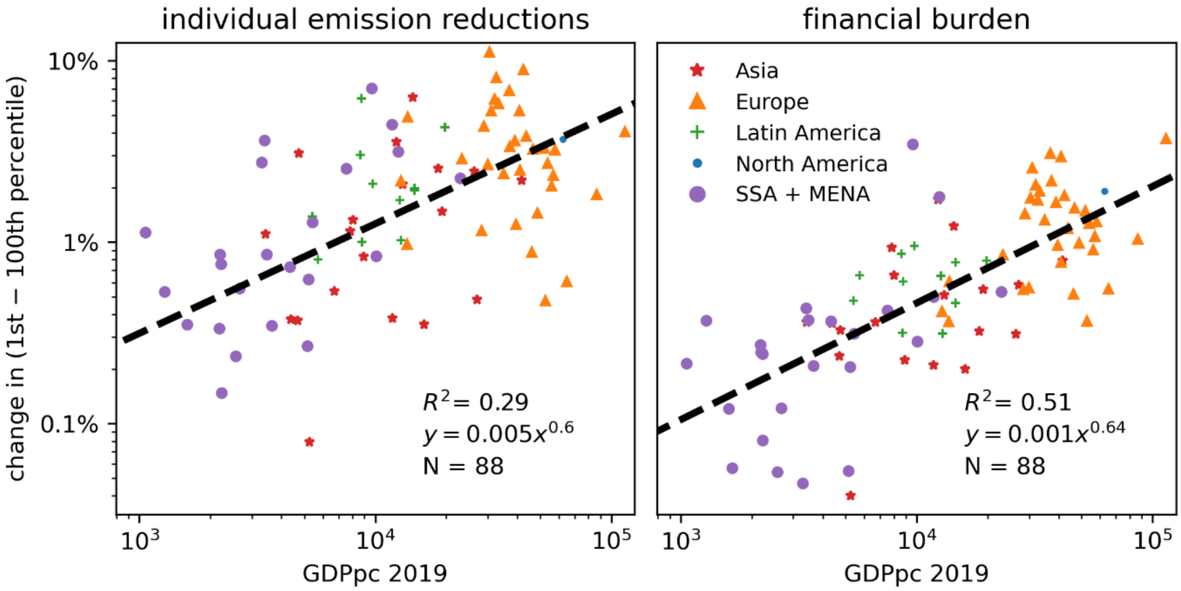

Figure 4-4: Progressivity gain from luxury carbon tax compared to uniform carbon tax
The 'fairness' (or more precisely progressivity) gain is measured by considering the difference (between luxury and uniform design) in differences (between the top and bottom percentile) as illustrated in Figure 4-3 Panel (c). Figure 4-4 on the left side shows the 'additional progressivity gained' through the luxury design with respect to individual emission reductions. It displays how much the gap in percentage emission reductions between the top 1% and bottom 1% amplifies in favour of the bottom 1%. Figure 4-4 Panel (b) illustrates the same but in terms of financial burden i.e. the share of disposable income that is spent on the tax. Clearly the effect of a luxury tax scales with the average income (GDPpc) of countries. It is thus most beneficial to introduce luxury carbon taxes in high-income countries to achieve fair climate policy. One outlier, Madagascar, on the left side of the plot is not depicted.

Table 4-1 summarises a few international statistics across major countries and aggregate regions.

Table 4-1: Tax design impact comparison

		World	**USA**	**South Africa**	**China**	**India**	**Europe**	**SSA+ MENA**	**Latin America**	**Rest of Asia**
Total emissions reductions	Luxury	6%	7.8%	6.3%	5.0%	1.6%	7.0%	3.3%	3.5%	7.5%
	Uniform	6%	8.4%	6.1%	5.2%	1.3%	6.6%	3%	2.8%	7.5%
Revenue from national top 10 %	Luxury	25%	23%	51%	34%	24%	23%	38%	41%	24%
	Uniform	23%	21%	44%	33%	20%	21%	33%	35%	22%
Revenue from luxury (ϵ_d>1)	Luxury	52%	42%	53%	44%	43%	65%	50%	63%	63%
	Uniform	37%	27%	36%	37%	24%	48%	34%	45%	50%

4.3.3 Tax revenue with multiple objectives

Several planned carbon tax policies have been rejected by the public because they put a high burden on low-income households (Congress, 2021; Mehleb, Kallis and Zografos, 2021). But carbon taxes can even decrease poverty if revenue is redistributed appropriately. For example, it has been shown for Peru that at a carbon price of $50/tonne, extreme poverty could be reduced by 17% if revenue is redistributed to the poorest (Malerba, Gaentzsch and Ward, 2021). This offsets some of the abated emissions, so there is a short-term trade-off between social protection and mitigating emissions. But can we find a revenue allocation where carbon emissions are reduced by a large margin while low-income households are protected from the tax? For answering this question, we conduct a simple numerical experiment: Every country redistributes the tax revenue back to a specified number of households starting with the poorest. The revenue is spent such that their prior consumptions levels are retained and recipients are effectively exempted from the tax. In the first round, only the first percentile is paid back, then the first plus the second, then first plus second plus third and so forth. The remaining revenue after redistribution is invested into retrofitting homes. We did this across all countries and aggregated the results in Figure 4-5 (a) – (c). Figure 4-5 Panel (b) demonstrates how the investments affect emissions. It shows that redistribution increases emissions because it increases consumption. Retrofitting further lowers emission. We plot the magnitude of the effect. At a maximum, if all revenue is invested into retrofitting, it lowers total household emissions by another 1%. Here it is important to keep in mind that this result concerns only one year of revenue recycling. Over several years, let us say 10 years, investments in retrofits can therefore reduce global household emissions by ~10%. Reductions achieved through retrofits are also permanent and thus the effects of retrofitting are substantial. In case all revenue is redistributed back to households, it offsets nearly all emission reductions prior to revenue recycling, which is roughly ~6%. Figure 4-5 Panel (b) also shows the point where the two mechanisms, redistribution and retrofitting, cancel each other out. This ‘zero-trade-off point’ is roughly located at the 35th percentile. From a global perspective ~1/3 of the population can benefit from redistribution without compromising climate mitigation at all. Figure 4-5 Panel (c) shows the reductions in emissions (y-axis) as a function of how many percentiles receive revenue redistribution. Per country decision-making is more policy relevant. Therefore, in a next step, we calculate the zero-trade-off point for every country. Panel (d) correlates the national zero-trade-off points with the national Gini index of consumption expenditure. The correlation is modest but statistically significant and important. The higher the inequality of consumption in a country the more households can receive redistribution, starting with the poorest, without offsetting reduced emissions. The most redistribution can, and thus arguably should, happen in unequal societies in Latin America and Africa including South Africa. In these countries then, richer percentiles would fully carry the burden of reducing emissions. Panel (e) illustrates the lesson learned that revenue allocation should not just depend on the absolute level of income (GDP/capita) but also on the inequality of household consumption.

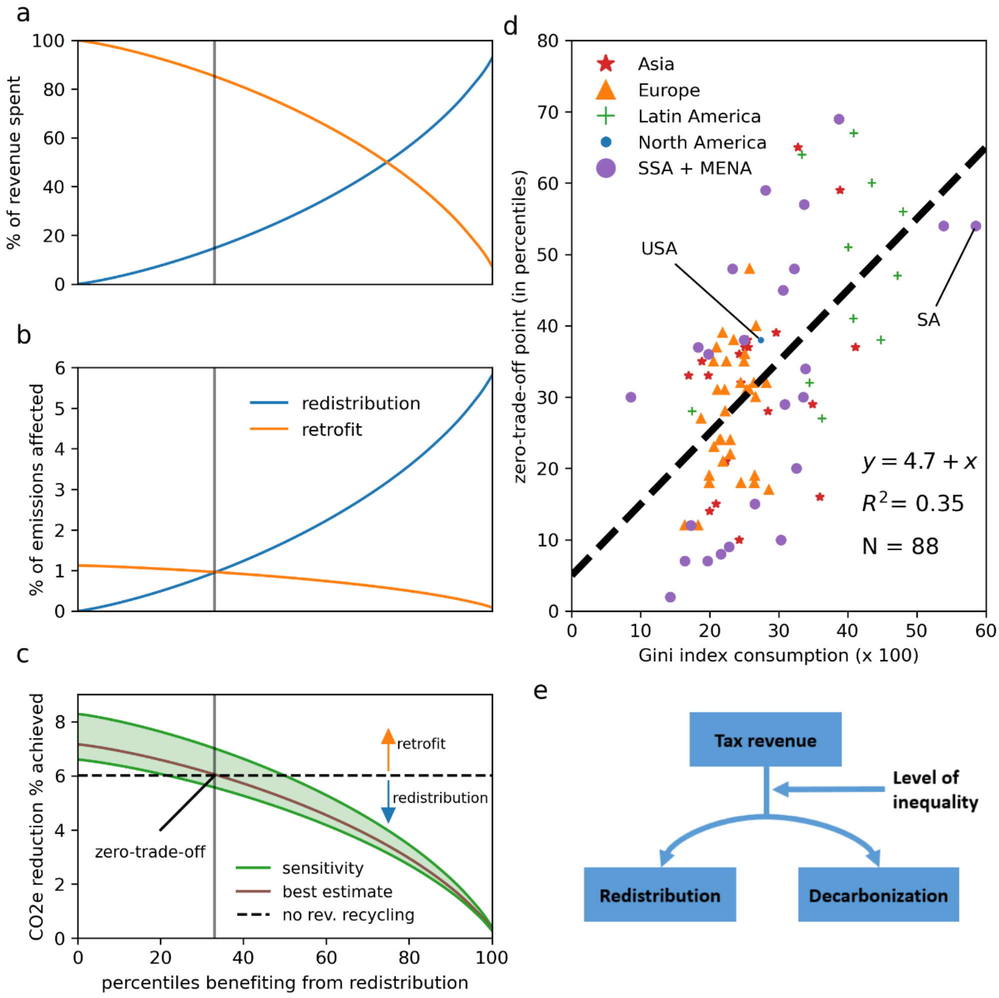

Figure 4-5: Revenue recycling trade-off

Notes: Panel (a) illustrates the share of revenue that is spent on redistribution (blue) or retrofit (orange) as a function of how many percentiles benefit from redistribution. The x-axis is plotted below Panel (c) and is the same for Panel (a) to (c). Panel (b) shows the effect on emissions. We plot the magnitude of the effect. Redistribution increases emissions. Retrofit reduces emissions. Panel (c) depicts how revenue allocation interferes with yearly emission reductions. The horizontal dashed line indicates how much emissions are reduced by the luxury carbon tax policy without investing any revenue. To the left, when x equals zero, no household receives redistributed revenue and all revenue is used for retrofits. The green range indicates a sensitivity analysis where the upper and lower bounds represent a doubling and halving of retrofitting costs respectively. To the right, when x equals one hundred, every percentile receives redistributed revenue. Panel (c) also points out the global zero-trade-off point. This is the point where revenue is allocated to retrofitting and redistribution such that it does not interfere with the yearly emissions balance of the carbon tax. Panel (d) plots the Gini index of consumption expenditure per country (x-axis) against the national zero-trade-off points (y-axis). Panel (e) illustrates the lesson learned that more revenue should be allocated to redistribution if consumption inequality is high.

4.3.4 Tax dynamics

Carbon taxes and their distributional implications are often exclusively studied in a static comparative model probing the very short-term consequences. But carbon taxes are part of dynamic and complex economies and their success ultimately depends on emission abatement over time. At a minimum then, it should be tested how the luxury carbon tax performs when facing ongoing economic growth and population growth. Here we distil a simple dynamic model in order to evaluate impact on the Paris climate goals. The model builds on 'vectors' of household consumption for 88 countries from 2020 to 2100. Figure 4-6 illustrates the structure of the model with (v) denoting exogenous parameters that vary with each scenario and (f) fixed in all scenarios.

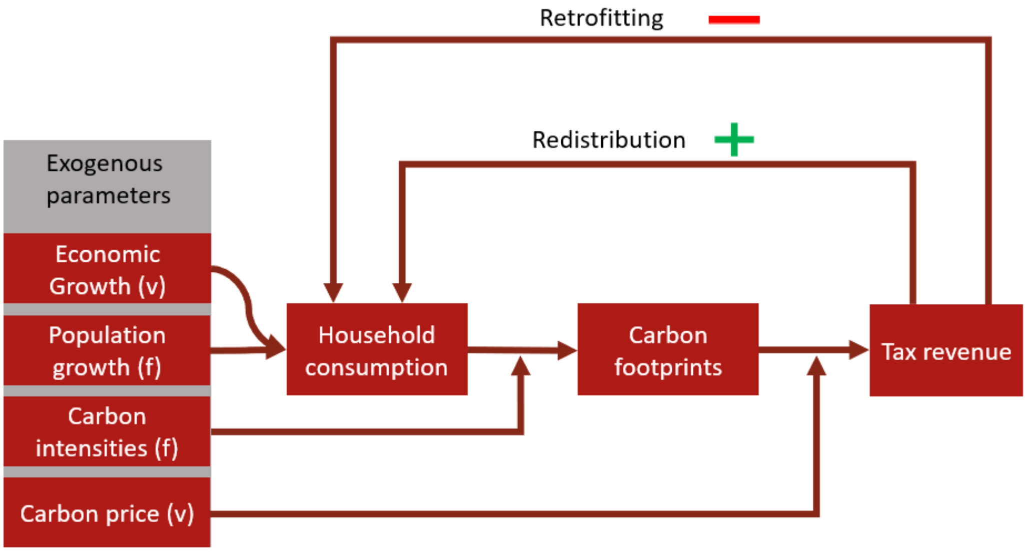

Figure 4-6: Dynamic model structure
Notes: This figure illustrates the core structure of the dynamic model. Exogenous drivers are economic growth, population growth, carbon intensity evolution, and carbon prices. Endogenous variables are household consumption, carbon footprints and tax revenue. Retrofitting of dwellings is a negative feedback and redistribution is a positive feedback. Retrofit reduces demand and thus reduces tax revenue and redistribution increases demand and thus increases tax revenue. However, the system exhibits no escalating or stabilizing behaviour emerging from these feedbacks. The magnitude of the effects is too small.

There is a range of scenarios. All scenarios differentiate prices by country type and assume a linear carbon price trajectory as outlined in the method section 'Average carbon prices and price trajectories'. Table 4-2 provides a scenario overview.

Table 4-2: Dynamic model scenario overview

Scenario key	BAU	LP	MP	HP	LP.RR	MP.RR	HP.RR	LG1	LG2
Scenario	Business as usual	Low price	Medium price	High price	Low price, retrofit, redistr.	Medium price, retrofit, redistr.	High price, retrofit, redistr.	Low growth, medium price	Low growth, low price
Luxury carbon tax	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Retrofit	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Redist.	No	No	No	No	Yes	Yes	Yes	Yes	Yes

4.3.5 Towards the Paris Agreement

First, we explore the influence of the average carbon price by employing three distinct price scenarios: Low price, medium price and high price. The goal is not to find the optimal carbon price but to test the model sensitivity. We compare each scenario to a business-as-usual counterfactual and a 2 degree consistent emission pathway as well as 1.5 degree consistent pathway. Figure 4-7 Panel (a) plots the carbon prices introduced in 2022 across country types and price scenarios. Panel (b) illustrates the linear carbon price trajectories for high-income countries across price scenarios

The low price scenario (LP) (blue line in Figure 4-7 Panel (c)) substantially reduces emissions compared to business as usual (red line Figure 4-7 Panel (c)). By the end of the century ~180 GT are saved cumulatively speaking. This is significant but far less than what is needed for household emissions to stay within a Paris-consistent pathway. For comparison, 180 GT are required by 2039 for the 1.5 degree pathway. However, given that our model focuses on selected tax effects like demand reduction and revenue recycling but not on innovation or social tipping points (Otto et al., 2020), it is not expected to fulfil the Paris agreement on its own. Nonetheless, the high price scenario (HP) alone achieves savings consistent with a 2 degree pathway by 2040 and abates cumulatively ~70 GT emissions up to this point. Revenue recycling further increases carbon savings. Investing into retrofits alongside high carbon prices achieves consistency with a 2 degree pathway (HP.RR scenario) until nearly 2050. The 1.5 degree pathway, however, stays out of reach even with the most ambitious policy. Only in the very short-term (the first 3 years) does the high price scenario reduce demand enough to stay within the 1.5 degree pathway. Afterwards the effect of setting a high carbon price is overwritten by ongoing economic growth. Notably, under all scenarios global household consumption keeps growing albeit at lower rates than under business as usual. Consumption growth pathways are depicted in Supplementary Figure 8. The higher the carbon prices, the lower is consumption growth. Accordingly, the lowest emissions occur for low growth pathways. In the low growth scenarios (LG1 + LG2) we reduce economic growth rates across all countries and years by 50%. LG1 applies medium carbon prices and LG2 low ones. When global growth is already low, it is reasonable not to overprice emissions. The LG1 pathway is the only pathway which is 2 degree consistent beyond 2050. Note that we do not distribute growth rates in an equitable manner. In the real world, it is advisable that developing nations maintain high growth rates until they reach a decent level of income while rich nations enter a steady-state of throughput or even decrease output towards sustainable levels (O'Neill et al., 2018). Later this century, when carbon intensities are low through technological progress but global GDP further growths, luxury carbon taxes have little impact. For the second half of the century there must be other mechanisms in place for reducing emissions to zero. This could be a mix of post-growth policy and radical technological innovation, such as for instance absolute caps on conspicuous consumption plus entirely novel materials and energy carriers.

4.3.6 Financial rebound and low policy adoption

The modelling approach in this study is proof-of-principle, not a realistic assessment of future events and there are various limitations to the current model. As economies become more energy efficient, studies suggest rebounds of up to 50% (Chitnis et al., 2013; Brockway et al., 2021). Here we do not measure energy rebound but we do take financial savings into account. The principle is similar – savings in one place lead to expansion in another or even in the same sector. After taxation, households have a different spending profile than before taxation. Most of the time the difference in their total expenses is minor (<1%). Demand reduces, but they have to pay the tax and so households roughly end up with overall expenses similar to before taxation. Sometimes, the sum of expenses ends up less than before tax and thus they save money. A more substantial saving occurs after retrofitting a household. According to our model, this reduces spending on heat and electricity by 50%. This money is then free to be spent elsewise. We estimate how financial rebound affects global emissions trajectories in a medium price scenario by assuming an average consumption basket with average carbon intensity at every time step. We find the effect to be of modest magnitude. By 2030 cumulative differences in emissions are ~2GT across all countries and by 2050 they are ~20GT. The effect by 2050 is substantial but less than for example the difference between the low price and the medium price scenario at cumulatively ~32 GT until 2050.

Further, there are numerous real-world barriers to implementation of the here proposed policy. The biggest barrier is that few or no countries adopt a carbon tax as stringent as proposed. Therefore, we take into account a corresponding sensitivity analysis with respect to the medium price scenario. What if only the USA adopts the policy or only Europe? What country has the largest impact on global emissions? We measure how cumulative emissions savings change as a function of the countries adopting the policy. The results are depicted in Figure 4-7 Panel (e). The USA would be the most significant country to adopt a luxury carbon tax on household consumption, followed by Europe, India, Russia and China. Over time, India would be more significant than China, even if they both introduce the same average carbon price. The carbon intensity of consumption decreases twice as fast in China as compared to India and Chinese population growth and economic growth slow down over time.

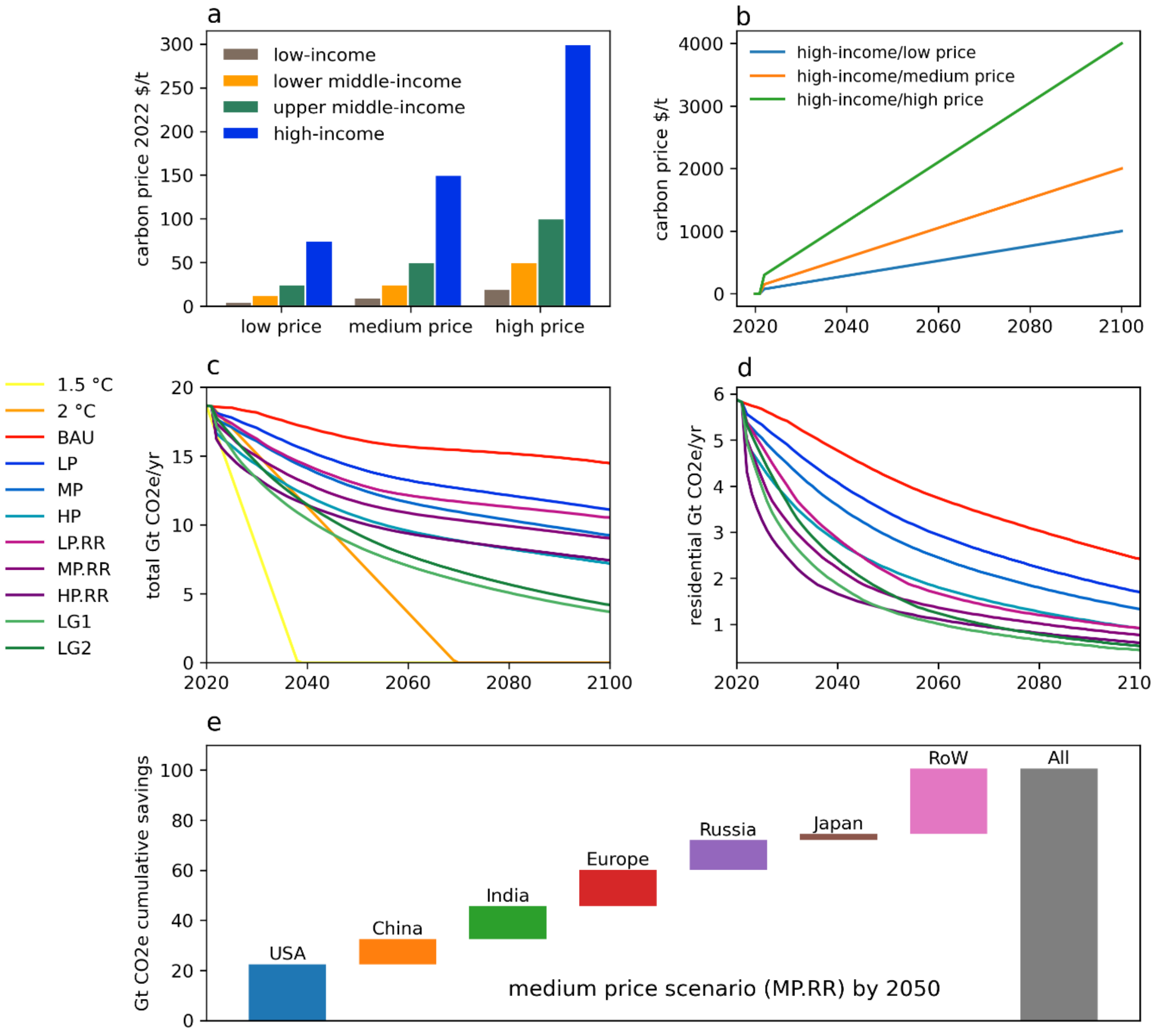

Figure 4-7: Emission pathways for household consumption in 88 countries

Notes: Panel (a) illustrates the initial carbon price level across scenarios. It also depicts the prices distinguished by country income level. Panel (b) shows how carbon prices change over time for high-income countries. The trajectories are linear after initial prices are introduced in 2022. Panel (c) shows total household emissions over time. The business as usual scenario is the red line. The linear slopes are the 1.5 degree (yellow) and 2 degree (orange) consistent pathways. Panel (d) shows emission pathways for residential energy use (heating and electricity) across all scenarios. Panel (e) shows cumulative emission savings by 2050 in the medium price plus retrofit and redistribution (MP.RR) scenario.

4.4 Future-proof climate policy

In Northern winter 2021 the energy crisis and inflation are in full swing. Europe faces gas and fuel shortages. Asian post-pandemic recoveries suffer under limited coal supply. Renewable energy supply has grown fast but not fast enough (Vinichenko, Cherp and Jewell, 2021). Making climate policy effective and equitable in times of severe supply constraints is a tough nut to crack. While the reasons for the crisis are manifold, ranging from a post-pandemic surge in demand to geo-political gambling, in the long-run costs always end up with households. At least, climate policies should take high-income households stronger into account than low-income ones. Here we have shown that luxury carbon taxation does that in a large number of countries in the global north as well as the global south. Despite advantages over conventional designs, luxury carbon taxation of household consumption only contributes significantly to the Paris climate goals if introduced promptly, universally and with high and rapidly rising carbon prices as compared to any policy currently in place. Although in 2021 the European Union Emission Trading Scheme's carbon price has reached all time heights (~100$/tonne), this policy still covers only 40% of European emissions and thus a fraction of what is needed globally. The scope of carbon pricing urgently needs to be extended. The USA could set an example. They are the largest emitter with respect to households and they carry huge historic climate debt. Demand-oriented climate policies in the USA could help achieve national and global climate goals. A luxury-focused design perhaps optimizes US carbon tax efforts with respect to effectiveness, justice and feasibility.

The purpose of this study is not broad discouragement of materialistic lifestyles. Luxury carbon taxes are not sin taxes, they are ecologically motivated and are considerate of distributional implications. They originate from a realist's perspective on global problems. Climate change and biodiversity decline are threats to the long-term prospects of human civilization and so far technological evolution has not caught up with the massive scale of economic output and its impacts (Haberl et al., 2020). Penalizing and reducing the output in parts must be an option. If future generations have fully solved some of the technological and social challenges we face today, for instance zero emission flying available on an equitable per capita basis, they might then release these activities from restraints. It cannot remain status quo to continue environmentally damaging luxury activities unabated while awaiting a technology fix.

As the 21st century progresses, the global economy evolves. Previously unthinkable markets emerge at record pace. Decentralized digital currencies and private space voyages are now ordinary. This creates novel challenges for climate policy and luxury carbon taxation in particular. In all likelihood, policies require a much higher degree of adaptation over time with respect to distinct markets than we have considered. For example, private space trips might not be affected much by a carbon price of any level as the financial resources of potential customers are vast and we have no information about how (if at all) this market responds to price changes. In any case, while luxury consumption remains prevalent alongside widespread deprivation around the world, tackling it should be a key part of climate policy.

4.5 Methods

4.5.1 Household consumption and emission accounts

The household accounts for consumption and emissions comprise 88 countries (including Europe, USA and BRICS nations). The years represented are 2019 in the static model, so pre-pandemic conditions, and 2020 – 2100 in the dynamic model. Emissions due to capital formation and government expenditure are not included. For a comprehensive list of countries please see Supplementary Table 1. Consumption is measured in international dollars $PPP at constant 2017 prices. The emission accounts are carbon equivalents. Besides carbon dioxide, methane, nitrous oxide and various F-Gases are included and appropriate global warming potentials have been applied (Brander, 2012). The emission accounts have been calculated employing a Multi-Regional Input-Output (MRIO) model based on the Global Trade Analysis Project (GTAP 9) for the year 2011 on the basis of a standard Leontief-matrix approach. The MRIO model is used to inform emission intensities and household accounts but is not further interacted with in the study. This means we do not test changes in the technology matrix and trade relationships of countries. Household consumption per income group is derived from the Global consumption database (World Bank, 2018) and Eurostat household data (Eurostat, 2015) in line with Oswald, Owen and Steinberger (2020); Oswald et al. (2021). For the USA and Japan, household surveys are from the U.S. Bureau of Labor Statistics (US Bureau of Labor Statistics, 2012) and the Japanese Statistics Bureau (Statistics Bureau Japan, 2019), respectively. Consumption has been aggregated to 14 categories according to type and purpose. Subsequently, we projected the data to 2019 combining national account data on household consumption from the World Bank (World Bank, 2019a), national population data from the World Bank (World Bank, 2021b) and historical trends of consumption-based carbon intensities from the Global Carbon Project (Global Carbon Project, 2021) for the years 2010-2018. The household consumption data from the World Bank and the carbon accounts from the Global Carbon Project are national aggregates. Therefore, the growth rates applied from 2011 to 2019 are uniform averages. This is less realistic than using a specific growth rate for each consumption category but it preserves the proportions of consumption and emissions estimated in line with the 2011 household surveys.

4.5.2 Interpolation of consumption

A good approximation to household expenditure distributions is a log-normal distribution (Battistin, Blundell and Lewbel, 2009). We interpolate from four or five income groups for each country to percentiles. This is done for consistency across countries and detail with respect to high- and low-income groups. First, we calculate a Gini coefficient per consumption category. Every Gini coefficient corresponds to a lognormal model via the following equation where σ denotes the log standard deviation, *G* the Gini coefficient and erf the error function (Crow and Shimizu, 1988).

$$G = erf\left(\frac{\sigma}{2}\right) \tag{4-3}$$

Solving for σ and combined with the mean of the data we can solve the cumulative quantile function of a lognormal distribution for population percentiles. The quantile function is as follows.

$$exp\left(\sqrt{2}\sigma erf^{-1}(2p-1)+\mu\right) = x \tag{4-4}$$

Here exp denotes the exponential function, erf^{-1} the inverse error function, p the upper percentile bound, μ the mean of the lognormal values and x the estimated income at the upper percentile bound. Deploying x, we estimate the consumption per category and per percentile and fix the distribution mean. Consumption category indices are omitted in equation (4-3) and (4-4) for simplicity.

Additionally, we interpolated gaps in the original data. For instance, for a few countries there is no reported data on the category package holiday. Data gaps occur in package holiday, recreational items and in vehicle purchases. We interpolate using a constant income elasticity of demand of 1. This way we operate with the reasonable assumption of demand proportional to income. The interpolated expenditure always constitutes 1% of total expenditure per capita. This percentage corresponds roughly to the global average in the named categories. An alternative approach would be to fill gaps by shifting expenditure from other consumption categories but this requires more assumptions about the detailed composition of expenditure. The proportion of all data points to be interpolated is ~3% but nearly negligible in terms of consumption volume and emissions. The interpolated data accounts for an additional 0.2% of consumption and another 0.5% of emissions. The additional emissions are based on the average global carbon intensity of the respective category.

4.5.3 Data cleaning

We removed a few outliers from income elasticities of demand and carbon intensities. The number of outliers is minor. In terms of income elasticities we assumed inferior goods ($\epsilon_d < 0$) to be normal goods with low elasticity ($\epsilon_d = 0.1$). This assumption is also of practical importance so that demand changes resulting from price changes do not exhibit opposing income and substitution effects (Autor, 2016). This concerned 14 values in the category Alcohol and Tobacco which is ~1% of all data. In terms of carbon intensities, we removed the outlier 'Heating and Electricity' in Belarus with a value of 92 kg/$. The value seems unrealistic and likely due to poor data quality on household spending in Belarus. None of these choices has a major impact on our results.

4.5.4 Income elasticity of demand

Why use the income elasticity of demand to adjust the carbon price? A high-income elasticity indicates that few rich people consume a good extensively while most people very little. An elasticity well below one suggests that a good constitutes a largely fixed amount across households' consumption baskets and a smaller share out of total for wealthy households. Therefore, the elasticity integrates information about the distribution and purpose of consumption (see Figure 4-2 Panel (b) for the correlation between income elasticity and Gini coefficient across 88 countries and 14 consumption categories).

An income elasticity is empirically derived via equation (4-5).

$$\log(Y) = a + b\log(X) \tag{4-5}$$

Where *Y* is consumption per good (i.e. one specific consumption category) and *X* is disposable income approximated by total expenditure. The coefficient *b* is the income elasticity of demand and otherwise denoted ϵ_d in this study. It represents how much the consumption in *Y* changes, given a change in *X,* and *a* is a coefficient estimating the income-independent part of consumption (Bofinger, 2019). When *b* is large, then *a* is small and vice versa. This is because when consumption is sensitive to the level of income, the income-independent component is small. Both, *a* and *b* are parameters describing the distribution of consumption across households but knowing *b* suffices. Equation (4-5) can be transformed into a power law of the following form.

$$Y = a * X^b \tag{4-6}$$

This form illustrates that consumption follows a non-linear pattern and the elasticity defines the scaling behaviour of consumption with disposable income. We find the income elasticity is in 98% of cases a number between 0 and 3.

4.5.5 Tax responsiveness

Modelling taxation across 88 countries requires pragmatism. We evaluate the households' responsiveness to the carbon tax by employing price elasticities of demand. The price elasticity ϵ_p is a standard parameter in economics and estimates the percentage change of quantity demanded in response to the percentage change in price. Again, for clarity we omit product indices. The price elasticity of demand is given by the following identity where *Q* denotes quantity and *P* price.

$$\epsilon_p = \frac{dQ}{Q}\frac{P}{dP} \tag{4-7}$$

Income elasticities are an easy-to-estimate parameter. Price elasticities on the other hand are hard to estimate from empirical data but we can rely on a theoretical model to infer them. Based on Sabatelli (2016), we map a price elasticity of demand onto each income elasticity of demand employing equation (4-8).

$$\epsilon_p = -\frac{1}{\rho}\overline{\omega}{\epsilon_d}^2 + (\frac{1}{\rho} - \overline{\omega})\epsilon_d \tag{4-8}$$

Here ϵ_p is the price elasticity of demand for a specific consumption category, ρ is the elasticity of the marginal utility of income, $\overline{\omega}$ is the mean share of a category in the entire consumption portfolio and ϵ_d is the income elasticity of demand. According to this model, price elasticities are proportional to income elasticities (to the squared additive inverse of income elasticities to be exact). If consumption is income-sensitive, it is also price-sensitive. The model is derived employing several neoclassical assumptions. For instance, it assumes additive preferences (utilities gained from different goods are independent of each other). Sabatelli shows that the map is consistent with empirical findings on price and income elasticities.

The parameter ρ is the only quantity that we have to derive from additional literature. It is nearly fixed around the world. Layard, Nickell and Mayraz (2008) estimate ρ across 50 countries and by means of 5 distinct data sets. They find very similar values across geographies with a mean value of -1.26 and with a max. value of -1.19 and a min. value of -1.31. Since the variation is small, we employ the mean estimate across all countries. A full parameter space of equation (4-8) is illustrated in Supplementary Figure 2.

The data we employ for household consumption is entirely in monetary terms. The purchasing power parity is associated with a physical consumption basket and a carbon intensity but there is no information about 'quantity demanded' as such. We briefly illustrate a calculation. If we for example have a price elasticity of 1.5, and increase the price of a good by 10%, then the demand is expected to reduce 15%. In monetary terms this means that $PPP 1000 per year are reduced by 15% to $PPP 850 per year. However, now the household has to pay the additional tax rate of 10%. Therefore, the total expenditure of the good after taxation is $PPP 935 = $PPP 850 * 1.1. Only $PPP 850 continue to be associated with a carbon intensity though. Let us assume the carbon intensity is 1kg/$. Then the emissions prior to taxation are exactly 1 tonne. After taxation the carbon emissions are 850 kg. This approach is in line with other isoelastic models of carbon taxation (Stretton, 2020).

4.5.6 Average carbon prices and price trajectories

We set differentiated carbon prices for countries based on income class. According to several recent studies, the appropriate level for carbon prices is likely beyond $100/tonne and must increase throughout the century (Guivarch and Rogelj, 2017; Kaufman et al., 2020; Bressler, 2021; Strefler et al., 2021). It has however been acknowledged that middle- and low-income countries cannot pay a very high carbon price early on (Bauer et al., 2020). It strains their development efforts and also goes against any logic of international justice. The cumulative emissions responsibility of high-income countries is much larger (Hickel, 2020). Carbon pricing policy is expanding around the globe but coverage so far is only ~20% of emissions and only ~4% are covered by carbon prices higher than $40/tonne (World Bank, 2021c). Moreover, the 2020s are a crucial decade to limit global warming. Therefore, we set the average carbon price in our medium scenario to $150/tonne for high-income countries, $50/tonne for upper middle-income countries, $25 dollars for lower middle-income and $10/tonne for low-income countries. These price levels are applied in the static model in which we do not vary prices because the distributional implications are independent of the price level.

In the dynamic model, however, there are additionally a low price and high price scenario. These scenarios explore the model's sensitivity to the price level. Prices for 2022 are depicted in Figure 4-7 Panel (a). The prices in the low-price scenario are the medium prices divided by 2 and in the high price scenario multiplied by 2. Moreover, prices increase year by year in linear steps which is illustrated in Figure 4-7 Panel (b) for high-income countries. Often in climate-economy models, carbon price trajectories are assumed to be exponential because this corresponds to exponentially growing return on investments and economic growth (i.e. pay more later because you are wealthier later)(Strefler et al., 2021). This however requires assumptions about the future of climate change impacts. For example, it implicitly assumes that economies continue to grow and flourish in a healthy way even with global warming beyond 2 degrees. These assumption have been heavily criticized (Keen, 2020). While we still assume conventional growth trajectories for this study and no climate feedback on growth, we do assume linear price trajectories so that large tax effects are not postponed to the second half of the 21st century. Target prices in 2100 are also based on ranges given in the literature (Guivarch and Rogelj, 2017; Strefler et al., 2021). They vary between $500/tonne and $4000/tonne depending on the scenario and the country's income level. A detailed table of prices is given in Supplementary Table 3.

4.5.7 Retrofit model and redistribution

Determining the costs and impact of retrofitting is complicated. Heterogeneity in housing types, interventions and supply prices makes this already difficult within local contexts. Here we aim for a pragmatic and simplistic approach in order to cover 88 nations and omit details around types of dwellings. We looked for a realistic estimate of costs per unit of net energy savings (Less and Walker, 2014). Considering costs per unit of energy is the key. Total costs are then proportional to total residential energy use which varies significantly by income group. Because high-income groups use more energy, costs for retrofitting richer households are larger. This is a reasonable assumption because dwellings of richer households are expected to be larger. The estimate we rely on is based on a meta-analysis of single-family housing retrofits in the U.S. The analysis arrives at an average of ~0.77$ per Megajoule (MJ) on-site energy savings in cold climate and at ~$ 0.42/MJ for warmer climate. We adopt the cold-climate costs for global north countries and the warmer climate average for global south countries, assuming both to be net energy savings i.e. including life-cycle energy and emissions of materials used.

Walker and Less also suggest that a deep retrofit reduces residential energy demand by ~50% which corroborates other findings on net emission savings of retrofits (Rabani et al., 2021). Although the variation is high and some studies suggest values larger than 50% (Filippi Oberegger, Pernetti and Lollini, 2020). We adopt 50% net reduction of residential energy demand for all households. For calculating retrofit costs, we require residential final energy over time. We projected final energy intensities from 2011 to 2019 based on trends in primary energy intensity given by the World Bank for 1995-2015 (World Bank, 2021a). This is a simplification since primary and final energy intensity can diverge but it is our best available estimate. For projecting final energy intensity beyond 2019 we assume a yearly decline in energy intensity of 1.1% uniformly across all sectors in line with the SSP2.

Another crucial component of the retrofit model is the number of dwellings that require retrofitting. We assume that the number of dwellings is equal to the number of households. We take household statistics from a UN survey (UN Population Divison, 2021). The data is nearly complete across global south countries and the only countries missing are Sweden, Denmark and Sri Lanka. Sweden and Denmark are taken from Eurostat (Eurostat, 2021) while Sri Lanka was estimated based on Statista (Statista, 2021). A limitation is that the age of data varies. Some most recent estimates go as far back as the early 2000s. Most country estimates are from the late 2010s though and we assume them to be representative of 2019. From 2019 onwards, for the dynamic model, we calculate households per capita and together with population growth rates are able to project the total number of households.

Redistribution works in a simplified way too. We redistribute to low-income households according to the zero-trade-off policy determined in the section ‘Tax revenue with multiple objectives’. A country-specific set of percentiles, depending on the consumption inequality within the country, retains their previous consumption level. They are effectively exempted from the tax. Zero-trade-off points change over time but we assume them to be fixed.

4.5.8 Carbon budget allocation

We explore the contribution of household carbon taxes to the Paris climate goals. For this purpose, we employ the IPCC-APR6 carbon budgets to stay within 1.5 degree Celsius and 2 degree Celsius with 83% probability (IPCC, 2021). The budgets need to be adjusted for the sample size and scope. We cover 88 countries and only household carbon footprints (i.e. no government and capital-related footprints). We arrive at budgets of ~160 Gt to stay within 1.5 degrees and ~480 Gt to stay within 2 degrees. There are several carbon budget estimates depending on climate system variables and probabilities considered (Rogelj et al., 2016), but the IPCC budget is a widely accepted reference point.

4.5.9 Dynamics: Economic growth, population, technology

The exogenous drivers are economic growth, population growth, carbon intensities and carbon price trajectories. The endogenous variables are household consumption, carbon footprints and tax revenue. We explore additionally a low economic growth scenario where growth rates are half as much as in the SSP2. Economic growth and population growth are based on the middle-of-the-road scenario of the Shared-Socio-Economic-Pathways (Neill et al., 2017) (SSP2). The SSP2 provides national GDP per capita (GDPpc) growth rates. We assume an elasticity of 0.83 between GDPpc and household consumption per capita (Oswald et al., 2021). Every GDPpc rate is multiplied by 0.83 to find consumption growth. For growth differentiated by consumption category, we employ income elasticities of demand fixed over time and normalize such that the total growth in consumption per capita matches the projections given by the SSP2 rates.

Consumption (excluding tax revenue) evolves according to equation (4-9).

$$C_{t+1,i} = \quad C_{t,i} * \left(1 + g_{t,i}\right) * \left(1 + \ \epsilon_{p_i} * \tau_{t,i}\right) + r_{t,i} \tag{4-9}$$

Here $C_{t,i}$ is consumption per capita at time *t* for category *i,* $g_{t,i}$ the normalized growth rate, ϵ_{p_i} the price elasticity of demand per category *i*, $\tau_{t,i}$ the tax rate and $r_{t,i}$ the effect of revenue recycling. The first bracket denotes the economic growth effect which is >1, the second bracket the tax effect which is <1 (because $\epsilon_{p_i} < 0$). While we differentiate growth across consumption categories, we assume uniform growth across income groups. As a consequence, within-country inequality does not change drastically. Largely fixed distributions imply that the income elasticity of demands can reasonably be assumed to be fixed because it is a measure of the distribution. These are not fully realistic assumptions but according to the SSP2 narrative, divergence from historical income inequality is only minimal.

Trends in consumption-based carbon intensities, a proxy to technology and energy system change, are extrapolated averages from historical trends given by the Global Carbon Project (Peters et al., 2011; Global Carbon Project, 2021). The historical data are from 2011 – 2018, so only recent trends. There are some smaller countries where the historical trend is not a decline in emissions intensity but an increase. In those countries we assumed a structural break with a yearly change rate of -1% until 2030 and -2% thereafter.

4.5.10 Limitations

The model is subject to various limitations. The quality of the model is constrained by quality of data. Employing a Multi-Regional Input-Output Model and household surveys for the year 2011 is somewhat outdated. To this day, however, there is no public data set across income classes and consumption categories in developing countries as comprehensive as the Global Consumption Database. And this data set aligns with the GTAP 9 model for 2011 (Oswald, Owen and Steinberger, 2020). Integrating recent and high-quality distributional data of household consumption into climate-economy models is a key challenge for future research. The implications of carbon taxation we explore are limited. We focus on price effects within broad consumption categories. In reality, interactions between goods are much more complex and price changes in one good imply increased or declined demand in another (cross-price elasticities). Markets are interdependent networks and consumer choices intricate. It is also expected that households substitute pricier goods with cheaper ones or with features closer to their preferences (such as organic vegetables vs. conventional ones). We control complexities in demand to some extent by the very aggregate nature of our consumption categories. For instance, one of our categories is ‘food’. There is no category outside of that which households could tend to for substitution. The dynamic model is highly stylized and serves limited purposes. We focus on household consumption only and interactions with industry, government institutions and other policies are not included. Endogenous innovation dynamics are not considered which is potentially a significant shortcoming over long periods of time, although assumed trends are extrapolations of past patterns and thus should reflect a realistic rate of innovation. The dynamic model is only appropriate for comparing the luxury carbon tax trajectories against counterfactuals but not meant to be an accurate forecast of future consumption or emissions.

Data accessibility

The study has been implemented in Python Anaconda. All data and code is available at https://github.com/eeyouol/ once a final version is published.

Acknowledgements

Y.O., J.K.S. and J.M.H. are supported by the Leverhulme Trust's Research Leadership Award 'Living Well Within Limits' (RL2016-048) project awarded to J.K.S. D.I. received funding from the UK Research and Innovation (UKRI) Energy Programme under the Centre for Research into Energy Demand Solutions (Engineering and Physical Sciences Research Council (EPSRC) award EP/R035288/1). The contributions of A.O. were supported by EPSRC Fellowship award EP/R005052/1. We would also like to thank the members of the 'Living Well Within Limits' project and the 'Economics and Policy for Sustainability' research group at the University of Leeds for feedback on early versions of this work.

Author contributions

Y.O., J.K.S., J.M.H., A.O., and D.I. conceived and designed the study. Y.O., J.K.S., J.M.H., A.O., and D.I. jointly developed and designed the methodology. Y.O. implemented necessary software and conducted the analysis. Y.O. wrote the initial draft. Y.O., J.K.S., J.M.H., A.O., and D.I. jointly wrote the final article version.

Conflict of interest

The authors declare no competing interests.

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5 Discussion and conclusions

First, I start by discussing the results considering previous literature and elaborate on their implications. Second, I interpret the results considering broader debates in economics, politics and society. Third, I summarize my findings and outline the overall contribution to the knowledge base. Fourth and last, I reflect on the limitations of my work as well as speculate about the future of inequality studies and redistribution modelling relevant for energy and carbon footprints.

5.1 Discussion of results

5.1.1 International final energy footprints of households

The international final-energy-expenditure elasticity (we find a value of 0.86) is an important parameter determining not only the relationship between global economic inequality and ecological impacts, but also the relationship between future economic growth and future energy requirements. Therefore, it is worth comparing it to the literature. It is not ideal to compare an international cross-country elasticity against within-country elasticities (see for instance Simpson's Paradox in Blyth (1972)), however, most previous energy footprint studies are restricted to single or few countries. Lenzen et al. (2006) find within-country primary-energy-expenditure elasticities of below one for India (0.86), Japan (0.64), Australia (0.78) and Denmark (0.86) and an elasticity of exactly one for Brazil. They explain the high elasticity in Brazil through income-dependent transport demand. They also conduct a pooled analysis across the five countries, employing a variety of regression models, and find an energy-expenditure elasticity of ~0.9 which is very close to our result across 86 countries. Literature surveys of within-country energy elasticities find a range of 0.64-1.01 for energy-expenditure and 0.4-0.95 for energy-income (Pottier, 2022), so 0.86 turns out to be a medium estimate (methods to estimate the respective elasticity may vary). The relationship between primary energy consumption and GDP per capita (PPP constant 2017) across countries allows for additional comparison. The international primary-energy-income elasticity is ~0.86 in 2011 (own calculation, data from Our World in Data, 2022) – so precisely in line with our estimate.

The next best comparison for an energy-expenditure elasticity is a carbon-expenditure elasticity. However, the two metrics should not be confounded to represent the same thing. Historically they are tightly related because of the large share of fossil fuels in the energy mix in most countries. In the future however, given a successful energy transition, it is possible for the two metrics to diverge. Within-country surveys find the carbon-expenditure elasticity to be between 0.7 and 1.2, and carbon-income elasticities to be 0.3 to 1 (Pottier, 2022). It is interesting to compare the international energy elasticity against the international carbon elasticity. Hubacek et al. (2017) measured cross-country carbon elasticities but took different income levels into account (distinguishing essentially between orders of magnitude at $1000, $10,000, and $100,000 GDP per capita). They found the elasticity at low incomes to be only 0.36, at high incomes to be 0.87. They do not report an elasticity across all countries in their sample.

We also find that Gini coefficients of energy are larger than Gini coefficients of expenditure across a range of countries. This is analogous to saying that the energy-expenditure elasticity within countries is sometimes above 1 and therefore contrasting with previous results on the energy-expenditure elasticity surveyed by Pottier (2022). Previous literature is very much limited to high-income countries, however. The results surveyed by Pottier predominantly focus on the United States, Australia and the United Kingdom. The only low- or middle-income countries surveyed are India, China and Brazil, and for Brazil the reported energy-expenditure elasticity is slightly larger than one. In any case, our finding broadly aligns with national carbon-expenditure elasticities found by Bruckner et al. (2022) and Hubacek et al. (2017) who report elasticities larger than one for various countries. Moreover, the energy-expenditure elasticity decreases with national income. The average income of countries in our sample with elasticity less than one is ~$PPP 26,000 GDP per capita, of countries with elasticity more than one ~$PPP 13,000. The fact that national elasticities decrease with average income is consistent with the literature, too (Liddle, 2015).

Going beyond aggregate energy-expenditure elasticities, we tested product-specific expenditure elasticities of demand to infer how the aggregate trends emerge. Comparing these elasticities needs to be conducted carefully, as methods for income and expenditure elasticity estimation can vary substantially. We consider expenditure elasticity of demand as specified by the coefficient in a simple bivariate log-log regression between total expenditure and expenditure per category. Previously in chapter two to four, we explicitly called this the ‘income elasticity of demand’, but to distinguish the different concepts in this paragraph, I differentiate between expenditure-elasticity and income-elasticity. The literature covers a wide range of methods to assess elasticities of demand including bivariate and multivariate approaches. This is of course also important for aggregate carbon and energy elasticities (see e.g. Lévay et al. (2022)), but the issue is even more pronounced at the product level. For instance, historically, there is an ample amount of literature estimating price and income elasticities of energy commodities such as gasoline (Espey, 1998). However most econometric studies take effects over time into account and distinguish between short-run and long-run elasticities.

That said, we find a large spread of product-specific expenditure elasticities around the world indicating cultural, economic and geographical diversity, but nevertheless with clear product-specific central tendencies. Consider the example of vehicle fuel and maintenance which comes close to representing a directly purchased energy commodity like gasoline. We consistently find a high national elasticity often above one making it a luxury good. This behaviour is especially pronounced in developing and emerging economies, whereas in Europe the elasticity is closer to one. Older meta-studies find a wide range of income elasticities of gasoline demand ranging from 0 to 2 employing a wide range of methods (Espey, 1998). Newer meta-studies find very low short-run and long-run income elasticities of gasoline demand between 0.1 and 0.3 contrasting considerably with our results (Havranek and Kokes, 2015). The large differences in results are likely due to differences in methods and not restricted to the difference between expenditure and income elasticities. None of these estimates applies a bivariate log-log model but panel-data and multivariate methods.

Looking to results from similar household data and methods, we can affirm our results. For instance Ivanova and Wood (2020) find a land travel expenditure elasticity of 0.95 for Europe – close to our average estimate for Europe slightly above 1. However their estimate also includes public transport and not just private fuel expenditure and therefore seems reasonably in line with ours. Ivanova and Wood (2020) also affirm the rest of our estimates. Food and clothing exhibit elasticities clearly below one and air travel exhibits elasticities far above one.

The overall final energy footprint Gini coefficient we find is 0.52 and aligned with previous literature finding 0.52 for 2010 and territorial primary energy (Lawrence, Liu and Yakovenko, 2013). Global energy inequality is expected to be lower than income and consumption inequality because the international elasticity is ~0.8-0.9. Gini coefficients for global income and consumption inequality are estimated at 0.6-0.7 (Milanovic, 2013; Liberati, 2015). However, our first energy inequality estimate is biased downward since the USA and Japan are not included in this figure. Indeed, correcting the sample to include the USA and Japan yields a Gini coefficient of 0.58 (own calculation). This is still somewhat lower than reports on global carbon inequality, which for 2014 find a Gini coefficient of 0.62 (Bruckner et al., 2022).

In terms of product-specific Gini coefficients, we find a range from 0.4 to 0.8. Clearly, the inequality of energy consumption per consumption category is correlated to the elasticity of demand – both are distributional descriptions. Luxury goods exhibit higher inequality than necessities. Interestingly, the total Gini coefficient can be well expressed as the weighted average of the product-specific Gini coefficients. This insight might be useful for further modelling of energy inequality since it allows a simple parameterization of total energy inequality.

We project energy inequality to be relatively stable under business as usual at a Gini coefficient of ~0.5 up to 2050. Our results emphasize doubling of household energy demand in 2050 with respect to 2011 and an increasing share of transport in total energy consumption. These results are partly consistent with the fossil fuelled pathway (because of high energy demand) as well as the rocky-road/regional-rivalry (because of high inequality) narratives of the Shared Socio-Economic pathways (Riahi et al., 2017). Given recent historical experience including vaccine inequality during the Covid19 pandemic, tensions in the Middle East and the Pacific, the Russian invasion of Ukraine as well as overall slow decarbonization in the global transport sector, these rather negative trajectories seem also consistent with reality to some extent. Importantly, we derive this unequal and energy intensive future only by employing income elasticities of demand for projections under a standard OECD economic growth and population trajectory without making use of any sophisticated socio-economic modelling.

Accordingly, our results demonstrate that current consumption patterns are a potential cause for a fossil fuel driven future, and on top of that, maybe even for geopolitical conflict and misery. It seems imperative to decouple household consumption from energy intensive goods and services wherever possible and at a minimum to cut oil and gas dependency. The 2022 Russian war against Ukraine has demonstrated the danger for Europe to rely on gas and oil imports for key sectors like residential heat and transport (IEA, 2022). While the West responded with tough economic sanctions on Russia, energy imports are the one sector in which Europe is unable (or slow) to cut ties and consequently further finances Putin's efforts to subdue Ukraine. New homes ought to be built according to passive architecture principles as much as possible and in addition by means of complete electrification. A new demand architecture also requires lowering the income elasticities of private transport through providing attractive alternatives, such as zones for bicycles and walking but also strengthened public transport.

5.1.2 Global redistribution of income and household final energy footprints

The literature on redistributive scenarios of emissions and energy is scarce, but existing results align with ours. For example, we find that the net change of global household energy consumption as a function of the global income distribution is modest. We estimate an upper bound of 7% energy demand increase under nearly complete global equality (Gini coefficient ~0.1) — in line with Rao's and Min's 8% for emissions (Rao and Min, 2018). The result only holds given contemporary statistical relationships between income and consumption as well as given the underlying technology. If any of those variables substantially changes, this upper bound is not valid anymore. Technology could for instance change the energy intensity in the residential sector and in transport. If let us say transport energy intensity decreases while residential energy intensity stays constant, the upper bound rises (expressed as percentage of total because under redistribution consumption shifts from transport to residential energy). The likelihood of such a scenario is difficult to assess, however. On the one hand, energy efficiency improvements in the residential sector are a proven energy efficiency strategy (Harvey, 2009) while the transport sector off-sets its own efficiency improvements by the tendency to foster larger vehicles over time (IEA, 2020). On the other hand, in some countries like the UK, retrofits for homes advance only slowly, if at all, and are hampered through various administrative and economic hurdles while the private sector is heavily investing into new transport technologies such as electric vehicles. For example, in the UK ~35% of people rent their accommodation (Office for National Statistics, 2022). Tenants are not allowed to change anything about their accommodation and landlords lack the incentives.

However, uncertainty in the upper bound of net energy increase is substantial, as demonstrated by Monte-Carlo simulation. Given random parameter changes (in income elasticities and energy intensities) representing the parameter confidence intervals, we find a possible maximum upper bound of ~33% increase (~210 EJ to ~280 EJ). It must be stated that this range of scenarios also includes outcomes where energy demand under global equity *decreases* by up to -15% (~210 EJ to ~180 EJ). Judging by the Monte-Carlo simulation these extremes are equally likely. With 90% probability, the resulting upper bound is between -5% and +20% (so between ~200 EJ to ~250 EJ). This can be considered high confidence that radical redistribution is not a dramatic energy demand driver. Nevertheless, even the Monte-Carlo simulation is not a fully comprehensive uncertainty assessment. We did not implement a systemic and dynamic model of redistribution and the economy. Studying the long-term consequences of redistribution requires different modelling approaches including probing feedbacks between the distribution of income and economic dynamics. For example, global income equality should yield high educational and health outcomes around the world. High educational and health outcomes might foster entrepreneurial activity which in turn might increase the rate of innovation and productivity and eventually energy demand. This is just a speculative causal chain of events for illustrative purposes and there is no evidence for it, nor against it, and ultimately it is dependent on the overall political economy.

The data-driven perspective on the composition of energy demand as a function of the income distribution is novel, however, from a theoretical economics perspective, the link between consumer demand and income distribution is well known. The distribution of income clearly influences aggregate demand and demand across specific markets (Muellbauer, 1975). We find that in an egalitarian world, with an income Gini coefficient of ~0.1 compared to today's ~0.6, energy demand for vehicle fuel decreases by ~17 EJ which is almost twice as much as the entire final energy demand of Germany or 80% of US oil demand for road transport. Therefore, a substantial fraction of oil dependency could be eliminated just through a more equal global income distribution. In the same scenario, however, global residential energy increases by 20 EJ, thus implying a trade-off, especially if heating continues to be provided through gas. While these effects seem very large at first glance, putting them into context of other drivers of future energy demand, suggests otherwise. Twenty Exajoule is less than half of the energy demand increase (48 – 67 EJ) projected in the moderate Representative Concentration Pathway (RCP 4.5) due to climate change adaptation (for instance because of increased air conditioning needs) (van Ruijven, De Cian and Sue Wing, 2019).

Indeed, it is surprising how 'cheap' it is to pay for eradicating extreme poverty through redistribution. Eradicating extreme poverty only requires contribution by the top 0.1% of income earners. Lifting everyone up to $PPP 10 consumption expenditure a day, still requires only capping income (GDP per capita) at ~$PPP 70,000 per year and only a contribution of the global top 3%. It should be noted that our income distribution model is far from perfect, and the limitations have been discussed extensively in chapter three. Yet these results are an important complement to the narrative that large economic growth is necessary to eradicate poverty (Roser, 2021). Roser demonstrates that lifting everyone in the world to the income of Denmark requires at least a 5x bigger economy than today (taking population projections for 2100 into account). Based on these results it seems indeed unlikely that no global economic growth at all is necessary to improve living standards around the world (which is sometimes suggested in popular discourse). However, Roser's analysis is limited to average national incomes, does not take environmental constraints into account and moreover does impose a rather ambitious goal – reaching Denmark's income. Considering lower, but still significant, thresholds for improving living standards (such as $PPP 10 a day), our results demonstrate that redistribution from the globally wealthy to the poor can play an important role in poverty eradication.

5.1.3 Luxury taxation of carbon footprints

The first significant contribution of our carbon taxation study is a model of the global carbon footprint distribution for 2019. It is in line with previous literature, although we find a lower global Gini coefficient of carbon footprints (0.56) than for example (Bruckner et al., 2022) (0.62). First our model is for 2019, not 2014, so therefore global inequality has decreased slightly through high growth rates in India, China and a few other countries and second our model is only concerned with household footprints and not capital formation or government expenditure contrary to Bruckner et al. (2022). Moreover, we harmonized the consumption expenditure data by employing log-normal models across all countries and all products. The log-normal harmonization underestimates inequality driven by the superrich (millionaires and billionaires): One reason is that in India the range captured by the log-normal model is constrained through the initial segmentation of the data. The lowest consumption segment comprises roughly one billion people, limiting the variation around the mean which is fed into the log-normal model. Accordingly, the underestimation is an outcome of representing chunky data with log-normal models, rather than a limitation of log-normal models themselves.

In fact, we can precisely quantify how much of the difference between Bruckner et al. (2022) and our results is due to the harmonization of data or due to actual effects. When we measure carbon inequality based on the original household expenditure data for 2011, we also find a Gini coefficient of ~0.62 (0.615 to be exact). If we use the log-normal model approach for 2011 instead of 2019 we find a Gini coefficient of ~0.605. Therefore, there is a slight underestimation due to the log-normal model but most of the difference is due to actual changes in the distribution.

The ratio metrics are mostly in line with the literature, too. The strongest divergence from previous results is at the very top. It has been suggested that the top 1% emit ~17% of the emissions (Chancel, 2021), while we find they emit ~10%. For the top 10% our results are more aligned with Chancel (2021) (45% vs. 48% respectively). He estimates total carbon inequality contrary to us estimating only household carbon inequality. Since our model is overall in line with other empirical assessments of carbon inequality calculated through consumption-based input-output modelling (Hubacek et al., 2017; Bruckner et al., 2022), we consider our results robust. Indeed, Hubacek et al. (2017) find that the top 10% of households emit ~35% of the total emissions. Our estimate therewith lies in-between maximum and minimum in the literature but towards the maximum.

We set distinct carbon prices for different countries depending on their average income level. There are few studies that have tested such assumptions, although this is clearly in line with effort-sharing and equity principles. In fact, considering equity in climate pathways, it is absolutely necessary to set higher carbon prices for high-income countries as long as one distributes remaining carbon budgets on an equal per capita basis (van den Berg et al., 2020) – which is what we have done. Our initial price of $150/tonne for high-income countries is comparatively high given that most studies still employ carbon prices between $40-80/tonne, even for high-income countries (Kaufman et al., 2020; Büchs, Ivanova and Schnepf, 2021). It is however in line with recent estimates of the social costs of carbon, including the impact of global warming on human mortality (Bressler, 2021). Furthermore, probabilistic assessments of how likely it is that countries achieve their nationally determined contributions for global climate goals are gloomy under current policy. For the US for instance the probability is just 2% (Liu and Raftery, 2021). This further supports the need to ratchet-up carbon prices from the beginning onwards and continuously over time.

The effect of an average carbon price of $150/tonne on national emission reductions in high-income countries is 4%-20% in the first year. The high variation stems from high variation in the carbon intensity of consumption and different price elasticities of demand. For most high-income nations, it is between 5% and 10% though which is roughly in line with the global average yearly reductions of 7.6% required to meet the 1.5°C climate target. This however concerns only immediate demand reduction. In later years, when the price increases in smaller steps, the price effect on carbon emissions is not that large anymore and consequently policy cannot exclusively rely on carbon taxation to be Paris-goal consistent, unless it can be shown that carbon taxation drives innovation and a shift in consumer preferences fast enough to fulfil the goals.

In terms of revenue, the luxury carbon tax we propose generates between 1-3% of GDP per year for most high-income countries and below 1% for the remaining income groups. This revenue budget is roughly in line with the magnitude of yearly energy investment needs to reach the Paris climate goals for high-income countries. For instance, the USA requires a yearly investment of ~$430 billion to achieve the 1.5-degree target and ~$370 billion to achieve the 2-degree target (McCollum et al., 2018). This makes ~2.2% and ~1.9% of American GDP respectively. While theoretically capable of paying for climate goals, the luxury carbon tax does not dramatically reshape the overall tax landscape, since taxes already make up substantial proportions of GDP in most countries. For example, in European countries all tax revenue taken together constitutes between 30% and 50% of GDP. This illustrates how intensively redistributive European economies already are (World Bank, 2022a). The global average is ~15% for tax revenue as a proportion of national GDP. This number refers to the magnitude of flows however and does not mean they redistribute resources in progressive and environmentally just ways. Some existing taxes are clearly progressive like income taxes in most countries, but others are regressive like taxes on goods and services because consumption is generally more important to low-income households. Tax revenues from commodity taxes make up, very roughly, one-third to one-half of all tax revenue across countries. One-third to one half of the global average of 15% is 5% to 7.5% of total GDP, or 10% to 25% for high-income countries in Europe (World Bank, 2022b). From that point of view, carbon taxes significantly add to taxes on goods and services but not as dramatically as sometimes presumed in public debates.

The distributional implications of luxury focused carbon taxation as opposed to uniform carbon taxation is the core focus of chapter four. We do implement one step that is entirely novel as compared to other distributional impact studies: We set carbon prices proportional to the income elasticity of demand while other distributional accounts at a maximum test the same carbon price on different products or exclusively implement a uniform carbon tax (Dorband et al., 2019; Büchs, Ivanova and Schnepf, 2021; Budolfson et al., 2021; Malerba, Gaentzsch and Ward, 2021; Steckel et al., 2021). This is crucial to bear in mind because the distinct designs are not necessarily one-to-one comparable.

Nevertheless, many of our findings corroborate the prevailing literature. First, we did test uniform taxes too and find that across many countries, uniform carbon taxation is progressive in terms of emissions abatements and in terms of financial tax incidence (before revenue recycling). This is especially the case for low- and middle-income countries. This is exactly in line with other studies (Dorband et al., 2019).

If we compare financial incidence curves across percentiles, we find results similar to other studies as well. For instance Burke et al. (2020) find a burden of 2% of income that must be spent on the carbon tax when the carbon price is £75/tonne in 2030 for the United Kingdom. The percentage range across deciles is a little more than 3% for the lowest decile and 1.5% for the highest 10% and but most deciles are located in a narrow range between 2.5% and 1.5%. We find a narrow range from 4% for the lowest percentile to 3.5% of disposable income for the highest percentile for the United Kingdom but our carbon price is also roughly twice their carbon price which matches the roughly doubled average incidence. Our results concern carbon-equivalents and theirs only carbon dioxide and ours refer to an earlier point in time (~2020 instead of 2030). Based on Steckel et al. (2021) we expect to find a slightly regressive pattern under uniform carbon taxation in India and a slightly progressive one in Indonesia — we do find both. In terms of individual level emission abatements we have few possibilities to compare the distributional implications to other studies because they are less often presented.

Perhaps the most interesting comparison is therefore not to numerical results from other studies but to a seminal idea in optimal tax theory. In 1927, Frank Ramsey showed that the optimal tax on goods and services is *inversely* proportional to their price elasticity of demand. This, he argued, is because in order to maximize tax revenue and social welfare (a combination of consumer surplus and producer surplus) demand and supply curves must be shifted as little as possible from equilibrium (Ramsey, 1927). Price inelastic goods thus must be taxed the most, and price elastic goods the least — exactly contrary to what we suggest. In our luxury tax design, taxes are proportional to the income elasticity of demand and therewith also proportional to their price elasticity of demand. Are we therefore completely wrong in doing so? Or is he? Ramsey's result is derived from a constrained optimization problem in which deadweight losses to the consumer's 'happiness' are minizmied given a certain revenue budget that needs to be 'extracted' (Mulligan, 2007). The budget is the constraint and happiness is the objective function. The problem is posed under rather restrictive assumptions. For instance, the problem makes no assumptions about the inherent social value of goods and services, very much in contrast to our approach. We do assume that luxuries have lower social value than necessities because, as the names suggest, necessities are consumed by everyone regardless of income for elementary purposes, and luxuries predominantly by wealthy minorities to indulge themselves. Within our framework, it is more important to access food and shelter than to go on holiday in line with the common-sense philosophy suggested by Shue (1993) (discussed in section 1.2.6.2). Ramsey did not make this distinction. Additionally Ramsey did not consider redistribution. If tax revenue is redistributed to low-income households for the consumption of necessities, it improves, in economic terms, social welfare by a greater extent than if a rich person consumes an additional luxury. This is because the marginal benefit of consumption for the poor is much greater than for the rich. Ramsey did not make this connection between *marginal benefit* and redistribution. Instead he explicity ignored the marginal utility of income at different levels of income. Nevertheless, Ramsey's contribution were of fundamental importance to the optimal tax theory during the 20th century and until today. His framework was elegant, the assumptions clearly stated and under those conditions he derived a specific result. The result was extended, amended and even replaced for practical purposes but never fundamentally turned on its head (Holcombe, 2002; Mankiw, Weinzierl and Yagan, 2009). Economists have been well aware that the assumptions given in Ramsey's problem are rather restrictive and that for policy making it would be better to allow greater freedom on how to tax goods and services. Or as Stiglitz put it '*there was something distinctly unpleasant about Ramsey's recommendations – it suggested taxing the necessities of life*' (Stiglitz, 2015). Yet Ramsey's problem is appropriate as a benchmark because it shaped an entire century of economic debate and triggered consideration of distributional implications.

Moreover, in light of our research, Ramsey taxation also is just not adapted to the constraints of the 21st century. As discussed in section 1.2.3, the ultimate constraint to contemporary economics is climate change (and planetary boundaries in general). Curiously, Ramsey even received the problem from Pigou, the father of environmental taxation theory, but they did not join the two fields. The intersection of both fields was treated by economists in various forms later on (Stiglitz, 2015), but not in terms of an empirical carbon tax application on data across many countries, as we have undertaken.

5.2 Context and related debates

5.2.1 Degrowth vs. Green Growth

A polarized debate in environmental economics and ecological economics revolves around the question 'how to live well without damaging the environment?' The debate is pretty much polarized between the camps 'degrowth' and 'green growth'. The core proposition of degrowth is that economic growth, expressed as the change rate of GDP per capita, is far too crude an indicator to denote social progress, and also is directly coupled to environmental impacts (there are other definitions of degrowth solely based on a reduction of material throughput but which in part have formed due to the debate with green growth and growth-agnostic positions see e.g. Hickel (2019)). In contrast, the core proposition of green growth is that economic growth presents a qualitative improvement in living standards and can be decoupled from environmental impacts, for instance through technological innovation and sectoral shifts from resource-intensive industries to service- and digital industries. My aim here is not to fully discuss these propositions, nor resolve them but to point out what our findings might have to do with them. For a good overview on the debate and terminology I suggest Van Den Bergh (2017); Van Den Bergh and Kallis (2012).

Energy- and carbon inequality as well as redistribution are issues intricately linked with the debate. As discussed before, large inequality across countries together with climate constraints suggests that some countries should *degrow* their energy and carbon footprints and others may increase it to raise living standards. For instance, transport altogether constitutes ~30% of household energy footprints and in vehicle fuel the top 10% consume 56%. Therefore, particularly the international inequality across private transport suggests that few people on the world use a large share of all available resources for luxury purposes and this kind of consumption could be *degrown,* without heavily impacting well-being. This is essentially also what we deliver proof-of-concept for in the global redistribution scenario in chapter three.

Nevertheless, our results do not as unilaterally make the case for degrowth as one might presume. First, the energy-emissions problem cannot exclusively be solved through reduction in consumption of the affluent. In fact, ~40% of all household energy demand is residential energy and the top 10% consume 'only' ~30% here. Energy for food is similarly distributed but makes up much less of the global energy demand (<10%). Both cases still represent large inequality but are also substantially less unequal than transport and show that a significant fraction of energy demand comes from the broader population. Furthermore, residential energy demand increases with global income redistribution as discussed in chapter three. Drastic redistribution is a scenario which corresponds to a degrowth-narrative in the sense that wealthy global groups strongly reduce their income and their energy demand while poorer groups strongly increase both – creating international equity and perhaps justice. Such a scenario illustrates that an equitable middle-income world still requires substantial amounts of energy despite not maintaining any superrich elite who drastically overconsume. Additionally, energy demand in any sector is most likely to grow substantially in the future (Semieniuk et al., 2021). Some scenarios arrive at much lower future energy demand. However, next to an energy sufficiency culture these scenarios assume much more advanced technology when compared to today (Grubler et al., 2018; Rao, Min and Mastrucci, 2019; Millward-Hopkins et al., 2020), and it is questionable whether the radical diffusion of such efficient technologies is realistic within the next few decades let alone whether the cultural alignment, required for a global sufficiency culture, across nations will happen within time frames consistent with climate goals. Diffusion of technology is one of the few aspects of society where evidence of rapid change is abundant (Ritchie and Roser, 2017), a point that green growth proponents repeatedly make, but that does not mean it necessarily happens in every sector. Either technology diffuses fast enough to make homes and other devices hyper-efficient as compared to today, thereby drastically lowering demand, or residential energy demand is most likely going to be at least as high as today and then clean energy supply is even more important.

Second, another key argument by green growth proponents against degrowth is that degrowth is not feasible because it is underpinned by 'idealist' political attitude. They argue that the core premise, that consumption and resource levels today are already too large, is false, given how poor most people are in the world. They argue that the (global) economy needs to be expanded accordingly (Milanovic, 2017). Moreover, some argue that degrowth is not possible because under 'realist' assumptions, including behavioural and sociological aspects of social evolution, people want to consume luxury and frivolous products (Trembath, 2021). Putting aside the nuanced debate on human needs and their satisfaction for a moment, that does seem true considering the income elasticities of demand we observe. After all, income elasticities of demand indicate what people do if they obtain an additional unit of income. First, people seem to consume to satisfy basic needs (therefore we call necessities necessities) and with more financial resources available, they considerably diversify consumption towards the 'luxury' goods, perhaps frequently including things that no one *really* needs, like flying to Spain for a long-weekend break. And in our dynamic analysis in chapter two, we accordingly show that luxury energy demand continues to grow if global income continues to grow. As the world grows richer, people devote more money to transport and travel. Other recent evidence against degrowth and idealist assumptions includes the NATO's response, and in particular Germany's updated military budget, to the Russian invasion of Ukraine. Approaching this topic requires going beyond household consumption but since we also dealt with tax revenue which feeds into government budgets, it still fits broadly within the scope of our discussion. After decades of political reluctance, Germany has decided to heavily increase investment into its military and to fulfil the NATO target of spending 2% of GDP on defence. Downscaling military expenditure can be considered a goal of degrowth. According to degrowth literature, the military does not contribute to the satisfaction of basic human needs, much like luxury goods and services, and moreover, it is resource and fossil fuel intensive (Hickel, 2021). However, it is far from obvious to argue that Germany pursued the wrong decision in face of international security threats. National security and defence capability is also a public good provided by the state (much like a clean environment for instance). In any case, it seems unlikely that in a world of growing international conflicts countries automatically tend to downscale their military. At least in the military sector then, and given no substantial political shifts, the degrowth premise of decreasing resource and energy throughput in ‘unnecessary sectors’ continues to be violated by contemporary events.

Returning to our focus on households, would capping or degrowing income mean taking away people’s wants? Perhaps, but not necessarily. There are several arguments against that proposition. First, it is important to observe that with increasing income the gap between income spent on consumption and savings grows as well. Consumption grows much slower than income. In other words, the expenditure-income elasticity is roughly 0.8, a fact we have demonstrated and utilized in chapter three. This suggests that the marginal utility of income decreases with increasing income. It also suggests that people do not have infinite wants but that there is an upper bound which is also known as the bliss-point hypothesis in economics (which was introduced by Frank Ramsey in his inquiry of intertemporal welfare economics (Ramsey, 1928)). Indeed newer evidence suggests there are such bliss points somewhere between $60,000 and $100,000 GDP per capita (Jebb et al., 2018), while others continue to argue that they do not exist (Killingsworth, 2021). Second, one line of literature suggests that the provisioning systems of the economy shape the demand for goods and services (Fanning, O’Neill and Büchs, 2020). To put it briefly, provisioning systems are all cultural or physical systems of how society and economy process resources into social outcomes. One often cited example is transport. Currently, transport is organized around the private travel mode ‘car’ in industrialized countries. This means we build roads which require concrete, factories that produce cars, which require massive quantities of metals and electronics, and so forth, all just to enable us to go from A to B. It could be different. We could in principle build public transport between cities so that cars are redundant and transform urban spaces to favour walking and bicycling. If we follow this line of thought, then consumption patterns could be drastically changed by the cultural and physical frameworks we embrace as a society. Indeed, first empirical studies provide evidence for this hypothesis (Vogel et al., 2021).

From chapter four more data emerges that is at odds with green growth. In line with much previously published literature (Haberl et al., 2020), we show that current household consumption trajectories are not sustainable and especially not feasible given the carbon budgets. Decoupling between consumption and carbon emissions is not happening fast enough on a global scale to avert rather grim climate change scenarios.

There is now evidence that shows that decoupling at the national level is possible, with respect to carbon emissions at least. Absolute decoupling of GDP growth and emissions has been achieved in 30 countries or so, for more than 20 even from a consumption-based perspective (Hubacek et al., 2021; Lamb et al., 2021). But we should not make the mistake to expect the whole globe to follow along, especially not in time for limiting global warming. In fact, in chapter four we did assume recent historic rates of carbon intensity decline, which includes the absolute decoupling rates in the respective countries, and even optimistic trends for countries that had increased emissions so far, and still the global business as usual scenario of emissions is far above the 2-degree target.

How far anyway can economic activity really be decoupled from impact? Some techno-optimists now argue that large parts of the economy can be moved to the Metaverse in the future (Metaverse is the virtual reality that the company Meta, formerly Facebook, is creating) which allegedly would enable absolute decoupling far beyond what is observed today (Smith, 2021). This is at odds however with scientific literature on the material and energy requirements of digitalization (Court and Sorrell, 2020). Based on this literature, it seems more likely that ‘efficiency’ runs into lower bounds. Even today’s most space-compact and yet versatile technology, the digital computer, is built employing a vast number of materials all which require heavy industrial activity, often with environmental impacts going beyond emissions, such as water pollution and land use impacts. Accepting this premise, demand-reduction, or at least demand-limiting policies, must play a role and go hand in hand with innovation to bring about change at scale (IPCC, 2022b).

Lastly, there is also some literature that moved beyond the distinction between degrowth and green growth. ‘Agrowth’ has been proposed as a third growth-agnostic option which acknowledges that GDP growth might as well be coupled to improvements in living standards at times but at other times possibly not or even be detrimental (Van Den Bergh, 2017). In any case, the future of economic growth is most likely a volatile and slow one, if we want it so or not (Burgess et al., 2021) and we should take the opportunity to focus on what matters – improving everyone’s well-being.

5.2.2 Capitalism and the economy

The debate around capitalism is a large and historically charged one and by no means I can make a substantial contribution at this point. However, I can point to a few of our results and speculate about what they might have to do with it. Capitalism is widely considered to be the predominant economic logic across the globe. The precise form of capitalism varies immensely however from laissez-faire capitalism in the United States with no social security nets to social market-economies in Europe and this only covers the democratic nations (Ranaldi and Milanović, 2022). There are also state-capitalist autocracies such as Russia or China in which the free-market is merely employed for economic development but detached from any notion of political freedom. The different types of national capitalism also produce different levels of income and wealth inequality and hence also different levels of energy and carbon inequality. Despite the diversity in capitalist economies around the world, capitalism is also understood as a global-level phenomenon. Capitalism refers to the overarching and globalized structure of economic exchange and to the groups who control the resource flows and own the assets, the capitalists (Harvey, 1982). After the Cold War capitalism was widely regarded as a superior economic system because the Soviet Union, a communist state, dissolved, while America, the centre of global capitalism, strived. In recent decades, and in conjunction with environmental problems and inequality, however, capitalism also has been widely criticized as an unsustainable and unjust system – even as a system that eventually needs to be overcome to create a truly better world, which is a thought dating back to Karl Marx (Hickel, 2019). There is also clearly a historical dimension to capitalism because people still debate what exactly capitalism is and how it emerged including the role of colonialism, historic aristocracy, patriarchy, forms of money and more.

Moving only tangentially to this complex topic, our work does three things: 1) It describes a symptom of capitalism, namely the large inequality in household energy and carbon footprints, 2) It probes alternative distributions of resources and thus indirectly explores alternative economic systems, 3) It probes redistribution within the current logic of capitalism in forms of taxes on goods and services. To be exact, we must refer to energy and carbon inequality as a 'not necessarily unique' symptom of capitalism because it is not entirely clear whether capitalism is the only system that produces large inequalities, or even the system that produces the largest inequalities. Historically, certainly, inequality in consumption is not a recent phenomenon but dates at least back to the agricultural revolution (so about 12,000 years) and the extent of inequality in pre-neolithic cultures is vastly uncertain and varied (Kohler et al., 2017; Kohler and Smith, 2018). It is also likely that ancient societies have been as unequal, consumption-wise, as they could have been, based on the concept of the Inequality Possibility Frontier, and modern societies are relatively equal compared to how unequal they *could* be. The Inequality Possibility Frontier says that a very poor society at the subsistence minimum cannot exceed a certain level of consumption inequality, because if it would, it would mean that a substantial share of the population must continuously live below the minimum subsistence level of consumption, which is by definition not possible (Milanovic, Lindert and Williamson, 2007). Therefore, when archaeologists determine a low Gini coefficient of consumption inequality in ancient societies, it does not necessarily mean they were materially and politically egalitarian, but perhaps 'materially very poor' on average. Nevertheless, while modern industrialized societies are likely far from how unequal they could be in principle, the inequalities are vast and still include material deprivation to the point of starvation and freezing to death for some people. This, for example, happens to many of the homeless in the United States and United Kingdom, but also to some low-income households (Coleman-Jensen et al., 2019). Accordingly, we can be confident that, when we explore radically different global income distributions, we also explore new economic systems, because it is unlikely that, let us say at a global income Gini coefficient of 0.1, redistribution mechanisms, wealth ownership and so on are exactly structured as of today. This invokes the question of where does capitalism stop? This question cannot be fully answered because it is not entirely clear what the defining features of capitalism are (especially with respect to our modelling framework). One essential feature however is the accumulation of private capital. This means that a private person, for the sake of popular imagination let us say Jeff Bezos in America, is theoretically allowed to possess infinite quantities of wealth. In the specific case of Jeff Bezos, that is mostly stock options due to his founding and ownership of the conglomerate Amazon. Since income is a yearly flow produced by the existing capital stock, income inequality is always related to wealth inequality in some way. National income, for instance, is the change rate in national capital (also called investment and depreciation) plus national consumption. Therefore, when we changed global income inequality to a Gini coefficient of roughly 0.1 in the most extreme scenario in chapter three, even while holding income elasticities of demand constant, the underlying capital ownership is implied to change too. Even more so, we have shown that the structure of energy demand does change given reduced inequality, which dovetails with a changed ownership structure on the supply side. For instance, a much more equal world, in which transport and oil consumption are reduced, likely also does not rely on the fossil fuel industry as much and plausibly could exhibit decentralized ownership of energy production assets (although in reality some renewable energy ownership is so far also very centralized e.g. offshore-wind in the UK is in the hand of a few large companies). An alternative ownership structure could possibly be related to socialism.

However, let us be clear: Socialism is a complex and historically charged term too and while the previous logic holds, it does not mean such scenarios automatically prescribe or even support socialism and especially not the autocratic and centralised socialism of the Soviet Union (this must be said because occasionally only saying the word, especially in the United States, evokes that presupposition). As there are many forms of capitalism, there are many forms of socialism. One form of socialism that is supported by some environmentalists today is democratic eco-socialism (Kovel and Löwy, 2001). This system entails a kind of economic democracy in which businesses become cooperatives, meaning they are owned by all employees at equal shares rather than only by the founder or the investor. Socialist systems can accordingly still be market-economies, even if ownership is decentralized.

Nevertheless, we have not exclusively pointed to radical system change within this thesis but also taken more gradual steps by employing (luxury) carbon taxes on goods and services. Taxes on luxury goods and services are progressive, but they do not to bring about extreme changes in the distribution of income or wealth. Indeed, as Ian Gough (2017) remarked, any tax on consumption, even if progressive in terms of total consumption expenditure, affects the very rich only marginally as most of their income is not spent on consumption but rather accumulates in their stock of wealth. Therefore, it must be clearly stated that taxes on goods and services, as we have tested them here, are not game changers in the sense that they overhaul the global capitalist system. More subtle and indirect systemic effects however might be observable — peer effects and shifts of households towards less or at least greener consumption can gradually change the overall system as well.

5.3 Summary and contribution to the knowledge base

In this section, I briefly summarize the findings of this thesis and the overall contribution to the knowledge base. In chapter one, I have reviewed the literature around economic inequality, climate change and redistribution and discussed how they are all interrelated. In chapter two, I have quantified how unequal household energy footprints are distributed internationally. In fact, in chapter two I have also significantly expanded the scope of the energy footprint literature, shifting the debate from a focus on within-country inequalities in high-income countries (Pottier, 2022) to international disparities and countries in the Global South (IPCC, 2022a). In chapter two, I also introduced the fact that international and national energy disparities are shaped by the unequal demand for luxury and necessity goods and the tendency to consume large quantities of private transport among high-income households. This sectoral pattern had previously been demonstrated for household carbon footprints on a national level and on a regional level for Europe (Ivanova et al., 2015; Gough, 2017) but not internationally for energy footprints. In chapter three, we introduced a simple yet innovative model of global income and household energy redistribution, for the first time taking sectoral resolution on the demand-side into account. Through sensitivity analysis, we found that lower global income inequality substantially influences household energy demand across sectors and constitutes an opportunity to eradicate (energy) poverty as well as possibly an opportunity to mitigate climate change. Therefore, this model goes substantially beyond previous models of energy and carbon redistribution (Chakravarty et al., 2009; Chakravarty and Tavoni, 2013; Rao and Min, 2018) which all only analysed aggregate energy or carbon emissions. In chapter four, I utilized the differentiated nature of household consumption (necessities vs. luxuries) for climate policy in order to explore different designs of carbon taxation. I integrated information about the income elasticity of consumption into carbon taxation rates — suggesting a novel carbon tax design. By testing this carbon tax design across 88 countries including the USA, Europe, India, China etc., I also added to the scope of distributional carbon taxation studies. Previous studies investigating distributional implications of carbon tax designs are limited to single countries or specific country groups (Dorband et al., 2019; Malerba, Gaentzsch and Ward, 2021; Steckel et al., 2021) and do not test differentiated carbon taxation of household consumption compared to uniform taxation. Employing this model, I found that luxury-differentiated carbon taxes are more progressive across all countries, and especially in high-income countries, while similarly effective at abating carbon emissions. Moreover, I have suggested that carbon tax revenue can be invested into residential retrofitting programmes which further would reduce household emissions. Subsequently, I inferred an ‘optimal’ revenue allocation (optimal in the sense that it is one optimized policy option for revenue allocation, but not necessarily the best out of all thinkable revenue allocation designs, that is, mathematically speaking, locally optimal but not globally) between the two goals of redistribution to the poor and carbon emissions abatement, contingent on the inequality of consumption in any given country – we find that highly unequal countries should redistribute more to low-income households compared to lower inequality countries. These insights extend the space of possible climate policies, adding to the established and often considered ‘optimal’ revenue recycling in form of equal per capita lump-sum transfers (Mintz-Woo, 2022). In sum, chapter four delivers new perspectives on the relationship between national and international consumption-inequalities and carbon taxation.

In this chapter, I have so far systematically compared my results to the literature and found that they appear robust and put my findings into the context of broader debates in economics, politics and society. I specifically have elaborated on how the results fit into the debates around green growth versus degrowth and their relationship to the overall economic system, namely capitalism. Lastly, in section 5.4, I reflect on the limitations and shortcomings of my work and speculate about what these imply for the future of inequality and redistribution studies in the field of energy and carbon inequality.

5.4 Limitations and outlook

Even if today’s capitalist systems are not at the outer edge of the Inequality Possibility Frontier (Milanovic, Lindert and Williamson, 2007), today’s inequalities are utter injustice, particularly with respect to rapidly diminishing carbon budgets. If we want to live in a fairer world, we must reduce economic inequalities as well as energy and carbon inequalities. The redistribution of economic and physical resources that I explored, therefore, does not constitute the end of an inquiry but only its beginnings.

5.4.1 New data, new models

What are the ways forward? Our research falls in line with a trend towards higher data resolution and accessibility. Today’s possibilities for gathering, storing and distributing data are vastly different than they were only a few decades ago. Herendeen and Tanaka (1976) were able to study energy intensities of consumer products for one country, the USA; we were able to study the same for 88 countries and based on much improved accounts of economic trade. This progress is not only owed to the rapid development in computational power but also builds on a concerted international effort to collect and harmonize data – it is about social coordination as much as about computational efficiency. Therefore, a defining feature of future energy and carbon inequality as well as redistribution studies is likely increased resolution of data.

We covered many countries and income groups while applying high sectoral resolution, and even employed this in redistribution studies of energy where it constitutes an entirely new feature. We have not, however, considered socio-demographic features other than income and consumption, that is, horizontal inequalities. There are already some energy and carbon inequality studies considering age, gender, profession, political orientation, detailed geographical location, see for instance Büchs and Schnepf (2013). Yet overall they remain rare in the carbon and energy inequality literature and only a few studies consider countries of the Global South (Pachauri, 2004; Baltruszewicz et al., 2021).

The accumulation of accessible socio-demographic data and consumer spending data has only just begun. Behind closed doors, in the technology conglomerates of the 21st century, and even smaller players in the background, like insurance companies and credit card companies, hides an unfathomable wealth of data on people and their behaviour: their demand for goods and services, their demand for energy commodities, possibly entire personality profiles. How much of this will ever be accessible to the public is unclear and there are of course ethical problems too. But ultimately the future of household and consumer analysis looks to be highly granular and might *almost* happen in real time. There are already first economic studies employing such high-resolution corporate data sets, for instance on the economic impacts of the first Covid-19 lockdowns in spring 2020 (Chetty et al., 2020) or indeed to estimate carbon footprints (Kilian et al., 2022). Even if corporate data does not come to play a substantial role, the high-resolution trend nevertheless marches on. Government agencies, national, regional, and particularly local administrations contribute their fair share.

Despite fast evolution of the data landscape, visible gaps remain. Input-Output models (especially multi-regional ones) only evolve slowly because assembling, verifying, and harmonizing the national account data is a cumbersome task for statisticians and economists. For example, the newest GTAP version that exists now, is GTAP 10, and only refers to 2014. Another substantial data gap for inequality studies is insights into the life of the super-rich, that is, billionaires and multi-millionaires. The long tails of the wealth, income and consumption distributions are significantly underrepresented, and although first efforts have been made to close the gaps, they mostly rely on modelling rather than primary data, and if primary data is considered, then only through very limited samples (Otto et al., 2019; Chancel, 2021).

A first opportunity for future research is perhaps to calculate international energy- and carbon footprints over time, with higher resolution of income groups and potentially even taking other socio-economic characteristics into account. There is a great need to observe household consumption over time and to test the influence of policies. Does European climate policy influence household consumption? To take a concrete and quantifiable example, if we consider the energy intensity – income elasticity space of household consumption in Figure 2-4, how does it evolve over time? How does policy shift energy intensities and income elasticities? Another immediate opportunity for further research is to use the most recent and highly granular carbon footprint data, such as in Bruckner et al. (2022) and Chancel (2021), to investigate the distributional effects of carbon taxation.

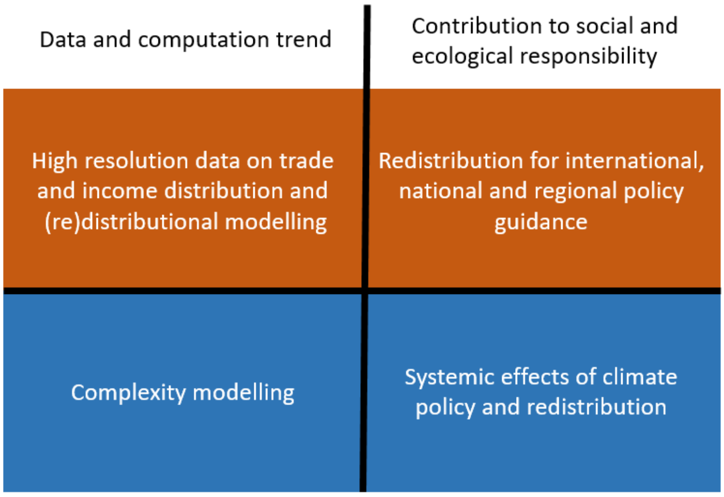
5.4.2 (Re)distribution, complexity and system science

Another prominent research perspective we have largely ignored in this thesis, but that could have large implications for inequality and redistribution studies, is to model the economy as a complex adaptive system. Complexity- and system science has been rapidly evolving over the last few decades, including in economics and energy studies. In complexity economics, there has been much work on how income and resource distributions emerge from the micro-interactions of agents (Asano et al., 2021) and also since the financial crisis 2008, its ideas have taken a strong standing in the field of 'systemic finance'. Complexity ideas also have been applied to the production side (Hidalgo, 2021), describing the economy as a network of industries. The structure of this industry network determines not only the generation of income but also its distribution (Hartmann et al., 2017). Most complexity-oriented models are aimed at reproducing essential observable features of economies such as business cycles (Asano et al., 2021) or cascading failures in the banking system (Papadopoulos, 2019) (as observed 2008) but hardly ever to reimagine the economy. Why not assume a novel productive structure of the economy and test its behaviour under plausible assumptions of complex system behaviour? What implications do radically different income distributions have across the economy? Are there important feedbacks to consider? Some distributional questions and climate policies are already increasingly studied in the complexity-oriented literature, for example: How do heterogeneous agents react to redistributive policies and different carbon taxation regimes? Agent-based modelling of climate policies and their distributional implications is a rapidly growing research field, compare for instance Castro et al. (2020); Foramitti, Savin and van den Bergh (2021) or Konc et al. (2022).

Another concrete case of systemic modelling where (re)distribution is likely to play a greater role is within Integrated Assessment Models of climate and economy. These models are large and are prominent informers of the climate reports of the Intergovernmental Panel on Climate Change, but inequality has played a marginal role so far. The models usually combine computable general equilibrium models with climate models. Now there are efforts to integrate income distribution more explicitly in those models (van Ruijven, O'Neill and Chateau, 2015) but there is room to make the links between the distribution of income, energy and emissions more explicit. For example, new integrated models could explore differentiated and luxury-oriented carbon pricing, such as we have conducted in chapter four, but considering more variables in economic production, demand and climate feedbacks.

5.4.3 A blueprint for further research – (Re)distribution in the 21st century

Eventually, three trends will shape (re)distribution research in the 21st century: First, high-resolution data and high-resolution (re)distributional modelling enables better guidance for policy to create just and sustainable outcomes. Second, integration of (re)distribution in complexity-oriented models will yield better understanding of policy trade-offs and feedbacks. Third, redistribution is not just a matter of economic resources but of climate change, ecological stability and ultimately of survival. It is therefore key that (re)distribution research in the 21st century takes social as well as ecological responsibility seriously. Figure 5-1 summarizes this blueprint for (re)distribution research in one matrix.



Data and computation trend	Contribution to social and ecological responsibility
High resolution data on trade and income distribution and (re)distributional modelling	Redistribution for international, national and regional policy guidance
Complexity modelling	Systemic effects of climate policy and redistribution

Figure 5-1: A blueprint for (re)distribution research in the 21st century

To conclude allow me one more historical note. One-hundred years ago, in his famous essay 'Economic possibilities for our grandchildren', John Maynard Keynes argued that the 'economic problem' could be completely solved in the 2020s. He thought it plausible that everyone in Europe and America will have enough resources not to worry at all about income, and that in the long-run this would also happen to every other nation (Keynes, 1930). He imagined a high degree of automation that makes labour redundant and people free of work. This is clearly not the case. Keynes' utopia did not emerge, even though he correctly predicted that the average real income will be between four to eight times larger than in 1930s America and Europe. In the United Kingdom and the United States it is ~5.5x larger than in 1930 (Roser, 2022). Income and resource poverty are still pervasive globally and within countries, as we have seen throughout this thesis. Most people also still work long hours for income and subsistence. To be fair, Keynes did not foresee climate change as we face it today and he also assumed no major wars would happen. In 2022, with frightening temperature anomalies happening in the Antarctic (Sciencealert, 2022) as well as a major war within Europe, all this seems far away. But given his correct predictions about real income in Western nations, inequality remains a central force standing in the way of good living standards for all. If utopia is ever to emerge, (re)distribution research will have delivered.

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Appendix A. Supplementary information 1

SUPPLEMENTARY INFORMATION FOR:

Large inequality in international and intranational energy footprints between income groups and across consumption categories

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Supplementary Note 1

Supplementary Table 1: Data applied

Real world system	**Data representation**	**Spatial scope**	**Temporal scope**	**Income granularity**	**Sectoral granularity**
Household Expenditure South/Developing/Emerging	The Global Consumption Database (GCD) by the World Bank	92 countries	2010	4 income groups	87 Consumption Categories
Household Expenditure North/Developed	The Eurostat data tables on household expenditure patterns	30 countries	2010	Quintiles	41 Consumption Categories
Supply Chains	The Global Trade Analysis Project – GTAP	140 regions	2011	/	57 industries
Energy System	IEA Energy Balances from the UK data service (UK Data Service, 2018)	142 countries	2011	/	26 industries
Overall		**86 countries**	**2011**	**mixed**	**reduced**

Supplementary Table 2: Country coverage and sample description

Name data	**Sample size**	**Income resolution**	**Temporal scope**	**% of Global GDP 2011 in GTAP**	**% of Global Population 2010**	**Countries covered**
Global Consumption database (GCD)	N = 56	4 income segments	2010	~ 30%	~ 70%	Albania, Armenia, Azerbaijan, Bangladesh, Belarus, Benin, Bolivia, Brazil, Burkina Faso ,Cambodia, Cameroon, China, Colombia, Cote d'Ivoire, Egypt, El Salvador, Ethiopia, Ghana, Guatemala, Guinea, Honduras, India, Indonesia, Jamaica, Jordan, Kazakhstan, Kenya, Kyrgyz Republic, Lao PDR, Madagascar, Malawi, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Namibia, Nepal, Nicaragua, Nigeria, Pakistan, Paraguay, Peru, Philippines, Russia, Rwanda, Senegal, South Africa, Sri Lanka, Tanzania, Thailand, Togo, Uganda, Ukraine, Vietnam, Zambia
Eurostat Household budget surveys	N = 30	Quintiles	2010	~26%	~ 8.4%	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain ,Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway,

						Poland, Portugal, Romania, Sweden, Slovenia, Slovakia, Turkey, United Kingdom
Added together	N = 86	/	2011, since the GTAP is 2011	~56%	~ 78.4%	Union of above

Supplementary Note 2

Scaling up expenditure volumes: Initially both databases come in the form of “micro-level” surveys which is a sample of households from each country stating their yearly expenditures. They do not initially display the national expenditure volume per income class per product in each country. They display expenditure per household in the case of Eurostat and per capita in the case of the Global Consumption database. This is why these surveys have to be scaled up to national volume.

In terms of the Eurostat two preparatory steps are necessary. The expenditure data in the Eurostat database comes for 30 countries in a unit called “parts per mille” that is the same as percentage wise proportions of expenditure per COICOP category. Another data table called “Mean household expenditure across income quintile and COICOP category” delivers the actual spend volume of an average household. The mean expenditure comes in the unit “Purchasing Power Standard (PPS) per household” which is an international exchange rate with respect to the Euro. This average total expenditure volume then had to be distributed via the proportions. In order to scale up the expenditure volumes to national level the number of households per country is needed. In Eurostat this number is given via the data-table called “Conventional dwellings by occupancy status, type of building and NUTS 3 region (cens_11dwob_r3)”.

Scaling up the Eurostat survey results to national level happens via the following simple calculation:

$$E_{i,j,k} = S_{i,j,k} \times M_{i,j,k} \times \ HH_{j,k}$$

where E is the total expenditure volume per country, S is the spend proportion given per product, M the mean total expenditure volume per household and HH the number of households in each country. The indices stand for:

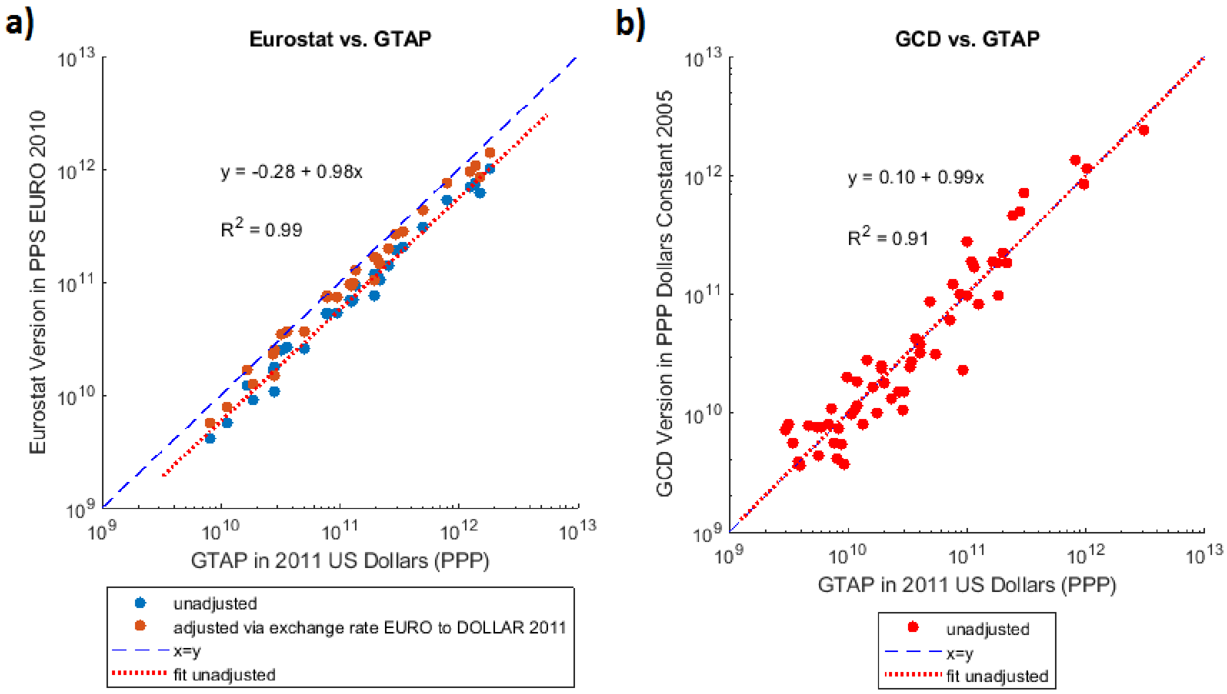
i = Product

j = Income Quintile

k = country.

The GCD comes in a different initial format. There is expenditure data per capita available. This per capita value can then be multiplied (scaled up) via the population in each country in order to arrive at national volumes.

Important is that the resulting volumes make sense. Since we do not have final household consumption per income group in the GTAP, we must compare the national expenditure volume from Eurostat and GCD to GTAP. Figure 6 demonstrates the results. It is clearly visible that despite smaller deviations the volumes coming from the GTAP (x axes) are consistently similar to the calculated volumes coming from Eurostat and GCD (y axes).



Supplementary Figure 1: Comparing final household expenditure in GTAP, Eurostat and GCD

The Eurostat volumes are systematically somewhat smaller very similar. The comparison of the respective results with the GTAP is not as accurate and systematic as the one with Eurostat. Yet, the results fall into a reasonable range with none leaving the corresponding order of magnitude they should be in according to the GTAP model. This is what figure 1 (b) shows.

There are, moreover, five countries available that occur in both expenditure databases, Eurostat and GCD. These are:

1) Latvia

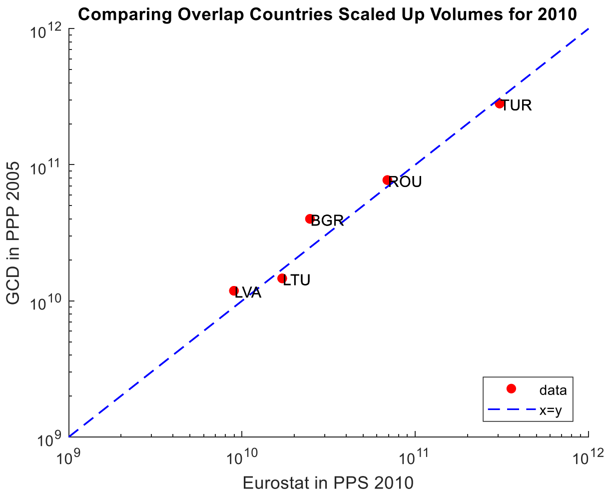
2) Lithuania

3) Bulgaria

4) Romania

5) Turkey

Conveniently, we can also compare both methods to scale up the surveys on the basis of these five countries. The results here are very similar which is a strong indication for the underlying empirical quality of the surveys and supports both methods to scale up to national level. Note however that two different currency units are at work here. Once USD PPP at constant prices with reference to 2005 and once Euro PPS version with 2010 as reference. However since both units are meant to capture physical trade volumes for the same year, 2010, the comparison is appropriate.



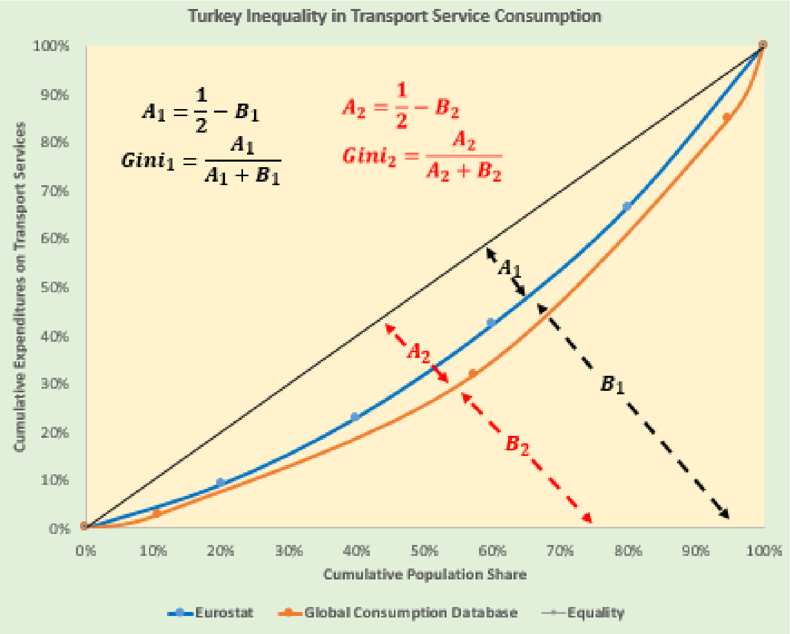
Supplementary Figure 2: Expenditure volume comparison for the Eurostat and GCD overlap. In general, we can note that the data relates well to each other.

Supplementary Note 3

Comparing inequality systematics in Global consumption database vs. Eurostat: The World Bank data is segmented into four invariable income groups across all countries:

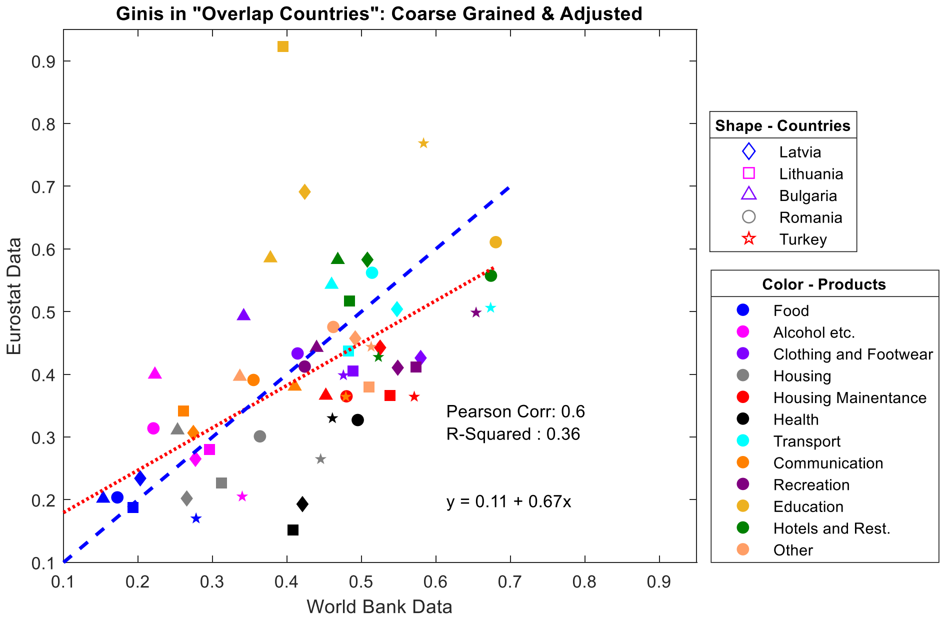
- Lowest—below \$2.97 per capita a day
- Low—between \$2.97 and \$8.44 per capita a day
- Middle—between \$8.44 and \$23.03 per capita a day
- Higher—above \$23.03 per capita a day.

The Eurostat data on the other hand comes divided into quintiles for each country, thus the thresholds for the five cut-off points vary with each country. The Eurostat version is usually the one better to investigate inequality and distributional issues because it preserves the necessary properties for computing inequality metrics, such as scale independence, population independence etc. (Cowell, 2009). The World Bank systematic violates these principles but since a significant amount of our data is based on it, we investigated to what extent it does so. We compared the Lorenz Curves and corresponding Gini coefficients for the "overlap countries" that is the five countries that occur in both data bases: Turkey, Latvia, Lithuania, Bulgaria and Romania. Supplementary Figure displays how a direct comparison between the two databases for a specific product group can look like. It displays the Lorenz Curve for expenditures in the COICOP category Transport Services based on the Eurostat data (blue) vs. based on the GCD data (orange). Both curves are very similar with the inequality in the second Lorenz Curve a bit more pronounced. Supplementary Figure 4 on the other hand illustrates the results for all five overlap countries and 12 aggregated COICOP product groups. One sees that the results are systematic for all groups except education. We see product groups pretty much gathering around the x=y line that is Food, Alcohol etc., Clothing, Transport, Hotels and Restaurants. Some fall systematically below that line which means they tend to exhibit higher inequality in the World Bank data e.g. Housing and Housing Maintenance as well as Health.



Supplementary Figure 3: Comparing Lorenz Curves of Gini Coefficients.

Why is education in **Supplementary Figure** diverging so far from the x = y line as well as from the model fit? The definition of what has been measured in the GCD surveys is stated as "*Education this group covers educational services only. It does not include expenditures on educational materials, such as books and stationery, or education support services, such as healthcare services, transport services, catering services and accommodation services. It includes education by radio or television broadcasting."* The definition is similar for the Eurostat data. Thus, we have to assume that most likely it is due to differences in the applied surveys. We apply the Gini small sample correction by Deltas 2003.



Supplementary Figure 4: Comparing Gini Coefficients World Bank Systematics vs. Eurostat Systematics

Supplementary Note 4

Supplementary Table 3: Mapping COICOP to GTAP: Correspondence to the International Standard Industrial Classification of Economic Activities Revision 3.1 (ISIC Rev. 3.1) is used to map the COICOP to GTAP. For a full list of the GTAP sectors please consult https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp.

COICOP ID 1999	**Category**	**GTAP sectors associated**
1.1	Food	1,2,3,4,5,6,8,9,10,11,14,19,20,21,22,23,24,25,26
1.2	Non-alcoholic beverages	8,25,26
2.1	Alcoholic beverages	26
2.2	Tobacco	26
2.3	Narcotics	8,25
3.1	Clothing	7,12,27,28,31,33,37,42,47,54,55
3.2	Footwear	27,29,47,54,55
4.1, 4.2	Actual rentals for housing, Imputed rentals for housing	47,54,57
4.3	Maintenance and repair of the dwelling	30,31,33,34,37,42,46,54,56
4.4	Water supply and miscellaneous services relating to the dwelling	41,45,54,56
4.5	Electricity, gas and other fuels	13,15,16,17,32,33,37,43,44
5.1	Furniture and furnishings, carpets and other floor coverings	13,27,28,29,30,31,33,36,37,41,42,46,47
5.2	Household textiles	27,30,33,42,47
5.3	Household appliances	13,27,37,41,46,47,54
5.4	Glassware, tableware and household utensils	13,29,30,33,34,37,41,42,47
5.5	Tools and equipment for house and garden	13,30,33,37,39,41,47,54
5.6	Goods and services for routine household maintenance	13,27,29,30,31,32,33,36,37,41,42,54,55
6.1	Medical products, appliances and equipment	33,39,41
6.2	Outpatient services	54,55,56
6.3	Hospital services	56
7.1	Purchase of vehicles	35,36,38,39
7.2	Operation of personal transport equipment	32,33,34,37,38,39,40,41,47,48,49,54,56
7.3	Transport services	35,48,49,50
8.1	Postal services	51
8.2	Telephone and telefax equipment	40
8.3	Telephone and telefax services	51,54
9.1	Audio-visual, photographic and information processing equipment	31,33,40,41,46,47,54
9.2	Other major durables for recreation and culture	27,29,30,37,38,39,41,42,47,48,56
9.3	Other recreational items and equipment, gardens and pets	13,18,27,29,30,31,33,34,37,41,42,47,54,55,56
9.4	Recreational and cultural services	48,51,54,55,56
9.5	Newspapers, books and stationery	31,33,37,40,41,42
9.6	Package holidays	48,50
10.1,10.2,10.3,10.4,10.5	Education	56
11.1	Catering services	47

11.2	Accommodation services	47
12.1	Personal care	27,28,31,33,37,41,42,47,55
12.3	Personal effects n.e.c.	29,30,33,34,37,41,42,47
12.4	Social protection	56
12.5	Insurance	53
12.6	Financial services n.e.c.	52,54
12.7	Other services n.e.c.	47,52,54,56

Supplementary Note 5

Supplementary Table 4: IEA to GTAP mapping: Correspondence to the International Standard Industrial Classification of Economic Activities Revision 3.1 (ISIC Rev. 3.1) is used to map the IEA to GTAP as well.

IEA Sectors	**GTAP Sectors associated (Names or IDs)**
Iron and steel	Ferrous metals
Chemical and petrochemical	Petroleum, coal products Chemical, rubber, plastic products Ferrous metals
Non-ferrous metals	Petroleum, coal products Metals nec
Non-metallic minerals	Mineral products nec
Transport equipment	Motor vehicles and parts Transport equipment nec Machinery and equipment nec Manufactures nec
Machinery	Chemical, rubber, plastic products Metal products Motor vehicles and parts Transport equipment nec Electronic equipment Machinery and equipment nec Manufactures nec
Mining and quarrying	Coal Oil Gas Minerals nec Construction
Food and tobacco	1, 4, 8, 10, 12, 19-26, 33
Paper, pulp and printing	Textiles, Paper products, publishing Metal products Manufactures nec
Wood and wood products	Wood products Leather products Manufactures nec
Construction	Construction
Textile and leather	Textiles Wearing apparel Leather products Mineral products nec Motor vehicles and parts Manufactures nec
Non-specified (industry)	27-31, 33,34,37,39,41,42
Domestic aviation	Air transport
Road	Trade (direct/fuel and indirect way)
Rail	Transport nec
Pipeline transport	Transport nec Electricity Gas distribution
Domestic navigation	Water transport
Non-specified (transport)	Transport nec Recreational and other services
Residential	Gas manufacture and distribution (direct way/heating)
Commercial and public services	14,18,27,30-34,37-42, 51-56
Agriculture/forestry	1-13

Fishing	Fishing
Non-specified (other)	Public Administration, Defense, Education, Health
Zero energy dummy	Dwellings (because no energy associated with dwelling rents)

Supplementary Note 6

Aggregation of COICOP consumption categories: We have aggregated the COICOP consumption categories to a resolution of 14 categories for the main results. Supplementary Table depicts precisely which COICOP categories we aggregated to the ones displayed in the main results.

We selected the aggregation based on what is the smallest common denominator between databases with the additional consideration of what yields the most useful insight: Where can we make useful distinctions between products and their energy intensity as well as their income elasticity of demand? Therefore, for example, wheat and rice might not be very different in terms of these properties. This is why we kept Food a general category. However, Package Holiday is fundamentally different to food commodities with respect to both aspects. Often these criteria coincide with a product being a significantly large share of energy footprints, for example in terms of Food, Vehicle Fuel or Heating and Electricity. Sometimes, however, as in the case of Package Holiday the overall contribution to the total energy footprint is not that large but our data allowed us to attain granularity and yield a useful distinction between low-income consumer and high-income consumers.

Supplementary Table 5: Aggregation mapping of consumption categories

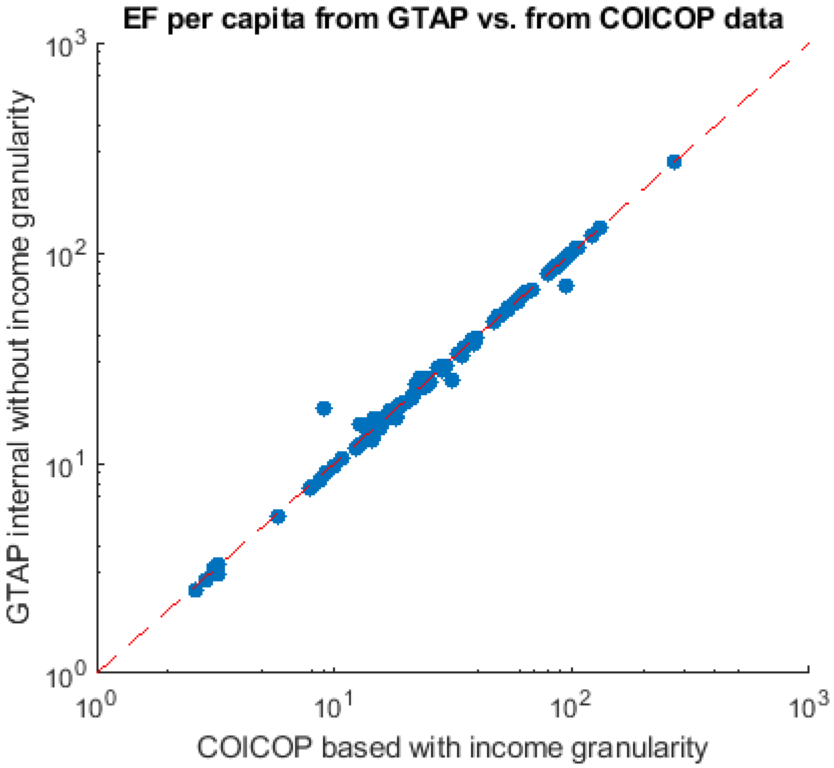
Consumption categories aimed at in our analysis	**COICOP Version 1999 IDs associated**
Food	01.1.2,01.1.3,01.1.4,01.1.5 01.1.6, 01.1.7, 01.1.8,01.1.9,01.2.1,01.2.2
Alcohol and Tobacco	02
Wearables	03
Other housing	04.1, 04.2, 04.3, 04.4
Heating & Electricity	04.5
Household Appliances and Services	05
Health	06
Vehicle Purchase	07.1
Fuel for own vehicles	07.2
Other transport (Land transport, Airtransport, Watertransport, Other transport modes)	07.3.1, 07.3.2, 07.3.3,07.3.4,07.3.5,07.3.6
Communication Tech. and Equip.	08, 09.1, 09.5
Recreational items	09.2, 09.3, 09.4
Package Holiday	09.6
Education & Finance & Other Luxury	10, 11, 12.1, 12.2, 12.3.1, 12.3.2, 12.4, 12.5, 12.6, 12.7

Supplementary Note 7

Computing energy-intensities and energy footprints: The national energy footprints are computed as detailed in the main method section "Input Output Modelling of Energy footprints". Potentially, there are three ways to compute energy intensities and derive the granular energy footprints per income group and COICOP category. All three possibilities are related to the fact that we use RAS balancing in order to translate between the COICOP expenditures and the ones in the GTAP.

1) One might divide the computed energy footprints per country and per COICOP category by the balanced expenditures, that is the column sum of C_i, in equation (7). This gives a set of energy intensities that if applied to the national level GTAP expenditures exactly reproduces the national energy footprints. The GTAP expenditures however are missing income granularity. This is why they have to be applied to the original expenditure coming from the databases in Eurostat and GCD. However, in this case the national energy footprints do not exactly match the ones produced by the GTAP.
2) Take the energy footprints and divide them by the balanced spends to attain energy intensities. This time also split up the balanced spends according to income group proportions in the original COICOP data. Then multiply with the energy intensities. This would work if the spends were 100% complete in the original COICOP data. However since there are some gaps, interpolations to distinguish income groups are necessary.
3) Take the energy footprints and divide them by the original COICOP expenditure to attain energy intensities and afterwards use these energy intensities to multiply them with the original and granular COICOP expenditure per income group and consumption category. This produces up to 99% the correct national footprints but also renders income granularity as found in the original household budget surveys. It only misses some minor portion of the entire energy footprints for a few countries because there are some gaps in the original expenditure data.

We applied option three because it almost perfectly captures national footprint volumes and on top of that, it preserves the original income granularity. Option one implies large trade-offs in terms of national footprints and option two does not capture the original expenditure distribution based on household budget surveys. **Supplementary Figure** illustrates how well the actual average national footprint per capita (y-axis) is reproduced by the approach No.3 (x-axis).



Supplementary Figure 5: National average energy footprints per capita. The figure depicts energy footprints computed according to approach No. 3) above (x-axis) vs. the national volumes computed via the GTAP (y-axis).

Only for four countries there are significant differences (here >|+/-10%|) in the energy footprints per capita. This is mostly because of missing expenditure data. These countries are listed in Supplementary Table .

Supplementary Table 6: Countries with significant differences in energy footprints due to different RAS balancing approaches. Based on granular approach vs. non-granular approach.

Name	GTAP ID	Average Energy footprint per capita (COICOP with granularity and gaps)	Average Energy footprint per capita (GTAP without granularity and gaps)	% difference
Honduras	44	9.02 GJ/yr	18.3 GJ/yr	-50.67%
Cyprus	56	93.85 GJ/yr	70.12 GJ/yr	+33.84%
Jordan	100	31.28 GJ/yr	25.06 GJ/yr	+24.81%
Benin	112	12.93 GJ/yr	15.34 GJ/yr	-15.70%

Supplementary Note 8

Elasticity to logistic regression to power-Law: We assume that energy footprints are a function of consumption and that consumption is a function of income. The latter is captured by the elasticity of demand which is defined as the percentage change of demanding a good, given a one percentage change in income (Lehfeldt, 1914; Steinberger, Krausmann and Eisenmenger, 2010) or formally

$$\epsilon = \frac{\frac{dQ}{Q}}{\frac{dI}{I}}. \qquad \text{Elasticity of Income}$$

These elasticities can be interpreted as the exponent of a power law. The crucial insight is that the derivative of the natural logarithm is equal to 1/x

$$\frac{d}{dx}\ln(x) = \frac{1}{x}$$

$$\mathrm{d}\ln(x) = \frac{dx}{x}.$$

Now the expression dx/x is similar to our percentage ratios in the definition of elasticity. Therefore it follows

$$\epsilon * \frac{dI}{I} = \frac{dQ}{Q}$$

$$\mathrm{d}\ln(Q) = \epsilon * \mathrm{d}\ln(I)$$

$$\ln(Q) + k = \epsilon * \ln(I) + c \qquad \text{Logistic Regression}$$

$$Q * e^k = I^\epsilon * e^c$$

$$Q = I^\epsilon * e^{c-k} \qquad \text{Power Law}$$

Set $e^{c-k} = a$, *Q* = *y*, *I* = *x*, *ϵ* = *b* and one arrives at

$$y = a * x^b$$

These power law relationships allow us to model the consumption of goods not only as function of income but determine either proportional, escalating, decaying or saturating behaviour. The "intermediate version" of a logistic regression model connects these concepts directly to the empirical data.

An interesting view on the connection between log-log regressions and their interpretations as elasticity comes also from "reasoning the other way around". Assume the general case of "logged" variables Y and X.

$$\log(Y) = a + \mathrm{b}\log(X)$$

$$\frac{d}{dX}\log(Y) = \frac{d}{dX}(a + \mathrm{b}\log(X))$$

$$\frac{dY}{dX}\frac{d}{dY}\log(Y) = \frac{d}{dX}(a + \mathrm{b}\log(X))$$

$$\frac{dY}{dX}\frac{1}{Y} = b * \frac{1}{X}$$

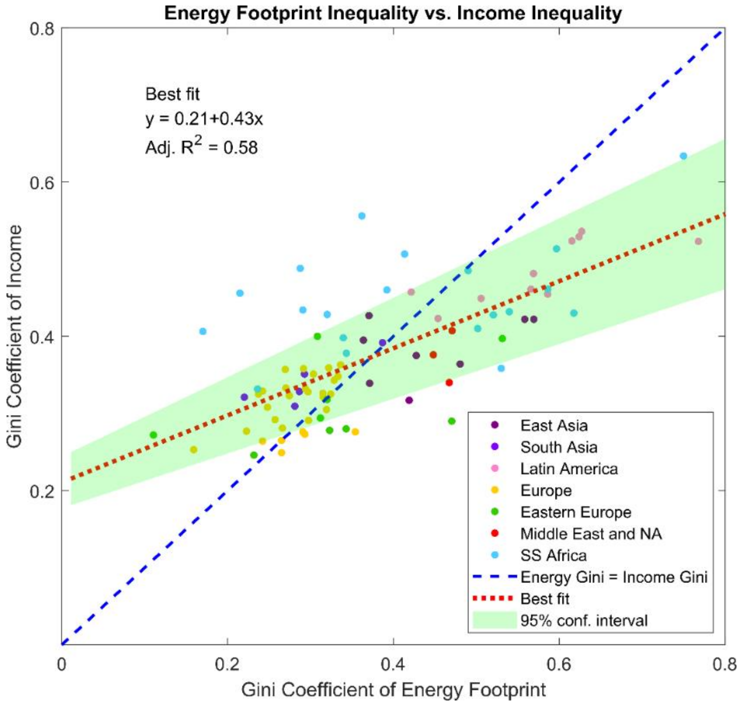
$$\frac{dY}{Y} = b * \frac{dX}{X}$$

$$b = \frac{\frac{dY}{Y}}{\frac{dX}{X}} \coloneqq \epsilon$$

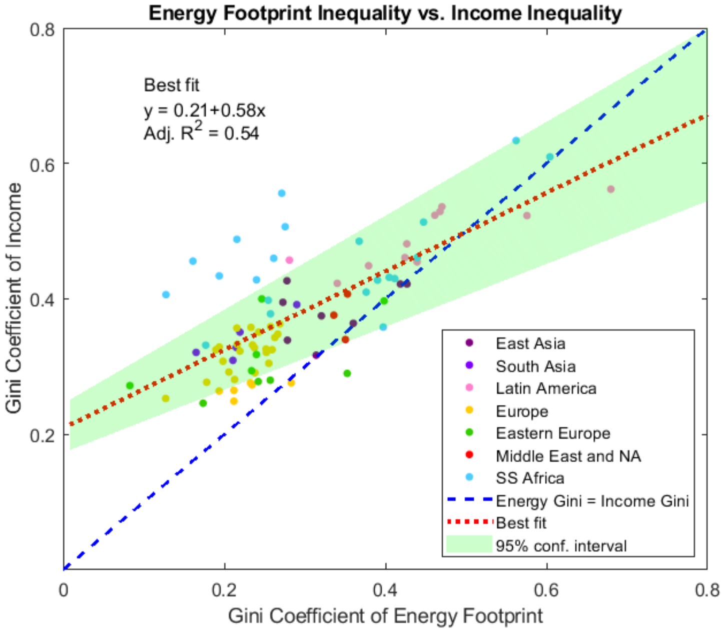
This proves that the coefficient b in a general log-log regression is directly interpretable as an elasticity.

Supplementary Note 9

National income inequality compared to energy inequality: Energy inequality exhibits a wider spread and faster growth than income inequality, no matter whether the small-sample bias correction is applied to the measured Energy footprint Gini coefficient as in the main text or not.



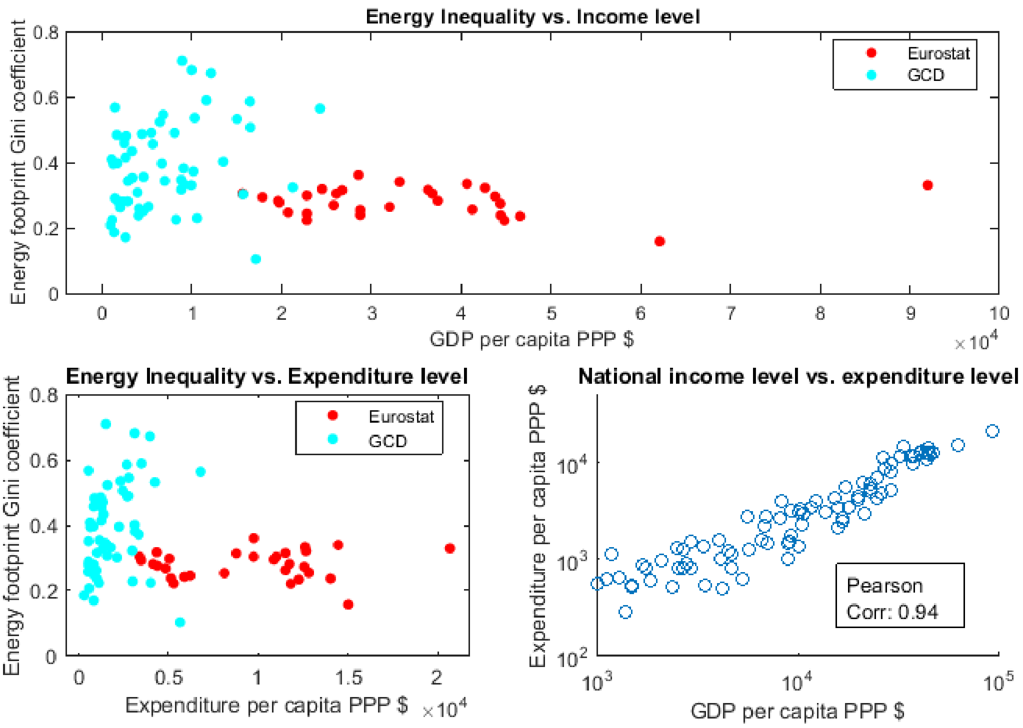
Supplementary Figure 6: Energy footprint inequality vs. income inequality (corrected for small sample bias).



Supplementary Figure 7: Energy footprint inequality vs. income inequality (not corrected for small sample bias).

Supplementary Note 10

Energy inequality and income level: There is no systematic relationship between income level per capita and energy inequality of a country. The same goes for expenditure level per capita, which is also uncorrelated with energy inequality. This makes sense, since it highly correlates with income.



Supplementary Figure 8: Energy inequality and income level

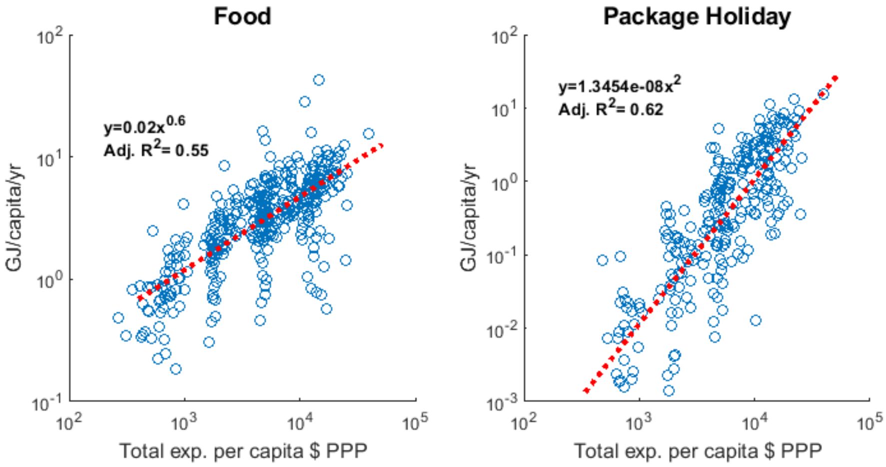
Supplementary Note 11

Supplementary Table 7: Regional energy inequality

Gini coefficient	East Asia and Pacific	South Asia	Latin America and Caribbean	Europe	Eastern Europe and Central Asia	Middle East and North Africa	Sub-Saharan Africa
total	0.42	0.26	0.49	0.27	0.39	0.38	0.48
Food	0.33	0.18	0.33	0.20	0.26	0.21	0.47
Alcohol and Tobacco	0.37	0.11	0.57	0.28	0.28	0.27	0.72
Wearables	0.47	0.26	0.44	0.36	0.46	0.35	0.51
Other housing	0.48	0.61	0.54	0.26	0.40	0.36	0.66
Heating and Electricity	0.39	0.20	0.31	0.20	0.37	0.22	0.47
Household Appliances and Services	0.50	0.38	0.61	0.40	0.49	0.42	0.62
Health	0.50	0.30	0.57	0.36	0.50	0.41	0.65
Vehicle Purchase	0.56	0.48	0.80	0.57	0.66	0.88	0.81
Vehicle Fuel and Maintenance	0.53	0.56	0.64	0.34	0.54	0.71	0.81
Other transport	0.56	0.32	0.38	0.39	0.47	0.33	0.63
Communication	0.57	0.47	0.55	0.32	0.47	0.50	0.74
Recreational items	0.57	0.42	0.63	0.38	0.68	0.54	0.87
Package Holiday	0.60	0.74	0.85	0.54	0.52	0.78	0.87
Education & Finance & Other Luxury	0.44	0.38	0.61	0.39	0.50	0.42	0.70

Supplementary Note 12

International energy footprint elasticity of consumption categories: We show that energy footprints decomposed by consumption category do not always decouple from increasing total expenditure, i.e. our proxy to income. Here for example we depict the consumption categories Food and Package Holiday. Food does get less energy intense at higher expenditures but Package Holiday does not. This is visible by the steep slope of the best-fit line. Package Holiday exhibits internationally an energy footprint elasticity of 2 while Food does exhibit one of 0.6. These two graphs stand in direct relationship and contrast to Figure 1 in the main text. There we show the scaling of energy footprints with overall expenditure but here we differentiate between consumption categories.



Supplementary Figure 9: Scaling of energy footprints with total expenditure by consumption category

Supplementary Note 13

Multivariate regression explaining energy inequality: We conducted a multivariate regression in order to explain the observed levels of energy inequality. The variables chosen were Fossil fuel share (to represent energy mix), Degree of urbanization, and Manufacturing value added to GDP as well as Agriculture value added to GDP for representing industrial production structures. None of the tested variables proves significant.

Supplementary Table 8: Multivariate regression results

Regression Statistics	
R Square	0.03
Adjusted R Square	-0.02
Standard Error	0.35
Observations	78

	Coefficients	*SE*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.80	0.28	-2.85	0.01	-1.36	-0.24
Fossil fuel % of total energy consumption by	0.13	0.19	0.71	0.48	-0.24	0.51
Urban population % of total	0.24	0.36	0.65	0.52	-0.49	0.96
Manufacturing value added % of total GDP	-0.01	0.22	-0.06	0.96	-0.45	0.43
Agriculture,forestry, fishing value added % of total GDP	0.19	0.12	1.53	0.13	-0.06	0.44

The data for independent variables in this section is all based on the open source World Bank repository (World Bank, 2019).

Supplementary Note 14

Supplementary Table 9: Business as usual future energy inequality across all consumption categories

		2011	**2030**	**2050**
Gini coefficient	Total	0.52	0.48	0.50
1	Food	0.45	0.41	0.43
2	Alcohol and Tobacco	0.60	0.62	0.66
3	Wearables	0.54	0.50	0.52
4	Other Housing	0.70	0.61	0.61
5	Heating and Electricity	0.45	0.41	0.41
6	Household Appliances and Services	0.66	0.60	0.60
7	Health	0.56	0.54	0.56
8	Vehicle Purchase	0.79	0.74	0.76
9	Vehicle Fuel and Maintenance	0.70	0.64	0.63
10	Other Transport	0.60	0.57	0.63
11	Communication	0.73	0.71	0.71
12	Recreational Items	0.77	0.73	0.74
13	Package Holiday	0.82	0.80	0.82
14	Education & Finance & Other Luxury	0.66	0.62	0.64

Supplementary Note 15

Further statistics applied: The probability density functions of Figure 3 in the main text have been computed via a Kernel density estimator with Matlab. Code and formula can be found here: https://uk.mathworks.com/help/stats/ksdensity.html.

The rank correlations measured with respect to Figure 4 in the main text are according to “Spearman’s rho” which is a Pearson correlation coefficient computed from the ranks of the data. These too have been computed with Matlab where code and formulas can be found here: https://uk.mathworks.com/help/stats/corr.html.

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Appendix B. Supplementary information 2

Supplementary information for

Global redistribution of income and household energy footprints: A computational thought experiment

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Contents of supplementary information

Supplementary Note 1: Log-normal distribution

We calculate income for 1000 income groups. These represent the entire world population as of 2011. In order to do so, we solve equation (1) the cumulative distribution function of the log-normal distribution for *x*. The parameters here are, *p* = cumulative population, *x* = income, μ is the mean and is the standard deviation of the logged income values. *Erf* denotes the error function.

$$p = \frac{1}{2} + \frac{1}{2} erf \left[\frac{ln(x) - \mu}{\sqrt{2}\sigma} \right] \tag{1}$$

In order to translate between the mean and standard deviation of the "logged" incomes and the "non-logged" incomes we use the following equations (2) and (3) (Wicklin, 2014). The parameters are as follows: μ is the mean and σ is the standard deviation of the logged income values, while μ_X is the mean of the non-logged incomes and σ_X the standard variation of the non-logged incomes.

$$\mu = ln \left(\frac{{\mu_X}^2}{\sqrt{{\sigma_X}^2 + {\mu_X}^2}} \right) \tag{2}$$

$$\sigma = \sqrt{ln \left(1 + \frac{{\sigma_X}^2}{{\mu_X}^2} \right)} \tag{3}$$

From the relationship between the normal distribution and the error function follows directly the following form (Crow and Shimizu, 1988).

$$Gini\ coefficient = erf \left(\frac{\sigma}{2} \right) \tag{4}$$

Supplementary Note 2: The nature of prediction and our model

The ultimate goal of any model is to make some sort of prediction. This means being able to say something about the behaviour of a system over time or over the range of another variable. The variable on whose basis we want to make a prediction is the degree of inequality. How suited is our model to make such a prediction? We have seen in section 3.3 that the uncertainty in some results is substantial but major trends are robust. Prediction however requires testing a model against data. An issue with our model is that it introduces circumstances that have no empirical equivalent, not on global scale nor on a national one. We isolate income redistribution as the only “control” variable and the overall size of the economy is preserved. There is no economy in history that ever experienced “pure” redistribution while holding total output constant. This is why we have little appropriate data to test against. We still attempt two more evaluations of this. Can we observe, for instance, a relationship between income inequality and the composition of energy consumption across countries, as is postulated by our model on a global level? Our model is one of global scale but country level data might provide an additional benchmark. Therefore we tested the relationship between income inequality and the share of transport energy out of the total national energy consumption. We find no significant relationship. Yet countries all around the world have vastly different income levels and energy demand is determined by that to a large degree. The relationship between income inequality and energy demand might be blurred by this. Thus, it be would too fast to conclude that the model makes a false prediction. Moreover, we do find a weak to moderate relationship between income inequality and carbon emissions from transport (R-Squared ~0.185) based on World Bank data, demonstrating that more unequal countries have a larger share of emissions from transport. Supplementary Figure 8 depicts that relationship.

The model itself relies on relationships inferred empirically and thus, provided that these relationships remain stable, the model should have predictive power. Another fact that we can clearly observe is that high-income countries do have a much greater share of their energy footprint in transport than low-income countries. Therefore, if the income gap between countries were to aggravate, let us say in the event that high-income nations like the U.S. and Germany further experience economic growth while nations like India or countries in Sub-Saharan Africa stagnate (e.g. because of climate hazards), it could be that rising income inequality is accompanied by a further increase in transport energy demand. Supplementary Figure 9 portrays the current trade-off between residential energy use and energy use in transport (including vehicle fuel and maintenance, vehicle purchases and package holiday) considering income a third dimension.

Supplementary Note 3: Normalizing expenditure

A caveat of the modelling principle applied is that with an elasticity larger than one, predicted expenditure per consumption category, at some point, outstrips the total expenditure that is used to predict it in the first place. This happens because then the expenditure per category rises faster than the total expenditure. Moreover, using power laws to predict expenditure per category does not suffice to precisely allocate total expenditure across consumption categories. They would not perfectly add up to 100% of total expenditure, even if no single category outstrips total expenditure. It is important to normalize the predicted values in such a way that 100% of total expenditure is composed of corresponding sub-shares. Therefore, the initial predictions, which do not take any predictive bounds into account yet, are only taken to generate the budget share that is spend per population segment on different consumption categories. These budget shares are subsequently used for splitting the predicted total expenditure. This is a simple normalization procedure that rescales the values to the proper interval. It does not change anything about the predicted proportions of consumption categories within the overall consumption.

At first, we use a given income per capita of group *j* to predict an expenditure per capita of group *j* through equation (5).

$$total\ consumption\ expenditure_j = 2.6\ income_j{}^{0.83} \tag{5}$$

From now on total consumption expenditure is denoted C_j. From this total expenditure value, we then can derive expenditure per consumption category *i*, denoted c_{ij} by similar power laws (all parameter values are found in Supplementary Table #2).

$$c_{ij} = a_i C_j{}^{b_i} \tag{6}$$

Then, we calculate the share s_{ij} of c_{ij} among the sum of all *n* predicted consumption categories.

$$s_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \tag{7}$$

Subsequently we can just multiply s_{ij} and C_{ij} to arrive at the properly rescaled expenditure per category, here denoted z_{ij}.

$$z_{ij} = s_{ij} * C_j \tag{8}$$

Supplementary Note 4: Sensitivity analysis elasticities

We conducted a Monte-Carlo simulation in section 3.3 to investigate the robustness of results. This simulation however was only based on uncertainty results from Oswald, Owen, & Steinberger, 2020 and our own statistical models.

The literature is inconclusive about income elasticities of demand for products and services. In particular, the important energy related elasticities for transport fuel and residential fuels are disputed. The elasticities also vary over space and time. The range in the literature is large, for instance, for gasoline anything from 0.1 to 2, with most around 1 and shortly below, have been reported (Finke, Rosalsky and Theil, 1983; Espey, 1998). Havranek and Kokes argue that high elasticities (>1) are due to publication bias and conclude that much lower elasticities for transport fuel of around 0.2 are close to the real average (Havranek and Kokes, 2015). Studies also usually distinguish between short-run and long-run elasticities. It has been shown that over the long-run, in countries as the U.K. for instance, income elasticities of demand decrease, which is possibly a consequence of rising average income over time (Fouquet, 2014). At higher incomes and consumption levels, the marginal utility of consumption for many products and services diminishes, hence the decreasing income elasticities.

One issue is that all these results are at the country level and studies did not investigate elasticities over the range of various countries taken together. This makes comparison difficult because it is a fundamentally different question to ask how the consumption of a good varies within one country or over the entire globe. We also work with a specific product aggregation. For example, vehicle fuel and maintenance are one consumption category in our model and this might make the elasticity behave differently from other reported results.

Despite challenges in comparison, the here applied elasticities of demand agree with a lot of the literature. Food (as a product bundle) for example is a basic good with an elasticity smaller than 1 and purchases of private vehicles a luxury good with elasticities far greater than 1. The general tendency for package holiday and all sorts of financial services to exhibit elasticities greater than 1 is also in agreement with the literature on luxury consumption and international travel. We also conducted a comparison to average within-country elasticities from Oswald et al., 2020 and the differences are rather small (see Supplementary Figure 4). We do differ with a significant share of the literature on income elasticities of residential energy and transport fuels. Both are often reported to be significantly lower than 1 (Havranek and Kokes, 2015; Schulte and Heindl, 2016). A fuel elasticity for our model lower than 1 makes no sense given that globally private transport vehicles are definitely not a basic good and we need to account for the vast number of people in the Global South not owning cars etc. Still we conduct a sensitivity analysis of our results with both energy-related elasticities put notably lower. Once we set only the elasticity of heat and electricity down to 0.7 from 0.88 (sensitivity run 1) and once we set down both, the elasticity of heat and electricity as well as the elasticity of vehicle fuel (sensitivity run 2 – vehicle fuel elasticity is put down to 1.2 from 1.77). All other parameters are kept the same way as in the default settings. All results refer to a variant of section 3.1 of the main text.

We find that in sensitivity run 1, the overall energy demand increases and energy inequality decreases slightly. Moreover, the total energy-expenditure elasticity drops from slightly above 1 to slightly below one. This is an important qualitative change in the behaviour of the model. However, the difference is not yet large enough to cause a dramatic shift in re-distributional outcomes. The energy costs of equity is with 10% still quite moderate. The trade-off between transport and residential energy still exists, though is of lower magnitude. In the second sensitivity run, the re-distributional differences are larger. The energy costs of equity increases considerably to 17%. Now, lower-income people tend to spend more on energy in general but richer people not drastically more. The trade-off between residential and transport energy further diminishes. This world could be loosely interpreted as one in which income inequalities are not treated at all but high-income people around the world grow more environmentally conscious avoiding more of energy-intensive transport — an unlikely scenario. Sensitivity run 1 illustrates that even under a qualitative change major results remain stable. Sensitivity run 2 illustrates that, on the contrary, re-distributional consequences could be substantially different if spending patterns of people were to change radically and across various sectors.

Result	**Default parameters**	**Sensitivity run 1**	**Sensitivity run 2**
Gini coefficient total energy 2011	0.57	0.53	0.49
Total energy demand 2011 in Exajoules	209	241	233
Energy costs of equity (going from σ_X = 26800 down to σ_X = 2680)	6.7%	10%	17%
Over all energy-expenditure elasticity	1.06	0.95	0.92
Over all energy-income elasticity	0.88	0.78	0.76
Share transport σ_X = 53600	32%	28%	20%
Share transport σ_X = 2680	18%	14%	16%
Share heating and electricity σ_X = 53600	37%	45%	50%
Share heating and electricity σ_X = 2680	48%	58%	57%

Supplementary Note 5: Alternative distributions, alternative worlds?

Another source of uncertainty is whether the observed effects of changes in inequality (effect on total energy demand and so forth) are somehow unique features of the log-normal model. The parameterization of the lognormal model allows us to control the standard deviation but no other feature of the distribution, as for example the overall shape. We approached reduced inequality in an alternative way already in section 3.2 by setting specific minima and maxima, and the overall influence of income redistribution on energy remains the same – there are modest increases in aggregate demand, sectoral shifts from transport to residential and less energy poverty. Assuming a consistent shape as in section 3.1 is probably a realistic assumption. The global economy is a single interconnected system and absolute growth rates across income groups vary but are proportional to the level of income (Alvaredo et al., 2018a)—much like in theoretical Brownian motion models that can generate lognormal distributions (Hajargasht and Griffiths, 2013). Yet, so far, this is not an exhaustive investigation of the relationship between shape and inequality and its influence on energy demand. Other parameterizations of the global income distribution allow for other ways to control the shape of the distribution and history demonstrated that the nature of the global income distribution can change (Lakner and Milanovic, 2016). Moreover, the “rules” of the global economy are not “cast in stone” forever but can be disrupted by social or technological change. These are ever more important considerations now that ecological and social crises are omnipresent and could potentially give rise to entirely different income distributions.

How would energy demand change as a function of the inequality if the distribution had an entirely different shape? We used three further models to investigate that question: 1) A Weibull distribution – because it represents the evolution from a skewed and unequal distribution to a symmetric and equal one 2) A normal distribution — this way we can test whether the observed relationship between income inequality and household energy demand is constant, even if the income distribution were symmetric instead of asymmetric and 3) A standard Pareto distribution — hereby, we can test how much of a difference it makes to the observed patterns, if income inequality under constant mean evolves according to the Pareto Index instead of the lognormal standard deviation. These tests are to be understood as additional thought experiments, not as an accurate representation of reality.

We find that the results based on the Weibull distribution and its shape (controlled by the shape parameter k which is inversely related to the Gini coefficient—if k goes up, the Gini goes down) do not differ much from the main results based on the lognormal model. All major trends remain the same. Even if income were to follow a normal distribution, changes in inequality, under constant mean income, would follow the same trends. Although the inequality range that can be meaningfully investigated under a normal distribution is narrow and just goes from a Gini coefficient of roughly 0.05 to 0.2 (otherwise the normal distribution would reach negative income values in the left tail). In this range, the consequences are extremely minor (under all distributions). If income were to follow a Pareto distribution, there is unsurprisingly extreme polarization between rich and poor, particularly if the Pareto Index is close to 1. Interestingly, none of the aggregate trends change significantly as compared to the lognormal model. There is the same trade off in total energy and the same trade-offs in sectoral composition between transport and residential energy use when going from high to low inequality. The only clearly outstanding feature of the Pareto distribution is that the extremely rich (e.g. the top 0.1%) receive extreme amounts of incomes and consume extreme amounts of energy and everyone else very little.

Supplementary Figure 14 depicts the inequality of all tested distributions vs. the total global household energy demand.

Supplementary Table 1: Real-world vs. model. The references for the real-world values in this table are Oswald et al., 2020, ourworldindata.org, the World Bank open data repository or our own calculation. A value 90% that of the actual real-world value is considered high in accuracy, 70-90% medium and everything below that is considered of low accuracy.

Measure	**Unit**	**Real world**	**Model**	**Accuracy in %**	**References real-world data**
Distribution related measures					
Global income distribution shape	*None*	World Inequality Lab data on national income per adult equivalent	Log normal model cdf	99.6% (high)	(Alvaredo *et al.*, 2018b)
Global income Gini coefficient	*None*	0.6-0.7, 0.64	0.63	>90% (high)	(Anand and Segal, 2008; Milanovic, 2013), own calculation from (Alvaredo *et al.*, 2018b)
Global household expenditure Gini coefficient	*None*	0.59	0.54	>90% (high)	(Oswald, Owen and Steinberger, 2020) and extended version for this paper
Global final energy Gini coefficient	*None*	0.57	0.57	100% (high)	(Oswald, Owen and Steinberger, 2020) and extended version for this paper
People living below 1.9 $ PPP in 2011	*Per cent*	13.5%	6%	40% (low)	(Beltekian and Ortiz-Ospina, 2018)
People living below 10 $ PPP in 2011	*Per cent*	68%	50%	73% (medium)	(Beltekian and Ortiz-Ospina, 2018)
Scale related measures					
Global GDP (scale of the economy)	$ PPP 2011	95.2 trillion	95.2 trillion	100% (high)	(World Bank, 2020c)
Global household expenditure (scale of expenditure)	$ PPP 2011	46.72 trillion (deflated from 2017 dollars)	44 trillion	95% (high)	(World Bank, 2019)
Total household final energy consumption	Exajoule	231	209	90% (medium)	(Oswald, Owen and Steinberger, 2020) and extended version for this paper

Supplementary Table 2: Default parameters. Package holiday is the only category where standard parameters are derived from an unweighted cross country regression because it performs much better than the population-weighted version.

	elasticity (*b*)	coefficient (*a*)	MJ/$
Income to expenditure	0.83	2.6	/
Food	0.62	7.745739	1.35
Alcohol and Tobacco	0.91	0.040184	1.21
Wearables	0.92	0.110155	2.88
Other housing	1.24	0.012748	1.30
Heating and Electricity	0.88	0.149723	35.77
Household Appliances and Services	1.03	0.030121	3.23
Health	1.04	0.028578	2.41
Vehicle Purchase	1.60	0.000073	2.05
Vehicle Fuel and Maintenance	1.77	0.000029	19.37
Other transport	0.84	0.076674	6.52
Communication	1.26	0.004269	1.96
Recreational items	1.56	0.000110	2.50
Package Holiday	2.05	0.00000023	6.86
Education & Finance & Other Luxury	1.25	0.014520	1.65

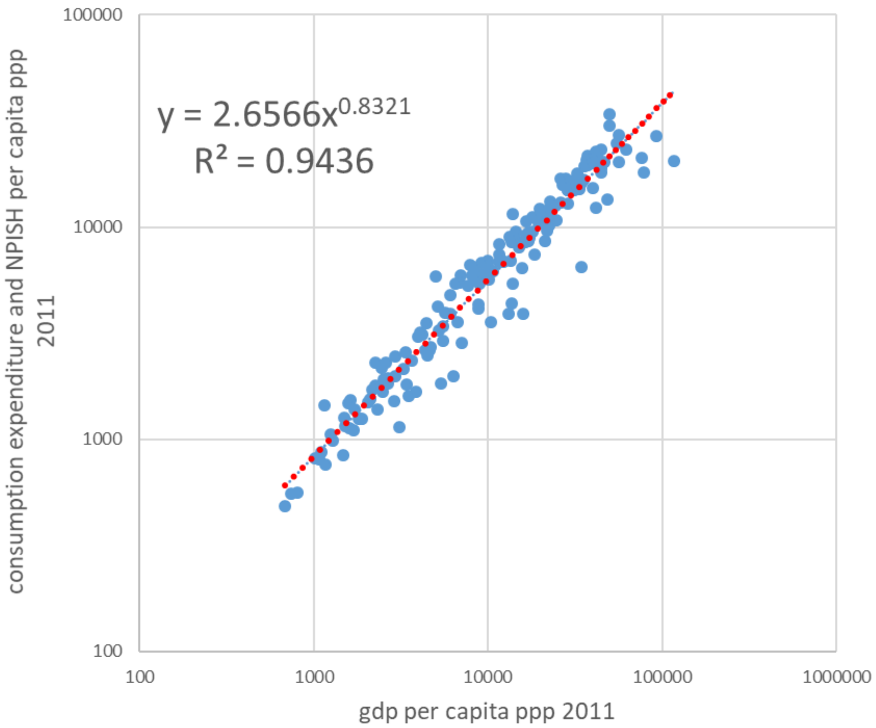
Supplementary Table 3: Constant elasticities weighted regression results

Consumption category	**r-squared**	**b**	**a0**	**exp(a0) = a**	**se_b**	**CI 95% low**	**CI 95% high**	**b/se_b**	**N**
Food	0.85	0.62	2.05	7.75E+00	0.01	0.60	0.65	46.77	379
Alcohol and Tobacco	0.69	0.91	-3.21	4.02E-02	0.03	0.85	0.97	28.64	375
Wearables	0.88	0.92	-2.21	1.10E-01	0.02	0.89	0.96	52.18	379
Other housing	0.83	1.24	-4.36	1.27E-02	0.03	1.18	1.29	42.78	379
Heating and Electricity	0.81	0.88	-1.90	1.50E-01	0.02	0.84	0.93	40.24	375
Household Appliances and Services	0.90	1.03	-3.50	3.01E-02	0.02	1.00	1.07	57.70	379
Health	0.72	1.04	-3.56	2.86E-02	0.03	0.98	1.11	31.46	378
Vehicle Purchase	0.75	1.60	-9.52	7.31E-05	0.05	1.50	1.69	31.74	342
Vehicle Fuel and Maintenance	0.85	1.77	-10.45	2.89E-05	0.04	1.70	1.85	46.70	375
Other transport	0.69	0.84	-2.57	7.67E-02	0.03	0.78	0.90	29.00	377
Communication	0.83	1.26	-5.46	4.27E-03	0.03	1.20	1.32	43.47	378
Recreational items	0.75	1.56	-9.12	1.10E-04	0.05	1.47	1.65	33.49	376
Package Holiday	0.41	1.48	-10.06	4.26E-05	0.11	1.27	1.69	13.67	274
Education & Finance & Other Luxury	0.89	1.25	-4.23	1.45E-02	0.02	1.21	1.30	54.27	379

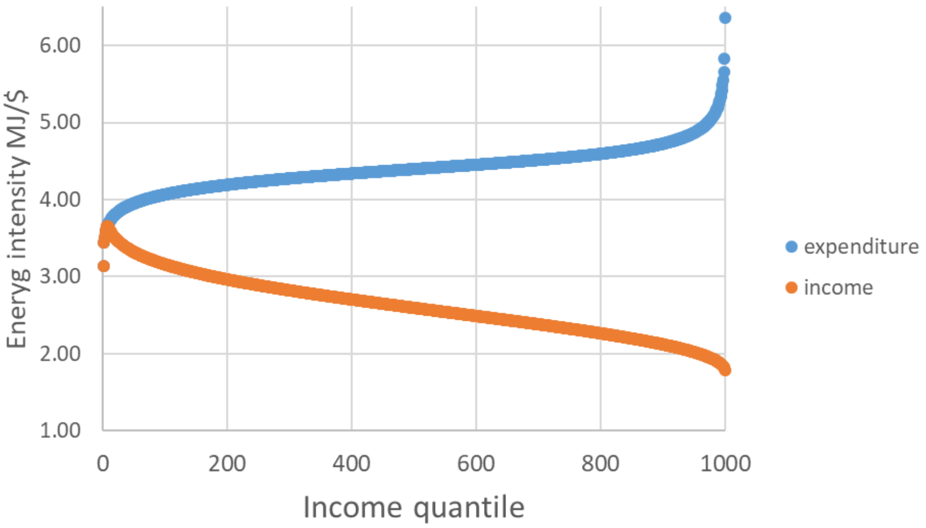
Supplementary Table 4: Non-constant elasticities weighted regression results. Non-constant elasticities over the global income spectrum exhibit high variation and are found not to be generally significant. An example for this is illustrated in Supplementary Figure 13 for the category food: Whereas the first two elasticities, in the lower half of the data, are significantly different from each other, this is not the case for the upper half. This might be a data resolution bias or a bias due to the vast heterogeneity in the underlying consumption surveys from the Global consumption database (World Bank, 2018) and the household budget surveys by Eurostat (Eurostat, 2015) which were used to compute elasticities.

	weighted				non-weighted			
b (elasticity)								
	1st quartile	2nd quartile	3rd quartile	4th quartile	1st quartile	2nd quartile	3rd quartile	4th quartile
Food	0.84	0.49	0.59	0.60	0.81	0.30	0.49	0.47
Alcohol and Tobacco	1.03	1.74	-0.31	0.84	1.17	0.83	0.55	-0.03
Wearables	1.06	1.56	1.31	0.76	0.91	1.03	1.11	0.19
Other housing	1.08	0.26	0.27	0.61	1.17	1.52	0.98	0.36
Heating and Electricity	1.01	0.57	0.57	0.42	1.08	0.86	0.36	0.21
Household Appliances and Services	0.92	1.04	1.29	0.82	1.06	1.24	1.17	0.75
Health	1.29	1.69	0.92	1.12	1.23	1.35	1.23	0.61
Vehicle Purchase	1.25	2.86	1.63	1.74	1.24	1.70	2.09	1.44
Vehicle Fuel and Maintenance	1.71	0.96	1.90	1.21	1.68	1.92	1.72	0.26
Other transport	1.29	1.24	0.53	0.69	1.28	0.62	0.53	1.20
Communication	1.29	1.56	1.00	0.54	1.50	1.19	0.82	0.10
Recreational items	1.40	2.19	1.88	1.03	1.73	2.16	1.85	0.46
Package Holiday	0.24	2.91	2.87	1.00	1.24	2.88	2.11	1.06
Education & Finance & Other Luxury	1.11	1.20	1.92	1.61	1.17	1.55	1.59	0.23
b confidence interval 95% upper value								
Food	0.94	0.74	0.96	0.76	0.89	0.62	0.94	0.78
Alcohol and Tobacco	1.28	2.39	0.58	1.19	1.43	1.46	1.34	0.51
Wearables	1.19	1.96	1.58	0.97	1.07	1.41	1.55	0.70
Other housing	1.29	0.88	1.03	0.93	1.48	2.24	1.77	1.10
Heating and Electricity	1.22	0.92	1.01	0.54	1.27	1.45	1.18	0.60
Household Appliances and Services	1.06	1.40	1.70	1.10	1.22	1.59	1.54	1.26
Health	1.59	2.26	1.59	1.47	1.58	2.04	2.02	1.45
Vehicle Purchase	1.72	3.73	2.95	2.12	1.88	3.01	3.68	2.38
Vehicle Fuel and Maintenance	2.07	1.61	2.38	1.45	2.06	2.52	2.32	0.83
Other transport	1.48	1.58	1.38	1.25	1.54	1.22	1.38	1.84
Communication	1.57	2.01	1.22	0.69	1.75	1.59	1.20	0.66
Recreational items	1.84	2.96	2.66	1.29	2.05	2.98	2.79	1.29
Package Holiday	1.41	4.85	4.21	1.56	2.30	4.16	3.76	2.33
Education & Finance & Other Luxury	1.32	1.58	2.32	1.78	1.35	1.94	2.04	0.97
b confidence interval 95% lower value								
Food	0.74	0.23	0.22	0.45	0.72	-0.03	0.03	0.15
Alcohol and Tobacco	0.77	1.10	-1.20	0.48	0.92	0.21	-0.25	-0.58
Wearables	0.92	1.16	1.04	0.55	0.74	0.65	0.68	-0.32
Other housing	0.87	-0.36	-0.50	0.29	0.86	0.80	0.18	-0.38
Heating and Electricity	0.81	0.21	0.13	0.30	0.90	0.27	-0.46	-0.18
Household Appliances and Services	0.78	0.68	0.87	0.54	0.89	0.88	0.79	0.24
Health	1.00	1.12	0.25	0.78	0.89	0.66	0.45	-0.23
Vehicle Purchase	0.79	1.99	0.30	1.37	0.59	0.40	0.50	0.49
Vehicle Fuel and Maintenance	1.35	0.32	1.41	0.97	1.31	1.32	1.11	-0.31
Other transport	1.09	0.89	-0.33	0.13	1.02	0.01	-0.32	0.56
Communication	1.01	1.10	0.78	0.39	1.24	0.80	0.45	-0.45
Recreational items	0.96	1.43	1.10	0.76	1.41	1.34	0.91	-0.36
Package Holiday	-0.93	0.97	1.52	0.44	0.18	1.60	0.46	-0.21
Education & Finance & Other Luxury	0.90	0.81	1.53	1.44	0.98	1.16	1.14	-0.52

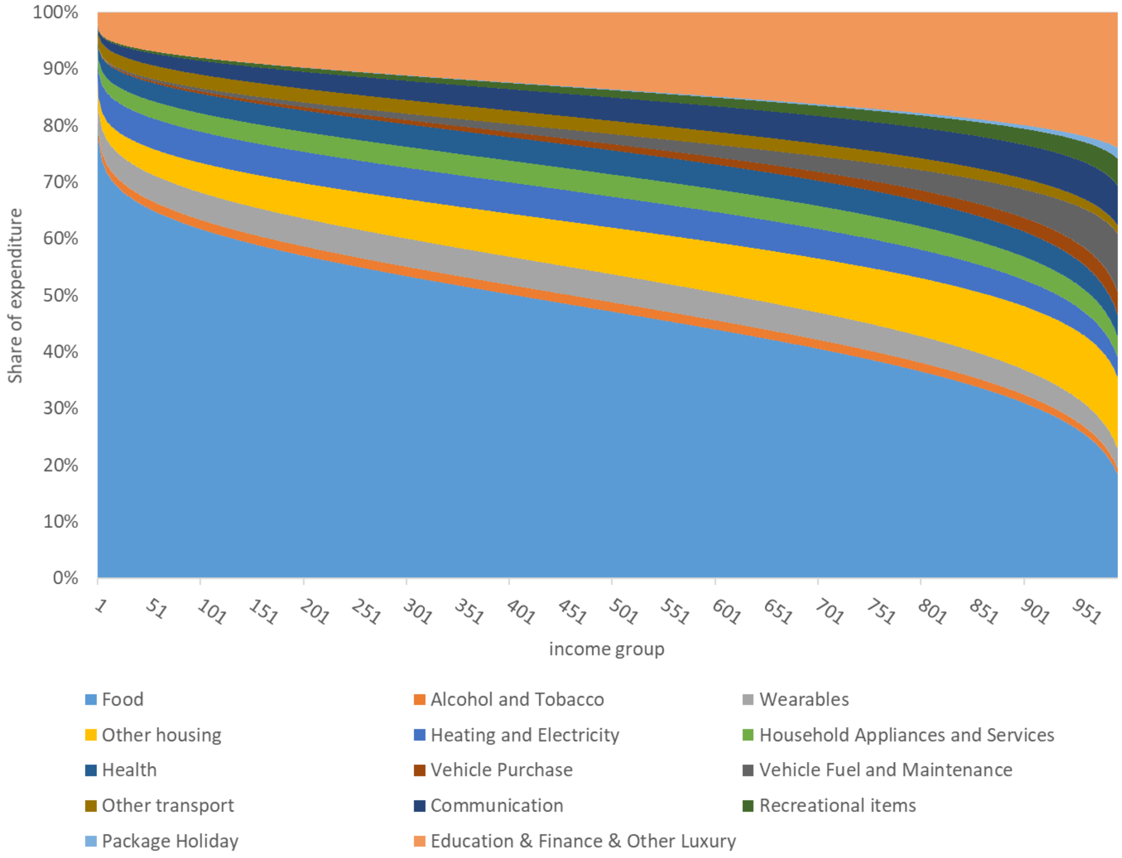
Supplementary Figure 1: GDP per capita and household consumption expenditure. This empirical relationship is used for modelling income to expenditure and is based on data by the World Bank (World Bank, 2019, 2020c).



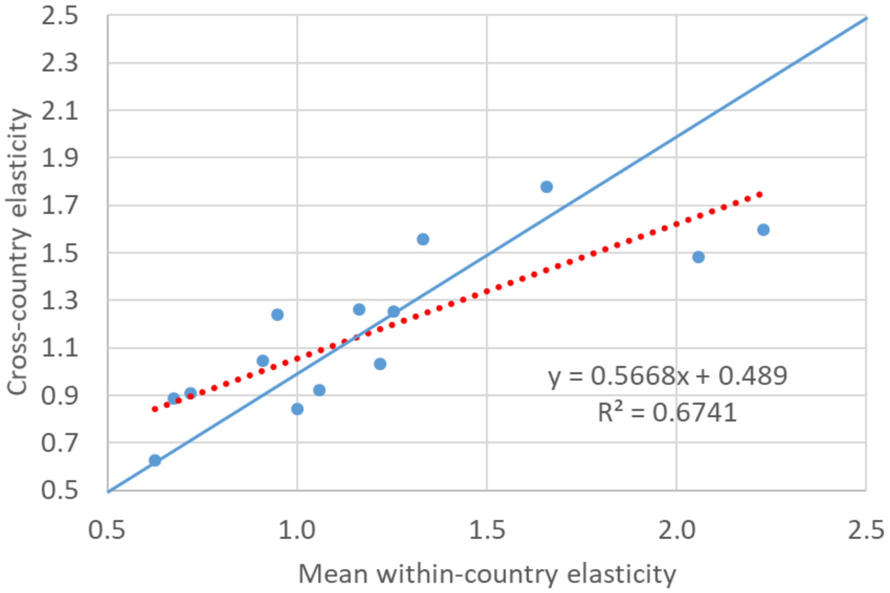
Supplementary Figure 2: Energy intensity per income group. Our average energy intensity of expenditure increases slightly with quantile and sharply at the beginning and at the end of the distribution. This is a result of using homogenous energy intensities across the entire global distribution. This also means that our average energy-expenditure elasticity is slightly large than one (1.06). It is important to note that our energy intensity is of household consumption only. Moreover, our average income-energy elasticity is significantly less than one and therewith clearly in line with the literature (0.88). Average energy intensity of income thus decreases. This difference between income and expenditure energy elasticity is because households spend a decreasing share of their entire income when incomes rise. Usually the energy-GDP elasticity is measured to be less than one varying between 0.7-1, yet results remain uncertain and sometimes insignificant (Liddle and Huntington, 2019). On a country level, it has been measured that consumption-based energy elasticities of household expenditure can be larger than one (Oswald, Owen and Steinberger, 2020). This also has been measured and affirmed for carbon elasticities of household income (Hubacek et al., 2017). Results are mixed however and there are also a variety of countries with elasticities <1. Since in our model the overall expenditure elasticity being larger than unity is an “emergent” feature due to (empirical) energy intensities and elasticities on a product level we keep it this way and argue that it is a reasonable assumption. We test however for sensitivity of major results in supplementary note 4.



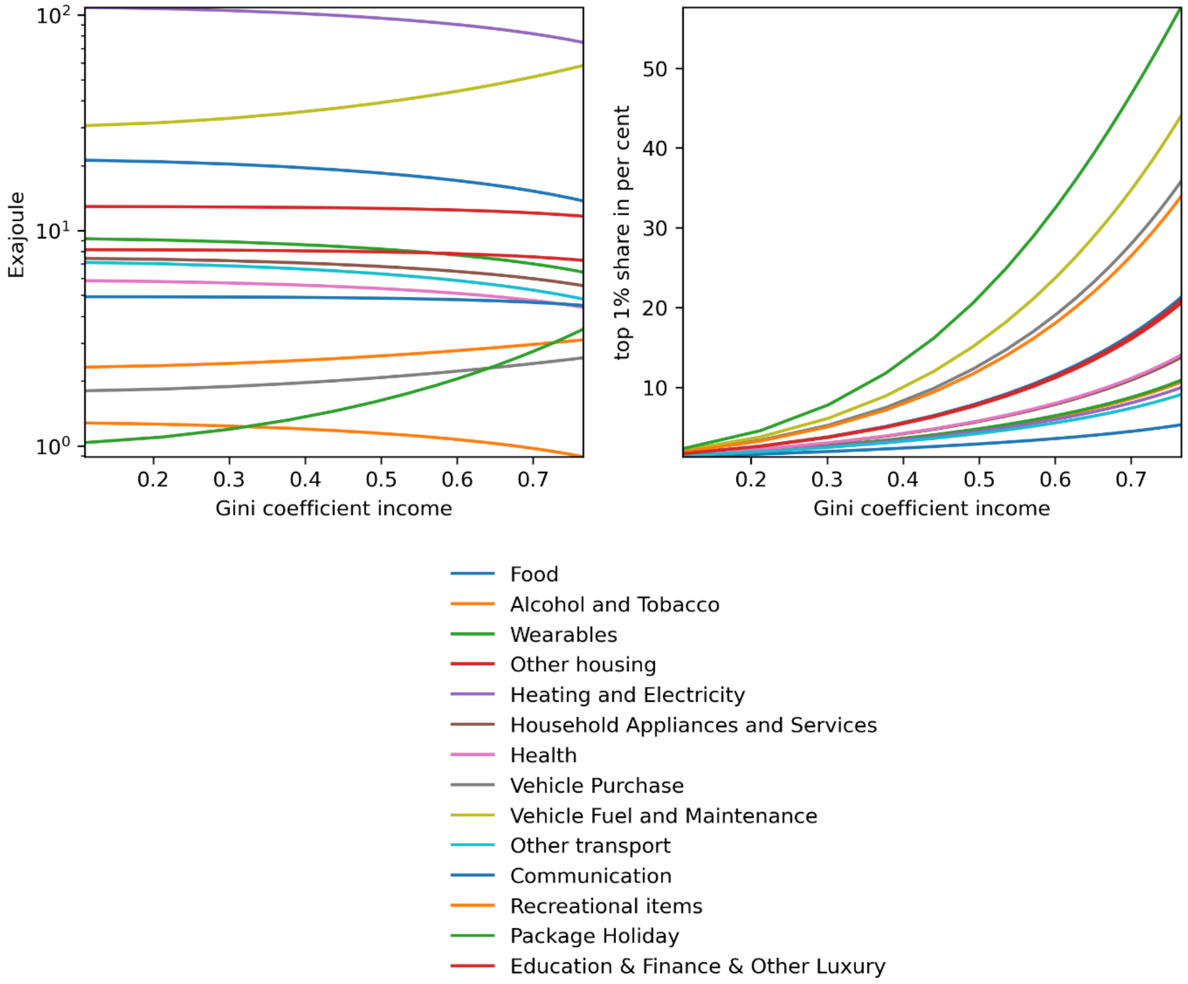
Supplementary Figure 3: Budget share allocation. Our model fulfils the important empirical law "Engel's law". With increasing income the share spent on food decreases. This figure depicts the budget allocation of expenditure over all 1000 income groups (1000 is the max. of the x-axis). The budget share is sensitive to the estimated parameters.



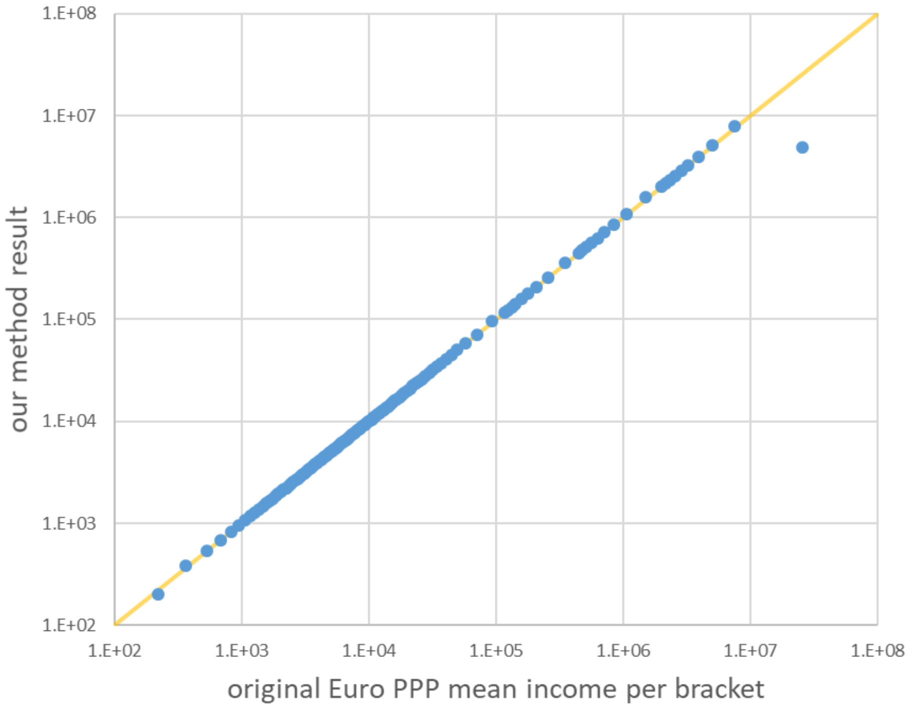
Supplementary Figure 4: Cross-country vs. within-country elasticities. Here we correlated the population-weighted cross-country international elasticities of consumption and average within-country elasticities from Oswald et al., 2020. The linear correlation is good (with unweighted elasticities even better at an R-Squared of 0.87) and illustrates that consumption with increasing income within countries (national-scale) behaves similarly to consumption across the entire world (global-scale). The most notable difference between within-country and cross-country elasticity is in vehicle purchases and package Holiday which both are larger than 2 in within-country results and rather around 1.5 in a cross-country perspective (when weighted). In the unweighted case, package holidays is still above 2 and vehicle purchase is ~1.9. The red dotted line is the linear fit. The blue continuous line is the one-to-one line.



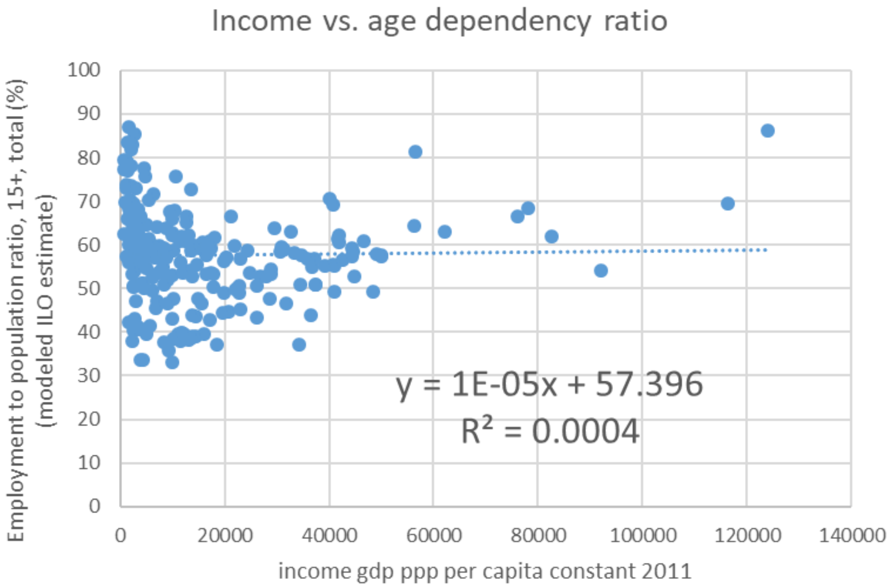
Supplementary Figure 5: Total energy per consumption category. This figure is complementary to Figure 4 and Figure 5 of the main paper. It illustrates the absolute energy consumption per consumption category as a function of the income Gini coefficient as well as the energy share of the top 1% global income earners.



