ENVIRONMENTAL RESEARCH
LETTERS

ACCEPTED MANUSCRIPT • OPEN ACCESS

The energy and carbon inequality corridor for a 1.5°C compatible and just Europe

To cite this article before publication: Ingram S. Jaccard *et al* 2021 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/abfb2f

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is **© 2021 The Author(s). Published by IOP Publishing Ltd**.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by/3.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the article online for updates and enhancements.

This content was downloaded from IP address 193.174.19.69 on 28/05/2021 at 13:26

The energy and carbon inequality corridor for a 1.5°C compatible and just Europe

Ingram S. Jaccard[1], Peter-Paul Pichler[1], Johannes Többen[1,3], and Helga Weisz[1,2]

[1] Social Metabolism and Impacts, Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, PO Box 60 12 03, Potsdam, 14412, Germany
[2] Department of Cultural History & Theory and Department of Social Sciences, Humboldt-University Berlin, Unter den Linden 6, Berlin, 10117, Germany
[3] Gesellschaft für Wirtschaftliche Strukturforschung (GWS) mbH, Heinrichstraße 30, 49080 Osnabrück, Germany

Keywords: energy and carbon footprints; inequality; energy for decent life; 1.5 degree target, Europe

Abstract: The call for a decent life for all within planetary limits poses a dual challenge: Provide all people with the essential resources needed to live well and, collectively, not exceed the source and sink capacity of the biosphere to sustain human societies. We examine the corridor of possible distributions of household energy and carbon footprints that satisfy both minimum energy use for a decent life and available energy supply compatible with the 1.5°C target in 2050. We estimated household energy and carbon footprints for expenditure deciles for 28 European countries in 2015 by combining data from national household budget surveys with the Environmentally-Extended Multi-Regional Input-Output model EXIOBASE. We found a top-to-bottom decile ratio (90:10) of 7.2 for expenditure, 3.1 for net energy and 2.6 for carbon. The lower inequality of energy and carbon footprints is largely attributable to inefficient energy and heating technologies in the lower deciles (mostly Eastern Europe). Adopting best technology across Europe would save 11 EJ of net energy annually, but increase environmental footprint inequality. With such inequality, both targets can only be met through the use of CCS, large efficiency improvements, and an extremely low minimum final energy use of 28 GJ per adult equivalent. Assuming a more realistic minimum energy use of about 55 GJ/ae and no CCS deployment, the 1.5°C target can only be achieved at near full equality. We conclude that achieving both stated goals is an immense and widely underestimated challenge, the successful management of which requires far greater room for maneuver in monetary and fiscal terms than is reflected in the current European political discourse.

Introduction

Decarbonising the energy system in accordance with the Paris Agreement requires a deep transformation of both the supply and the demand side (1,2). On both sides, however, necessary transformation is restricted by different factors. On the supply side, there exist economic and physical upper limits of how much energy can be provided from renewable sources by 2050 on the one hand, and how much CO2 removal infrastructure is used to compensate for remaining emissions from fossil fuels on the other. On the demand side (3), by contrast, there are lower bounds on how much energy is minimally required for a decent standard of living (2,4), depending on existing non-energy infrastructures and services and assumptions about their future transformation (3), as well as the prevalent social ideas about what constitutes a decent life (4,5). Maximum energy supply and minimum energy use describe the corridor in which the simultaneous achievement of climate targets and a decent standard of living for all is possible and, at the same time, restricts the distribution of available energy services among the population. If this dual objective is taken seriously in European climate policy, then there are practical limits to how unequal the society of the future can be, which go beyond the purely political (6). In fact, a limited energy supply creates an obvious, if rarely acknowledged, zero-sum game where energetic over-consumption by some must be compensated by less consumption by others.

In Europe, the differences in household energy and carbon footprints are large within and between different regions (7–9). Final energy footprints ranged from less than 50 GJ per capita to over 200 GJ per capita in 2011 (9), and carbon footprints from below 2.5 tCO2eq per capita to 55 tCO2eq per capita (10). The published 1.5°C global decarbonisation scenarios also show very large differences in the assumed average per capita final energy consumption (15-100 GJ/capita) in 2050, depending on assumptions about how much energy is needed for a decent life, or how large the future supply will be (1,2,4).

In this paper, we assess under what conditions European energy use inequality is compatible with the achievement of global climate goals and a decent standard of living, taking both inequality within and between European countries into account. We analyze the distribution of energy and carbon footprints and intensities across European expenditure deciles and final consumption categories in 2015, and compare this structure to a counterfactual, where all European expenditure deciles use the best technology available in Europe in 2015. Finally, we examine how the energy inequality across European expenditure deciles would need to change in order to achieve the dual goal of climate protection and a decent standard of living for all.

While the European Green Deal recognizes that inequalities in income, energy infrastructure, energy consumption, and carbon emissions, lead to different responsibilities and capacities in achieving the energy and emission savings targets (11), a quantification of the corridor for a 1.5°C compatible and just transition in Europe is missing in the literature.

Materials and methods

Income-stratified national household energy and carbon footprints

We used the Environmentally-Extended Multi-Regional Input-Output (EE-MRIO) model EXIOBASE for 2015 (version3.7, industry-by-industry) (12) and the European national household budget survey (HBS) macro-data from EUROSTAT for 2015 (13) to calculate income-stratified national household energy and carbon footprints (together denoted as environmental footprints in this paper). The EUROSTAT HBS publishes mean household expenditure by income quintile, in purchasing power standards (PPS), by COICOP consumption category, country and year. We chose EXIOBASE as the EE-MRIO for this study because of its European focus, with nearly all countries in the EUROSTAT HBS also found as stand-alone countries in EXIOBASE, its detailed sectoral resolution and environmental extension data, and its year coverage.

To integrate HBS data into EXIOBASE we created correspondence tables between the EXIOBASE sectors and the matching COICOP consumption categories used in the HBS. To this end we used the relative expenditure shares of each income quintile on the COICOP consumption categories in the HBS to disaggregate the matching EXIOBASE national household final demand expenditure per sector by income quintile. Using standard input-output techniques we calculated 'total' (i.e. direct and indirect supply chain) energy and carbon intensities per EXIOBASE sector, and multiplied them with the income-stratified EXIOBASE national household final demand expenditure, to estimate the supply chain part of national household energy and carbon footprints by national income quintile.

We report energy footprints based on two different energy indicators. In our empirical results (Figures 1 to 3) we use the extension 'energy carrier net: total' from EXIOBASE, which includes final energy use and losses (14,15). This energy indicator represents primary energy and the resulting footprint is termed 'net energy footprint' in the rest of the paper. We use this indicator to capture the heterogeneity in the efficiency of energy supply and demand technologies across expenditure groups. For the calculation of the corridor (Figure 5) we use net energy without losses, which represents final energy, to be compatible with the supply and demand scenarios from the literature, which report final energy. The results from this indicator are termed 'final energy footprint.' Please note that the primary and final energy extensions we used in the model are not strictly equivalent to the indicators total primary energy supply and final energy from international energy statistics, because the former apply the residence principle while the latter apply the territorial principle (12,16).

For calculating the carbon footprint, we used the EXIOBASE greenhouse gas (GHG) emission extensions CO2, CH4, N2O, SF6, HFCs, and PFCs (all in CO2-equivalent), from combustion, non-combustion, agriculture and waste, but not land-use change (12). Direct household energy use and carbon emissions are included in the environmental footprints.

European household expenditure deciles

To calculate European household expenditure deciles, we first ranked the population weighted national income quintiles (140 in total: 28 European countries x 5 national income quintiles each) according to their mean household expenditure in PPS, and then aggregated the result to 10 European expenditure groups. For brevity we call these expenditure deciles, or simply deciles, through the rest of the paper. Our coverage of European countries is limited to those with data available in both the EUROSTAT HBS and EXIOBASE. This resulted in a country sample for 2015 that includes the non-European Union (EU) members, Norway and Turkey, and excludes the EU members Italy and Luxembourg.

Units of analysis

The unit of analysis for our energy and carbon footprint calculations is the household. We normalized our results to average adult equivalent per household, as this is the method used in the EUROSTAT HBS to account for different household sizes. The first adult in the household is given a weight of 1.0, each adult thereafter 0.5, and each child 0.3 (17).

To calculate the corridors for achieving the dual goal of climate protection and a decent standard of living for all, we converted the total (economy-wide) per capita final energy values from the scenario literature to household final energy footprints per adult equivalent using the following factors: For the average European share of total final energy footprint attributable to households in 2015, we used the factor 0.65, and for the average European adult equivalent to population ratio in 2015, a factor of 0.63 (see supplementary information (SI), 'Units of analysis' section). Numerically this results in almost identical values for per capita final energy and household final energy footprints per adult equivalent.

Estimates of minimum final energy use for a decent life are from (2) and (4), while maximum supply of decarbonised final energy compatible with the

1.5°C (and 2°C) target is from the decarbonisation scenarios in the International Institute for Applied Systems Analysis (IIASA) scenario database (1,18).

As inequality measure we use the 90:10 ratio, i.e. the expenditure or the environmental footprint of the top European expenditure decile divided by that of the bottom European expenditure decile. Thus, an expenditure 90:10 ratio of 5 means that one adult equivalent in the top decile spent 5 times more on average than one adult equivalent in the bottom decile.

Counterfactual

We construct a counterfactual energy distribution which applies the empirical best technology available in 2015 to remove differences in the efficiencies of energy supply and use across all expenditure deciles. Based on this, we calculate for each value combination of maximum final energy supply from four 1.5°C and one 2°C supply scenarios (1,18) and minimum energy use from two 1.5°C compatible demand scenarios (2) and (4), the maximum possible inequality as 90:10 ratio, in a way that preserves the relative distance between the deciles. All data, formulas and procedures are described in more detail in the SI.

Results and discussion

Environmental footprints are less unequal than expenditure

Increasing expenditure generally translated into larger environmental footprints across European expenditure deciles (Figures 1a-c). However, the energy and carbon inequality was much lower than the expenditure inequality, corroborating previous results (19). In our sample the top-to-bottom decile (90:10) ratio was 7.2 for expenditure, 3.1 for net energy and 2.6 for carbon. Total expenditure ranged from 0.2 trn€ to 1.3 trn€ between bottom and top decile, or 5263€ to 38110€ per adult equivalent (ae), the net energy footprint from 2.9 EJ to 9.0 EJ (or 86 GJ/ae to 270 GJ/ae), and the carbon footprint from 233 MtCO2eq to 607 MtCO2eq (or 7.0 tCO2eq/ae to 18.1 tCO2eq/ae).

The reason for this is evident from Figures 1d-f. Both the energy intensity of consumption, measured as net energy footprint per € expenditure (d), and the carbon intensity of energy, measured as carbon footprint per net energy footprint (f), decreased from bottom to top expenditure decile. The average net energy intensity of consumption decreased from 16.3 MJ/€ in the bottom decile to less than half (7.1 MJ/€) in the top decile. Likewise, the average carbon intensity of net energy was higher in the bottom decile (81 tCO2eq/TJ) compared to the top decile (67 tCO2eq/TJ). The carbon intensity of consumption in Figure 1e combines the effects of the intensities displayed in Figures 1d and 1f. For all intensities, the variance is highest in the bottom deciles (Figures 1d-f).

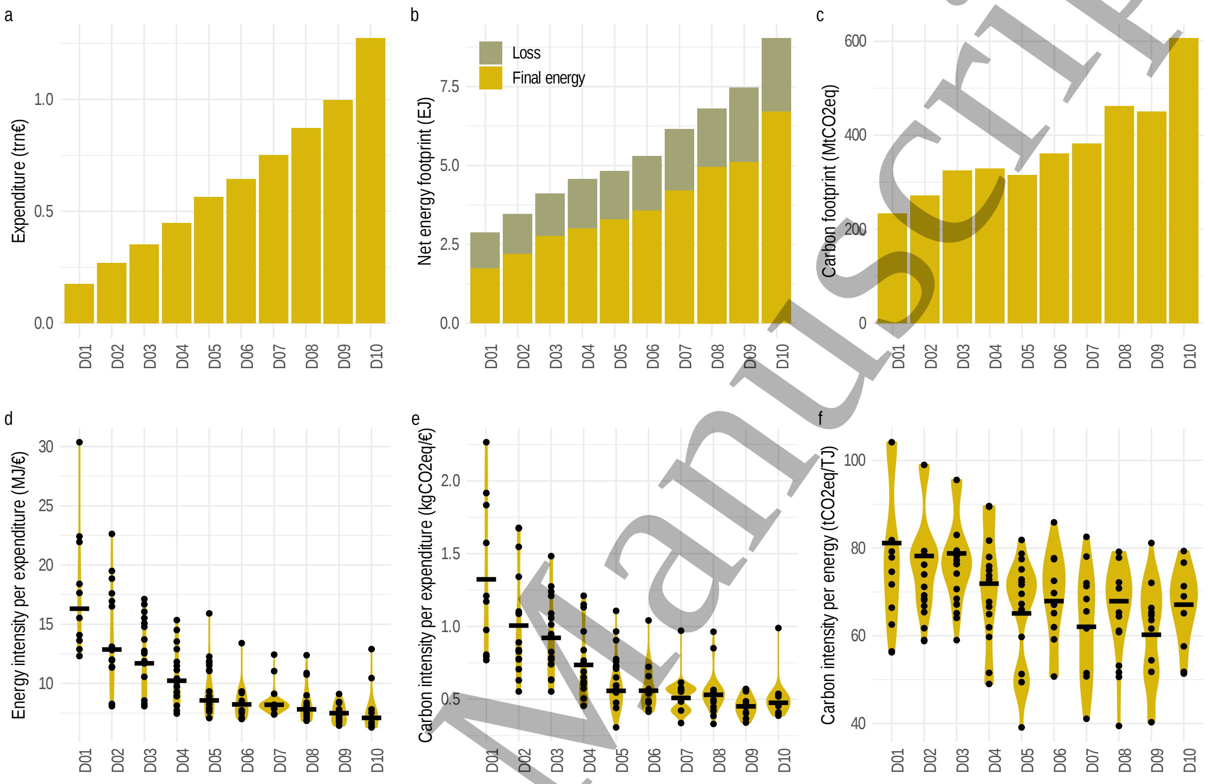

Figure 1: Household final demand expenditure and environmental footprints and intensities across European expenditure deciles. Total expenditures (a), net energy footprint (composed of final energy footprint and losses) (b), and carbon footprint (c) per decile. Energy intensity of consumption as net energy footprint per expenditure (d), carbon intensity of consumption as carbon footprint per expenditure (e), and carbon intensity of energy as carbon footprint per net energy footprint (f).

The different intensities of household consumption across European expenditure deciles can be attributed to a combination of two plausible causes: first, the composition of consumption baskets could systematically differ according to the level of household expenditure (20). Second, the energy and carbon intensity within individual final consumption categories could systematically differ across expenditure levels. Single country studies cannot usually capture this variation because, due to the homogeneous product assumption of input-output models, the national sectoral energy and carbon intensities are uniform. However, since household purchasing power is distributed very unequally across European countries, many

Eastern European households, for example, end up in the lower expenditure deciles and Scandinavian households tend to be in the higher ones (see SI, Figure S1). This allows us to capture part of the variance in energy and carbon intensities across European expenditure deciles (Figure 2).

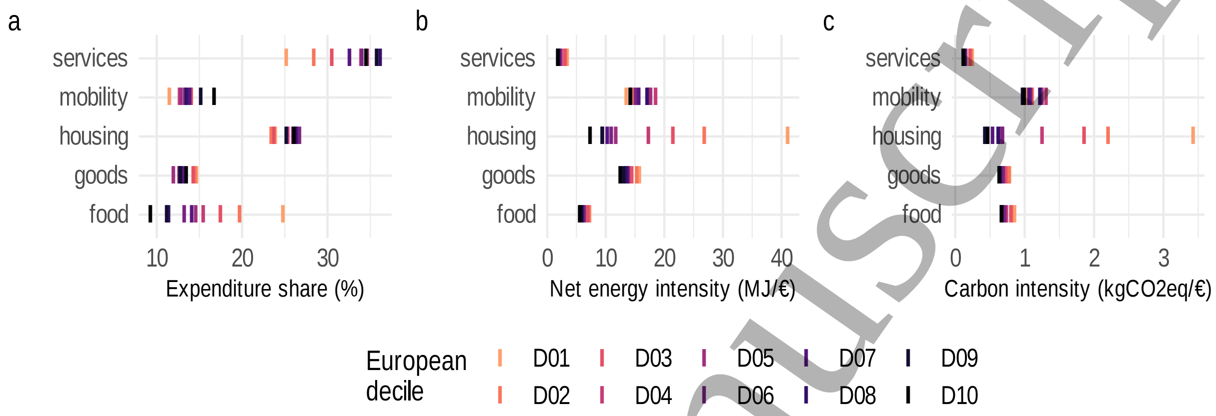

Figure 2: Final consumption category household expenditure shares (a) and environmental intensities (b and c) of European expenditure deciles.

In this regard, the housing sector stands out with a carbon intensity of consumption more than 6 times higher in the bottom decile (3.4 kgCO2eq/€) than in the top decile (0.5 kgCO2eq/€). Housing had the highest variance in energy and carbon intensity among expenditure deciles, and for the bottom deciles, it was the most energy and carbon intensive category. Overall, with increasing expenditure decile, the shares of mobility and services increased and the shares of food and goods decreased. Households in the top decile spent about 35% on services, which had the lowest energy and carbon intensities of all final consumption categories, compared to 25% in the bottom decile.

The tendency for energy and carbon intensity to decrease with increasing affluence has been reported at the global level between countries (21–24) and also within Europe (19,25,26). In many countries of Eastern Europe, more than 80% of households are in the bottom four expenditure deciles, while in many high-income countries the figure is less than 20% (see SI, Figure S1).

The high intensities in the bottom four European expenditure deciles can be attributed in large part to more inefficient and dirtier domestic energy supply and demand technologies for heating and electricity generation in Poland, Bulgaria, the Czech Republic, and Romania. Poland alone was responsible for about 40% of total coal combustion for heat production in Europe in 2015 (27), and had a higher average intensity of carbon per MJ of heat delivered than both Europe and the world (28). We did not account for energy subsidies here, but different subsidy levels in different countries could also influence energy and carbon intensities (29).

Inequality across final consumption categories

The five final consumption categories, housing, mobility, food, goods, and services, contributed very differently to the environmental footprint of European households in 2015 (Figure 3). On average, housing and mobility were the two largest categories, accounting for about two thirds of both the energy and carbon footprints. In addition, the sectoral footprint variation across the expenditure deciles was also high (Figure 3). For housing there was very little systematic difference between deciles in both the energy and the carbon footprint. The bottom four deciles even had higher carbon footprints from housing than most top deciles, which can be explained by the extreme differences in intensity shown in Figure 2. Mobility was the most unequal category, with footprints in the top decile 10 times higher than the bottom decile, corroborating findings in (10) and (9). Goods was the second most unequal final consumption category (90:10 ratios of 5.5 for energy, 5.4 for carbon), similar to services (90:10 ratios of 5.4 for energy and 4.9 for carbon) and then food (90:10 ratios of around 2 for both footprints).

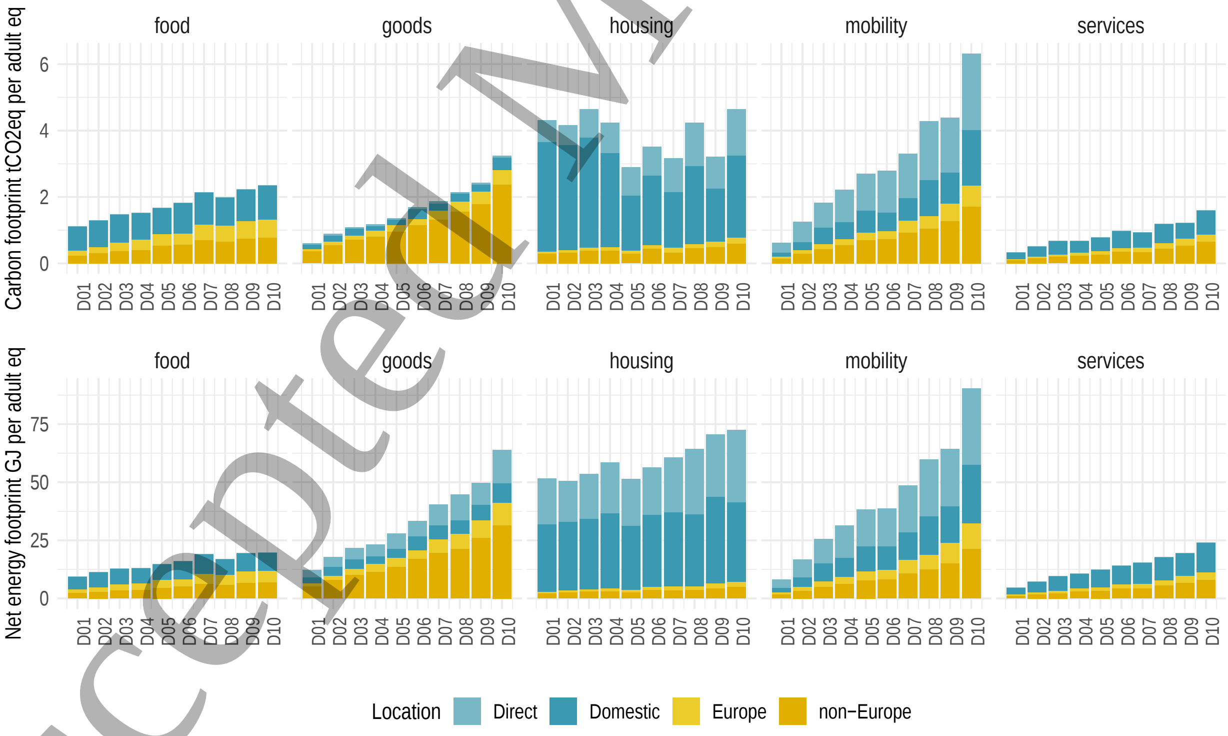

Figure 3: Household net energy and carbon footprints by final consumption category and European expenditure decile in 2015, further broken down by source and location. 'Direct' (direct energy use and carbon emissions from households) plus 'Domestic' (energy

use and carbon emissions along the domestic national supply chain) make up that part of the household footprint coming from within national borders, while 'Europe' is the part from other countries within the sample (plus Italy and Luxembourg), and 'non-Europe' from all other countries.

The geographical source of the energy and carbon footprints also varies by consumption category (Figure 3). The housing footprint was almost entirely domestic, with the direct environmental footprint for heating and cooling accounting for 20% for net energy use and 24% for carbon emissions, and the rest embedded primarily along the domestic supply chain. The mobility footprint, on the other hand, was around one fourth non-European. The majority of the mobility footprint came from vehicle fuel, either directly from households, or indirectly, i.e. embedded along the supply chain. The goods footprint was mostly non-European, while services and food were both around one third non-European. These results suggest that proposed future carbon border-adjustment mechanisms (11) will especially impact the mobility and goods footprints of the higher deciles, and to a lesser extent the food and services footprints.

A 1.5°C compatible Europe

Global 1.5°C compatible decarbonisation scenarios achieve a similar climate outcome with different assumptions about the transformation of energy supply and demand, from renewable capacity, and deployment of carbon-capture-and-storage (CCS), to socio-technological demand transformation. Table 1 shows some final energy values for the year 2050 from seven different decarbonisation scenarios, already converted from total GJ/capita to household GJ/adult equivalent. The original total GJ/capita scenario values are for different world regions (OECD, West EU, Global North, and Global), depending on the regional disaggregation of the scenarios, and so should not be interpreted as perfectly comparable with each other. For the purposes of our study, however, we are simply interested in the range of scenario values within which to situate our household environmental footprint results, presented below in the 'Inequality in a 1.5°C compatible Europe' section and in Figure 5.

Table 1: Decarbonisation scenarios. Scenario: Shared Socioeconomic Pathways (SSP) 1-1.9, 2-1.9, and 2-2.6 (2°C scenario) (1), IEA Energy Technology Perspectives Beyond 2 Degrees (IEA ETP B2DS) (2), Global Energy Assessment (GEA)-efficiency (18), Low Energy Demand (LED) (2), Decent Living Energy (DLE) (4). Type: distinction between supply-side and demand-side scenarios. GEA-efficiency categorized as a 'mix' due to some bottom-up quantifications of final energy demand in some sectors. Final energy in 2050: final energy estimates for 2050 per scenario, converted from total GJ/capita to household GJ/adult equivalent. The original total GJ/capita values are for different world regions (OECD, West EU, Global North, and Global), depending on the regional disaggregation of the scenarios.

Scenario	Type	Final energy in 2050: household GJ/adult equivalent
SSP2-2.6	supply-side	119
SSP2-1.9	supply-side	98
SSP1-1.9	supply-side	90
IEA ETP B2DS	supply-side	87
GEA-efficiency	mix	66
LED North	demand-side	55
LED global	demand-side	28
DLE	demand-side	16

The various global supply-side 1.5°C scenarios (SSP1-1.9, SSP2-1.9, GEA-efficiency, IEA ETP B2DS) (1,2,18) would see the European household final energy footprint falling from the 2015 level of 38 EJ to around 22-33 EJ by 2050, equivalent to a per adult equivalent reduction from a 2015 average of 112 GJ (final energy) to around 66-98 GJ. The differences in final energy in 2050 in the scenarios reflect different model assumptions about the rate of expansion of renewable energy, efficiency improvements and conservation, and CCS capacity. All these scenarios rely on CCS, which is still a fairly speculative technology, and we therefore interpret them as ranges for the upper limits of 1.5°C compatible energy supply (1,18).

It is more difficult to determine a lower limit for the minimum amount of energy use required for a decent standard of living. Such a lower limit depends strongly on the prevalent socio-cultural idea of what constitutes a decent life, and, perhaps even more strongly, on the physical infrastructure available to deliver this. The two global demand-side scenarios, Low Energy Demand (LED) (2) and Decent Living Energy (DLE) (4), that attempt to define such a limit conclude that, in principle, a very low household final energy use, between around 16-55 GJ/ae could be sufficient. However, these scenarios rely on socio-technological transformations on a scale that, especially at the lower end, far exceed the current political discourse on the subject. Both scenarios are 1.5°C compatible without resorting to any CCS but they implicitly (LED) (2) or explicitly (DLE) (4) assume near full equality of consumption across the population. To put these low energy numbers in perspective, the average household final energy footprint in our sample was 112 GJ per adult equivalent in 2015. The high estimate in the LED scenario is about the same as the final energy footprint of the bottom European expenditure decile (52 GJ/ae).

Based on these two constraints, the upper limit on the supply side and the lower limit on the demand side, it is possible to make a generalized estimate of how much inequality in the distribution of energy use is numerically possible, if at the same time global warming is to be kept below 1.5°C and a decent standard of living for all is to be made possible. Before we can make this evaluation, we must take into account the existing large differences in the technological efficiency of energy supply and use (Figure 2).

Counterfactual: empirical best technology per final consumption category

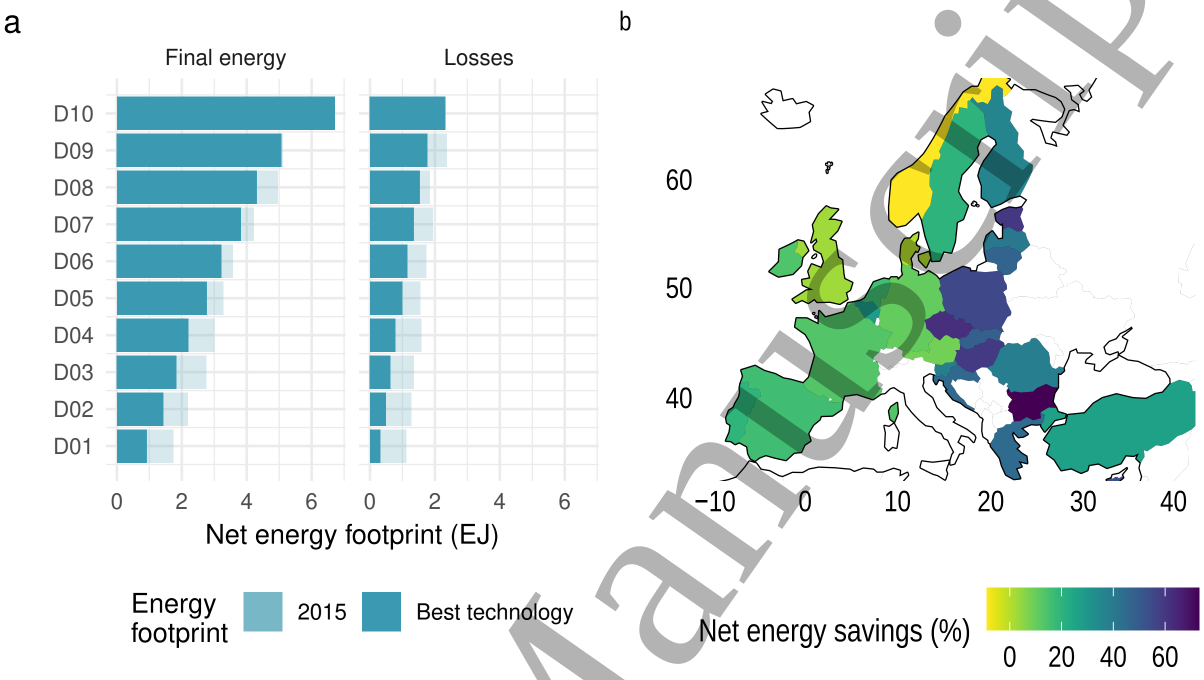

Figure 4: Energy savings if all deciles used the best technology per final consumption category available in 2015: by a) expenditure decile and b) country.

Our results show that in 2015, higher-income households in higher-income countries had access to the most energy-efficient energy services across the final consumption categories (Figure 2). Since we are interested in the largest numerically possible inequality in the distribution of energy footprints from actual household consumption, we calculated a counterfactual in which all European deciles use the best technology available in 2015 (Figure 4).

Around 11 EJ net energy would have been saved in total in 2015, if all deciles had the same energy intensity per final consumption category as the top decile (5.3 EJ from final energy and 5.7 EJ from avoided losses). The average net energy footprint would have been 131 GJ/ae instead of 164 GJ/ae, and the net energy footprint of the bottom decile would have been less than half (-57%) its 2015 value (Figure 4a) with a 47% reduction in final energy use and 72% fewer conversion losses. The saved energy would have been especially large in Eastern Europe, over 60% for Bulgaria and the Czech Republic for example (Figure 4b). Poland would have saved the most in absolute terms, at 1.8 EJ. Energy inequality would have been higher, at a 90:10 ratio of 7.3 (for both net and final energy; close to expenditure inequality, at 7.2, as the differences in intensity per decile are removed but differences in the consumption baskets remain), compared to our actual 2015 energy inequality estimate of a 90:10 ratio of 3.1 (net energy; 3.9 for final energy).

Inequality in a 1.5°C compatible Europe

Based on this counterfactual distribution of the energy footprint using homogeneous technologies, we scaled down the final energy footprint across European expenditure deciles to meet supply constraints on average and, where necessary, adjusted the distribution to not undershoot minimum energy use in any decile (Figure 5).

Both the DLE and LED scenarios satisfy final energy demand for a decent standard of living and are compatible with the 1.5°C target without resorting to CCS technologies (2,4). The DLE scenario explicitly envisions absolute global equality (a 90:10 ratio of 1) in energy consumption, except for small differences in required energy consumption based on climatic and demographic factors, as well as differences in population density (4). The LED scenario does not explicitly discuss distributional aspects beyond giving different final energy values for the Global North (around 55 household GJ/ae) and the Global South (around 21 household GJ/ae) (2). However, due to the bottom-up construction of these demand scenarios, these values can be interpreted as estimates for available final energy supply. The energy supply scenarios do not include specific details about how the energy footprints are distributed within countries (1,30). They achieve energy savings through the replacement of carbon-intensive fossil fuels by cleaner alternatives, efficiency improvements including the electrification of final energy, and some measures towards energy conservation (1).

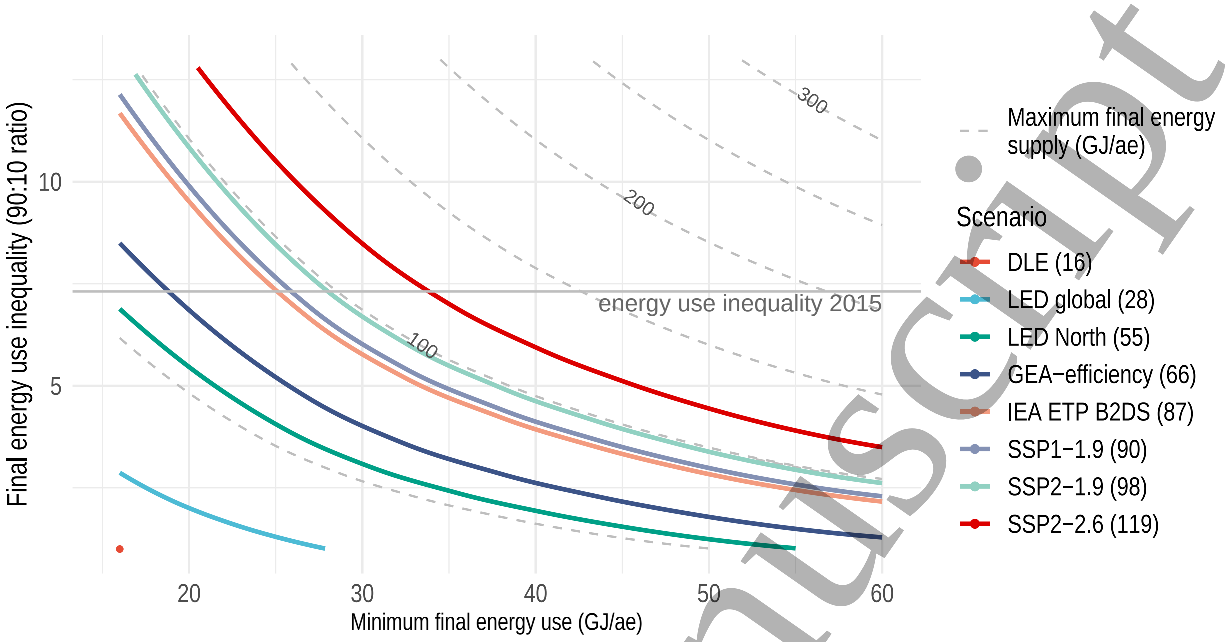

Figure 5: The maximum available average final energy supply (colored scenario lines and dashed elevation lines, in household GJ/adult equivalent) in the 1.5°C compatible scenarios, and for comparison one 2°C scenario (SSP2-2.6), together with the assumed minimum final energy use (household GJ/adult equivalent) for a decent life, determine the maximum level of final energy use inequality (expressed as 90:10 top-to-bottom decile ratio) while achieving both goals. Energy inequality was calculated for harmonized best technology per final consumption category.

The colored curves in Figure 5 represent constant average household final energy footprints according to the different scenarios. The slopes of the curves connect different assumptions about minimum final energy use for a decent life (on the x-axis) with the corresponding maximum final energy inequality that is consistent with the available final energy supply. The figure shows that at the 2015 inequality level, even the 1.5°C scenarios with high CCS deployment (SSP2-1.9, SSP1-1.9, IEA ETP B2DS) can only be achieved with extremely low minimum energy use assumptions (about 28 GJ/ae (LED, global average)). To achieve these scenarios with the still ambitious but much more realistic 55 GJ/ae (LED, Global North), the 90:10 ratio would need to be reduced by about two-thirds. The GEA-efficiency scenario would allow almost no inequality at this minimum energy use, and to achieve the SSP2-2.6 scenario, the 90:10 ratio would still need to be cut by about half.

Conclusions

Our empirical results show that the most obvious and urgent challenge is that the carbon and energy intensities of the poorest households, especially in Eastern Europe, must converge with those in the top expenditure deciles. In practice, this corresponds to the need for large-scale investments in the technical efficiency of heat, electricity and hot water supply and use (25). New and existing transition funds for lower-income countries need to be targeted, and at an appropriately large scale, to reduce the high intensities of consumption in the lower deciles (11,31). Improving technical efficiency is already a major part of EU policy. However, according to EUROSTAT, a majority of households in the lowest decile experience severe material deprivation (32), suggesting that their energy use would need to be increased to ensure a decent standard of living unless efficiency can be improved even further.

Even under the bold assumption that the energy and emission efficiencies of all expenditure deciles converge, and demand develops as in the 1.5°C scenarios, our results show that a drastic reduction in the inequality of energy footprints can only be avoided if either massive negative emissions or very low minimum final energy use for decent living standards are assumed, both of which present immense challenges.

The practical feasibility of achieving the necessary pace and scale of CCS deployment is highly contested. Actual deployment over the past 10 years has been very slow, with only 20 large scale facilities in operation in 2020, capturing in total only 40 million tons of CO2 (33). To mitigate CO2 emissions on the order of the 1.5°C-2°C scenarios with heavier CCS deployment, it has been estimated that the CCS industry would need to be more than twice the size of the current global oil industry in terms of volume by 2050 (34). High costs, safety and environmental concerns are further barriers to a rapid deployment of CCS (35–37).

Ensuring a decent standard of living for all at the targeted minimum final energy level of the demand-side scenarios (between around 16 to 55 household GJ per adult equivalent (2,4), down from an average of 112 household GJ/ae) requires a fundamental reorganization of almost all areas of life and economy. It seems hard to imagine how, for example, the living space per capita can be reduced from about $40m^2$ to $30m^2$ (LED) (2), let alone to $15m^2$ (DLE) (4), or that air travel can be capped at one short-to-medium-haul return flight every three years per person, which is an assumption behind the DLE scenario (4).

The key finding of our study, however, is that any increase in minimum energy use for a decent life, like any reduction in available energy supply, inevitably increases the need to redistribute the energy footprint across countries and expenditure groups, i.e. to reduce the energy use of the higher expenditure deciles ever more drastically. Achieving this seems at least as difficult politically. The idea of capping the energy use of higher-income households plays virtually no role in current climate and energy policy. Our results show that such strategies will be inevitable, unless very low minimum energy use of 28 GJ/ae plus heavy deployment of CCS are realized. Realistically, in addition to measures to reduce average environmental footprints, further instruments to reduce inequality in energy use and intensity must be developed to ensure a just transition that "leaves no one behind," as promised by the European Green Deal (11).

Particularly in the coming phase of necessary restructuring of the European economy, a social protection mechanism of whatever kind assuring a decent life will play a central role. However, the current institutions of Europe, and the eurozone in particular, offer their member states, especially the less prosperous ones where the challenges of a green transformation are greatest, little monetary or fiscal leeway to strengthen or introduce such measures. In the eurozone, implementation fails due to the lack of a common economic policy, as well as the fact that the European Central Bank (ECB) (unlike other central banks) only has a mandate to stabilize prices, but not to provide full employment or other effective means of social protection for European citizens (38). In general there is a great need for action to increase the scope for national and/or EU-wide policy making; both to ensure the social protection of citizens and to enable the necessary investments to restructure infrastructure and the economy (39).

Strong carbon pricing and progressive compensation schemes could have a positive distributional effect besides the effect on absolute emission reduction (40,41). In addition, other distribution and transfer instruments (42), such as wealth and inheritance taxes, or more progressive expenditure, consumption and income taxes (43), will have to be discussed in order to reduce the large differences in purchasing power within and between the countries of Europe, at least as long as expenditure remains coupled to environmental footprints (44).

Our study highlights the challenges largely implicit in the 1.5°C scenarios with respect to securing a decent standard of living for all, and provides further evidence that achieving this dual objective likely requires a shift in the current policy focus on growth in favor of decreasing environmental impacts and increasing social equity (44,45). Although our empirical investigation is limited to countries in Europe, we contend that our main conclusions apply in a similar or stronger form to the global achievement of climate and equity goals, as articulated in the sustainable development goals.

Associated Content

Data

All data, relevant tables, and fully reproducible R code are available at: https://gitlab.pik-potsdam.de/pichler/europe.inequality.

Author Information

Corresponding Author

*email: pichler@pik-potsdam.de

Author Contributions

I.S.J., P-P.P., and H.W. designed research; I.S.J. and P-P.P. performed research; I.S.J., P-P.P., J.T., and H.W. interpreted results; and I.S.J., P-P.P., J.T., and H.W. wrote the paper.

Notes

The authors declare no competing financial interest.

Acknowledgements

The publication of this article was partially funded by the Open Access Fund of the Leibniz Association. The authors thank Jakob Napiontek who provided valuable mathematical assistance and two reviewers for critically reading the manuscript and suggesting substantial improvements.

References

1. Riahi K, Vuuren DP van, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change. 2017 Jan;42:153–68.

2. Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum D, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy. 2018 Jun;3:517–25.

3. Creutzig F, Roy J, Lamb WF, Azevedo IML, Bruine de Bruin W, Dalkmann H, et al. Towards demand-side solutions for mitigating climate change. Nature Climate Change. 2018 Apr;8(4):260–3.

4. Millward-Hopkins J, Steinberger JK, Rao ND, Oswald Y. Providing decent living with minimum energy: A global scenario. Global Environmental Change. 2020 Nov;65:102168.

5. Rao ND, Min J, Mastrucci A. Energy requirements for decent living in India, Brazil and South Africa. Nature Energy. 2019 Dec;4(12):1025–32.

6. Leach M, Reyers B, Bai X, Brondizio ES, Cook C, Díaz S, et al. Equity and sustainability in the Anthropocene: A social–ecological systems perspective on their intertwined futures. Global Sustainability. 2018;1.

7. Ivanova D, Vita G, Steen-Olsen K, Stadler K, Melo PC, Wood R, et al. Mapping the carbon footprint of EU regions. Environmental Research Letters. 2017;12(5):054013.

8. Gore, T., Alestig, M. Confronting carbon inequality in the European Union. Oxfam International; 2020.

9. Oswald Y, Owen A, Steinberger JK. Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nature Energy. 2020 Mar;5(3):231–9.

10. Ivanova D, Wood R. The unequal distribution of household carbon footprints in Europe and its link to sustainability. Global Sustainability. 2020;3.

11. European Commission. Communication on The European Green Deal [Internet]. European Commission - European Commission. 2019 [cited 2020 Jul 6]. Available from: https://ec.europa.eu/info/publications/communication-european-green-deal_en

12. Stadler K, Wood R, Bulavskaya T, Södersten C-J, Simas M, Schmidt S, et al. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. Journal of Industrial Ecology. 2018;22(3):502–15.

13. Eurostat. Database - Household budget surveys - Eurostat [Internet]. 2021 [cited 2020 May 22]. Available from: https://ec.europa.eu/eurostat/web/household-budget-surveys/database

14. Usubiaga-Liaño A, Behrens P, Daioglou V. Energy use in the global food system. Journal of Industrial Ecology [Internet]. 2020 [cited 2021 Mar 31];24(4):830–40. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12982

15. Vita G, Rao ND, Usubiaga-Liaño A, Min J, Wood R. Durable Goods Drive Two-Thirds of Global Households' Final Energy Footprints. Environmental Science & Technology [Internet]. 2021 Mar [cited 2021 Mar 31];55(5):3175–87. Available from: https://doi.org/10.1021/acs.est.0c03890

16. Eurostat. Physical Energy Flow Accounts (PEFA): Manual 2014. Eurostat; 2014.

17. Eurostat. Description of the data transmission for the Household Budget Survey (HBS) for the Reference Year 2015 Version: 3 [Internet]. 2016. Available from: https://ec.europa.eu/eurostat/documents/54431/1966394/HBS2015_Transmission_DOC_V3.2018_05_22.pdf

18. IIASA. GEA Scenario database (public) [Internet]. 2012 [cited 2020 Oct 1]. Available from: https://tntcat.iiasa.ac.at/geadb/dsd?Action=htmlpage&page=about

19. