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

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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.

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%[1]. Oxfam adds that in 2017, *"82% of all wealth created went to the top 1%"*[2]. 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[3,4]. Climate change is likewise high on the global agenda and so is energy's role in decarbonizing the economy[5,6]. Numerous studies have shown that economic inequality translates to inequality in energy consumption as well as in emissions[7–9]. This is largely because people with different purchasing power make use of different goods and services[10] 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[3,9]. 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[11,12]. Recent scenario work demonstrates that reorganizing and reducing energy demand can ease the shift to a low-carbon energy system[13] 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[14]. Whatever a person does in her or his 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[15]. Some end-use services are essential to people's life while others are "luxuries" that people enjoy[16]. 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[17]. Some studies highlight that if we increase living standards of the poor we jeopardize achieving climate goals[18–20]. Various authors, however, have raised the question of whether providing the poor with a "decent living standard" requires curbing "luxury" elsewhere[16,21]. 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[22–24]. 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[24].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[25]. 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[26–30]. We employ a Global Trade Analysis Project (GTAP 9) based Multi-Regional-Input Model (MRIO) for the year 2011[31]. 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[32] (Brazil, Russia, India, China, South Africa), and Eurostat Household Budget Surveys, which includes all 28 economies of the European Union plus Norway and Turkey[33]. We find that international and intranational inequality both are large, to the extent that the bottom half consumes less than the top 5%.

Energy footprints and expenditure

Energy footprints per capita generally grow as a function of income or expenditure[28,34]. 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 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.

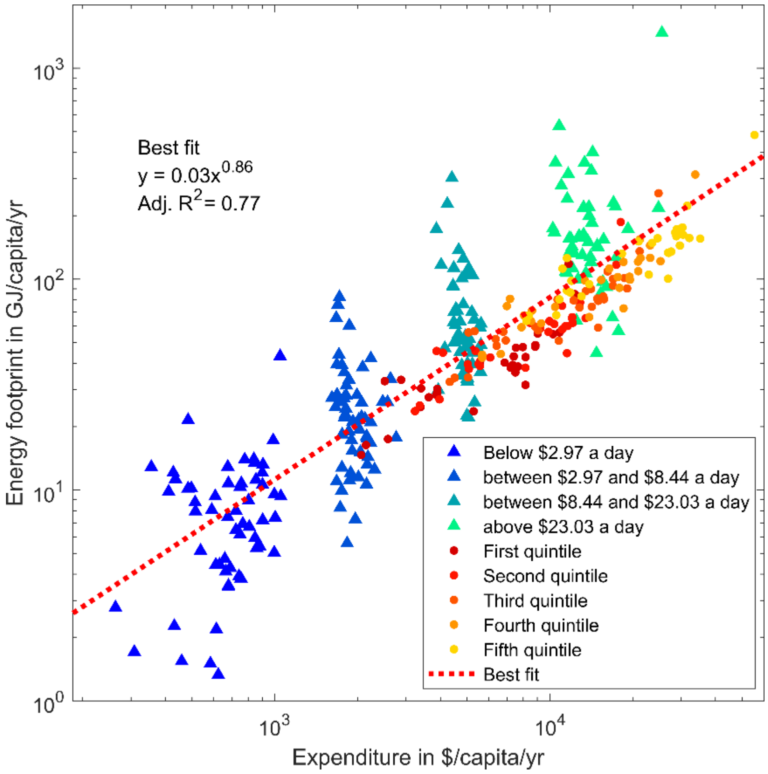

Figure 1: Energy footprints vs. expenditure. *Energy footprints scale sublinearly with expenditure. Adj. R-squared 0.77, p-value= 1.91e-119. Triangles represent GCD data and dots Eurostat data.*

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, 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. This 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[35]. 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.