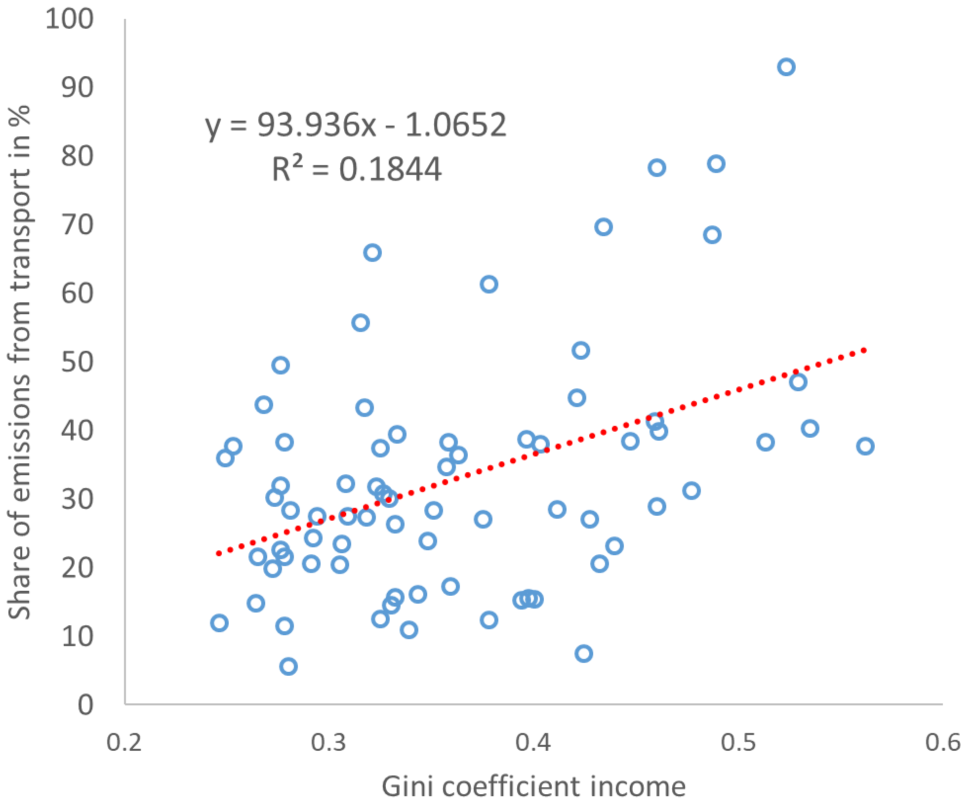
Supplementary Figure 6: Method of computing mean income for income groups. We just take the lower and upper bound of an income bracket and take the average to compute mean income per group. We compared our method, applied to World Inequality Database data (Alvaredo et al., 2018b) using their lower and upper bounds, against their original results of mean incomes. The comparison results into a one-to-one relationship, except at the very long tails of the distribution (PPP refers to PPP Euro here). We also tested a version of our simulations applying high resolution numerical integration to the log-normal CDF. The results only change negligibly.



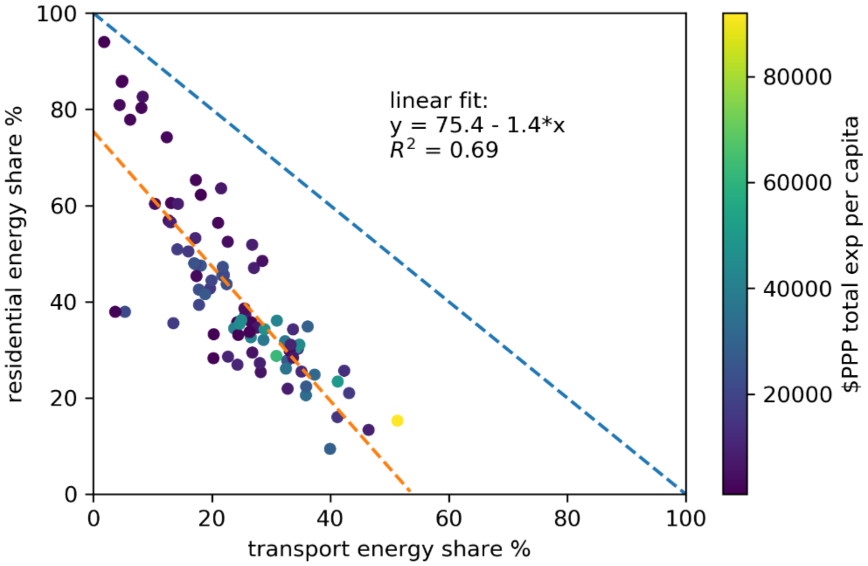
Supplementary Figure 7: Age dependency ratio vs. income. We tested whether there is a relationship between the income level of a country (World Bank, 2020c) and its age dependency ratio (World Bank, 2020a) in order to translate per adult equivalent data to per capita data (because it is assumed that the adult population is sufficiently close to the working age population). There is high variation and no significant relationship.



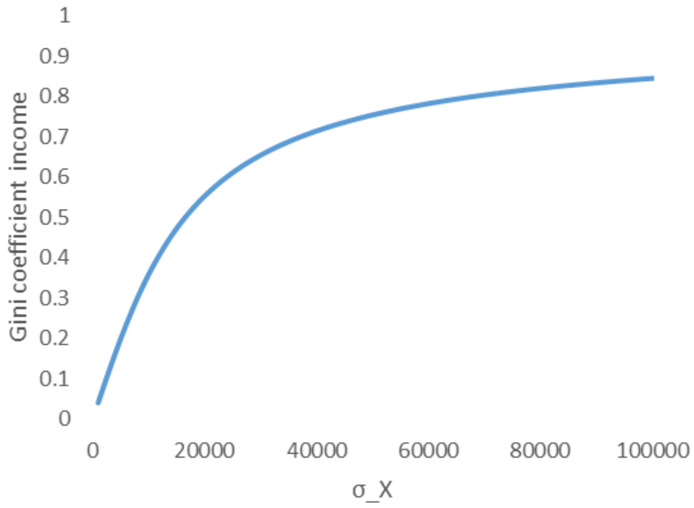
Supplementary Figure 8: Carbon emissions from transport vs. income inequality in 2011. The correlation between emissions from transport and income inequality was observed for instance here (Tomkiewicz, 2019) and can be reproduced through World Bank open-source data (World Bank, 2020d, 2020b). The fit is weak to moderate but, considering that many different income levels are included, a fit that explains nearly a fifth of transport emissions is quite remarkable.



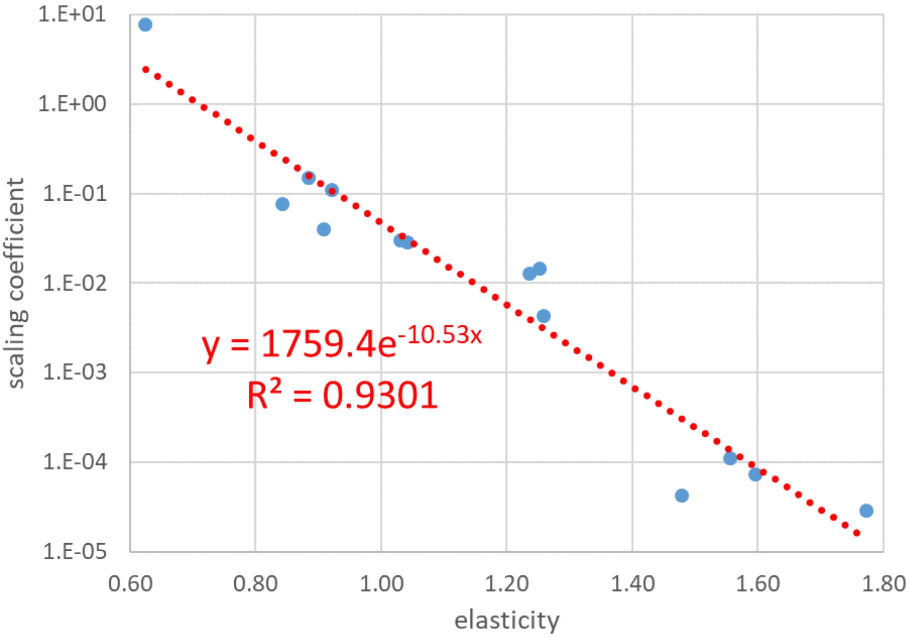
Supplementary Figure 9: Share transport energy vs. share residential energy. The linear fit is the dashed orange line. The dashed blue line depicts the one-hundred-percent-frontier of consumption. The trade-off between residential and transport energy is clear. Yet there is a growing gap between the consumption frontier and the trade-off, implying that consumption overall diversifies. The source for the data is Oswald et al. (2020).



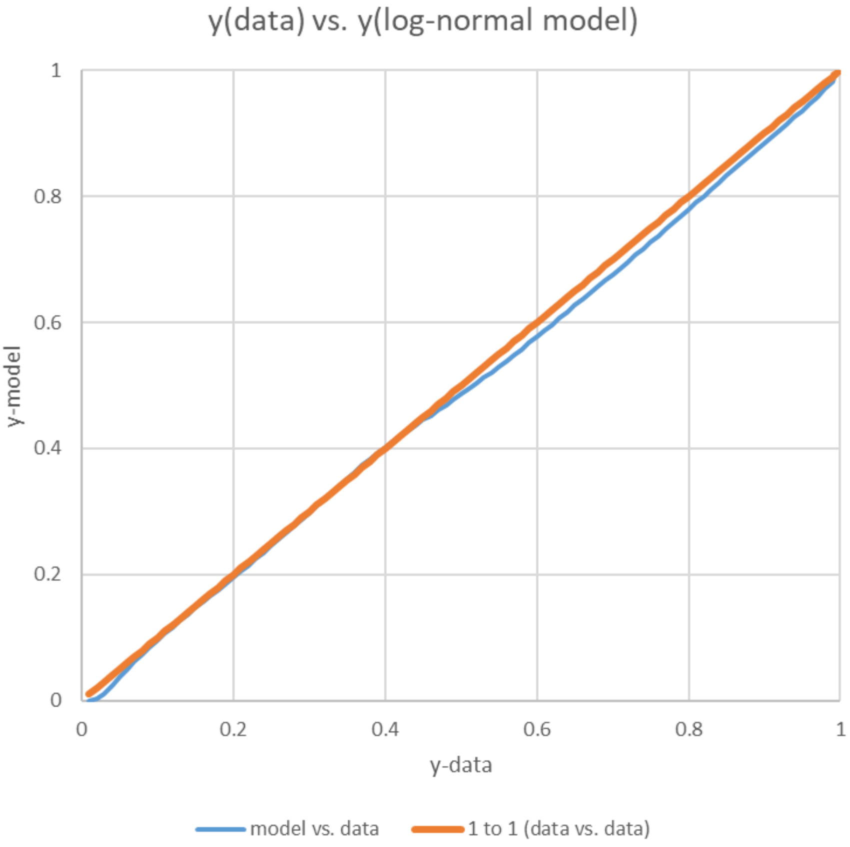
Supplementary Figure 10: Relationship between sigma_X of the log-normal distribution and its Gini coefficient. This graph relates to supplementary equations number three and four.



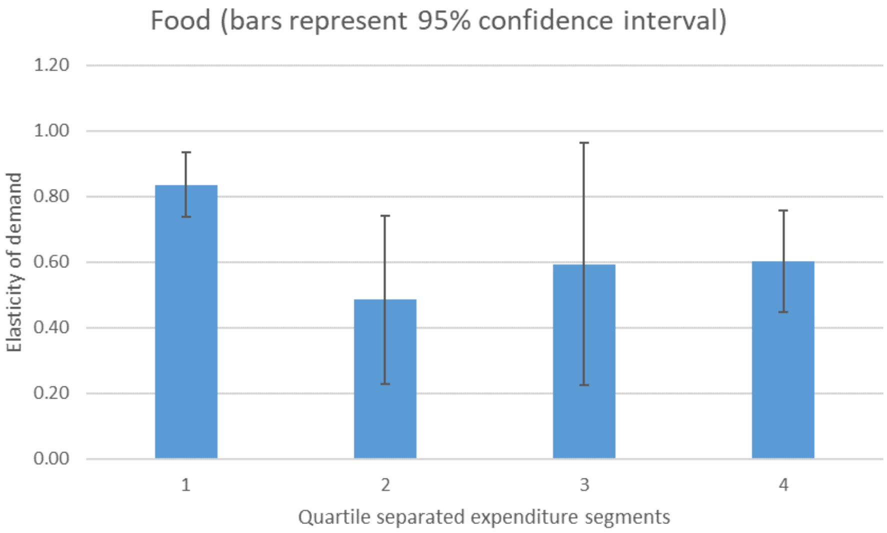
Supplementary Figure 11: Exponential relationship between elasticities and scaling coefficients. This relation is applied in the sensitivity analysis and the Monte-Carlo simulation. If the elasticity is altered we adjust the scaling coefficient accordingly.



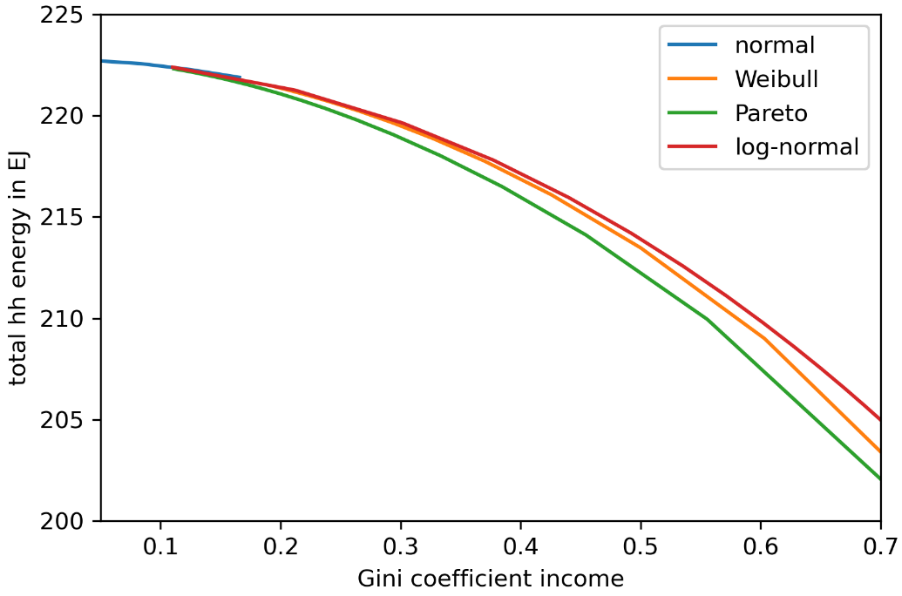
Supplementary Figure 12: Log-normal model fit validation. The y-dimension represents the cumulative population as in Figure 2 of the main paper. The orange line depicts the case if model and data would match perfectly. The blue line depicts how they actually relate. We minimized the residual sum of squares as a function of the log-normal standard deviation (the only free parameter in our log-normal model because the mean is fixed) in order to achieve the best fit.



Supplementary Figure 13: Income elasticities of food – the details



Supplementary Figure 14: Alternative distributions and total energy



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Appendix C. Supplementary information 3

Supplementary information for

Luxury carbon taxes on household consumption across 88 countries

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Contents of supplementary information

Supplementary Note 1: Carbon pricing literature review.

Some economists argue that carbon pricing is one of the best and fastest instruments to curb emissions (Edenhofer, Franks and Kalkuhl, 2021), while others oppose that its effects are small and insufficient for tackling the climate crisis (Rafatya, Dolphin and Pretis, 2020; Green, 2021). There is likely a difference in impact between emission trading schemes and carbon taxation (Green, 2021) with taxation performing slightly better, although some studies report the opposite (Foramitti, Savin and van den Bergh, 2021). The degree of impact seems to be a matter of interpretation, too. For instance, Green (Green, 2021) argues that ~2% per year less growth rate in CO2 emissions from 1990 to 2010 in Finland achieved through carbon taxation is not a very large effect, while roughly the same magnitude is considered “big margins” by others (Mideksa, 2021). Proponents of carbon pricing point out the systemic effects including driving innovation (van den Bergh and Savin, 2021) and social network effects (Konc, Savin and van den Bergh, 2021). A major parameter is the carbon price itself: A price of $100/tonne implies a more drastic outcome than a carbon price of 10$/tonne. The price level has been debated extensively and often has been based on the social costs of carbon (SCC). The SCC estimate and monetize climate change impacts. The concept is highly controversial because it is very difficult to quantify future impacts precisely. Estimates range from a few dollars to thousands of dollars per tonne (Wang et al., 2019). It is moreover difficult to incorporate the full range of climate change impacts on humans and societies and SCC are dependent on other divisive parameters like the discounting rate. On top of that, recent studies suggest that the mortality-costs of carbon, that is the human lives lost due to global warming, are consistently underestimated in SCC and amplify the SCC by a factor of ~7 (Bressler, 2021). One approach to circumvent these issues is to set the carbon price not according to SCC but simply to a level deemed sufficient for reaching net-zero emission targets. For the USA to be in line with the Paris Agreement (i.e. net-zero emissions in 2040) this requires a price of ~$100/tonne in 2025 and $150-200/tonne in 2030 (Kaufman et al., 2020). In any case, state-of-the-art methods demonstrate that the price must be set well beyond $100/tonne for high-income countries. And while carbon pricing is expanding across high-income and upper-middle income nations, it remains consistently below this level and not comprehensive across sectors (World Bank, 2021). With this in mind, this study tests carbon taxes on household consumption even if countries already feature implemented carbon markets.

Supplementary Note 2: Carbon taxation in the context of energy justice.

The debate around fairness in terms of emission trading schemes (ETS) sets different priorities than the one for carbon taxation. For ETS, the main concern is the allocation of permits among industries, for carbon taxation, it is how different household groups are affected. In public and political discourse carbon taxes are frequently perceived as unfair (Carattini, Carvalho and Fankhauser, 2018; Savin et al., 2020). Carbon taxes affect energy services that people rely on and the tax makes them more expensive because emissions originate from energy. Under uniform carbon prices, the most carbon-intensive energy consumption is hit the hardest, for instance heating or car fuel. Often only direct energy emissions are considered. Heat or fuel applications emit a significant share of their life-cycle emissions on-site. Other consumer products, for example laptops or furniture, create emissions primarily in supply chain stages. This is unfair because the higher the income, the stronger the consumption basket of a household leans towards supply-chain embodied footprints and low-income households spend a much greater fraction of disposable income on direct energy use. A famous example for unrest emerging from these issues is the yellow vest movement in France which was partially motivated through rising fuel taxes (Mehleb, Kallis and Zografos, 2021). By now, across several European countries, environmental policy proposals are shaped by carbon taxation of this kind. For example, traffic and heating focused carbon taxation (including revenue redistribution to low-income households) are a central aspect of the 2021 political agenda of the German Green Party. A failed attempt to stricter carbon taxation is the lately rejected Swiss Carbon Act which would have included a near doubling of carbon prices from $131/tonne for fuel and gas to $229/tonne (Congress, 2021). As long as carbon taxation policies do not take into account the structure and diversity of household energy profiles, they are bound to be rejected or remain only partially implemented. A stronger appeal to “(international) energy justice” and “decent living energy” suggests resolution.

Energy justice is characterized through addressing the “What, who and how?” (Jenkins et al., 2016). An equitable energy transition must ensure that social structure and stratification are recognized. Inequalities in wealth, income, consumption, energy demand and emissions are found in all countries (Hubacek et al., 2017; Alvaredo et al., 2018; Oswald, Owen and Steinberger, 2020) and thus reducing inequalities emerges as monumental but quintessential task of social policy in the 21st century. Furthermore, scholars have refined theories of energy provision for human needs satisfaction (Rao and Baer, 2012; Brand-Correa and Steinberger, 2017). One finding is that the amount of energy per capita necessary to secure decent living standards is far lower than is the average in high-income countries and in particular 1-2 orders of magnitude lower than the energy consumption of top percentiles (Rao, Min and Mastrucci, 2019; Millward-Hopkins et al., 2020). Energy footprints of affluent households could, in principle, be reduced substantially without destroying livelihoods.

Supplementary Note 3: Normalizing the total and average costs of carbon.

For clarity of equation (2) in the main text, let us consider an elementary example. Let the carbon price be \$50 per tonne for households demanding two goods. Good number one is responsible for 80% of household emissions (say 8 tonnes), good number two for 20% (2 tonnes). Good number one with $\epsilon_d = 0.5$ will be adjusted to 25\$/tonne and a good two with $\epsilon_d = 2$ to a price of 100\$/tonne. Before adjustment they satisfy equation (1s).

$$8\ tonnes * 50\frac{\$}{tonne} + 2\ tonnes * 50\frac{\$}{tonne} = \$500 \tag{1s}$$

With adjustment by income elasticity this becomes as follows.

$$8\ tonnes * 25\frac{\$}{tonne} + 2\ tonnes * 100\frac{\$}{tonne} = \$400 \tag{2s}$$

The intervention changed not only the price per good but also the total costs of carbon in the economy from \$500 to \$400. The average is now \$40/t instead of \$50/t. Therefore, equation (2) of the main text needs to be normalized so that the average costs of carbon are preserved. In the example this is multiplying by 5/4.

Supplementary Note 4: Alternative tax designs.

Carbon taxes can be made progressive via several designs other than our luxury tax design. Indeed, the carbon price could just be made zero for necessities and high for luxuries. This is by default progressive because the higher the income, the more households spend on luxuries relative to their total expenditure. For example this has been shown by Steckel et al. (2021) for India and other Asian economies in the case of transport fuel. A step further would be to offer subsidies for low-income households in combination with taxes for high-income households. Subsidies include revenue redistribution, which we elaborate on in the section "Tax revenue with multiple objectives ". Another prominent proposal is progression by level of consumption or environmental impact, as for example the frequent flyer levy (Chapman et al., 2021). Income taxes are of this type too. Higher incomes are often taxed at higher rates. Correspondingly higher emissions per capita could be taxed at a higher rate. If the policy goal is to reduce conspicuous consumption and inequality, this is a viable option, but it is challenging to track information about every household's carbon footprint. At a minimum, it requires detailed and dynamically updated declarations of consumption expenditure which likely bumps into concerns around privacy. We do not include an analysis of this tax design but it certainly is of interest to future studies. Instead, we demonstrate that the luxury tax can be made even more progressive by further increasing the prices on luxury goods while decreasing the tax levied on necessities. For instance, we can adjust the carbon price by the cubed income elasticity to amplify price differentials, as displayed for the USA and South Africa in Supplementary Figure 4.

Supplementary Table 1: List of countries.

name	code	income_category	regional_1	regional_2
Albania	ALB	Upper middle income	Europe	North
Armenia	ARM	Upper middle income	Europe	North
Azerbaijan	AZE	Upper middle income	Asia	North
Bangladesh	BGD	Lower middle income	Asia	South
Belarus	BLR	Upper middle income	Asia	North
Benin	BEN	Low income	SSA + MENA	South
Bolivia	BOL	Lower middle income	Latin America	South
Brazil	BRA	Upper middle income	Latin America	South
Burkina Faso	BFA	Low income	SSA + MENA	South
Cambodia	KHM	Lower middle income	Asia	South
Cameroon	CMR	Lower middle income	SSA + MENA	South
China	CHN	Upper middle income	Asia	South
Colombia	COL	Upper middle income	Latin America	South
Cote d'Ivoire	CIV	Lower middle income	SSA + MENA	South
Egypt, Arab Rep.	EGY	Lower middle income	SSA + MENA	South
El Salvador	SLV	Lower middle income	Latin America	South
Ethiopia	ETH	Low income	SSA + MENA	South
Ghana	GHA	Lower middle income	SSA + MENA	South
Guatemala	GTM	Upper middle income	Latin America	South
Guinea	GIN	Low income	SSA + MENA	South
Honduras	HND	Lower middle income	Latin America	South
India	IND	Lower middle income	Asia	South
Indonesia	IDN	Lower middle income	Asia	South
Jamaica	JAM	Upper middle income	Latin America	South
Jordan	JOR	Upper middle income	SSA + MENA	South
Kazakhstan	KAZ	Upper middle income	Asia	North
Kenya	KEN	Lower middle income	SSA + MENA	South
Kyrgyz Republic	KGZ	Lower middle income	Asia	North
Lao PDR	LAO	Lower middle income	Asia	South
Madagascar	MDG	Low income	SSA + MENA	South
Malawi	MWI	Low income	SSA + MENA	South
Mauritius	MUS	Upper middle income	SSA + MENA	South
Mexico	MEX	Upper middle income	Latin America	South
Mongolia	MNG	Lower middle income	Asia	South
Morocco	MAR	Lower middle income	SSA + MENA	South
Mozambique	MOZ	Low income	SSA + MENA	South
Namibia	NAM	Upper middle income	SSA + MENA	South
Nepal	NPL	Low income	Asia	North
Nicaragua	NIC	Lower middle income	Latin America	South
Nigeria	NGA	Lower middle income	SSA + MENA	South
Pakistan	PAK	Lower middle income	Asia	South
Paraguay	PRY	Upper middle income	Latin America	South

Peru	PER	Upper middle income	Latin America	South
Philippines	PHL	Lower middle income	Asia	South
Russian Federation	RUS	Upper middle income	Asia	North
Rwanda	RWA	Low income	SSA + MENA	South
Senegal	SEN	Lower middle income	SSA + MENA	South
South Africa	ZAF	Upper middle income	SSA + MENA	South
Sri Lanka	LKA	Upper middle income	Asia	South
Tanzania	TZA	Low income	SSA + MENA	South
Thailand	THA	Upper middle income	Asia	South
Togo	TGO	Low income	SSA + MENA	South
Uganda	UGA	Low income	SSA + MENA	South
Ukraine	UKR	Lower middle income	Europe	North
Vietnam	VNM	Lower middle income	Asia	South
Zambia	ZMB	Lower middle income	SSA + MENA	South
Austria	AUT	High income	Europe	North
Belgium	BEL	High income	Europe	North
Bulgaria	BGR	Upper middle income	Europe	North
Cyprus	CYP	High income	Europe	North
Czech Republic	CZE	High income	Europe	North
Germany	DEU	High income	Europe	North
Denmark	DNK	High income	Europe	North
Estonia	EST	High income	Europe	North
Spain	ESP	High income	Europe	North
Finland	FIN	High income	Europe	North
France	FRA	High income	Europe	North
Greece	GRC	High income	Europe	North
Croatia	HRV	High income	Europe	North
Hungary	HUN	High income	Europe	North
Ireland	IRL	High income	Europe	North
Italy	ITA	High income	Europe	North
Lithuania	LTU	High income	Europe	North
Luxembourg	LUX	High income	Europe	North
Latvia	LVA	High income	Europe	North
Malta	MLT	High income	Europe	North
Netherlands	NLD	High income	Europe	North
Norway	NOR	High income	Europe	North
Poland	POL	High income	Europe	North
Portugal	PRT	High income	Europe	North
Romania	ROU	Upper middle income	Europe	North
Sweden	SWE	High income	Europe	North
Slovenia	SVN	High income	Europe	North
Slovak Republic	SVK	High income	Europe	North
Turkey	TUR	Upper middle income	Europe	South
United Kingdom	GBR	High income	Europe	North

Japan	JPN	High income	Asia	North
United States	USA	High income	North America	North

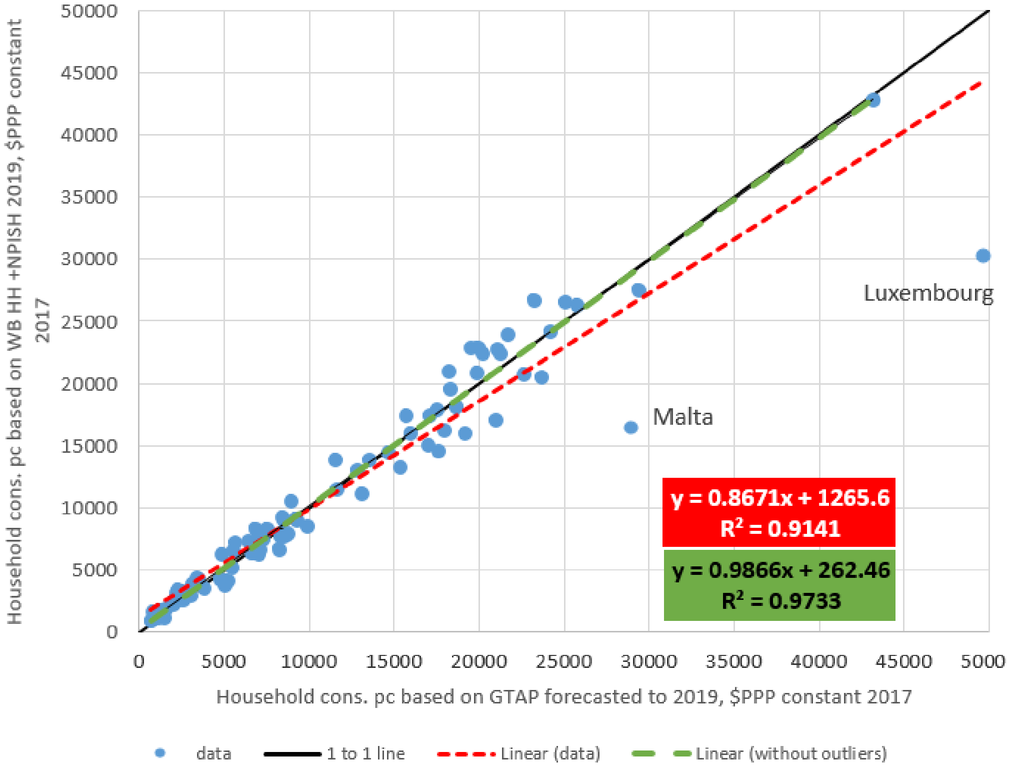
Supplementary Table 2: Global warming potential applied. These factors are based on Brander (2012). The importance of these factors to our study of carbon taxation is limited. It is mostly relevant for evaluating carbon budget consistency. Therefore, we worked with a simplified understanding of global warming potentials not considering time horizons and also homogenizing across distinct greenhouse gases. Important is that the factors are uniformly applied across household groups so that that they do not distort distributional implications of tax policies.

Greenhouse Gas	**Global warming potential factor applied**
Methane (CH4)	25
Nitrous oxide(N2O) 298	298
A mix of any other (HFC, PFC etc.)	6000 (best guess of lower bound, high uncertainty and may is conservatively estimated)

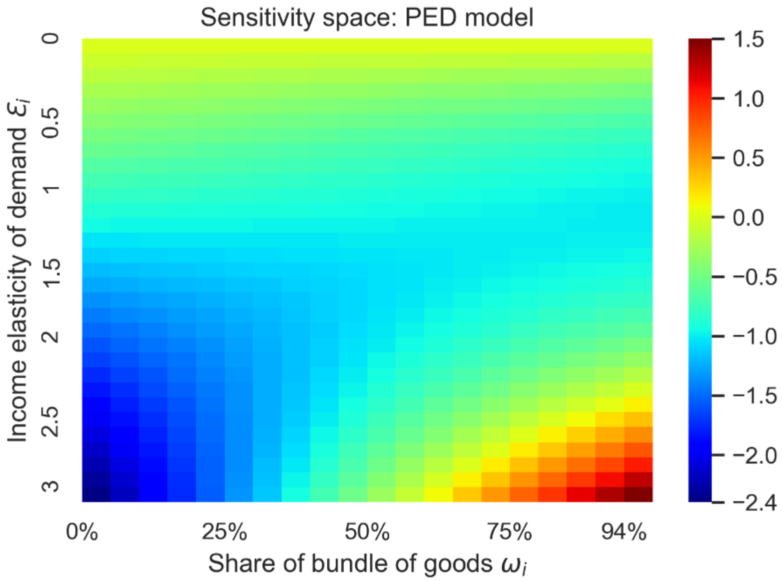
Supplementary Table 3: Carbon prices. The unit is $/tonne of carbon equivalents.

	scenario\income category	low-income	lower middle-income	upper middle-income	high-income
2022	low price	5	12.5	25	75
2022	medium price	10	25	50	150
2022	high price	20	50	100	300
2100	low price	500	500	500	1000
2100	medium price	1000	1000	1000	2000
2100	high price	2000	2000	2000	4000

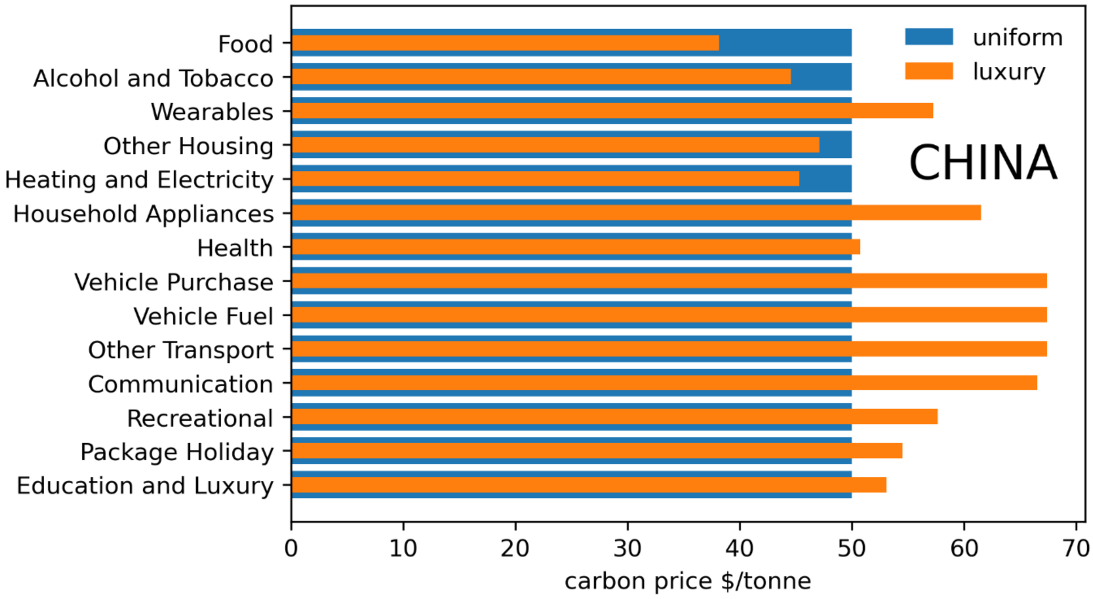
Supplementary Figure 1: Now-casting GTAP 9 household expenditure. To check consistency of the now-casting from 2011 to 2019, we compared the adjusted GTAP 9 numbers against World Bank household consumption figures for 2019. The GTAP consumption data is recorded in Market Exchange rates (MER), so they also had to be converted to Purchasing Power Parity (PPP).



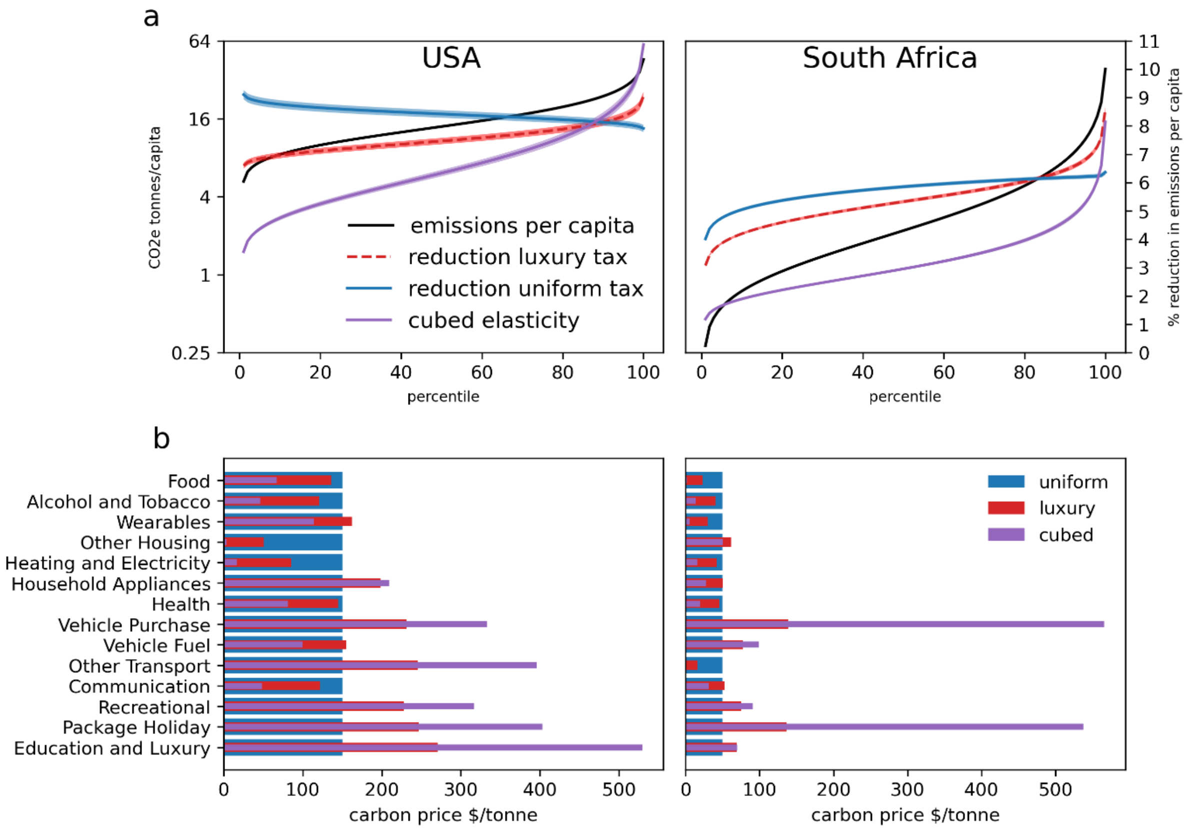
Supplementary Figure 2: Sensitivity price elasticity model. We conducted a sensitivity analysis of equation (4-8) in the methods (Sabatelli's model (Sabatelli, 2016)). The translation from income elasticity demand (ϵ_d) (y-axis) to price elasticity of demand (ϵ_p) (colour-map) is sensitive to the percentage share that the bundle of goods contributes to the overall consumption portfolio (x-axis). When ϵ_d is above 2, then a low share implies a strongly negative price elasticity. On the other hand, if the share of the good becomes large, the price elasticity is small or in the extreme cases of a share being larger than 70% even positive. This 'extreme' where the share is >70% and the ϵ_d > 2.5 never occurs in the real-world. The intuition behind that is clear because it would mean that an individual spends more than 70% of their total expenditure on a luxury good. The most extreme share contributed by a luxury good is vehicle fuel in Honduras in the highest income segment with 45%. However, this is by the far the most extreme example we observe. The US vehicle fuel shares are for example around 10%. Ruling the red-region out, we only observe negative price elasticities. The rest of the behaviour space seems sensible. A low share of consumption plus a high income elasticity of demand imply that the good is not very essential and thus with higher prices demand reduces substantially. Goods that have a low income elasticity of demand are basic goods and thus translate to weakly price elastic demand (green and yellow zones in the upper region of the plot).



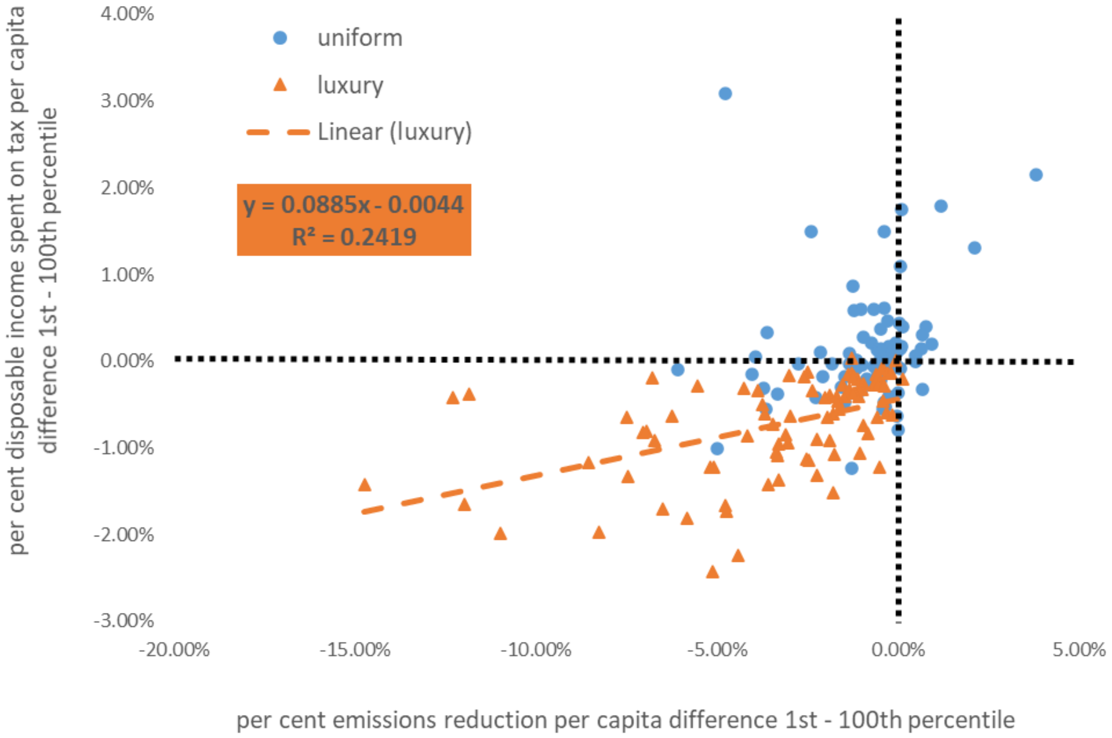
Supplementary Figure 3: China carbon prices. This figure displays carbon prices in the static model for the uniform and luxury scenario in China.



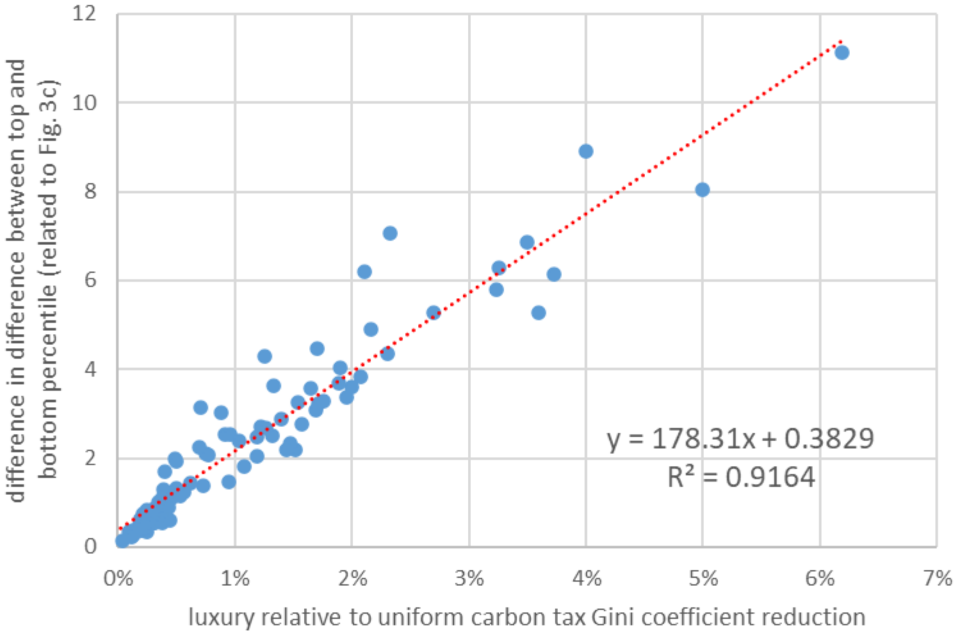
Supplementary Figure 4: Cubed elasticity weighting. Here we did not weight the carbon prices by the income elasticity of demand in equation (4-2) of the main text but by the cubed income elasticity of demand. This generates greater price differentials between blanket and luxury tax and makes luxury carbon taxes even more progressive.



Supplementary Figure 5: Financial burden vs. emission reductions progressivity. This plot shows how the tax impact on emissions per capita compares to impact on share of disposable income spent on the tax. The takeaway message is that what is progressive in terms of emissions is not necessarily progressive in terms of financial burden under a uniform carbon tax but what is progressive in terms of emissions is also progressive in terms of financial burden under a luxury carbon tax. Luxury carbon taxes are therefore generally progressive, even before recycling revenue. The luxury tax incidence (orange triangles) difference between the 100th percentile (highest income) and the 1st percentile (lowest income) is negative in both cases which means that the 100th percentile has to reduce emissions more and pay a greater share of their disposable income on the tax.

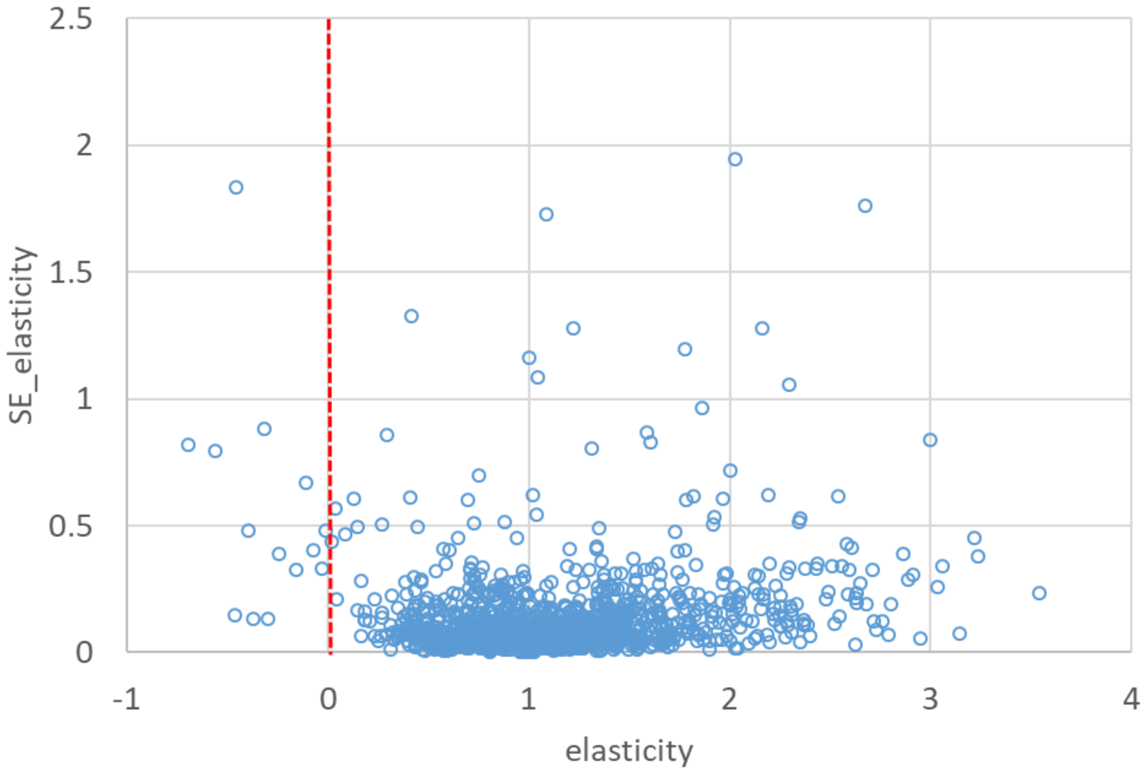


Supplementary Figure 6: Relationship between impact difference for top and bottom percentile and national Gini coefficient of emissions. This figure shows the relationship between the data displayed in main text Figure 3 Panel (c) and the carbon tax impact on national Gini coefficients of emissions.

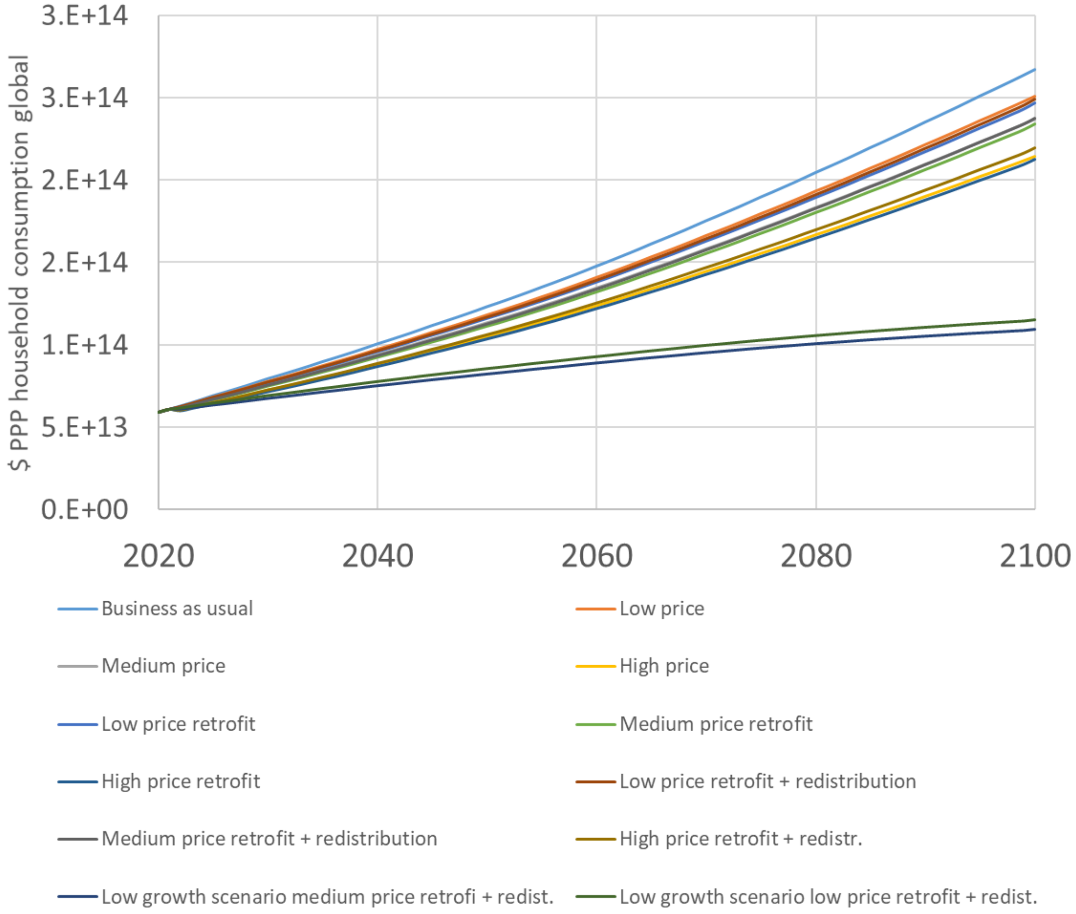


Supplementary Figure 7: Elasticity robustness analysis.

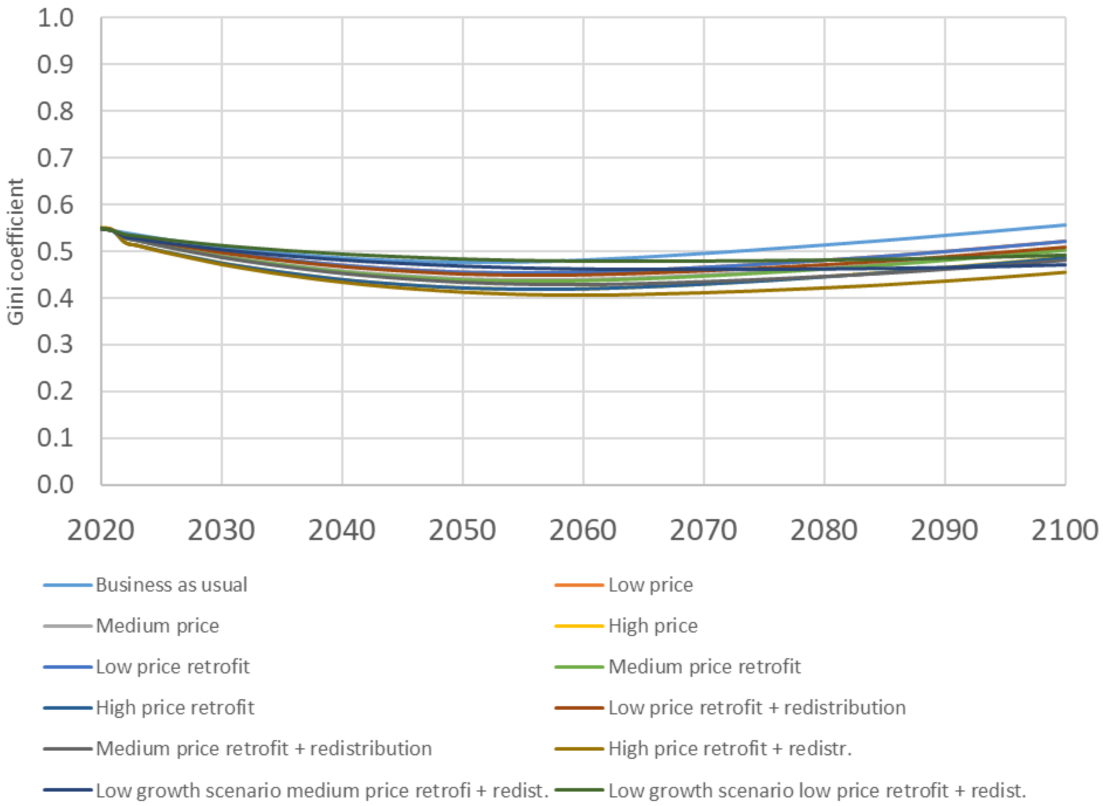
We investigated how reliable the income elasticities of demand are across all countries, by comparing the size of the standard error to the elasticity and also correlate it with the R-Squared of each model. We find that ~95% are reliable, that is have high R-Squared (>0.7) and a coefficient of variation being less than 50%. Roughly 85% of the elasticities attain R-Squared of >0.9. Apart from the bulk being reliable data, there are outliers that point to very uncertain data which occur mostly in small low-income countries, for example in Madagascar. We assume a limit to uncertainty in line with the distribution of standard errors in order to avoid hyper-sensitivity of the tax response model. We assume, in line with the distribution, that a 50% standard error is the maximum uncertainty. Where we interpolate expenditure data with an elasticity of 1 or 0.1 for inferior goods, we assume maximum uncertainty. It does not matter whether we calculate elasticities directly based on the original 2011 data or the now-casted 2019 version. This is because the proportions across consumption categories remain the same during the now-casting process, so the income elasticities are fixed as well.



Supplementary Figure 8: Household consumption trajectories.



Supplementary Figure 9: Household emissions international Gini coefficient trajectories.

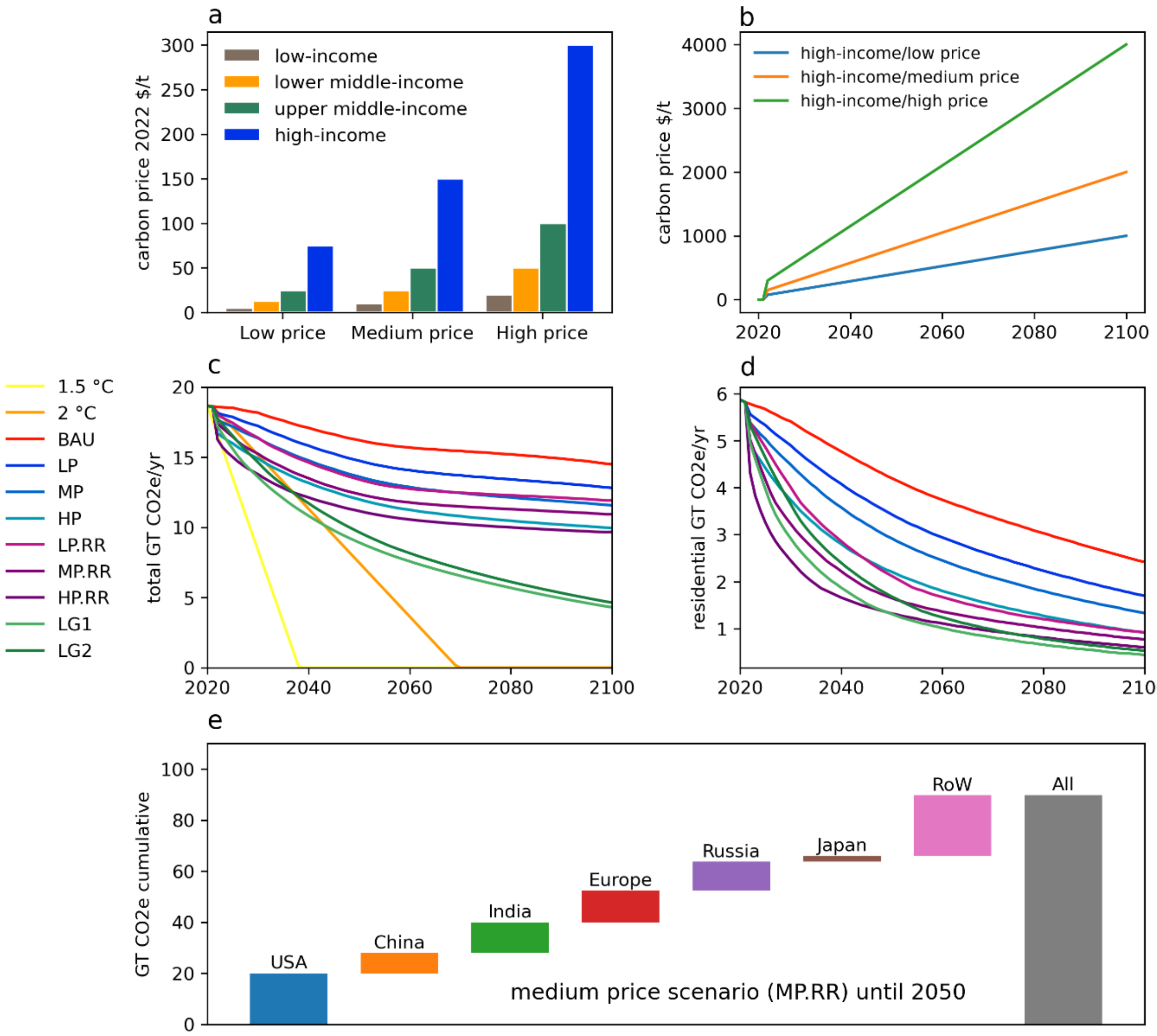


Supplementary Figure 10: Dynamics alternative description.

In this Figure we have extended equation (7) of the methods to additionally account for a consumer response on technology evolution. This term is denoted $B_{t,i}$.

$$C_{t+1,i} = \quad C_{t,i} * (1+g_{t,i}) * \left(1+\ \epsilon_{p_i} * \tau_{t,i}\right) * (1+\ B_{t,i}) + r_{t,i} \tag{3s}$$

The factor $B_{t,i}$represents households' response to improvements in technology or in other words –to a decrease in carbon intensity. If a carbon price is set in year *t*, then technology improves by a certain rate by year *t+1*. Here we assume that demand bounces back, i.e. takes note of this technology improvement, and increases demand again accordingly. Overall, the adjustment interferes moderately with cumulative emissions reductions until 2050 and causes ~10% less abatement.



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