nature energy

ARTICLES
https://doi.org/10.1038/s41560-020-0579-8

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 that result from energy use. Detailed measures of this inequality are required to ensure an equitable and just energy transition. Here we calculate final energy footprints; that is, the energy embodied in goods and services across income classes in 86 countries, both highly industrialized 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 in 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 added[2] that in 2017 "82% of all wealth created went to the top 1%". Inequality is now recognized as a decisive force of our time and has been linked to issues that range 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 emissions[7–9]. This is largely because people with different purchasing power make use of different goods and services[10], which are sustained by different energy quantities and carriers.

Most studies that consider 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[14] argue that different social practices entail different patterns of energy consumption[14]. 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 on distinct amounts of energy and 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, whereas 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. By contrast, travel holidays and plasma televisions 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 luxuries being curbed elsewhere[16,21]. Some have suggested limiting the per capita energy consumption and emissions of high consumers to create space to provide essential energy services for those left behind[22–24]. International climate goals are threatened by the emissions of high-income countries and individuals. Chakravarty et al.[24], 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 when 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 multiregional input–output 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 of the (at the time) 28 economies of the European

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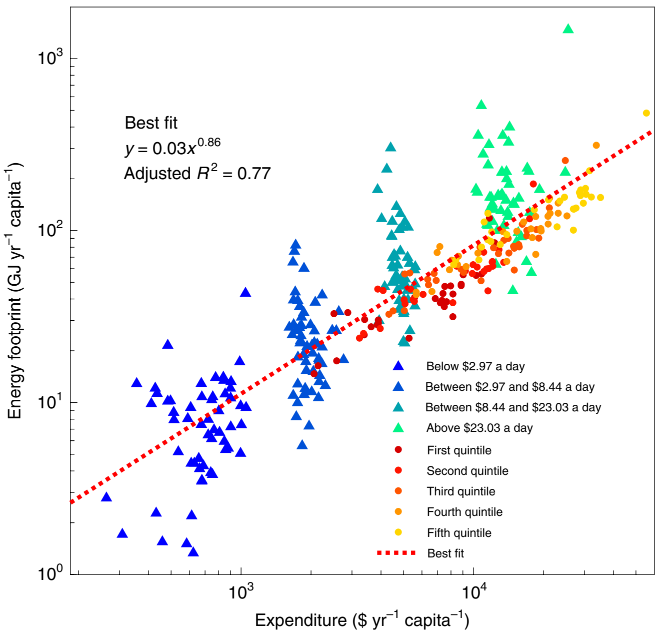

Fig. 1 | Energy footprints versus expenditure. Energy footprints scale sublinearly with expenditure (adjusted $R^2 = 0.77$). Triangles and dots represent GCD and Eurostat data, respectively.

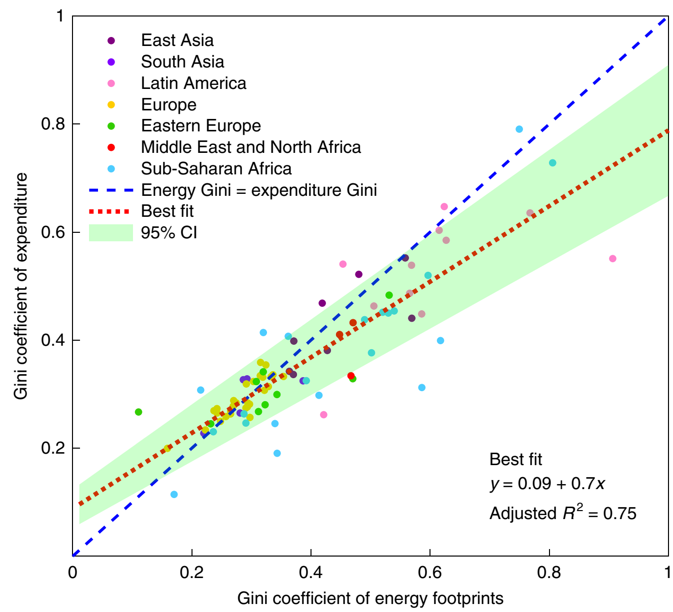

Fig. 2 | Energy footprint inequality versus expenditure inequality for 2011. Energy footprint inequality scales in a superlinear way with expenditure inequality (adjusted $R^2 = 0.75$). The energy footprint inequality is generally larger than expenditure inequality. The best fit line (red dotted line) therefore has a lower slope than the linear scaling line (blue dashed line). CI, confidence interval.

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 four to five income groups, resulting in 374 population segments (see Fig. 1). We fit a power law and find that energy footprints scale sublinearly with expenditure. Expenditure at higher levels becomes slightly 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 European range of energy intensities. This is caused by the structure of the GCD 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.

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 Fig. 2, implying that energy footprints vary more widely in their inequality than expenditure does. When expenditure is highly unequal in a country (that is, it 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 (for example, Gini coefficients in Namibia are 0.7 for expenditure versus 0.8 for energy, whereas Paraguay's are 0.64 for expenditure versus 0.77 for energy). Metrics are more likely to be similar at lower expenditure inequality. 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[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.

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 the responsiveness of the quantity demanded for a good or service to a change in income; for example, what greater percentage of a good is consumed if income rises by 1%. If consumption of that good increases by exactly 1% then the elasticity is 1, if consumption increases by less than 1% then the elasticity is less than 1 (a basic good) and if it increases by more than 1% then the elasticity is above 1 (a luxury good)[8].

We observe wide variations in energy intensities and elasticities across consumption categories. Package holidays, for instance, comprise 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 Fig. 3a using probability density functions. The upper row (Fig. 3a) depicts the indirect energy use categories food, package holidays or other housing, whereas the lower row (Fig. 3c) shows the direct energy use categories heat and electricity as well as vehicle fuel and operation (for simplicity, summarized as vehicle fuel). The averages of the distributions are shown as dashed lines. The average energy intensities of food and other housing are similar,

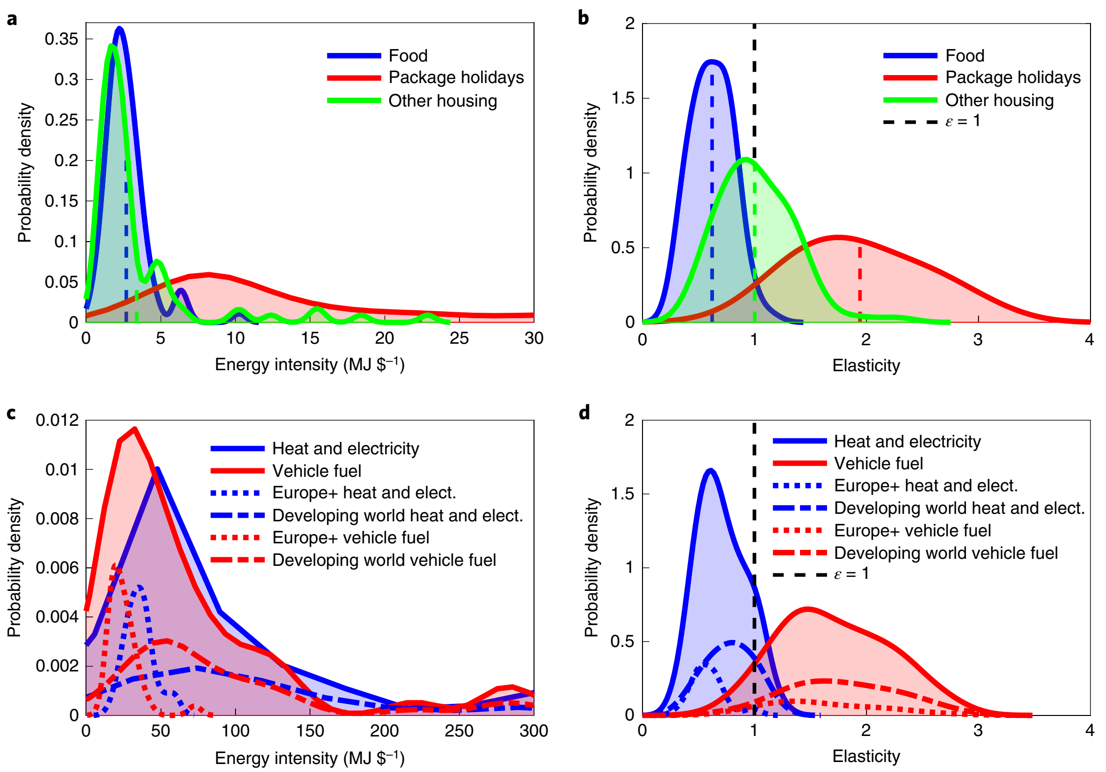

Fig. 3 | Energy intensity and elasticity spectra. a–d, The probability density functions of the energy intensities (**a**,**c**) and income elasticities (**b**,**d**) are shown for different consumption categories. Panels **a** and **b** (**c** and **d**) refer to indirect(direct) energy use categories. The coloured vertical dashed lines in **a** and **b** depict the mean of the distributions, whereas the black vertical dashed lines in **b** and **d** represent an income elasticity of 1. In **a**, the mean of the package holidays is difficult to see as it located at 22.5 MJ $^{-1}. For direct energy use, one clearly can distinguish between the distributions in European countries plus Turkey (Europe+) and developing economies, which are represented by 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.

whereas that of package holidays is clearly distinct (at 22.5 MJ $^{-1}). The corresponding elasticities of package holidays are also high, with an average elasticity ~2 (Fig. 3b). The elasticity of food and other housing is, on average, ~0.6 and ~1, respectively.

In Fig. 3c we show the spectrum of energy intensities in the heat and electricity and vehicle fuel direct energy use categories. Aside from 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 $^{-1}. The wide range in these categories is a result of both technological and price differences. Figure 3d, by 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 elasticity, such as heat and electricity, distributes energy more uniformly in society.

Is there a general relationship between energy intensity and elasticities of consumption categories? We take the population-weighted mean of energy intensities and elasticities across all sample countries to investigate that question. The population-weighted mean guarantees that the energy intensities and elasticities most in use are represented effectively. If both attributes are low then we label a consumption category basic and low intensity, whereas if both are high then 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 (Spearman's $\rho = 0.52$, 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.

We also observe that the result of Fig. 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 holidays and 92% of vehicle fuel are found in the luxury and high intensity quadrant, whereas 94% of food is found in the basic and low intensity quadrant.

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

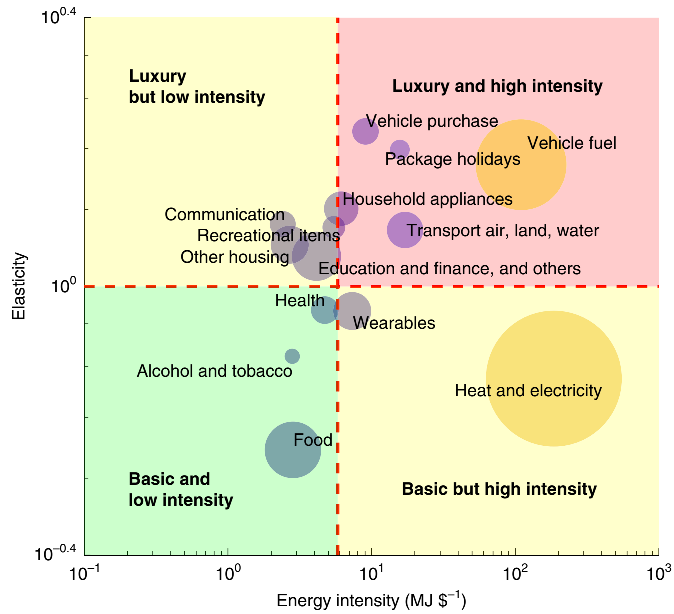

Fig. 4 | Elasticity versus energy intensity. The energy intensity of MJ €$^{-1}$ for Eurostat-based data was converted via the 2011 average exchange rate to MJ $$^{-1}$. For indirect energy consumption (dark circles), the income elasticity of demand correlates with the given energy intensity (rank correlation: Spearman's $\rho = 0.52$, 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, which exhibits low elasticity but the highest energy intensity.

Table 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 holidays	0.82	—	76%	0%
Education and finance and 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%

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 with 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%), whereas the lowest 10% consume almost 20 times less, ~2%. There are three categories where the bottom 10% are entirely excluded from energy consumption so far: recreational items, package holidays and vehicle purchases. Recreational items comprise goods such as 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 such as 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.

The distribution (Lorenz curves) of different consumption categories are shown in Fig. 5. Figure 5a depicts the Lorenz curves for the entire sample whereas Fig. 5b 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 the results are similar when considered over all countries. Air-transport-related activities such as package holidays have the steepest Lorenz curves. Vehicle fuel and other transport are likewise very unequal. Food and residential energy use, by contrast, are a little less unequal than the total average.

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- 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^{-1} or occasionally even greater than 300 GJ yr^{-1} (see Fig. 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 30 GJ yr^{-1} capita^{-1} and 38% consume less than 10 GJ yr^{-1} capita^{-1}—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 10 GJ yr^{-1} capita^{-1}. This is a dramatic difference, enabled by considering intranational 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, but how much 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 ~1,000 GJ yr^{-1} capita^{-1}. Were everyone to use that much energy, we would require ~7,600 EJ

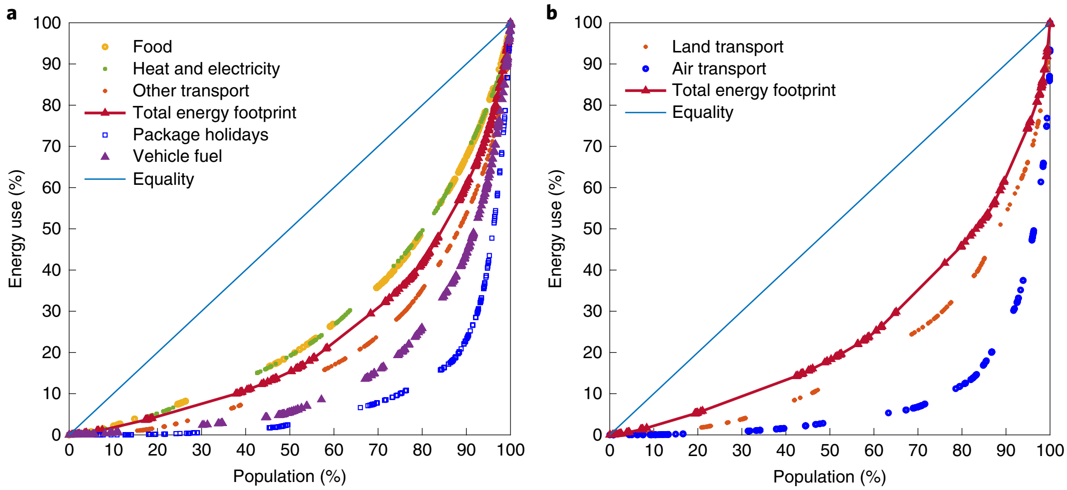

Fig. 5 | International Lorenz curves. a, The international inequality of energy footprints across all income classes within the 86 countries taken together are shown for different consumption categories. Embodied energy in food and direct residential energy consumption—in the form of electricity and heat—exhibit the least inequality, but, with Gini coefficients of 0.45 can still be described as highly unequal. The highest inequality occurs in transport-related energy consumption: vehicle fuel as well as package holidays, with the latter relying often on flights. **b**, A graph that accentuates the difference in energy inequality for land and air transport in the developing world (56 countries), with air transport being clearly more unequal.

of final energy on this planet, which is ~27 times more than we currently use[39].

Transport, which has been encountering difficulties in transitioning to low-carbon alternatives, has been identified as a problematic sector before[40]. We show that transport-related consumption categories are among the most unequal ones. Moreover, we measure greater inequality in air transport compared to public land transport (see Fig. 5b). Large parts of the population are almost or entirely excluded from aviation, and 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) and 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 into fossil fuel dependency. It has previously been suggested that many of the engineering obstacles 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. We clearly only observe the footprints of private expenditure, and not of public provision, but both health and education 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 is thus 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, which 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 if economic growth is mostly distributed to high-income people as 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 Fig. 2, we can anticipate that increasing expenditure inequality will be translated into even larger energy inequality.

We projected expenditure and population levels into the future for the two years 2030 and 2050 to test this reasoning. We did so by making use of long-term GDP projections by the Organisation for Economic Co-operation and Development 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 the education and finance and other luxury category. Other subsistence such as 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 holidays remains highly unequal and its Gini coefficient increases slightly to 0.82 in 2050. Figure 6 displays major trends in household energy footprints by aggregated consumption categories. Transport-related energy footprints increase their share of the total, whereas 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

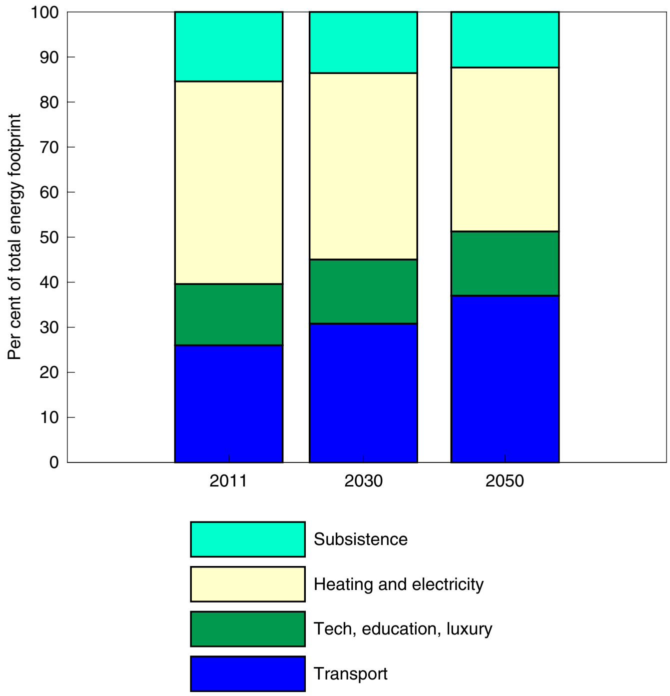

Fig. 6 | Business-as-usual trends for household energy footprints. The business-as-usual scenario is a simple computational experiment extrapolating expenditure patterns and energy consumption on the basis of projected economic growth and population trends. More money is spent on high elasticity goods,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

to reduce significantly, and even increases by 2050 in several crucial consumption categories.

However, persisting inequality can be prevented through appropriate intervention. We can classify four types of consumption categories as illustrated through the four quadrants in Fig. 4. Due to 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 decarbonize. We therefore recommend moving towards considerable 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). Proceeding 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 in the case of education and health) while maintaining an agenda of full decarbonization. For the lower left-hand quadrant (low intensity, low elasticity), the public investment agenda of decarbonization 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, as such measures will not be affordable nor 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. We therefore suggest that the next step in this research should be the exploration of energy demand distribution scenarios that test the measures suggested. 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 v.1999)[44] and can therefore 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, which can be aligned with GTAP sectors. In comparison with primary energy, final energy is closer to the energy that people actually make use of, it approximates the amount of energy that operates on site to provide a certain service and also better represents the energy capacity required to replace fossil fuels with low-carbon alternatives (for instance, solar or wind), which 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.

On the basis of 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. We represent inequality by showing the distributional Lorenz curves and the corresponding Gini coefficients. 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 MRIO is based on 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. We make use of the GCD by the World Bank and the Eurostat data tables on household expenditure patterns to differentiate between consumer groups according to income. 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. This is equivalent to the percentage of total expenditure that a household spends a year on a given category. The mean total expenditure of households therefore has to be distributed across the different categories according to these percentages. Subsequently, both expenditure databases have to be scaled to the 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 expenditure data of the GCD is given per capita, and total population is provided. Supplementary Fig. 1 demonstrates that the scaled-up national expenditure volumes fit to the national expenditure volumes of households in the GTAP (correlations with adjusted $R^2 = 0.99$ for Eurostat and adjusted $R^2 = 0.91$ for the GCD). Although 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 by twofold. First, international aviation and shipping bunkers have to be included, which has been achieved 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 transport not elsewhere classified (n.e.c.) sector comprises commercial vehicle use as well as supporting transport activities (for example, for an Amazon delivery) and that the trade sector includes private fuel purchases. We then simply took the ratio of both sectors with respect to their common total; for instance, if both sectors together were 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 equal the trade sector volume (in \$), F_i equal the total road energy in terrajoules, K_i equal the commercial road energy use in terrajoules, and P_i equal the private road energy in terrajoules, we then define

$$K_i = \left(\frac{N_i}{N_i + M_i}\right) F_i \quad (1)$$

$$P_i = F_i - K_i \quad (2)$$

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 the transport n.e.c. and trade sectors; however, considering the large sample size and non-existent international data for this purpose, it is an efficient way of distinguishing between direct and indirect energy in road transport. A comparison with greenhouse gas emissions by source data from Eurostat yields that the attained ratios for European countries differ by at most 20%. 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, which is not unreasonably far off.

The currency transformation (Euro purchasing power standard to international dollar) has been conducted via the yearly average exchange rate of 2011, where \$1.39 = 1€.

Input–output modelling of energy footprints. The GTAP is a quadratic input–output table and hence we can apply standard environmentally-extended input–output analysis.

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

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

where **f** is the energy extension, **x** is the total industry output and ^ denotes matrix diagonalization. The Leontief (L) multiplier is given by

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

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

$$q_i = \mathbf{e}L\mathbf{Y}_{\mathbf{h},\mathbf{i}} \tag{5}$$

where $\mathbf{Y}_{\mathbf{h},\mathbf{i}}$ is the demand vector of households. We want to access footprints per consumption category in the format of the household surveys, the COICOP; we thus compute

$$Q_i = \widehat{\mathbf{e}L}C_i \tag{6}$$

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 energy footprint per category in GTAP; C_i is a balanced concordance matrix that translates between the two datasets. Now if we take the sum of each column in Q_i and divide it by the total original spends for the respective category, we attain the energy intensity of a consumption category (as, for example, used in Figs. 3 and 4). We then 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 and IEA energy balances come with a different product and service classification than the GTAP, which is why it is necessary to transform them into a GTAP format. Transforming the IEA energy balances into a 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). The equivalent sectors have thus 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 those in 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. An iterative proportional balancing technique has been applied to overcome this blackbox, mathematically equivalent to RAS balancing[49]. 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 (for example, between the Euro purchasing power standard and US Dollar purchasing power parity). Afterwards, let C^1 be the initial distributed concordance matrix between the COICOP system and the GTAP system. The column sum in C^1 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, C^1 will then 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^1 will 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 ^ denotes matrix diagonalization. This procedure is repeated 500 time; r and s often saturate 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 consumption category (Z) on total expenditure per capita (X), along the different income classes and over all countries as follows:

$$\log(Z_{i,j}) = a + b\log(X_i) \tag{8}$$

where i is the country index and j is the consumption category index. The coefficient b is directly interpretable as an elasticity (see Supplementary Section 8); 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[8]. If an elasticity is not significant it is not considered for the analysis in the section '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 the function $L(x_i)$ (here L denotes the Lorenz curve and not, as in equation 4 and 5, the Leontief multiplier)

$$y_i = L(x_i) \tag{9}$$

where

$$x_i = \sum\nolimits_1^i P_i/P_{\text{global}} \tag{10}$$

x_i is the cumulative population share of country i, ranked by per capita energy in y_i, P_i is the population of country i and

$$y_i = \sum\nolimits_1^i E_i/E_{\text{global}} \tag{11}$$

where y_i is the cumulative energy consumption share of country i and E_i is the energy consumption of country i. The energy Gini coefficient is then[8,50]

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

We want to compute Gini coefficients of individual countries. Our sample size is then reduced to four or five 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[51]

$$G_{\text{corrected}} = \left(\frac{n}{n-1}\right)G \tag{13}$$

where n is the sample size.

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[52]. We applied the projected world average to countries where no long-term forecasts are available. We applied income growth rates to our proxy for income; that is, 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[53]. There are two important features for a distributional scenario that we did consider but did not yet implement: 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 tested a variation of this scenario in which we applied the average historical final energy intensity decline, but it does not affect the distributional results at all. As global GDP grew on average by 3.1% per year from 1971 to 2015 (based on World Bank data)[54] and final energy on average by 1.8% per year during the same period (based on IEA data), the average energy intensity (in final energy) declined by around −1.3% per year. We applied this rate uniformly to the here measured energy intensities. In this version, household energy footprints rise to ~216 EJ by 2030 (that is, they increase by ~50%) and to ~285 EJ by 2050 (that is, 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 as it does not account for region- or sector-specific technological 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 assumed that the amount of expenditure represented the physical quantity consumed and thus directly translated to the energy quantity consumed; for example, we were 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[55]. 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 GCD 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 ref. [56].

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 on reasonable request. Source data for Figures 1 to 6 are provided with the paper.

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.

Received: 18 July 2019; Accepted: 10 February 2020;
Published online: 16 March 2020

References

1. Alvaredo, F., Chancel, L., Piketty, T., Saez, E. & Zucman, G. *World Inequality Report 2018* (World Inequality Lab, 2018).
2. *Reward Work, Not Wealth* (Oxfam, 2018).
3. Hubacek, K., Baiocchi, G., Feng, K., Sun, L. & Xue, J. Global carbon inequality. *Energy, Ecol. Environ.* **2**, 361–369 (2017).
4. Krieger, T. & Meierrieks, D. Income inequality, redistribution and domestic terrorism. *World Dev.* **116**, 125–136 (2019).
5. Rockström, J. et al. A roadmap for rapid decarbonization. *Science* **355**, 1269–1271 (2017).
6. Steffen, W. et al. Trajectories of the Earth system in the Anthropocene. *Proc. Natl Acad. Sci. USA.* **115**, 1–45 (2018).
7. Teixidó-Figueras, J. et al. International inequality of environmental pressures: decomposition and comparative analysis. *Ecol. Indic.* **62**, 163–173 (2016).
8. Steinberger, J. K., Krausmann, F. & Eisenmenger, N. Global patterns of materials use: a socioeconomic and geophysical analysis. *Ecol. Econ.* **69**, 1148–1158 (2010).
9. Ivanova, D. et al. Environmental impact assessment of household consumption. *J. Ind. Ecol.* **20**, 526–536 (2015).
10. Galvin, R. & Sunikka-blank, M. Economic inequality and household energy consumption in high-income countries: a challenge for social science based energy research. *Ecol. Econ.* **153**, 78–88 (2018).
11. Creutzig, F. et al. Towards demand-side solutions for mitigating climate change. *Nat. Clim. Chang.* **8**, 268–271 (2018).
12. Baker, L. Of embodied emissions and inequality: Rethinking energy consumption. *Energy Res. Soc. Sci.* **36**, 52–60 (2018).
13. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
14. Shove, E. & Walker, G. What is energy for? Social practice and energy demand. *Theory, Cult. Soc.* **31**, 41–58 (2014).
15. Fell, M. J. Energy services: a conceptual review. *Energy Res. Soc. Sci.* **27**, 129–140 (2017).
16. Shue, H. Subsistence emissions and luxury emissions. *Law Policy* **15**, 39–59 (1993).
17. *Access to Electricity (% of Population)* (World Bank, 2019); https://data.worldbank.org/indicator/eg.elc.accs.zs
18. Hubacek, K., Baiocchi, G., Feng, K. & Patwardhan, A. Poverty eradication in a carbon constrained world. *Nat. Commun.* **8**, 912 (2017).
19. Scherer, L. et al. Trade-offs between social and environmental sustainable development goals. *Environ. Sci. Policy* **90**, 65–72 (2018).
20. Lamb, W. F. & Rao, N. D. Human development in a climate-constrained world: what the past says about the future. *Glob. Environ. Chang.* **33**, 14–22 (2015).
21. Rao, N. D. & Min, J. Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.* **138**, 225–244 (2018).
22. Goldemberg, J. Basic needs and much more with one kilowatt per capita. *A J. Hum. Environ.* **14**, 190–200 (1985).
23. Jess, A. What might be the energy demand and energy mix to reconcile the world's pursuit of welfare and happiness with the necessity to preserve the integrity of the biosphere? *Energy Policy* **38**, 4663–4678 (2010).
24. Chakravarty, S. et al. Sharing global CO_2 emission reductions among one billion high emitters. *Proc. Natl Acad. Sci. USA* **106**, 1–5 (2009).
25. Rao, N. D., Min, J. & Mastrucci, A. Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy* **4**, 1025–1032 (2019).
26. Owen, A., Scott, K. & Barrett, J. Identifying critical supply chains and final products: an input–output approach to exploring the energy–water–food nexus. *Appl. Energy* **210**, 632–642 (2018).
27. Steinberger, J. K., Timmons Roberts, J., Peters, G. P. & Baiocchi, G. Pathways of human development and carbon emissions embodied in trade. *Nat. Clim. Chang.* **2**, 81–85 (2012).
28. Wu, X. D., Guo, J. L., Meng, J. & Chen, G. Q. Energy use by globalized economy: total-consumption-based perspective via multi-region input–output accounting. *Sci. Total Environ.* **662**, 65–76 (2019).
29. Wiedmann, T. O. et al. The material footprint of nations. *Proc. Natl Acad. Sci. USA* **112**, 6271–6276 (2015).
30. Moran, D. Carbon footprints of 13,000 cities. *Environ. Res. Lett.* **13**, 064041 (2018).
31. Peters, G. P., Andrew, R. & Lennox, J. Constructing and environmentally-extended multi-regional input–output table using the GTAP database. *Econ. Syst. Res.* **23**, 131–152 (2011).
32. *Global Consumption Database* (World Bank, 2018); http://datatopics.worldbank.org/consumption/
33. *Consumption Expenditure of Private Households (hbs)* (Eursostat, accessed 1 September 2018); https://ec.europa.eu/eurostat/cache/metadata/en/hbs_esms.htm
34. Wiedenhofer, D., Lenzen, M. & Steinberger, J. K. Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications. *Energy Policy* **63**, 696–707 (2013).
35. Isreal-Akinbo, S. O., Snowball, J. & Gavin, F. An investigation of multidimensional energy poverty among South African low-income households. *S. Afr. J. Econ.* **86**, 468–487 (2018).
36. Narasimha, D. R. & Shonali, P. Energy access and living standards: some observations on recent trends. *Environ. Res. Lett.* **12**, (2017).
37. Brand-Correa, L. I. & Steinberger, J. K. A framework for decoupling human need satisfaction from energy use. *Ecol. Econ.* **141**, 43–52 (2017).
38. Steinberger, J. K. & Roberts, J. T. From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975-2005. *Ecol. Econ.* **70**, 425–433 (2010).
39. Service, U. D. *IEA Energy Balances* (accessed 1 October 2018); https://stats2.digitalresources.jisc.ac.uk/index.aspx?r=129421&DataSetCode=IEA_CO2_AB
40. Davis, S. J. et al. Net-zero emissions energy systems. *Science* **9793**, eaas9793 (2018).
41. Devlin, S. & Bernick, S. *Managing Aviation Passenger Demand with a Frequent Flyer Levy* (New Economics Foundation, 2015).
42. Shepherd, A. *Zero Carbon Britain: Making it Happen*. (Centre for Alternative Technology, 2017).
43. Alvaredo, F., Chancel, L., Piketty, T., Saez, E. & Zucman, G. The elephant curve of global inequality and growth. *AEA Pap. Proc.* **108**, 103–108 (2018).
44. *Classifications of Expenditure According to Purpose* (United Nations, 1999).
45. Milanovic, B. Global income inequality in numbers: in History and Now. *Glob. Policy* **4**, 198–208 (2013).
46. Liberati, P. The world distribution of income and its inequality, 1970–2009. *Rev. Income Wealth* **64**, 248–273 (2015).
47. Lawrence, S., Liu, Q. & Yakovenko, V. M. Global inequality in energy consumption from 1980 to 2010. *Entropy* **15**, 5565–5579 (2013).
48. Duro, J. A. On the automatic application of inequality indexes in the analysis of the international distribution of environmental indicators. *Ecol. Econ.* **76**, 1–7 (2012).

49. Miller, R. E. & Blair, P. D. *Input–Output Analysis: Foundations and Extensions* 2nd edn (Cambridge University Press, 2009); https://doi.org/10.1017/CBO9780511626982
50. Dorfman, R. A formula for the Gini coefficient. *Rev. Econ. Stat.* **61**, 146–149 (1979).
51. Deltas, G. The small-sample bias of the Gini coefficient: results and implications for empirical research. *Rev. Econ. Stat.* **85**, 226–234 (2003).
52. *GDP Long-Term Forecast* (OECD, accessed 8 October 2019); https://data.oecd.org/gdp/gdp-long-term-forecast.htm
53. *World Population Prospects 2019* (United Nations, accessed 8 October 2019); https://population.un.org/wpp/
54. *GDP (Constant 2010 US$)* (World Bank, 2019); https://data.worldbank.org/indicator/NY.GDP.MKTP.KD
55. Girod, B. & de Haan, P. More or better? A model for changes in household greenhouse gas emissions due to higher income. *J. Ind. Ecol.* **14**, 31–49 (2010).
56. Min, J. & Rao, N. D. Estimating uncertainty in household energy footprints. *J. Ind. Ecol.* **22**, 1307–1317 (2018).

Acknowledgements

Y.O. is supported by the Leverhulme Trust's Research Leadership Award 'Living Well Within Limits' (RL2016–048) project awarded to J.K.S. J.K.S was partly supported by an International Academic Fellowship of the Leverhulme Trust (IAF-2018–018). The contributions of A.O. were supported by EPSRC Fellowship award EP/R005052/1. We also would like to thank M. Baltruszewicz, J. Vogel, J. Millward-Hopkins, P. Brockway and L. 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.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41560-020-0579-8.

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