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Oswald, Y, Owen, A orcid.org/0000-0002-3872-9900 and Steinberger, JK orcid.org/0000-0002-5925-9602 (2020) Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nature Energy*, 5. pp. 231-239. ISSN 2058-7546

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

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

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6
7 **Inequality in energy consumption, both direct and indirect, affects the distribution of benefits**
8 **resulting from energy use. Detailed measures of this inequality are required to ensure an equitable**
9 **and just energy transition. Here, we calculate final energy footprints: the energy embodied in goods**
10 **and services across income classes in 86 countries, both highly industrialised and developing. We**
11 **analyse the energy intensity of goods and services used by different income groups, as well as their**
12 **income elasticity of demand. We find that inequality in the distribution of energy footprints varies**
13 **across different goods and services. Energy intensive goods tend to be more elastic, leading to**
14 **higher energy footprints of high-income individuals. Our results consequently expose large**
15 **inequality in international energy footprints: the consumption share of the bottom half of the**
16 **population is less than 20% of final energy footprints, which in turn is less than what the top 5%**
17 **consume.**

18 Income and wealth inequality have been increasing within most major economies since the 1980s.
19 The top 1% of global income earners benefit the most from economic growth, having increased their
20 income share substantially, from 15% to more than 20%¹. Oxfam adds that in 2017, “82% of all wealth
21 created went to the top 1%”². Inequality is now recognized as a decisive force of our time and has been
22 linked to issues ranging from the environmental performance of nations to domestic terrorism^{3,4}.
23 Climate change is likewise high on the global agenda and so is energy’s role in decarbonizing the
24 economy^{5,6}. Numerous studies have shown that economic inequality translates to inequality in energy
25 consumption as well as in emissions⁷⁻⁹. This is largely because people with different purchasing power
26 make use of different goods and services¹⁰ and different goods and services are sustained by different
27 energy quantities and carriers.

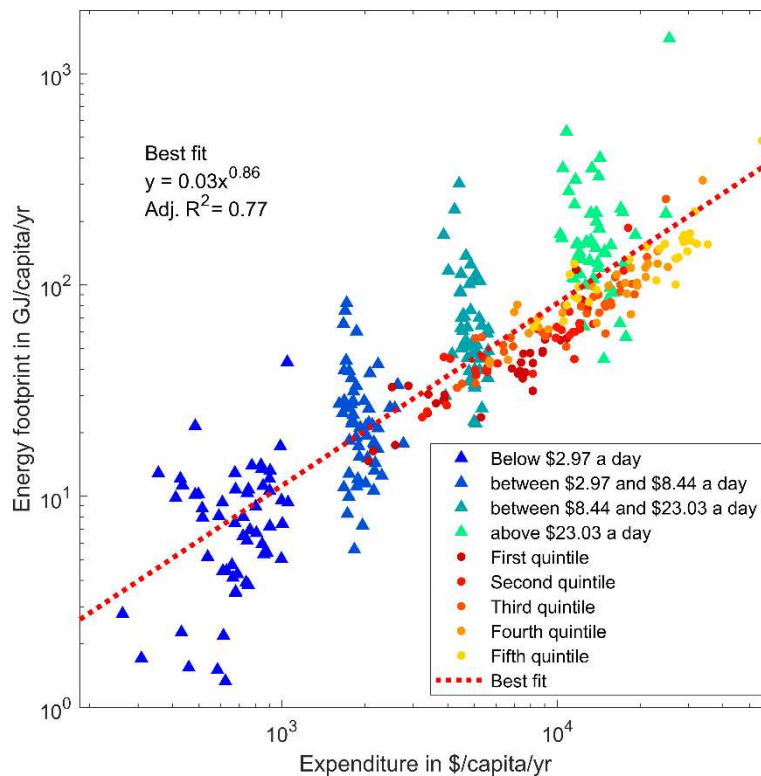
28 Most studies considering energy footprints and inequality focus on single countries. International and
29 consumption-granular comparisons remain restricted to carbon inequality instead of energy^{3,9}.
30 Moreover, in energy transition research, the production and supply side have been the dominant
31 focus. The demand side has received much less attention – and when it is considered, it is usually from
32 a technological perspective^{11,12}. Recent scenario work demonstrates that reorganizing and reducing
33 energy demand can ease the shift to a low-carbon energy system¹³ but it is largely projected to happen
34 through techno-economic means. A starting point for change can be to understand how people’s
35 everyday practices constitute the foundations for the energy system. What do people need energy
36 for? And how much? Shove and Walker (2014) argue that different social practices entail different
37 patterns of energy consumption¹⁴. Whatever a person does in her or his life affects the *energy*
38 *footprint* left behind. Going to work by internal-combustion-engine car instead of electric bicycle
39 reinforces distinct supply chains building their products upon distinct amounts of energy and upon
40 distinct fuels, oil in the first case, electricity in the latter. Consequently, energy system design is not
41 just an engineering issue but a social one too.

42 Energy is not purchased or used for its own sake, but for the end-use services it delivers¹⁵. Some end-
43 use services are essential to people’s life while others are “luxuries” that people enjoy¹⁶. For example,
44 cooking, heating, and access to health or education infrastructure are fundamental to individual well-
45 being and even to survival. In contrast, travel holidays and plasma TVs may be desirable, but are not
46 essential. Not all people on earth benefit from essential energy services. Roughly one billion people
47 still do not have access to electricity¹⁷. Some studies highlight that if we increase living standards of
48 the poor we jeopardize achieving climate goals^{18–20}. Various authors, however, have raised the
49 question of whether providing the poor with a “decent living standard” requires curbing “luxury”
50 elsewhere^{16,21}. Some have suggested limiting per capita energy consumption and emissions of high-
51 consumers to create space to provide essential energy services to those left behind^{22–24}. Indeed,
52 international climate goals are threatened by the emissions of high-income countries and individuals.
53 Chakravarty et al. (2009), for instance, have shown that the potential for climate change mitigation
54 through the reduction in emissions of one billion high emitters is far greater than the threat of granting
55 the poorest 2.7 billion a basic level of emissions that comes with decent living standards²⁴. Thinking in
56 terms of emissions is crucial to climate change mitigation but it is secondary in thinking about living
57 standards. Energy enables living standards, not emissions²⁵. This is why we have to consider the
58 distribution of energy in the first place. In this context, it is important to consider both the global
59 distribution and the purpose-specific consumption of energy by income classes.

60 We built an energy and expenditure extended input-output model that distinguishes between income
61 groups of households. Input-output models draw on a long tradition of calculating the environmental
62 impacts related to the production, flows and consumption of goods including their emissions, water,
63 land, material and energy footprints^{26–30}. We employ a Global Trade Analysis Project (GTAP 9) based
64 Multi-Regional-Input Model (MRIO) for the year 2011³¹. This model is then extended via household
65 expenditure patterns from two different sources: the Global Consumption Database (GCD) of the
66 World Bank, which comprises developing and emerging economies including the BRICS states³² (Brazil,
67 Russia, India, China, South Africa), and Eurostat Household Budget Surveys, which includes all 28
68 economies of the European Union plus Norway and Turkey³³. We find that international and
69 intranational inequality both are large, to the extent that the bottom half consumes less than the top
70 5%.

71 **Energy footprints and expenditure**

72 Energy footprints per capita generally grow as a function of income or expenditure^{28,34}. We now test
73 this hypothesis across a significant sample of 86 countries and 4-5 income groups resulting into 374
74 population segments, shown in Figure 1. We fit a power law and find that energy footprints scale
75 sublinearly with expenditure. Expenditure at higher levels becomes mildly less energy intense,
76 corresponding to weak relative decoupling. However, this result does not differentiate between
77 different consumption categories. It is notable that the European income quintiles and their
78 corresponding energy footprints per capita exhibit low variation with the respective expenditure
79 amounts. On the other hand, the data for developing countries reveals four, clearly distinct, clusters
80 with considerable vertical variation, both above and below the EU range of energy intensities. This is
81 caused by the structure of the Global Consumption database and its four invariant income thresholds
82 ($< \$2.97$, $< \$8.44$, $< \$23.03$ and $> \$23.03$ per capita a day). They comprise technological, geographical
83 and consumption differences. For example, in Belarus there is much more heating gas used than in
84 Thailand, at a similar expenditure level, resulting in very different energy footprints.

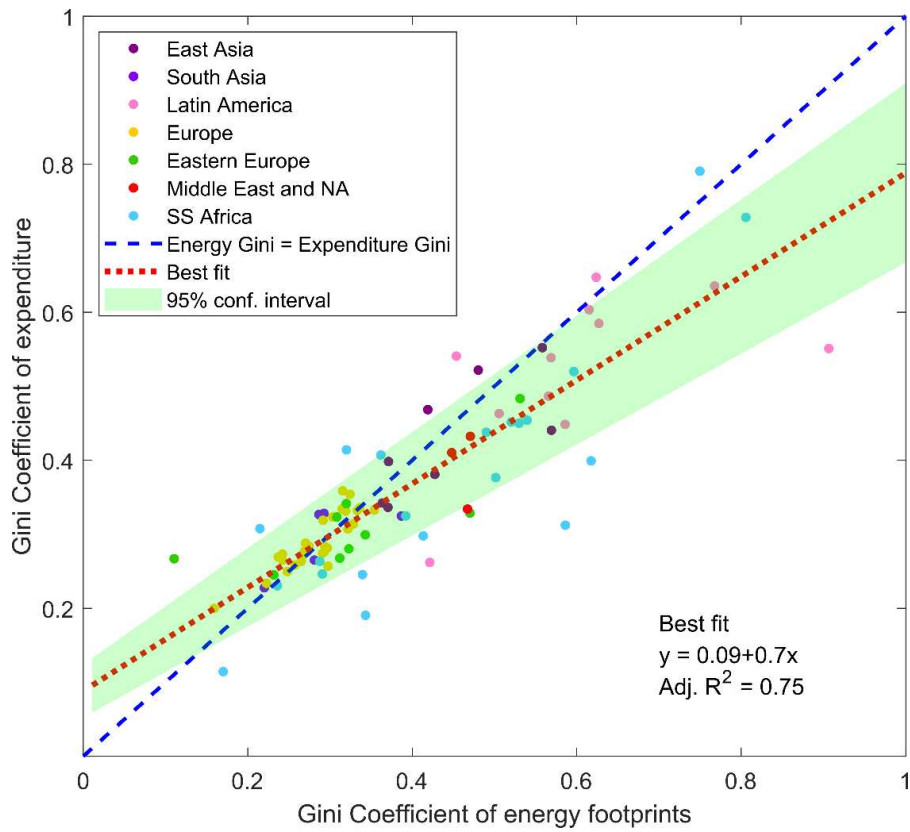


85
86 **Figure 1: Energy footprints vs. expenditure.** Energy footprints scale sublinearly with expenditure. Adj. R-squared 0.77, p-
87 value= 1.91e-119. Triangles represent GCD data and dots Eurostat data.

88 **Intranational inequality**

89 In terms of intranational inequality, the Gini coefficients of expenditure have a slightly narrower range
90 than the Gini coefficients of energy footprints, as shown in Figure 2, implying that energy footprints
91 differ more widely in their inequality than expenditure does. When expenditure is highly unequal
92 within a country, i.e. has a high Gini Coefficient, the corresponding inequality in energy footprints will
93 tend to be even larger. This is particularly the case for Sub-Saharan and Latin American economies
94 (e.g. Gini coefficients in Namibia are 0.7 for expenditure vs. 0.8 for energy, Paraguay: 0.64 for
95 expenditure vs. 0.77 for energy). At lower expenditure inequality, metrics are more likely to be similar.

96 This is the case for many of the European countries considered. This pattern is even more pronounced
 97 when comparing income inequality and energy inequality, see Supplementary Note 9. South Africa,
 98 for example, is consistently reported to be one of the most unequal societies in the world, with high
 99 unemployment and with substantial energy poverty³⁵. Failure in economic inclusion causes exclusion
 100 from energy provision. Most people cannot afford electricity and thus retreat to consuming dirty fuels
 101 or very little energy.



102

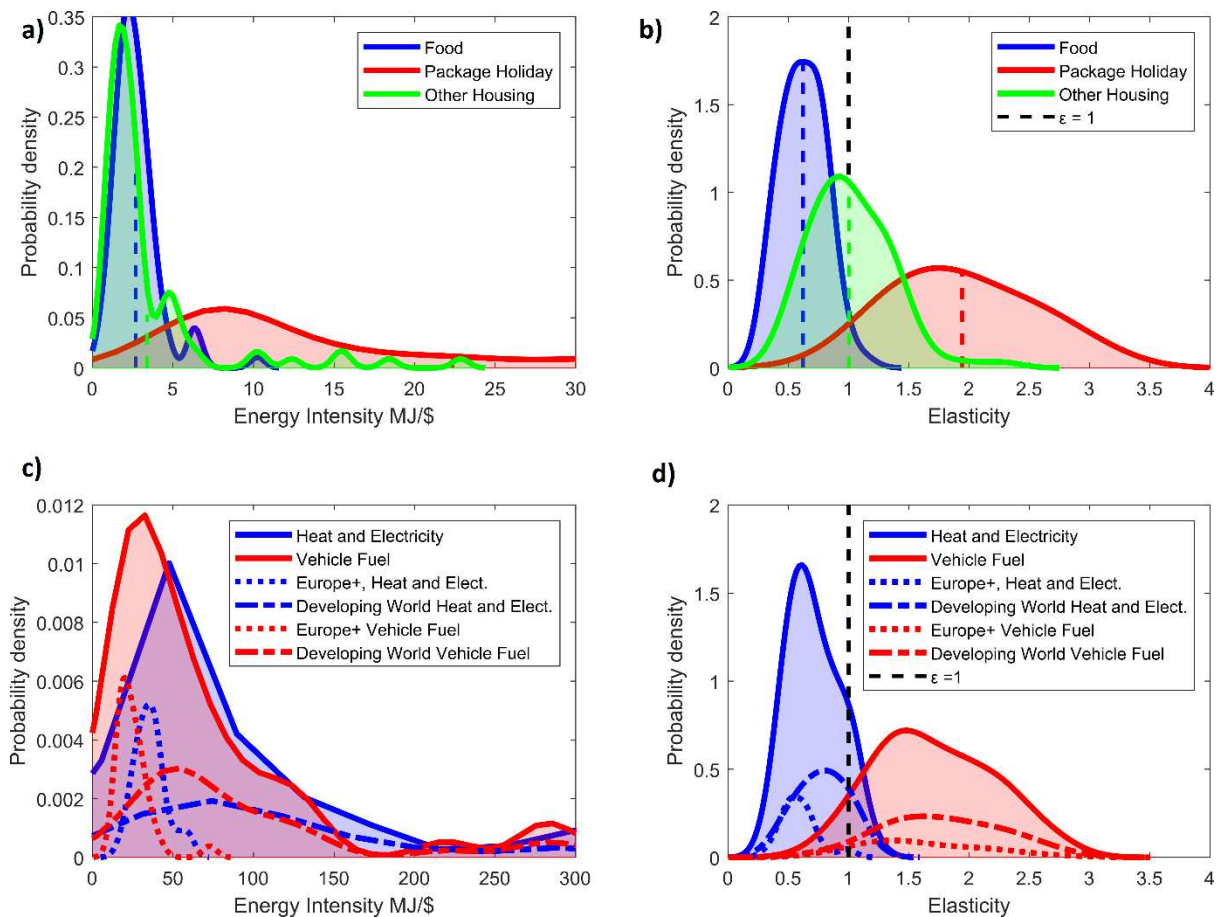
103 **Figure 2: Energy footprint inequality vs. expenditure inequality for 2011.** Energy footprint inequality scales in a superlinear
 104 way with expenditure inequality (Adj. R-squared 0.75). The energy footprint inequality is generally larger than expenditure
 105 inequality. Therefore, the best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

106 **The interaction of income elasticity of demand and energy intensity**

107 We measured the energy intensity and income elasticity of demand of different consumption
108 categories over all countries in the sample. We defined energy intensity as the energy footprint
109 intensity, which is the energy footprint of a consumption category divided by the money spent by the
110 end-consumer. Income elasticity of demand measures how much more % of a good is consumed if
111 income rises by 1%. If it increases by exactly 1%, then the elasticity is 1. If it is less, the elasticity is less
112 than 1 (basic good), and if it is more the elasticity is above 1 (luxury good)⁸.

113 We observe wide variations in energy intensities and elasticities across consumption categories.
114 Package Holidays, for instance, comprises all sorts of transport services, including flights, and thus
115 exhibits large energy intensities and large variation. Food products and “Dwelling Maintenance and
116 Water supply” (denoted here as “Other Housing”) feature lower energy intensities around the world.
117 This is depicted in Figure 3 (a) and (c) using probability density functions. The upper row, with (a) and
118 (b), depicts the indirect energy use categories Food, Package Holiday or Other Housing. The lower row
119 , with (c) and (d), shows the direct energy use categories Heat and Electricity as well as Vehicle Fuel
120 and Operation (for simplicity summarised as Vehicle Fuel). The averages of the distributions are shown
121 as dashed lines. The average energy intensities of Food and Other Housing are similar whereas that of
122 Package Holidays is clearly distinct (at 24MJ/\$). The corresponding elasticities of Package Holidays, in
123 Figure 3 (b) are high too, with an average elasticity ~2. The elasticity of “Food” is on average ~0.6 and
124 of “Other Housing” ~1.

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



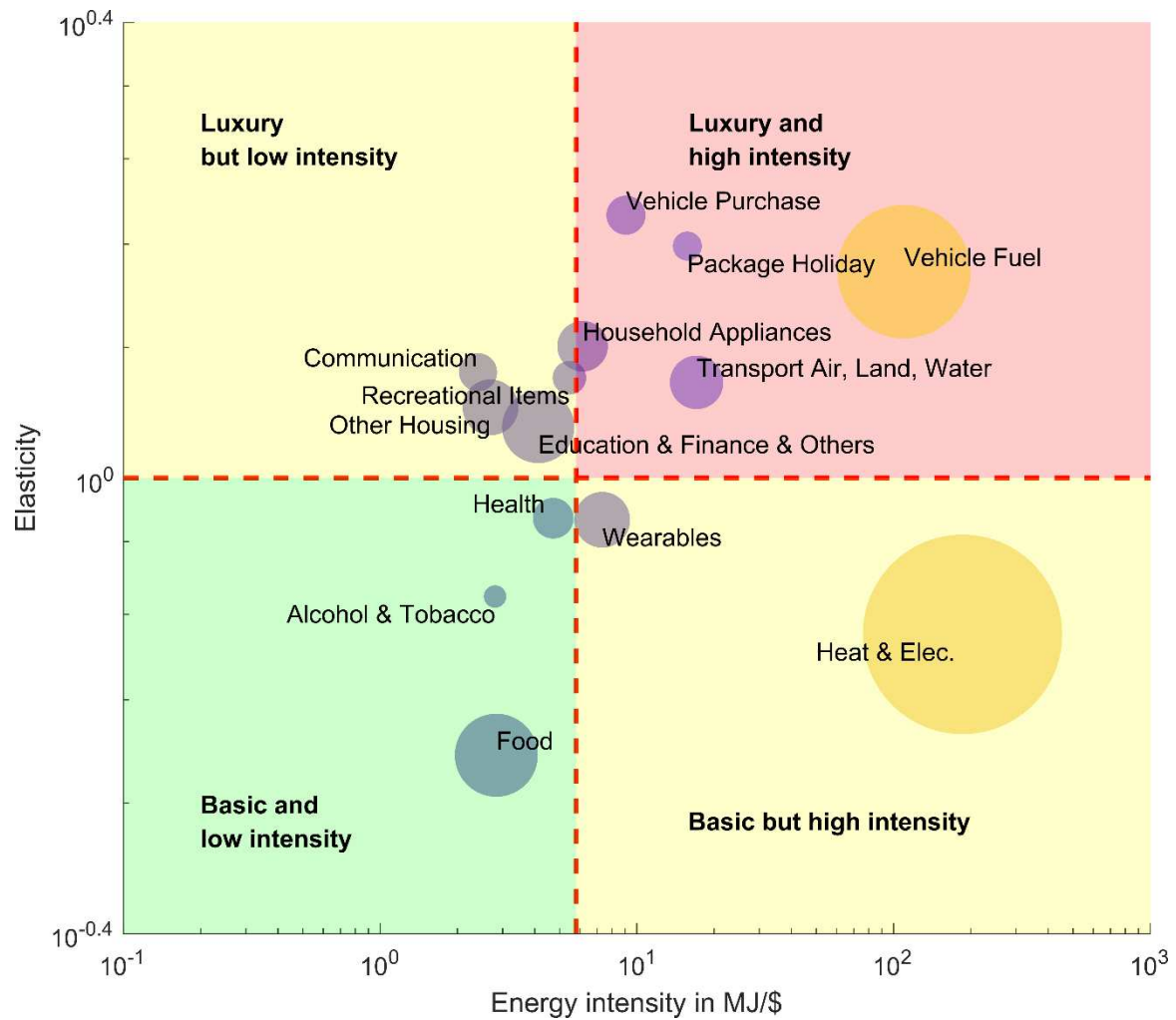
135

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

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

151 Figure 4 shows the result with a resolution of 14 consumption categories. The figure is segmented into
 152 four quadrants defined by an elasticity of 1 in the y-dimension and the median of the non-population
 153 weighted distribution in the x-dimension (red dashed lines). The size of the circles indicates the
 154 relative contribution of each category to the total energy footprint. We observe a moderate rank-
 155 correlation between the two variables if Heat and Electricity is excluded ($\rho = 0.52$, p -value=0.04). This
 156 means that for indirect/embodied energy footprints as well as for private vehicle fuel consumption,
 157 there is a significant tendency of energy intensive categories to be elastic. Note that all education and

158 health expenditure considered is private expenditure and not state-provided, explaining elasticities
 159 close to 1 and above.



160
 161 **Figure 4: Elasticity vs. Energy Intensity.** The energy intensity of MJ/€ for Eurostat-based data was converted via the 2011
 162 average exchange to MJ/\$. For indirect energy consumption (dark circles), the income elasticity of demand correlates with
 163 the given energy intensity (rank correlation: $\rho = 0.52$, p -value=0.04). The direct energy consumption (light circles) through
 164 Vehicle Fuel fits well into this relationship. The only category behaving fundamentally differently is Heating and Electricity,
 165 exhibiting a low elasticity but the highest energy intensity.

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

172 **International energy footprint inequality**

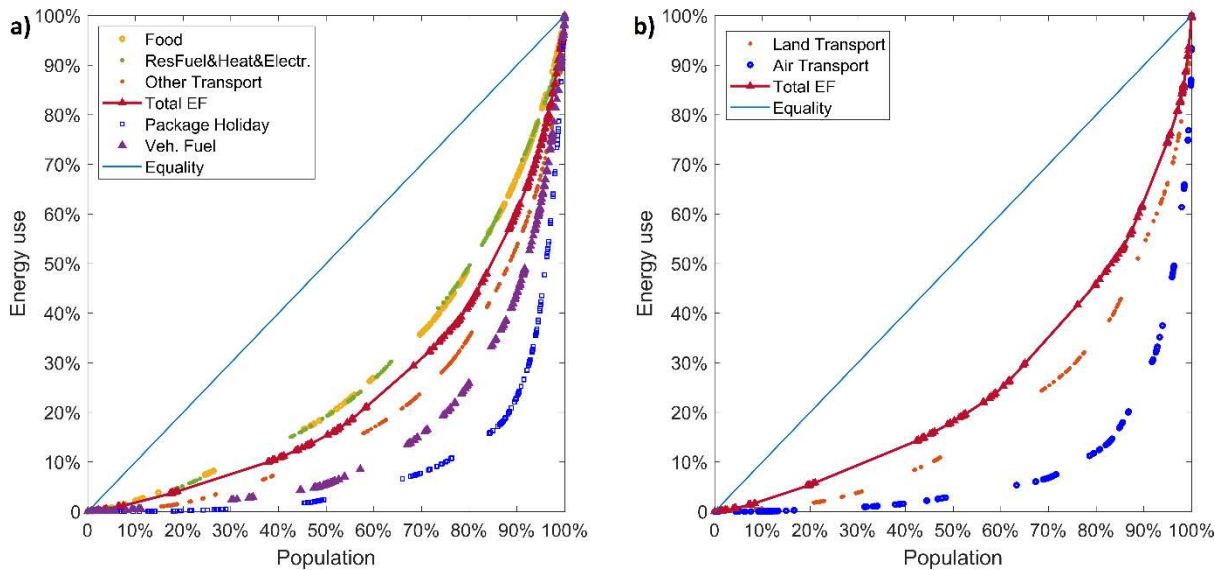
173 Considering all countries and income classes together, we obtain international distributions and
 174 inequality metrics. The ensuing total international energy footprint inequality is large, with a Gini
 175 coefficient of 0.52. The different consumption categories exhibit high variation, with Gini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

188 *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% |

189
 190 The distribution (Lorenz Curves) of different consumption categories are shown in Figure 5. Figure 5
 191 (a) depicts the Lorenz Curves for the entire sample while (b) emphasizes the difference between
 192 land- and air transport in developing and emerging economies (56 countries). In Land transport, the
 193 bottom 50% receive a bit more than 10% of the energy used and in Air transport they make use of
 194 less than 5%. On the other hand, the top 10% use ~45% of the energy for Land transport and around
 195 75% for Air transport. Air transport is a hugely unequal domain when considered across developing
 196 countries, and over all countries the results are similar. Air transport related activities, like Package
 197 Holiday have the “steepest” Lorenz Curves. Vehicle Fuel and Other transport are likewise very

198 unequal. Food and Residential energy use, in contrast, are a little less unequal than the total
 199 average.



200

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

208 **Implications of energy inequality**

209 Energy provision is considered a fundamental and integral development challenge^{36,37}. A minimum
 210 level of energy consumption is required to enable decent well-being. Our results demonstrate that
 211 energy consumption is far from equitable and varies to extreme degrees across countries and income
 212 groups. This suggests that the inequality in the distribution of final energy is impeding the Sustainable
 213 Development Goals, rather than enabling them. Many people suffer from energy deprivation, and
 214 quite a few are consuming far too much.

215 By combining intra country and inter country results, we obtain a higher granularity and wider range
 216 of energy footprints than comparable international studies that only operate at the national average
 217 level²⁸. At high incomes, final energy footprints per capita are frequently greater than 200 GJ/yr or
 218 occasionally even greater than 300GJ/yr (see Figure 1). This is one order of magnitude greater than
 219 what has been identified as necessary for a decent quality of life²². We also find that 77% of people
 220 consume less than 30GJ/yr/capita and 38% consume less than 10GJ/yr/capita – this lower end is
 221 almost certainly insufficient for a decent quality of life³⁸. Based on national averages we would
 222 measure, for example, that only 8% of the population consume less than 10GJ/yr/capita. This is a
 223 dramatic difference, enabled by considering intra-national inequality. Despite the improvement in
 224 resolution, our results are constrained by the income granularity present in the data. In Europe, the
 225 richest people we can observe are the top 20% of the population. What energy do the top 1%, 0.1%
 226 or 0.01% use? In the data for developing countries we occasionally attain a more fine-grained picture
 227 of the narrow top segments in a country because few people fall beyond the income threshold of >24\$
 228 a day. We find that the top 0.01% (~300 people) in Armenia for example have a final energy footprint

229 of ~1000GJ/capita/yr. If everyone would use that much, we would require ~7600EJ (Exajoule) of final
230 energy on this planet, ~27 times more than we currently use³⁹.

231 Transport has been identified as a problematic sector before, encountering difficulties transitioning
232 to low-carbon alternatives⁴⁰. We show that transport-related consumption categories are among the
233 most unequal ones. Moreover, we measure larger inequality in Air transport compared to public Land
234 transport in Figure 5 (b). Large parts of the population are almost or entirely excluded from aviation.
235 A similar trend can be observed surrounding the private vehicle. The top 10% consume ~55% of
236 mobility related energy, equivalent to 13.5% of total final energy demand, the vast majority of it fossil
237 fuel based. It is then questionable whether systems that serve only global minorities and are highly
238 dependent on fossil fuels are favourable in facilitating mobility. The mobility of a few locks the entire
239 energy and transport systems in to fossil-fuel dependency. It has previously been suggested that many
240 of the engineering challenges to “net-zero emissions energy systems” could be overcome or
241 moderated by rethinking demand⁴⁰. There are concrete policy proposals that address transport
242 demand such as a frequent flyer levy⁴¹ or reducing car dependency through urban planning as well as
243 committing to alternative vehicle technologies, including electric and hydrogen⁴².

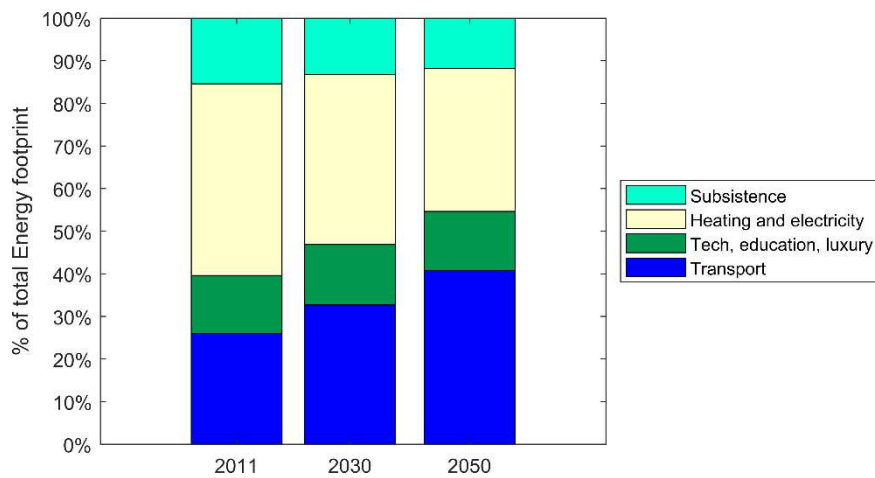
244 We find that that no consumption category is free from energy inequality and benefits equal
245 populations to an equal degree. We even observe energy inequality in health and education for
246 example. Clearly, we only observe the footprints of private expenditure and not of public provision,
247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

251 **Future energy inequality**

252 Our analysis delivers key insights into the relationship of socio-economic- and technological systems.
253 We observe that high income elasticities of demand most often coincide with high consumption-based
254 energy intensities. Their international spectra superpose. This superposition inevitably leads to
255 unequal distribution of energy footprints. With economic growth as a core goal of political and
256 economic processes, it is likely that this pattern will proceed and even aggravate in the future.
257 Particularly so, if economic growth is distributed mostly to high-income people as is suggested by
258 recent evidence⁴³. High-income individuals will then further expand their demand of high energy
259 intensity goods and their footprint will increase. The energy footprint of low-income individuals will
260 remain low. Ultimately, energy footprints will sheer further away from each other. From Figure 2, we
261 can anticipate that increasing income inequality will be translated into even larger inequality.

262 In order to test this reasoning, we projected expenditure and population levels into the future for the
263 two years 2030 and 2050. We did so by making use of long-term GDP projections by the OECD and
264 long-term population projections by the United Nations. According to this simple projection (which
265 does not take into account energy efficiency improvements, for instance), energy footprints would
266 more than double by 2030, and quadruple by 2050, with nearly half of the increase occurring in India
267 and China. Overall energy inequality remains quite stable, going from a Gini coefficient of 0.52 in 2011
268 to one of 0.49 in 2050. Considering consumption categories, 34% of the energy increase can be
269 attributed to “Vehicle Fuel” alone, another 30% to “Heat and Electricity”, and another 12% together
270 to “Other transport” and “Education & Finance & Other Luxury”. Other subsistence like “Food” and

271 “Wearables”, together contribute only 7% to the increase. By 2050, we see increased inequality in the
 272 categories with high income elasticity of demand >1. For instance, “Other transport” inequality is
 273 initially almost stable, going from a Gini coefficient of 0.60 to 0.57, but then increases to 0.66.
 274 “Package Holiday” remains at a high inequality and increases slightly to a Gini coefficient of 0.83 in
 275 2050. Figure 6 displays major trends in household energy footprints by aggregated consumption
 276 categories. Transport related energy footprints are increasing their share of total while subsistence,
 277 including Food and Housing, and Heating and Electricity decrease their share. The increase in transport
 278 energy is a disastrous development for a favourable climate, if transport continues to rely on fossil
 279 fuels. One crucial limitation of our projection is that we assume economic growth is uniformly
 280 distributed across income groups within countries, when we know that it tends to accrue to the
 281 wealthiest⁴³. Despite this limitation, we find that energy inequality is not likely to reduce significantly,
 282 and even increases by 2050 in several crucial consumption categories.



283

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

289 However, persisting inequality can be prevented through appropriate intervention. We can classify
 290 four types of consumption categories as illustrated through the four quadrants in Figure 4. Based on
 291 their distinct nature, the four types require type-specific policy and action. In our view, this could
 292 include:

293 **Quadrant 1 High intensity, high elasticity:** Dominated by transport and hard to decarbonise.
 294 Move towards significant taxation, curtailment and replacement with collective and low
 295 carbon alternatives including electrified trains, buses, bicycles and small bespoke vehicles at
 296 the individual level (depending on disability, age and professional requirements).

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

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

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

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

309 **Methods**

310 **Model overview**

311 We compute household energy footprints but not the footprints of government expenditure and
312 business-related capital formation. Household energy footprints cover 70% of all energy footprints. A
313 full description of the data and its constituents is provided in the Supplementary Table 2. The two
314 expenditure databases are constructed with respect to the Classification of Individual Consumption
315 according to Purpose (COICOP Version 1999)⁴⁴. Therefore, the two databases can be aligned with the
316 GTAP sectors. The GCD distinguishes between four different household income groups defined by the
317 World Bank. The Eurostat Household Budget surveys distinguish between quintiles. In terms of energy
318 data, we use final energy consumption provided by the International Energy Agency (IEA) for 2011 and
319 aligned with GTAP sectors. Final energy is closer to the energy that people actually make use of
320 compared to primary energy. It approximates the amount of energy that “operates on site” to provide
321 a certain service. It also better represents the energy capacity required to replace fossil fuels by low-
322 carbon alternatives. Low-carbon alternatives, for instance solar or wind, often do not exhibit big
323 differences between primary production and final use. Our database consists of the 86 countries
324 within the intersection of the IEA, GTAP and expenditure data, representing 78% of global population,
325 56% of global GDP and 64% of all final energy in 2011.

326 Based on the MRIO we then calculate energy footprints per consumption category, per nation, per
327 income group and per capita. We also compute income elasticities of demand and consumption-
328 based energy intensities per consumption category. For representing inequality, we show the
329 distributional Lorenz curves and the corresponding Gini coefficient. Both are comparable across a
330 wide range of studies^{45–47} and are relatively robust against outliers⁴⁸.

331 **Data and data treatment**

332 The energy extended multi-regional input output model (MRIO) is based on the Global Trade Analysis
333 Project (GTAP) 2011 and the IEA –Energy Balances of 2011. GTAP has been chosen because of its wide
334 scope (140 regions) and its availability for the year 2011, which match both with the scope of the IEA
335 data and the expenditure data. For differentiating between consumer groups according to income, we
336 make use of the Global Consumption Database (GCD) by the World Bank and the Eurostat data tables
337 on household expenditure patterns. The Eurostat expenditure data is given per quintile. The GCD is
338 given per four invariant income segments: “*Lowest—below \$2.97 per capita a day, Low—between*
339 *\$2.97 and \$8.44 per capita a day, Middle—between \$8.44 and \$23.03 per capita a day, Higher—above*
340 *\$23.03 per capita a day”*. The Eurostat expenditure data per consumption category comes in parts per
341 mille (ppm). This is equivalent to the percentage, of total expenditure, a household spends a year on
342 a given category. Therefore, the mean total expenditure of households has to be distributed across
343 the different categories according to these percentages. Subsequently, both expenditure databases
344 have to be scaled to national level. In the Eurostat case, the expenditure is given per household, so
345 we used the number of households as in the 2011 census to attain national expenditure volumes. The

346 Global Consumption Database data is given per capita as well as total population is provided. The
 347 supplementary Figure 1 demonstrates that the scaled-up national expenditure volumes fit to the
 348 national expenditure volumes of households in the GTAP (correlations with Adj. $R^2 = 0.99$ for Eurostat
 349 and Adj. $R^2 = 0.91$ for GCD). Even though we start from household units in the case of Eurostat and
 350 the GTAP, we generate per capita volumes in both cases, dividing the national level volumes by
 351 population.

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

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

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

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

377 Additional data for the income Gini coefficient has been acquired from the World Bank⁴⁹. Currency
 378 transformations from Euro to Dollar have been conducted via the yearly average exchange rate of
 379 2011, 1.39\$=1€.

380 **Input Output modelling of energy footprints**

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

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

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

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

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

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

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

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

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

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

398 **Transformations between databases and RAS balancing**

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

410 Mapping from Eurostat and GCD expenditure data to the GTAP is also based on the ISIC Rev. 3.1 as
411 reference. However, the national household expenditure volumes in total and per consumption
412 category are not 100% equal to the ones within GTAP. Moreover, when mapping one COICOP
413 consumption category to two or more GTAP sectors, it is unclear how much of the COICOP version
414 belongs where. For overcoming this "blackbox" an iterative proportional balancing technique has
415 been applied, mathematically equivalent to RAS balancing⁵⁰. As a first step the COICOP version is
416 scaled so that its volume exhibits the exact size of national GTAP household expenditures. This also
417 overcomes currency differences as for example between Euro PPS and Dollar PPP. Afterwards, let C^1

418 be the initial distributed concordance matrix between the COICOP system and the GTAP system. In C^1
 419 the column sum represents the expenditures per category in COICOP and the row sum the
 420 expenditures per sector in GTAP format. C^1 will be subject to significant error with respect to at least
 421 one of the sides. The goal is to minimize this error by iteration with respect to both sides. The next
 422 version of C , that is C^2 , is determined by calculating the row sum of C^1 , and then setting it into relation
 423 to the actual GTAP expenditures. The resulting ratio is denoted r^1 . Then C^1 will be multiplied by this
 424 ratio across its rows. From the resulting matrix one proceeds in a similar way with the column sum
 425 and compares it against the scaled COICOP expenditures. This ratio is denoted s^1 . Similarly C^1 will be
 426 adjusted by multiplying across columns. One iteration is formalized by

$$C^{i+1} = \hat{r}^i C^i \hat{s}^i \quad (7)$$

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

430 **Income elasticities of demand**

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

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

434 where i is the country index and j is the consumption category index. The coefficient b is directly
 435 interpretable as an elasticity (see supplementary material section 8). *Total expenditure of households*
 436 (X) functions as an approximation to income per household, which itself is not available. Only the
 437 thresholds separating the income segments are known. We validate the statistical significance of the
 438 elasticities by the students T-test which is given by b over its standard error⁸. If an elasticity is not
 439 significant it is not considered for the analysis in the section “The interaction of income elasticity of
 440 demand and energy intensity”.

441 **Inequality metrics**

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

444 The Lorenz curve can be described by

$$y_n = L(x_n) \quad (9)$$

445 where

$$x_n = \sum_1^n P_n / P_{global} \quad (10)$$

446

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

$$y_n = \sum_1^n E_n/E_{global} \quad (11)$$

448 where y_n is the energy consumption of country n. The energy Gini coefficient then is^{8,51}

$$G = 1 - 2 \int L(x)dx \quad (12)$$

449 We want to compute Gini coefficients of individual countries. Then our sample size is reduced to 4 or
450 5 data points on the Lorenz curve because we only have information on quintiles or four income
451 segments. However, we can apply a well-defined small sample bias correction⁵²

$$G_{corrected} = G * \frac{n}{n - 1} \quad (13)$$

452 where n is the sample size.

453 **Business as usual scenario**

454 The income growth rates are based on the long-term GDP forecast by the OECD which maintains
455 granular projections for each OECD member plus several other important economies including the
456 BRIC nations⁵³. For countries where no long-term forecasts are available, we applied the projected
457 world average. We applied income growth rates to our proxy for income: total expenditure. Based on
458 the projected total expenditure, we distributed consumption shares by our empirically determined
459 income elasticities. We projected population based on the United Nations long-term population
460 prospects where data is available for all countries in our sample⁵⁴. There are two important features
461 for a distributional scenario that we did consider but did not implement yet: first, varied growth rates
462 across income groups and, second, evolving technology. We kept energy intensities the same, a choice
463 that greatly simplifies the modelling exercise but contributes to converging energy footprints across
464 income segments because developing countries tend to have high energy intensities in direct energy
465 use and consequently higher projected energy demand. Both of these simplifications should be
466 revised in more sophisticated scenario work.

467 We also did test a variation of this scenario applying the average historical final energy intensity
468 decline but it does not affect the distributional results at all. Since global GDP grew on average by
469 3.1%/year from 1971 – 2015 (based on World Bank data)⁵⁵ and final energy on average by 1.8%/year
470 during the same period (based on IEA data), the average energy intensity (in final energy) declined by
471 ~-1.3%/year. We applied this rate uniformly to the here measured energy intensities. In this version,
472 by 2030 household energy footprints rise to ~240EJ, i.e. they increase by ~70%, and by 2050 to ~350EJ,
473 i.e. they more than double but do not quadruple. This may be a more realistic forecast of household
474 energy demand under business as usual. Inequality and share by consumption category, however,
475 remain completely unaffected by this modification since it does not account for region-specific or
476 sector-specific technology improvement. Our scenario should be understood as a simple
477 computational experiment extrapolating the observed expenditure and energy footprints of
478 households with the purpose of understanding energy inequality trends, not as an accurate prediction
479 of energy demand.

480 **Limitations**

481 We assume that the amount of expenditure represents physical quantity consumed and thus directly
482 translates to energy quantity consumed. For example, we are blind to whether somebody bought ten

483 Ford cars or one Ferrari. Analysis has shown that footprints can be overestimated for high-income
484 earners who spend on quality products that are priced high but do not use up more resources⁵⁶.
485 However, the authors note that differences between monetary based and physical unit based models
486 is limited, particularly for energy intensive and direct energy use categories such as fuel use and
487 aviation. Crucially, there is little physical consumption data available and the monetary data used here
488 is all in Purchasing Power Parities designed to capture and compare physical consumption baskets.
489 Nevertheless, in the future efforts should be undertaken to build up actual physical data. There are
490 further uncertainties arising from a variety of sources. For example, the underlying input-output
491 model is harmonized with respect to currencies and the individual national supply and use tables
492 which reduces detail and accuracy. The consumption expenditure surveys come with several caveats
493 including, survey design, non-response bias, sampling bias and so forth. The Global Consumption
494 Database is a compilation of diverse household budget surveys that have been harmonized and
495 extrapolated. On top of that, the transformations aligning the different databases cannot fully
496 overcome differences in sector and product classifications. Discussing all uncertainties in detail
497 however is not within the scope of this work. Here we highlighted some of the crucial ones when
498 interpreting our results and evaluating our approach. A comprehensive list of uncertainties in
499 household energy-footprint modelling can be found in Min and Rao (2017)⁵⁷.

500 **Data availability**

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

509 **Code availability**

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

512

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626

627 Acknowledgements

628 Y.O. is supported by the Leverhulme Trust's Research Leadership Award "Living Well Within Limits"
629 project awarded to J.K.S. J.K.S was partly supported by an International Academic Fellowship of the
630 Leverhulme Trust. The contributions of A.O. were supported by EPSRC Fellowship award

631 EP/R005052/1. We also would like to thank Marta Baltruszewicz, Jefim Vogel, Joel Millward-Hopkins,
632 Paul Brockway and Lukas Hardt for helpful discussions.

633 **Author Contributions**

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

636 **Competing interests**

637 The authors declare no competing interests.

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