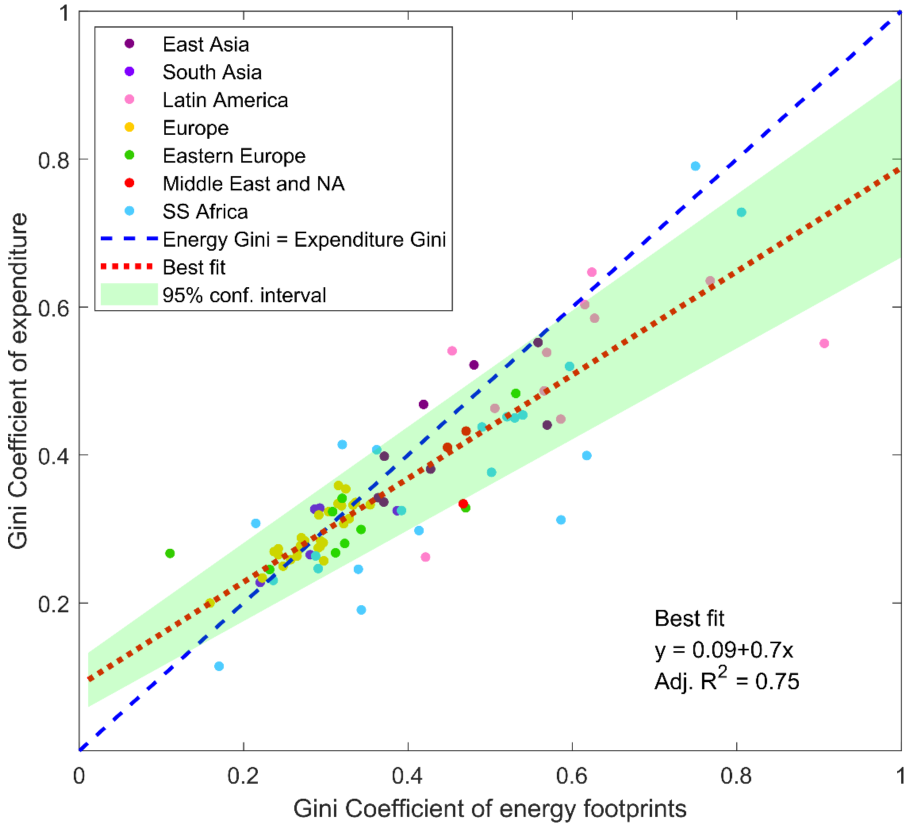

Figure 2: Energy footprint inequality vs. expenditure inequality for 2011. *Energy footprint inequality scales in a superlinear way with expenditure inequality (Adj. R-squared 0.75). The energy footprint inequality is generally larger than expenditure inequality. Therefore, the best fit (red line) has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

The interaction of 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)[8].

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 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 24MJ/\$). The corresponding elasticities of Package Holidays, in Figure 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 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 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.

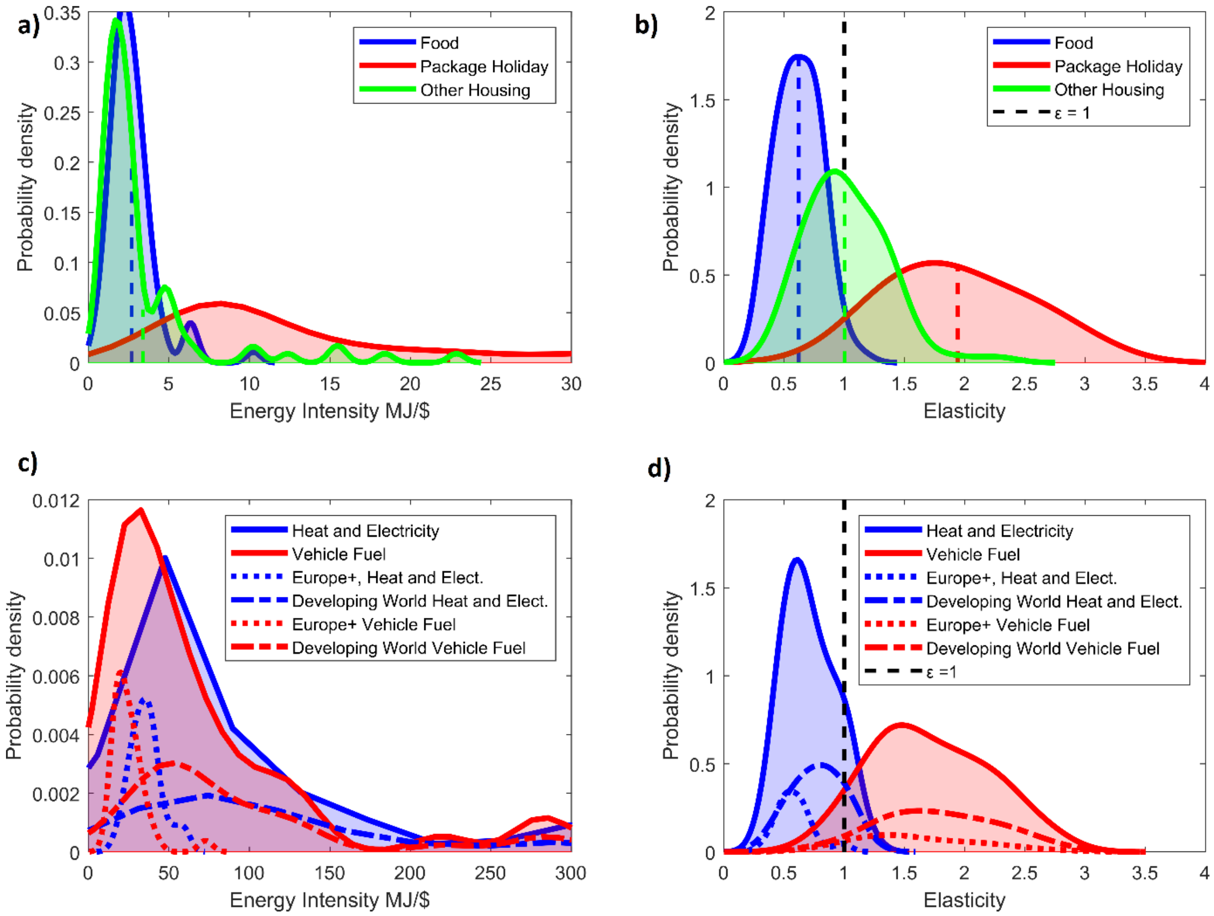

Figure 3: Energy intensity and elasticity spectra. *The figure displays the probability density function of the energy intensities (a-c) and income elasticities (b-d) of consumption categories. Panels (a) and (b) refer to indirect, and panels (c) and (d) to direct, energy use categories. The vertical 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 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 ($\rho = 0.52$, 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.

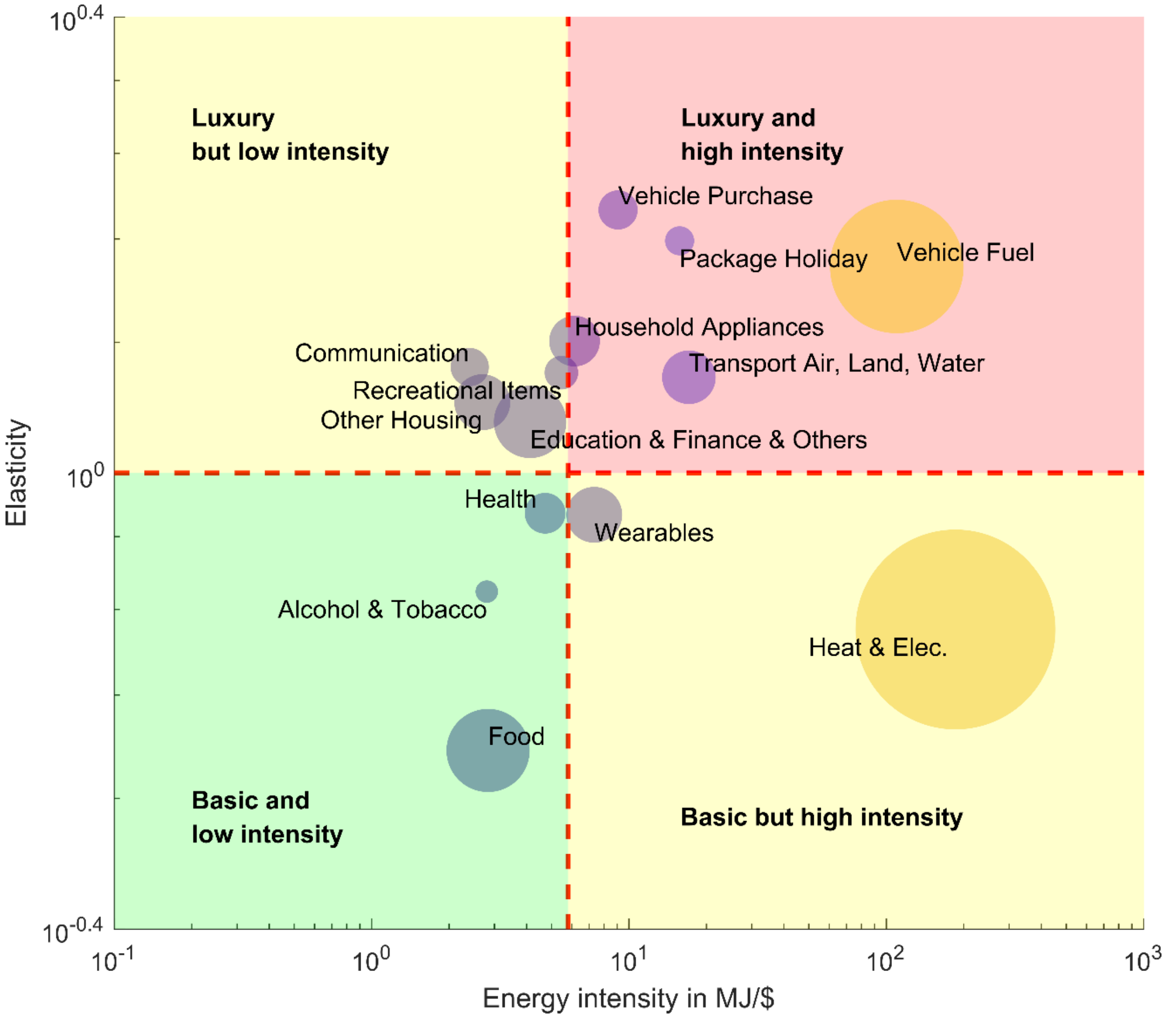

Figure 4: Elasticity vs. Energy Intensity. *The energy intensity of MJ/€ for Eurostat-based data was converted via the 2011 average exchange to MJ/$. For indirect energy consumption (dark circles), the income elasticity of demand correlates with the given energy intensity (rank correlation: ρ = 0.52, 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 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”.

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 1 provides an overview of inequality in international energy footprints distinguished by consumption category.

Table 1: Overview international energy footprint inequality over 86 countries

Consumption Category	Gini Coefficient	Top10% to Bottom10% 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 5. Figure 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.

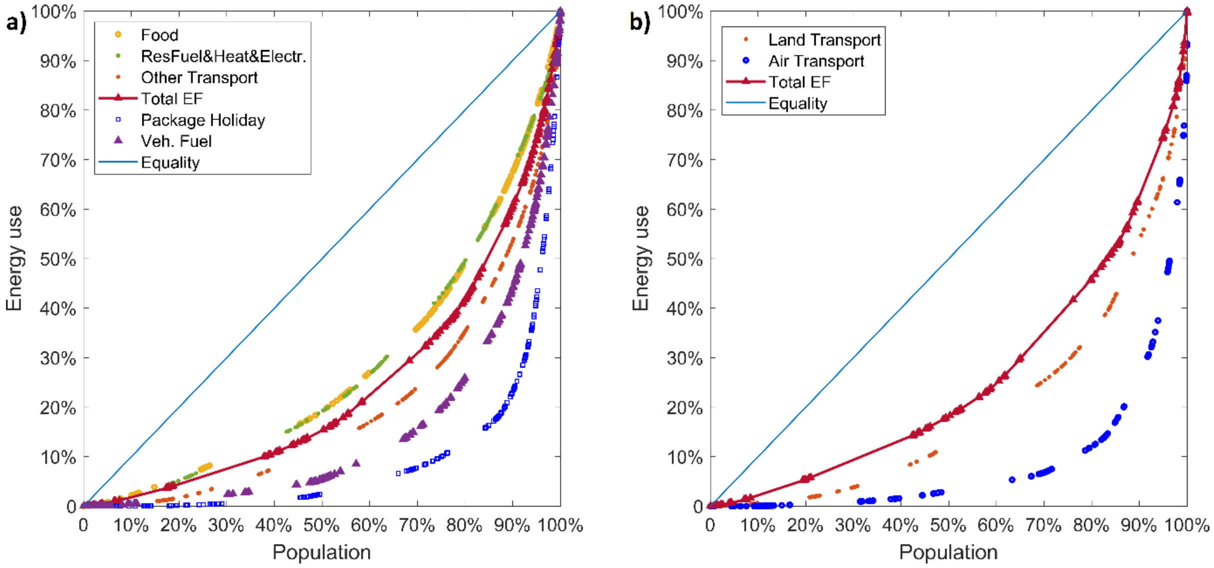

__Figure 5: International Lorenz Curves.__ Panel (a) shows the international inequality of energy footprints across all income classes within the 86 countries taken together, for different consumption categories. The overall energy footprint inequality is the red continuous line. Embodied energy in food 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.

Implications of energy inequality

Energy provision is considered a fundamental and integral development challenge[36,37]. 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[28]. At high incomes, final energy footprints per capita are frequently greater than 200 GJ/yr or occasionally even greater than 300GJ/yr (see Figure 1). This is one order of magnitude greater than what has been identified as necessary for a decent quality of life[22]. 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[38]. 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[39].

Transport has been identified as a problematic sector before, encountering difficulties transitioning to low-carbon alternatives[40]. 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 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[40]. There are concrete policy proposals that address transport demand such as a frequent flyer levy[41] or reducing car dependency through urban planning as well as committing to alternative vehicle technologies, including electric and hydrogen[42].

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.

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[43]. 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, we can anticipate that increasing income inequality will be translated into even larger 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 more than double by 2030, and quadruple by 2050, with nearly 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 0.49 in 2050. Considering consumption categories, 34% of the energy increase can be attributed to "Vehicle Fuel" alone, another 30% 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 the categories with high income elasticity of demand >1. For instance, "Other transport" inequality is initially almost stable, going from a Gini coefficient of 0.60 to 0.57, but then increases to 0.66. "Package Holiday" remains at a high inequality and increases slightly to a Gini coefficient of 0.83 in 2050. Figure 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[43]. Despite this limitation, we find that energy inequality is not likely to reduce significantly, and even increases by 2050 in several crucial consumption categories.

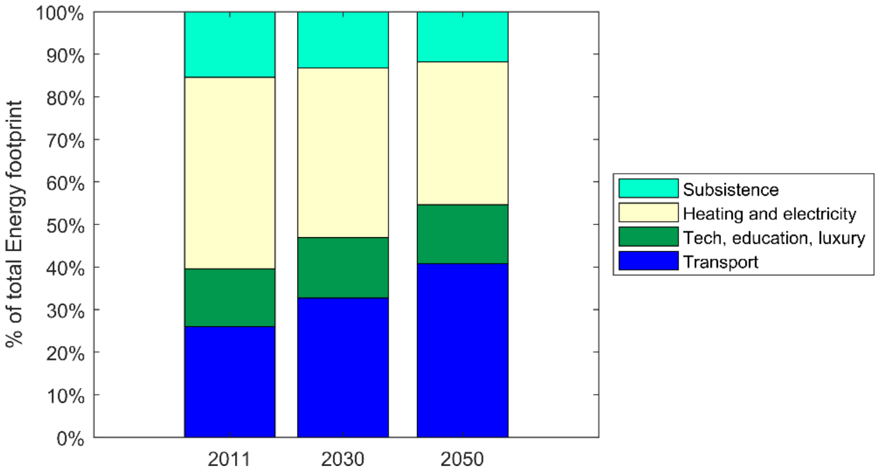

Figure 6: Business as usual trends for household energy footprints. *The business as usual scenario (BAU) is a simple computational experiment extrapolating expenditure patterns and energy consumption on the basis of projected economic growth and population trends. More money is spent on high elasticity 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 4. Based on their distinct nature, the four types require type-specific policy and action. In our view, this could include:

Quadrant 1 High intensity, high elasticity: Dominated by transport and hard to decarbonise. 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).

Quadrant 2 Low intensity, high elasticity: Consider redistributive efforts and move away from profit-based provision models, particularly if essential as in the case of education and health. Maintain agenda of complete decarbonisation.

Quadrant 3 Low intensity, low elasticity: Keep public investment agenda of further decarbonisation, but do not tax, since regressive.

Quadrant 4 High intensity, low elasticity: Dominated by electricity and heating and therefore in need of large-scale public programmes that retrofit buildings.

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.

Methods

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)[44]. Therefore, the two databases can be aligned with the GTAP sectors. The 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[45–47] and are relatively robust against outliers[48].

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

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

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

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[49]. Currency transformations from Euro to Dollar have been conducted via the yearly average exchange rate of 2011, 1.39$=1€.

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

$$e = f * \hat{x}^{-1} \qquad (3)$$

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

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

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

$$q_i = e * L * Y_{h,i} \qquad (5)$$

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

$$Q_i = \widehat{eL} * C_i \qquad (6)$$

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 3 and Figure 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.

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[50]. 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 initial 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

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

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.

Income elasticities of demand

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

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

where *i* is the country index and *j* is the consumption category index. The coefficient *b* is directly interpretable as an elasticity (see supplementary material section 8). *Total expenditure of households (X*) functions as an approximation to income per household, 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[8]. If an elasticity is not significant it is not considered for the analysis in the section “The interaction of income elasticity of demand and energy intensity”.

Inequality metrics

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

The Lorenz curve can be described by

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

where

$$x_n = \sum\nolimits_1^n P_n/P_{global} \tag{10}$$

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

$$y_n = \sum\nolimits_1^n E_n / E_{global} \tag{11}$$

where y_n is the energy consumption of country n. The energy Gini coefficient then is[8,51]

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

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[52]

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

where *n* is the sample size.

Business as usual scenario

The income 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[53]. 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[54]. 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)[55] 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 ~240EJ, i.e. they increase by ~70%, and by 2050 to ~350EJ, i.e. they more than double but do not quadruple. 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.

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[56]. 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 (2017)[57].

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.

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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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