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Emissions savings from equitable energy demand reduction

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Energy demand reduction (EDR) will be required to reach climate targets in the Global North. To be compatible with just transitions principles, EDR needs to be equitable. Equitable EDR may involve targeting high energy users while ensuring the satisfaction of needs for all, which could require increasing consumption of low users. Emissions impacts of equitable EDR approaches have not yet been assessed. This Article finds that capping energy use of the top quintile of consumers across 27 European countries can achieve considerable greenhouse gas emissions reductions of 11.4% from domestic energy, 16.8% from transport and 9.7% from total energy consumption. Increasing consumption of low energy users in poverty reduces these savings by only 1.2, 0.9 and 1.4 percentage points, respectively. Additional high annual emissions cuts of 7.3–24.0% would be required for Europe to meet globally equitable 2050 emissions budgets. Equitable EDR could make an important contribution to increasing public acceptance of such transformative action.

There is now wide recognition that energy demand reduction (EDR) in the Global North will be required to meet climate targets as supply-side measures that decarbonize energy use cannot be solely relied upon[1–4]. For instance, the latest report by the Intergovernmental Panel on Climate Change[4] estimates that demand-side strategies could contribute 40–70% of emissions reductions globally by 2050. Concurrently, the climate policy literature increasingly takes principles from energy and climate justice research into account[5–7], highlighting that EDR needs to be equitable. This Article aligns with well-established equity principles in the energy and climate justice literature that maintain that those who have contributed most to climate change and who have greatest capacity to act should carry the greatest responsibility for reducing energy demand and emissions (polluter pays/historical responsibility and capacity principles)[5,8–13]. At the same time, the energy and climate justice literatures maintain that every human should have the right to fulfil their basic needs and that those unable to meet their needs should be supported to do so[12,14–16].

Several concepts are relevant for conceptualizing equitable EDR, including 'consumption corridors'[17,18], the 'safe and just space of humanity'[19] and the 'good life within planetary boundaries'[20,21]. These approaches advocate reducing global energy use and associated emissions and material use to a level compatible with planetary boundaries[22,23] while ensuring that everyone's human needs[24,25] are met. The consumption corridor approach proposes to define minimum and maximum thresholds between which consumption of goods and services and related energy use and emissions can vary to achieve needs satisfaction for all within ecological limits without harming other people's ability to fulfil their needs now and in the future[17,18]. The literature stresses that consumption thresholds must be developed through democratic and participatory decisionmaking[18,26,27].

Equitable EDR would therefore target high energy users to bring energy use and associated emissions within planetary limits and ensure that everyone's basic energy needs are met. In large parts of the world, basic energy needs remain unfulfilled[28]. Because needs satisfaction is relative, shaped by social context, high levels of fuel and transport poverty, and hence unmet needs, continue to exist in countries of the Global North[14,29,30]. In the long term, provisioning systems[31] will have to be transformed to facilitate needs satisfaction at lower levels of energy

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use, but in the short term, facilitating needs satisfaction may require an increase in energy use by those whose needs are not currently met.

Previous research has estimated energy requirements that are compatible with climate targets while meeting people's basic needs or achieving certain wellbeing outcomes[3,32–35]. One previous study concluded that while eradicating energy poverty globally would increase global energy use by 7%, this could be counterbalanced by reducing energy use of individuals who consume more than the European average by 15% (ref. 36). However, the emissions reduction potential of equitable EDR, that is, cutting high-end energy consumption while ensuring sufficient energy resources to ensure basic needs satisfaction, has not previously been assessed.

This Article addresses this gap by first estimating emissions and energy impacts from downscaling high-level energy consumption across 27 European countries with and without increasing energy use of low-end consumers with poverty-level incomes. Second, we assess the contribution that such an equitable EDR strategy can make to Europe staying within its globally equitable share of the 1.5 °C compatible global carbon budget of 500 Gt CO$_2$ equivalent (GtCO$_2$e; 2020–2050)[4]. Third, we discuss justice implications and public acceptance of policies for equitable EDR. Our results show that capping energy use of the top quintile of consumers across 27 European countries can achieve considerable GHG emissions reductions of 11.4% from domestic energy, 16.8% from transport and 9.7% from total energy consumption. Increasing consumption of low energy users in poverty only marginally reduces these savings by 1.2, 0.9 and 1.4 percentage points, respectively. Additional high annual emissions cuts of 7.3–24.0% would be required for Europe to meet globally equitable 2050 emissions budgets. We argue that equitable EDR could make an important contribution to increasing public acceptance of such transformative action.

Emissions savings from equitable EDR

To illustrate emission reduction potentials of equitable EDR strategies in Europe, we assess through microsimulation greenhouse gas emissions reductions achievable by reducing high-level energy use in 27 European countries. Specifically, we model a reduction of energy use of the top decile, quintile and above-mean energy consumers to the level of energy consumption that is equivalent to the 90th / 80th percentile of the household distribution or the mean of energy consumption for different consumption domains (corresponding levels of energy use in Supplementary Table 2). The 27 countries consist of the pre-Brexit European Union except Austria, which was not included in the dataset. This study focuses on Europe to understand the scale of reduction required from countries with high current and historical contribution to climate change[13].

In addition, we assess whether overall emissions reductions can still be achieved if energy use of the bottom 20% of consumers with poverty-level incomes is raised to the 20th percentile of energy consumption of the whole sample. Choosing this definition of 'low energy consumption' is motivated by the assumption that low energy users in poverty are more likely to have unmet needs due to involuntarily low consumption compared to low energy users who are not in poverty. On the basis of our dataset, the following percentages of households in the bottom 20% of energy users are in poverty: 33% for home energy, 36% for transport and 49% for total energy.

The chosen thresholds of high and low energy use have only illustrative purpose for assessing emissions savings from a more equitable EDR approach. The thresholds of the top 10% / 20% and bottom 20% of energy consumers have been chosen because they represent typical thresholds in inequality research[37,38]. We acknowledge that in practice, thresholds would need to be chosen through democratic processes. Thresholds are defined separately for each country. Reductions are assessed for total emissions and energy use and for four separate consumption domains, which add up to the total of domestic energy, travel, food and all other consumption. Our analysis therefore covers all direct and indirect household energy use and emissions.

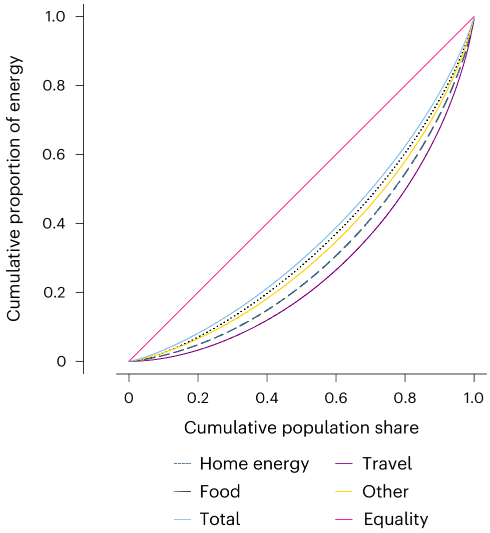


Fig. 1 | Inequality of energy use in 27 European countries. Lorenz curves for energy use related to home energy, travel, food, all other and total consumption. Lorenz curves depict cumulative shares of energy use compared to the cumulative share of population. Data: EU HBS 2015, 2010; Exiobase 3.7. The calculations include positive observations (across all consumption domains combined) and exclude the top 1% of outliers to address the infrequency of purchase problem. Sample size: 197,739 households.

To conduct this analysis, energy use and emissions are estimated for a representative sample of households in 27 European countries based on European Household Budget Survey (HBS) data. For 23 countries, 2015 data are used; 2010 data are used for Malta, Portugal, Slovenia and the United Kingdom, which were not included in the 2015 dataset at the time of data acquisition. The dataset has a total sample size of 275,614 households. Household energy use and emissions are estimated by combining HBS expenditure data with energy and emissions conversion factors derived from the multi-regional input–output database Exiobase so that all indirect energy use and emissions can be accounted for[39].

Energy use is very unequally distributed in the 27 European countries (Fig. 1 and Supplementary Table 1). The distribution is most unequal in the travel domain, where consumption by the top 10% and 20% of consumers accounts for 29.9% and 47.5% of total consumption, respectively, while the bottom 50% of consumers are responsible for only 20.4% of all consumption. Gini coefficients of 0.29 for total energy, 0.41 for home energy, 0.32 for food-related energy, 0.47 for travel-related energy and 0.35 for energy for 'other' consumption confirm high levels of inequality, especially for travel. Supplementary Fig. 1 and Supplementary Table 3 show Lorenz curves and Gini coefficients per country.

Figure 2 shows considerable energy use and emissions reductions from downscaling energy use of the top 10% or 20% of consumers to the level of the 90th or 80th percentile, respectively. Reducing energy use of the top 10% of consumers to the 90th percentile level leads to a fall of ~2.50 EJ or 4.4% of total emissions, ~0.81 EJ or 6.0% of domestic energy emissions and ~1.14 EJ or 8.3% of travel-related emissions across all 27 countries. Reducing energy use of the top 20% of consumers to the 80th percentile level has greater impact, resulting in a reduction of ~5.4 EJ or 9.7% of total emissions, 1.6 EJ or 11.4% of home energy emissions and ~2.3 EJ or 16.8% of travel emissions. In relative terms, reductions are therefore particularly high in the travel sector because energy and emissions intensities per unit of expenditure and inequality

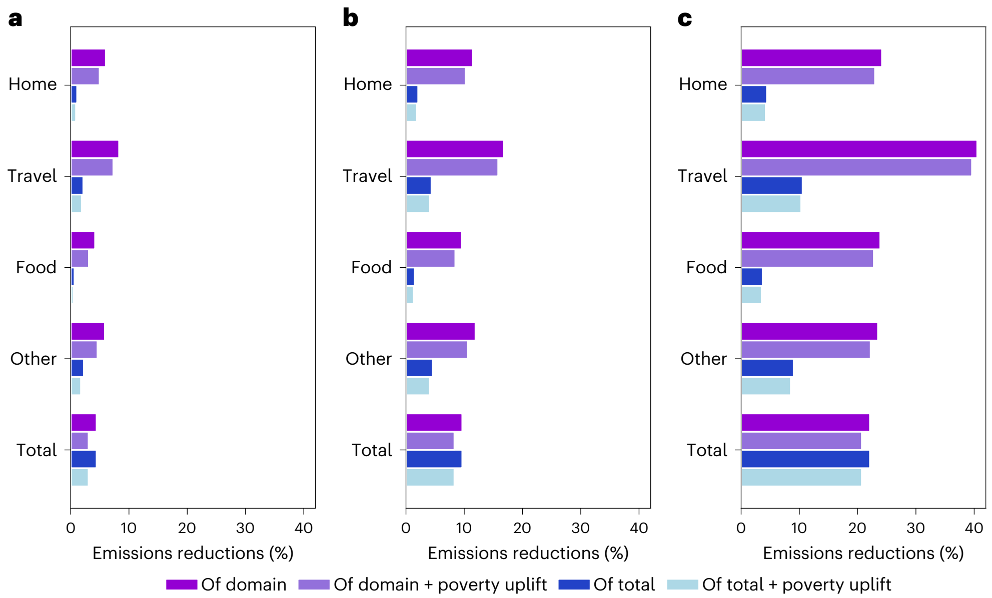


Fig. 2 | Emissions reduction of capping high-level energy use. Emissions reductions as a percentage of emissions in different domains (home energy, travel, food, all other consumption) and as a percentage of total emissions, with and without increasing energy use by low consumers in poverty to the 20th percentile ('poverty uplift'). **a**, Emissions reductions of limiting energy use by the top 10% of energy users to the 90th percentile. **b**, Emissions reductions of limiting energy use by the top 20% of energy users to the 80th percentile. **c**, Emissions reductions of limiting energy use by above-mean energy consumers to the mean. Data: EU HBS 2015, 2010; Exiobase 3.7. Calculations exclude the top and bottom 1% of emissions and income outliers and values at or below zero to address the infrequency of purchase problem. Sample sizes: home energy *n* = 259,921; travel *n* = 207,875, food *n* = 264,154, other consumption *n* = 266,222, total *n* = 266,252 households.

in consumption are highest in this domain. Supplementary Fig. 2 provides energy reductions in percentages.

A more radical downscaling of energy use above the mean to the mean (which applies to 42% of households in the sample) would result in a reduction of 12.1 EJ or 22.1% of total emissions, 3.5 EJ or 24.2% of home energy emissions and 5.6 EJ or 40.5% of travel emissions. Figure 2 also presents reductions for food and other consumption and reductions in all consumption sub-domains expressed as a percentage of total emissions.

Scaling up energy use of the bottom 20% of energy consumers who have poverty-level incomes to the level of the 20th percentile of energy consumption slightly increases emissions and energy use by ~0.13 EJ or 1.2% of home energy emissions, ~0.15 EJ or 0.9% of travel emissions and ~0.81 EJ or 1.4% of total emissions. Combining high-end reductions with increases at the bottom end therefore still leads to an overall decrease in emissions. For instance, reducing energy use by the top 20% of consumers to the 80th percentile while raising energy use by the bottom 20% of consumers in poverty to the 20th percentile results in overall cuts of 4.62 EJ or 8.3% of total emissions, ~1.44 EJ or 10.2% of domestic energy emissions and 2.16 EJ or 15.8% of travel emissions (Fig. 2).

Equitable energy reduction scenarios

Equitable EDR needs to consider not only equitable reductions within countries or regions but also globally equitable distributions of energy use and emissions. We therefore present annual and cumulative emissions scenarios from 2020 to 2050 to assess whether the equitable energy reduction approaches described above fit within the remaining carbon budget for the 27 European countries. The Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Report[4] identified a remaining global carbon budget of 500 $GtCO_2e$ that is compatible with a 50% chance of limiting global warming to 1.5 °C. We apply two definitions of the remaining carbon budget for the 27 European countries. The first, equal per capita (EPC) budget represents the 27 countries' share of the global IPCC budget based on their share of the global population (35 $GtCO_2e$). The second, Greenhouse Development Rights (GDR) budget, is based on GDR budgets calculated by Robiou du Pont et al.[8], which we adjusted to the updated global IPCC budget (15.1 $GtCO_2e$). Three cumulative emissions scenarios are examined to assess reductions from cutting energy use by the top 10% and 20% of energy consumers and those above the mean with and without increasing energy use by bottom-end consumers in poverty (Fig. 3).

Scenario (1) assesses an initial energy use reduction of top-level consumers in 2020 combined with an annual rate of emissions reduction of 1.4% for the whole population. This annual reduction rate is equal to the average annual fall in emissions for the European Union from 2010 to 2019[40]. Scenario (2) also assumes an annual reduction rate of 1.4% but reduces energy use by top-level consumers by an additional 10% every five years. Scenario (3) applies a set of different annual reduction rates that achieve the EPC and GDR budgets for Europe by 2050 with and without capping high-level energy use.

Results confirm that targeting energy demand from high-end consumers contributes to meeting climate targets over time, while increasing energy use by low-end consumers in poverty has relatively small impacts on this reduction. However, all pathways within cumulative emissions scenarios (1) and (2) exhaust the remaining EPC and GDR budgets before 2050 based on the recent average annual emissions reductions rate for Europe of 1.4%. For instance, the EPC budget for Europe would be exhausted by 2031 if energy use by the top quintile of energy consumers decreases to the 80th percentile of energy use and if their emissions fall by an additional 10% every five years. Even cutting energy use by above-mean consumers to the mean and reducing their emissions by 10% every five years would exhaust the EPC budget for Europe by 2038. Both of these examples assume that energy use by the bottom quintile of consumers in poverty is lifted to the 20th percentile. Not increasing energy use by these bottom quintile consumers would only delay the transgression of the EPC budget by one year, respectively.

Scenario (3) presents pathways with annual reduction rates that enable Europe to stay within globally equitable budgets. If energy use by high energy consumers remains unchanged, annual emissions reduction rates of 9.9% and 24.0%, respectively, would be required to stay within the EPC and GDR budgets. Cutting energy use by the top quintile of consumers to the 80th percentile would lower these annual reduction rates by 1.2 and 2.3 percentage points, respectively, and cutting energy use by above-mean consumers to the mean would reduce them by 2.6 and 5.4 percentage points, respectively. Additionally reducing emissions from above-mean users by 20% by 2025 would lower the required annual reduction rate for achieving the GDR budget by 11.5 percentage points (to a required annual emissions reduction of 12.5%). To put this into context, the average emissions reduction rate for the European Union during the first year of the global COVID-19 pandemic was equivalent to 10.7% (ref. 40). Lifting energy use of low consumers in poverty up to the 20th percentile would have only a relatively small impact on these annual reduction rates of between 0.1 and 0.3 percentage points (Supplementary Table 4). These results suggest that while targeting high energy use can help Europe to stay within its globally equitable carbon budget, it is not a sufficient measure on its own. However, targeting high energy users could be an important step in increasing the willingness of closer-to-average energy consumers to reduce their energy use and emissions, as it would demonstrate that efforts are differentiated by previous contributions to the climate emergency.

Fairness and acceptance of equitable EDR

To assess which types of household would most likely be affected by measures that limit energy use of high-end energy consumption, we conduct logistic regressions to determine which household characteristics are associated with belonging to the top 10% and top 20% of energy consumers on a per capita basis in different consumption domains. Results, expressed as average marginal effects[41], show that in the aggregate sample, high income and high education significantly increase the probability of belonging to the group of high-end total energy consumers. Larger household size, presence of children, old age and living in an urban area significantly decrease this probability. These findings are consistent with previous studies on determinants of household energy use or emissions[42–44].

For instance, belonging to the fourth income quintile increases the probability of being among the top 20% of total energy users by 19 percentage points compared with being in the bottom income quintile. Belonging to the top income quintile increases this probability by 41 percentage points. Living in a household in which at least one member has higher education increases the probability of being among the top 20% of energy users by 3 percentage points, the same as having a household representative who is employed.

Having an additional adult in the household decreases the probability by 8 percentage points, and the presence of at least one child decreases the probability by 18 percentage points. Living in an urban area decreases the probability by 2 percentage points (Fig. 4 and Supplementary Table 4). Results also show that people with older or retired household representatives are more likely to be high domestic energy users but less likely to be high travel energy users, compared to the base groups (Supplementary Table 5). Figure 4 confirms that the association is strongest with income, while the effect of additional household members reveals the role of economies of scale for energy use within households.

Supplementary Table 6 shows that results are reasonably consistent across countries, especially for income, number of adults and presence of children. The association between high income and high energy use is particularly strong in several countries with relatively high income inequality such as Bulgaria, Spain, Croatia, Hungary, Italy and Romania.

Questions remain around which policies would be best suited to targeting high energy demand and whether the public would support such policies. Public acceptance is an important factor for policymakers to adopt policies[45]. To better understand this, we conducted four deliberative workshops in England with 31 participants to assess public perceptions of policy options for targeting high energy consumption. The method of deliberative workshops is informed by the idea of deliberative democracy[46] and is intended to provide space for deliberation by participants with a broad range of energy-consuming practices and related attitudes (see Methods). There are strong reasons for public deliberation and participation in deciding what measures should be taken to change energy consumption[46]. In part, this is because everyone is affected by the nature of the measures taken to reduce energy consumption and the consequences of failure to mitigate climate change. Moreover, understanding the implications of policy measures is not solely the preserve of policymakers, scientists or academics. People across society have insights into how their lives would be affected by policy interventions.

Results reveal common reasons for support of and objection to policies that target high energy consumption (further details in Methods and Supplementary Information). Some of the main available policy options[47] for targeting high energy consumption were discussed, including (financial) (dis)incentives to adopt energy efficient or lower emitting behaviours such as taxes on frequent flights, energy or travel quotas or regulation that targets businesses. The arguments that participants made for or against such policies centred on several key themes, especially freedom and needs.

Some participants argued that policies that target high energy use, for example, through quotas for flights or car mileage, would not be favoured by the public as they would restrict freedom and choice. Such policies were also deemed unpopular given that certain lifestyles have become 'part and parcel of what people are able to do these days' (workshop 4). At the same time, many participants supported measures that would discourage or even ban energy consumption beyond a particular level, for instance, extensive business travel or family flights for holidays beyond one or two per year. Here participants argued that the climate emergency needs to be tackled urgently and that this is not possible if no restrictions are imposed. Several participants acknowledged that regulations that limit 'luxury' energy use would treat everyone equally and therefore fairly, which can be conducive to acceptance if

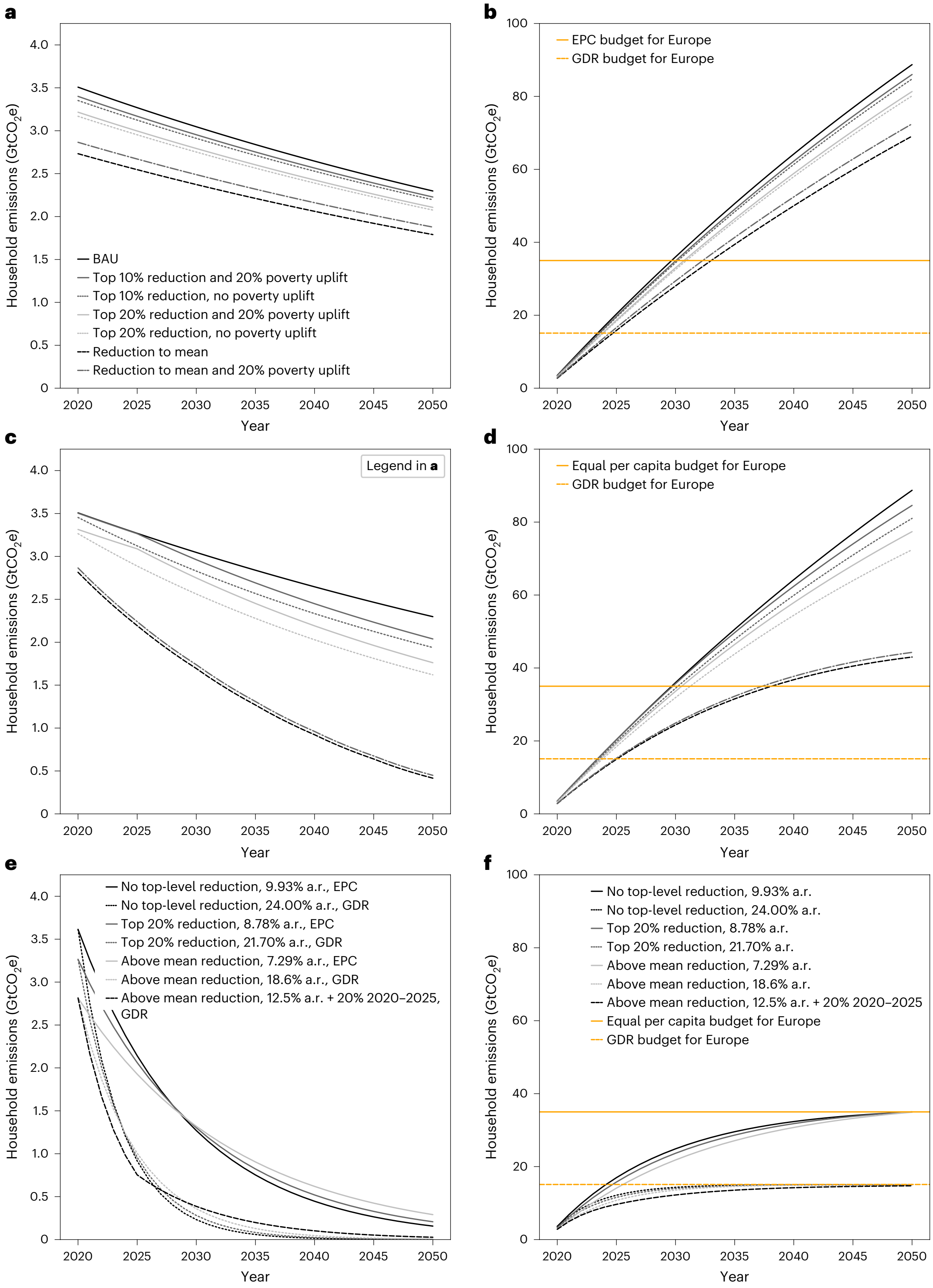
Fig. 3 | Equitable energy reduction scenarios in 27 European countries. **a**,**c**,**e**, Annual total consumption-based household emissions in $GtCO_2e$ 2020–2050 in 27 European countries. BAU, business as usual. **b**,**d**,**f**, Cumulative total consumption-based household emissions in $GtCO_2e$ 2020–2050 in 27 European countries. The orange line represents the carbon budget for the 27 European countries based on their EPC share of the 500 $GtCO_2e$ global carbon budget defined by the IPCC[4]. The dashed orange line represents the GDR carbon budget for the 27 countries based on Robiou du Pont et al.[8] **a**,**b**, Scenario (1): annual and cumulative emissions based on a one-off reduction of the top 10% and top 20% of energy consumers down to the 90th and 80th percentile of energy use, respectively, and reducing energy use above the mean to the mean, on top of an annual emissions reduction rate of 1.4% (average reduction for the European Union from 2010 to 2019). The top-end energy reduction scenarios without 'poverty uplift' (dotted and dashed lines) are compared with those that increase energy use of the bottom 20% of consumers in poverty up to the 20th percentile of energy use (solid lines and dashed-dotted line). **c**,**d**, Scenario (2): annual and cumulative emissions based on the same parameters as scenario (1) but with an additional emissions reduction of top-level energy consumers by 10% every five years. **e**,**f**, Scenario (3): annual and cumulative emissions based on annual emissions reduction rates (a.r.) that achieve the EPC and GDR budgets for Europe with and without top-level reductions. The dashed line in **e** refers to reducing above-mean consumption to the mean and an additional 20% emissions reduction by this group in the first five years. Data: EU HBS 2015, 2010; Exiobase 3.7. $n = 271,277$ households.

good reasons are provided, as travel and other restrictions during the COVID-19 pandemic have demonstrated.

Several participants stated that businesses should be regulated to reduce emissions of the products and services they provide. While regulation also restricts choice, it was considered fair and beneficial for the environment to require everyone in society to purchase low carbon products instead of leaving it to the market, so long as prices were affordable or subsidized.

Participants supported policies that restrict high energy use when low carbon alternatives are available. For instance, several participants argued it would be fair to tax or even restrict frequent flights if train connections are available or if people can holiday in their home country.

Much of the discussion on restricting high energy use through quotas focused on differential needs. Many participants argued it would be unfair to issue blanket energy rations, especially for necessities such as domestic energy, because some people have higher



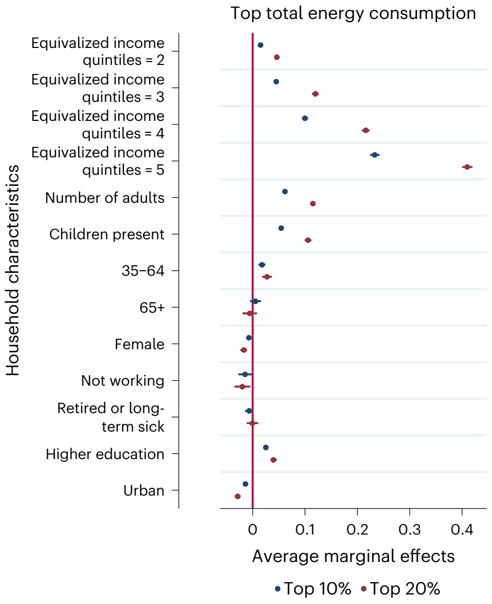


Fig. 4 | Relationship between household characteristics and high per capita energy use. Average marginal effects from logistic regressions on belonging to the top 10% and top 20% of total energy consumers. Coefficients represent the change in probability of belonging to the top 10% / 20% of energy users compared to the base category. Base categories are: bottom income quintile; age group 35–64; male household representative; household representative not employed; no one in household has higher education; rural location. The significance of coefficients is assessed with the *z* statistic, and the significance of the overall model with the Wald Chi-square statistic. Data: EU HBS 2015, 2010; Exiobase 3.7. The calculations exclude the top and bottom 1% energy consumption and income outliers and countries for which information in education and employment status is missing (Supplementary Table 5). $n = 208{,}539$ observations.

energy consumption requirements than others due to age or health issues. Conversely, energy quotas were considered fair if allowances for extra needs are available.

Discussion and Conclusion

Our results demonstrate that targeting high-level energy consumers can achieve considerable emissions reductions in Europe. This finding holds true even when the energy use of low energy consumers in poverty is increased to aid needs satisfaction. Results show that equitable EDR strategies in Europe would be defensible from a social justice perspective: targeting high-level energy consumers would mostly affect those with high household incomes and higher education, while reducing the risk of additional deprivation for the most vulnerable people in society. Even though some potentially less-advantaged groups such as people with older, retired or female household representatives are likely to be affected by measures in specific consumption domains such as domestic energy use, Supplementary Fig. 3 shows that low income reduces the likelihood for these groups to fall into the top energy use category.

Equitable EDR needs to consider not only equitable reductions within countries or regions but also globally equitable distributions of energy use and emissions. The scenario analysis in Fig. 3 demonstrates that targeting top-end consumers can make a contribution towards meeting globally equitable carbon budgets but that high annual reduction rates are required for Europe to meet these targets. Decreasing energy use by above-mean consumers to the mean, with an additional 10% fall in their energy use every five years on top of an annual reduction rate of 1.4% for the whole population, transgresses Europe's per capita budget by 2039 (without 'poverty uplift'). If energy use of low consumers in poverty is increased to the 20th percentile, the budget would be transgressed one year earlier by 2038. If energy use of high energy consumers is not targeted, annual emissions reduction rates of 9.93% and 24.00%, respectively, would be required to achieve the EPC and GDR budgets. Limiting energy use of above-mean consumers to the mean and reducing their emissions by an additional 20% in the first five years can reduce the annual emissions reduction rate required for achieving the GDR budget by 11.5 percentage points (to 12.5%). The scale of the required additional demand reduction across the whole population, alongside technological change, is evident if one recalls that emissions fell by an average of 10.7% across the European Union in the first year of the global COVID-19 pandemic[40].

Achieving globally fair energy demand and emissions reductions in Europe therefore presents a major policy challenge. Deliberative workshops discussed the main available policy options for targeting high energy use: taxation, quotas and structural change through regulation or infrastructure improvements. While support was expressed for regulations that create a level playing field and for financial incentives and caps if low carbon options are available, reservations were expressed that measures that target high energy use would limit personal freedom. However, the deliberative workshop results generally indicate support for a more equal distribution of energy use. While targeting high energy users may not in itself be sufficient for Europe to meet globally equitable carbon budgets, targeting high energy users while supporting needs satisfaction for all, thus creating greater equality in energy use, could increase public acceptance of the need for additional rapid annual energy demand reduction and technological change required for meeting these targets.

A range of policy options are available for supporting those who do not currently have the means to fulfil their basic energy needs. For instance, the energy poverty and energy justice literatures propose measures such as the provision of energy efficient social housing, targeted subsidies for energy efficiency home retrofitting and public transport, additional cash support through the social security system, reduced energy or public transport tariffs for people on specific benefits or the provision of Universal Basic Services for energy and transport, which could include an allocation of a free basic amount of renewable domestic electricity or public transport[14,48,49]. Allocating equal per capita energy quotas as discussed in the deliberative workshops could also address energy poverty, especially if the allocation accounts for special needs.

The deliberative workshop results indicate that policy framing and communication are likely to be important vehicles to increase public acceptance of EDR policies. For instance, common objections against equitable EDR can be addressed by highlighting justice, health and other co-benefits of reducing high energy consumption[50] and the urgent need to act collectively while expressing sensitivity to differentiated needs. However, the workshops did not discuss the scale of change required for rich regions such as Europe to reduce energy use and emissions in ways that are compatible with globally equitable emissions budgets. Future research is required to examine how public and political acceptance of reductions outlined in scenario (3) for above-mean energy consumers can be supported.

Methods

Concepts

Debates about equitable energy demand reduction (EDR) are informed by concepts such as 'consumption corridors'[17,18], the 'safe and just space of humanity'[19] and the 'good life within planetary boundaries'[20]. The proposal to reduce global energy use and associated emissions to a level compatible with planetary boundaries[22,23] while ensuring that everyone's basic needs[24,25] are met responds to a situation where, globally and nationally, overconsumption is paired with underconsumption. On the one hand, humanity as a whole, and countries in the

Global North in particular, are exceeding planetary boundaries[20,21]. On the other hand, basic needs of disadvantaged people within rich countries, and of large proportions of people within countries in the Global South, fail to be met[28,51].

Defining minimum levels of consumption has a history, building on theories of human needs[24,25]. These theories distinguish needs from wants or desires and identify a set of universal needs and culturally and historically variable needs satisfiers that must be met to enable adequate participation in society[24,25]. Examples of approaches that define minimum standards of consumption are the Minimum Income Standard that has been applied since 2008 in the United Kingdom and the Reference Budget Framework that has informed work on minimum consumption budgets in the European Union since 2010[52].

Setting upper limits for consumption is a more recent idea, and more controversial because it seems to conflict with individual freedom. Conceptually, the proposal draws on conceptions of positive freedom, which maintains that everyone has the right to have their basic needs fulfilled and a duty not to harm others' rights to needs satisfaction, now and in the future[17,18]. Consumption that contributes to exceeding planetary boundaries can thus be regarded as infringing on other people's rights to needs satisfaction, especially those of future generations. Some justifications for upper consumption limits rest on research that finds energy consumption above certain levels no longer contributes to substantial increases in human wellbeing[35]. The consumption corridor and needs satisfaction literatures stress that lower and upper limits of consumption would need to be democratically negotiated and adjusted over time[18,26,27].

Previous research has proposed a range of estimates for global energy requirements related to satisfying basic human needs in the future supported by advanced technological development and/or reduced energy demand through behaviour change, for instance of 15.3 GJ per capita (2050)[32], 26.1 GJ per capita (2050)[2] or 42.4 GJ per capita (2040)[53]. (Note that per capita figures for 2050 are calculated from total global energy use estimates of 245 EJ in Grubler[2] and an assumed global population of 9.7 billion; figures for 2040 are based on an estimate of 390 EJ of total global energy use in International Energy Agency (IEA)[53] and a global population of 9.2 billion). Other research assesses minimum energy requirements for needs satisfaction for specific countries or regions[33,34] and/or for achieving specific wellbeing outcomes such as life expectancy[33,35].

It is currently unclear how much 'room' will be available between minimum and maximum energy requirements where upper limits should be compatible with planetary boundaries and not harm anyone's right to satisfy their needs, including for future generations. Millward-Hopkins et al.[32] estimated that energy use could be minimized to 15.3 GJ per capita per year by 2050 if current state-of-the-art low carbon technologies replaced high carbon technologies and if energy use were reduced to levels of basic needs satisfaction.

At current emissions intensity per GJ, maximum per capita energy use equivalent to global per capita emissions compatible with 1.5 °C equate to 25.3–29.1 GJ per capita per year (based on estimated annual global per capita emissions within a 1.5 °C budget of 1.4 t per capita per year and of 1.6 t per capita per year for a 2 °C budget[20,54,55] and an emissions intensity of ~0.06 tonnes of CO_2 per GJ, using data from the International Energy Agency[56]). This would not leave much room between minimum and maximum thresholds, demonstrating the urgent need for further decarbonization of energy supply and transformation of provisioning systems[31,57] to increase the available 'room' between minimum and maximum levels of energy use. The available corridor may also depend on the level of inequality of energy use; Jaccard et al.[58] found that near equality of energy consumption and rapid improvements in the emissions intensity of energy could facilitate higher levels of per capita energy use, and thus greater needs satisfaction, at the same level of decarbonization, compared to more unequal patterns of energy use.

For comparison, mean per capita total energy consumption across the 27 countries included in this study was 122.5 GJ per year. Even energy use at the tenth percentile of the energy consumption distribution already stood at 52.7 GJ per capita per year (Supplementary Table 2). This demonstrates the scale of necessary action for rich countries to move energy use and emissions into the bounds of a globally equitable consumption corridor.

Data

Quantitative analysis in this article utilizes data from the latest available 2015 European Household Budget Surveys (HBS) and Exiobase 3.7. The HBS provides detailed household expenditures in Euros for 23 European countries, harmonized and disseminated by Eurostat. We add to the analysis four countries from the 2010 HBS dataset that were not included in the 2015 version at the time of data acquisition (Malta, Portugal, Slovenia and the United Kingdom). The total sample size for the 27 countries, which comprise the pre-Brexit EU-28 countries except Austria, is 275,614 households. The focus on European countries is useful for gaining insights into the scale of required action within rich world regions with high historical responsibility for climate change[59].

We aggregate detailed expenditure variables into broader categories for home energy (including electricity, gas, other fuels such as coal, coke and bottled gas), travel (including motor fuels, public transport, air and sea travel), food and all other goods and services. Household characteristics such as number of adults and children, age, gender, education and employment status of the household representative are created from the HBS member files. Household weights provided in the HBS are applied throughout to account for sampling and response bias.

The multi-regional input–output analysis Exiobase dataset (version 3.7) is utilized to estimate annual energy use (in GJ) and greenhouse gas emissions (in tonnes of CO_2 equivalents) per household and per person in the HBS[39]. Net energy estimates are used, which avoids double counting from the conversion of primary into secondary energy sources. To estimate emissions, we apply the Global Warming Potential (GWP100) metric[60] to convert different greenhouse gases (carbon dioxide, methane, nitrous oxide and sulphur hexafluoride) to CO_2 equivalents for 2015 (2010 for the United Kingdom, Malta, Portugal and Slovenia). Exiobase covers high sectoral detail (200 products), 49 countries (including all EU countries) and rest-of-the-world regions and a wide range of environmental accounts[39].

We use these data to estimate energy and greenhouse gas emissions for home energy, travel, food and all other consumption for each country in 2015/2010 in Exiobase, based on 2015/2010 purchasers' prices and accounting for global trade. We then divide energy and emissions from Exiobase by HBS expenditure per category and country to generate energy and emissions factors in GJ per Euro and kg CO_2e per Euro (Supplementary Table 7). Household expenditure is then multiplied by these factors to estimate household energy consumption and greenhouse gas emissions. Because expenditure in the HBS is provided in Euros, this method corrects for differences in price levels between countries. Lorenz curves and regression analysis are based on per capita, not household values to account for household size; per capita values are created by dividing household-level estimates by household size. Person-based weights are applied in the analysis of per capita figures where household weights provided by the HBS are multiplied by household size.

Qualitative analysis draws on data[61] collected for the 'high energy consumers' project of the United Kingdom Research and Innovation (UKRI) funded Centre for Research into Energy Demand Solutions. In this project, interviews were conducted with 31 high energy users in England in 2021, followed by four deliberative workshops to explore which energy-consuming activities exceed reasonable expectations and which, if any, interventions might fairly reduce excessive energy consumption. This paper utilizes the workshop data.

Table 1 | Deliberative workshop participant recruitment criteria

Workshop 1:	**Workshop 2:**
High mobility, high domestic energy consumption	**Low mobility, high domestic energy consumption**
Ten highest-consuming interviewees targeted for re-booking in workshop 1.	Min: 1×no car AND less than one return flight a year, on average
	Min: 1×<5,000 miles per year AND less than one return flight a year, on average.
	Min 1×any mileage per year AND no flights in last five years, on average.
	All: energy bills >£120 per month
Workshop 3:	**Workshop 4:**
High mobility, low domestic energy consumption	**Low mobility, low domestic energy consumption**
Every recruit fits at least one of:	Min: 1×no car AND less than one return flight a year, on average
3+ cars in household, 2+ cars personally, 15,000+ miles car travelled annually or 2+ return flights	Min: 1×<5,000 miles per year AND less than one return flight a year, on average.
All: energy bills <£80 per month	Min 1×any mileage per year AND no flights in last five years, on average.
	All: energy bills < £80 per month

The method of deliberative workshops gave space for discussion by participants with a broad range of energy-consuming activities and practices. This method begins from the idea of deliberative democracy, which holds that policies or other measures can be considered fair on the basis of 'justifiability to all affected'[46]. A number of deliberative and participatory methods already aim to inform climate change mitigation[62]. These include citizens' juries and assemblies such as the European Citizens' Panels organized by the European Commission and citizen climate assemblies in various countries, including France, Ireland, Poland and the United Kingdom[63]. However, deliberative events considering energy reduction are, to date, limited in number and location and there is uncertainty about whether they lead to more radical policy than would otherwise be expected[64]. Yet, participation matters for legitimacy and prospects of effective action. Despite their limitations, deliberative events already held offer insights into the role that deliberative democracy can take in setting boundaries for sustainable and fair energy consumption.

As detailed in Table 1, deliberative workshop participants were recruited such that each workshop represented one combination of high/low consumption of domestic and travel-related energy. The aim was to examine whether the views of reasonableness of energy use and reduction policies varied across the groups. Each workshop lasted for three hours, with seven to eight participants in each and 31 participants in total. Two additional facilitators ran smaller breakout sessions for most of the duration to facilitate a better exchange of views. The participants were provided with pre-workshop information on energy demand, the need for climate mitigation and the four broad policy approaches of economic (dis) incentives, rationing, structural change (for example, infrastructure improvements and regulation) and behaviour change, including the video at this link (https://mymedia.leeds.ac.uk/Mediasite/Play/f6e8043b3b4241b39c1e0f968e3e54cf1d).

In recruiting the sample for the high mobility and domestic consumption workshops, we used the 31 interviewees as a recruitment pool who had been sampled by professional recruiter, QA Research. These interviewees had been recruited as fitting the following criteria:

- Twenty high domestic and mobility energy-using households: that is, monthly bills over £120 per month and car mileage >10,000 miles per year, with additional sub-samples:
- Five super high domestic energy consumers (monthly energy bills over £160 per month) and
- Five super high mobility households:
    - One recruit with more than two personal vehicles,
    - One household with three plus vehicles,
    - One recruit driving >15,000 miles per year and
    - Two recruits who take four plus annual return flights. All recruitment factors applied to a 'normal' (that is, pre-COVID-19) year.

Participants for the other three workshop groups were also recruited by QA Research to reflect a mixture of levels of domestic and transport-related household consumption.

Analysis

To assess inequality of energy use, we apply common procedures of inequality analysis[65]. Lorenz curves, and our definitions of bottom and top 10% / 20%, are generated by first sorting observations by their energy use from the lowest to the highest and then dividing observations into ten (deciles) or five (quintiles) equally sized groups (for example, in a sample of 1,000 households, each quintile group would have 200 households). The lowest decile/quintile corresponds to the bottom, and the highest decile/quintile to the top 10% / 20% of energy consumers. This is done for each country separately.

Expenditure data that are collected through diaries are affected by the 'infrequency of purchase' problem where some recorded expenditures over-represent actual consumption during the observation period and where zero expenditures are recorded even though the household consumes these items using up stocks (these represent 'false zero' observations as virtually no household can live without using home energy, food or transport). The top 1% of energy users per country and observations at or below zero are, therefore, excluded from the distributional analysis as including them would skew results (the Methodological limitations section provides more details).

To assess inequality of consumption, mean energy use is calculated for each group and the whole sample (country-level values are weighted by population shares), and multiples are calculated of energy use of the top 10% and 20% of consumers compared to the bottom 50%. Energy use is also totalled up for each of these groups to calculate shares of total energy use (Supplementary Table 1). On the basis of per capita values per household, Gini coefficients are calculated for total energy use and each energy domain, and Lorenz curves are generated, depicting the cumulative share of energy use compared to the cumulative share of the population (Fig. 1, Supplementary Table 1 and Supplementary Fig. 1).

Impacts of equitable EDR options are assessed through microsimulation and emissions scenarios from 2020 to 2050. High energy users are defined as the top 10% and top 20% of household consumers per country and consumption domain. Defining two thresholds for 'high energy' use is useful for comparison. Our approach bears similarity to common definitions of high and low income and wealth groups, where official statistics customarily use the top and bottom 10% and 20% of the distribution as comparators[37,38]. However, choosing an approach based on the distribution of consumption is only one option for defining high energy users[66]. Therefore, the thresholds of the top 10% and 20% of energy consumption adopted in this article have only illustrative purpose; they are not intended to represent policy recommendations as, in practice, thresholds would need to be negotiated through democratic processes. High energy use could alternatively be defined with reference to remaining emissions budgets and other planetary boundaries[66]. However, the difficulty with this approach is that energy and emissions are not fixed as the emissions intensity per unit of energy depends on technological development.

This study defines low energy users who are at risk of having unmet energy needs as the bottom quintile of consumers with equivalized household incomes below the relative poverty line of 60% of median equivalized income (based on the Organisation for Economic Co-operation and Development (OECD) equivalization scale) for each country. This group makes up 33% of the bottom quintile of energy consumers for home energy, 36% for transport and 49% for total energy. Focusing on this group was based on the assumption that low energy use by those in poverty is more likely to be involuntary compared to low energy use by wealthier people and thus likely to represent unmet needs. Alternatively, 'low energy users' could have been defined as households in fuel or transport poverty based on the 'low income high cost' approach[67,68]. This approach was deemed unsuitable for the analysis of equitable EDR approaches because households in 'low income high cost' energy or transport poverty have mean energy consumption above the sample average. In addition, it would have been difficult to define equivalent groups for food, other consumption and total energy use poverty. Observations at or below zero and the top 1% of the distribution are excluded in the definition of groups of high and low energy consumers to address the infrequency of purchase problem and avoid skewed results (Methodological limitations section provides more details).

Equitable EDR options are then assessed through microsimulation by replacing, within each country and energy domain separately, energy use by the top 10% and 20% of consumers with energy use at the 90th and 80th percentiles, respectively, and by the bottom 20% of energy consumers in poverty with energy use at the 20th percentile (where, for example, the 90th percentile equates to the energy use of the 900th household in a sample of 1,000 households). For the 'mean' model, energy use above the mean is replaced with mean energy use; this applies to 42% of households in the sample.

Emissions reductions from capping high-level energy use are assessed by allocating emissions of the household at the 90th or 80th percentile to households in the top decile or quintile of emitters, respectively, separately for each country and consumption category. Because the households at the 80th and 90th percentiles of the energy and emissions distribution are the same, this approach is equivalent to calculating the emissions savings from reducing energy use by the high-end consumers down to the 90th and 80th percentiles. Emissions are then totalled up for each country and energy domain for (1) original energy use, (2) energy use with capped top-level consumption and (3) energy use with capped top-level energy consumption and increased energy use of low consumers in poverty. Differences in emissions (Fig. 2) and energy use (Supplementary Fig. 2) are then calculated between (1) and (2) and (1) and (3) and expressed as a percentage of original emissions and energy use.

Three emissions scenarios (Fig. 3) plot annual and cumulative emissions from 2020 to 2050. All three scenarios assume a reduction in top energy consumption in 2020, with and without increasing energy use of low consumers in poverty, alongside an annual emissions reduction for the whole population of 1.4% in scenarios (1) and (2). Variable annual reduction rates through which globally equitable emissions budgets are achieved are applied in scenario (3). In scenario (2), emissions of top-level energy consumers are reduced by an additional 10% every five years. The annual emissions reduction rate of 1.4% in scenarios (1) and (2) equates to the average annual reduction rate for the European Union between 2010 and 2019 (based on Eurostat data[40]). The extent to which the energy demand reduction scenarios are compatible with globally equitable targets is then assessed based on two different budgets for Europe. Each of these budgets assumes a global carbon budget of 500 $GtCO_2e$ from 2020 until 2050 that the latest IPCC report[4] estimated to provide a 50% chance of not exceeding 1.5 °C of global heating. The first equal per capita (EPC) budget calculates the 27-country share of the global IPCC budget based on these countries' proportion of the world population in 2020, which was 7%. This results in an EPC budget of 35 $GtCO_2e$. The Greenhouse Development Right (GDR) budget is based on Robiou du Pont et al.'s[8] GDR budgets. The GDR approach, which was developed by Baer et al.[9], is designed to allocate carbon budgets equitably across countries in the world based on capacity (wealth), responsibility (past emissions and projected business-as-usual emissions) and need (population size). We adjust Robiou du Pont's GDR budgets to the updated global IPCC budget and the period from 2020 to 2050 by calculating what proportion of their EPC budget for the 27 European countries is represented by the GDR budget (0.43). Our EPC budget of 35 $GtCO_2e$ is then multiplied by that proportion, generating a GDR budget of 15.1 $GtCO_2e$. For scenario (3), annual reduction rates are calculated through which both of these European carbon budgets can be achieved under different assumptions of energy use reductions among high-level energy consumers.

Logistic regressions are conducted to examine which types of household might be most affected by policies that target top-end energy consumers. Binary variables are created for belonging to the top 10% and top 20% of per capita energy users for each domain. Predictor variables are: equivalized income quintiles (using the modified OECD scale for equivalization and quintiles by country); number of adults; presence of children (binary variable); age categories of 15–34, 35–64 and 65 and over; having a female household representative; employment status (working, not working but of working age, retired); having at least one member in the household with a higher education degree (binary variable); and urban vs rural area (binary variable). All models control for country variables and exclude the top 1% of energy users, and weights are applied throughout. Supplementary Table 4 presents average marginal effects, which show the change in probability of belonging to the top 20% of energy users in each domain compared to the base category. Average marginal effects are based on computing probabilities for each observation in the dataset for each characteristic and then averaging these probabilities.

The data from the workshop deliberations were transcribed verbatim for analysis. The data were analysed through thematic analysis, which identifies key themes in the text and interprets participant statements[69]. Qualitative thematic analysis was conducted based on thematic coding with NVivo software, with a focus on examining discussions about policy options for energy demand reduction. Initially, a list of codes was developed deductively. Workshop headline codes included 'policy approaches', 'type of consumption' and 'views'. Additional codes were then generated through inductive analysis. A full list of codes can be found in the documentation of the archived dataset.[61]

Study design, data collection and analysis methods for the qualitative part of this study followed all relevant research ethics regulations and guidelines. Ethics approval was granted by the Research Ethics Committee for the Faculties of Business, Environment and Social Sciences at the University of Leeds (application AREA 19-160). All of the research participants provided informed consent for their participation, use of anonymized data in publications and data archiving.

Methodological limitations

The analysis in this article has several limitations related to data issues and approaches to scenario assessments.

The analysis is limited by the quality of data provided by the HBS. The HBS consists of country-level surveys on household expenditure without full harmonization of data collection approaches across countries. Expenditure data are often collected through individual and household-level expenditure diaries that are kept for short periods of time, for example, one or two weeks (the period of data collection varies by country). Short collection periods lead to the 'infrequency of purchase problem'[70]; some households may not record an expenditure on certain items during the observation period, even though they continue to consume these items using stocks.

Equally, some expenditures recorded during the observation period are higher than the actual amounts consumed when purchased stocks outlast the observation period (for example, a full tank of petrol) or when items are purchased infrequently (such as flights, furniture or appliances). While mean expenditure for the whole sample is assumed to be balanced, distributional analysis is problematic because high and zero values are inflated, over- and under-representing actual consumption, respectively[70]. Measures of inequality are therefore highly likely to be overestimated based on unadjusted expenditure data. To address the infrequency of purchase problem, we use a more aggregate approach in estimating energy and emissions intensities (for four consumption categories instead of more disaggregate categories) and values of zero and below zero expenditure (which arise when, for instance, a household is in credit with an energy company) and the top 1% of expenditure values per country and consumption domain are excluded from the analysis. As a result, the measures of inequality and the assessment of potential emissions reductions that result from capping the top 10% and 20% of energy consumption might be underestimated in this paper.

Additional limitations arise from the fact that household carbon and energy footprints are based on monetary expenditure instead of actual physical consumption data[71]. For instance, products within the same product category can have different energy and carbon footprints that are not reflected in the price (for example, more expensive local and organic food items might have a lower carbon footprint than cheaper products). Energy and carbon footprints are therefore probably overestimated for some expensive products (and hence for wealthier households that are more able to purchase these products) and underestimated for cheaper products (and less wealthy households). Existing literature discusses and assesses limitations associated with expenditure-based approaches[44,71].

It also needs to be noted that while the scenario data cover 27 European countries, the deliberative workshop data have been collected only in England. It is likely that public attitudes to equitable EDR policies vary across European countries, influenced by political, economic and socio-cultural contexts. England, and the United Kingdom more widely, is often regarded as having a strong liberal orientation that emphasizes individualism and freedom but is also shaped by a universal welfare approach as represented in the National Health Service, which puts greater emphasis on equality and solidarity[72]. Both of these traditions are likely to shape public opinion on EDR policies in England in specific ways. Deliberative workshop results therefore cannot be claimed to be representative of other countries. The workshop discussions focused on public attitudes and acceptance, but it is acknowledged that policymakers will also have to consider efficiency and effectiveness of policies in their decisionmaking. Because climate change needs to be tackled globally, this type of analysis would very much benefit from the inclusion of middle- and low-income countries. This is currently not possible because there are no comparable datasets with household-level expenditures that cover a larger number of countries. Creating harmonized household-level expenditure (or, even better, consumption) datasets for a larger number of countries would be an important first step for future research.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data used for this analysis are available from Eurostat (Household Budget Survey microdata 2015 https://ec.europa.eu/eurostat/web/microdata/household-budget-survey) and Exiobase (version 3.7) for energy and emissions data (https://www.exiobase.eu/). Qualitative workshop data have been archived with the UK Data Service and are available from https://doi.org/10.5255/UKDA-SN-855789.

Code availability

MATLAB code for extracting energy and emissions data from Exiobase and STATA code for the HBS analysis is available from the Research Data Leeds Repository https://doi.org/10.5518/1352.

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Author contributions

M.B. conceived the idea for the manuscript and designed the study. M.B. analysed the quantitative and qualitative data. M.B. wrote and revised the article. N.C., C.M. and K.L. designed the qualitative data collection. N.C. and C.M. collected and archived the data. N.C. and C.M. provided access to the working paper that describes the qualitative collection for this study. D.I. and M.B. extracted energy and emissions data from Exiobase. N.C., C.M., D.I. and K.L. provided comments on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41560-023-01283-y.

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Peer review information *Nature Energy* thanks Marine Cornelis, Dirk-Jan van de Ven and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used to collect the data.
Data analysis	Statistical analysis was conducted in Stata 17 MP and Excel. Qualitative data analysis was conducted in NVivo 12.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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Data used for this analysis are available from Eurostat (Household Budget Survey microdata 2015 https://ec.europa.eu/eurostat/web/microdata/household-budget-survey) and Exiobase (version 3.7) for energy and emission data (https://www.exiobase.eu/). Qualitative workshop data have been archived with the UK Data Service and are available from https://doi.org/10.5255/UKDA-SN-855789.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Results apply to all genders. The regression analysis includes an independent variable for female household representative which was based on self-identification in the European Household Budget Survey. We have otherwise not broken down findings by gender because our research question refers to the whole of population.
Population characteristics	The European Household Budget surveys cover population characteristics that are representative of the participating countries. Fig. 5 in the Methods section provides characteristics of the qualitative research participants.
Recruitment	Statistical analysis is based on secondary data. Participants for the European Household Budget Surveys were recruited through national survey statistics departments. Further details on recruitment, sampling error etc. can be found in the European Household Budget 2015 Quality Report: https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology. Participants for the qualitative workshops were recruited by the "High energy consumers" project of the UKRI Centre for Research into Energy Demand Solutions (EPSRC EP/R035288/1). Sampling for the project was conducted by QA Research https://www.qaresearch.co.uk/.
Ethics oversight	Data collection for the qualitative workshops was granted by the AREA (Faculties of Business, Environment and Social Sciences) Research Ethics Committee at the University of Leeds (application AREA 19-160).

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This paper uses both quantitative and qualitative data. Quantitative data from the European Household Budget Survey 2015 (2010 for four countries) is employed to estimate emission reduction of equitable energy demand reduction options. Qualitative data was collected through deliberative workshops to gain insight into public opinions on equitable energy demand reduction policies.
Research sample	European Household Budget Surveys are based on representative samples for each participating countries. Please see the user documentation on https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology and https://ec.europa.eu/eurostat/web/microdata/household-budget-survey for more detail. Deliberative workshops had sampled participants with high and/or low home energy and travel energy use in England, UK, please see details about sampling in the Methods section.
Sampling strategy	European Household Budget Surveys use stratified random sampling (with slight variations by country). For details please see the user documentation on https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology and https://ec.europa.eu/eurostat/web/microdata/household-budget-survey for more detail. Theoretical sampling was used for the deliberative workshops to represent one group each for combining high and/or low home energy and travel energy use in England, UK,. Please see details about sampling in the Methods section.
Data collection	European Household Budget survey data are collected through a mix of methods depending on the country, including face to face or phone/virtual interviews, manual or online surveys and manual or online expenditure diaries. For details please see the user documentation on https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology. Deliberative workshop data was collected through four facilitated face to face workshops which were audio-recorded with the permission of the participants.
Timing	The 2015 European Household Budget survey data have been collected between 2013 and 2016, depending on the participating country. Data only became available in 2021. For details please see the user documentation on https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology. Deliberative workshop data was collected during 2021.
Data exclusions	The analysis of emission reductions and regression analysis based on the European Household Budget Data excludes the top and bottom 1% of energy or emission and income outliers to address the infrequency of purchase problem and income outliers which can affect the poverty analysis. Inequality analysis also excludes observations with negative or zero emissions/energy/expenditure. This is

	described in the methods section. Exact sample sizes are stated for each analysis. The analysis of the qualitative workshop data did not apply any exclusions.
Non-participation	For details about survey response rates for the European Household Budget surveys please refer to the methodology documentation on https://ec.europa.eu/eurostat/web/household-budget-surveys/methodology. The deliberative workshops which had aimed to include 8 participants per workshop suffered from one dropout, resulting in a total sample of 31 participants.
Randomization	Not applicable as this study is not based on experiments.

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☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
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☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
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☒	☐ MRI-based neuroimaging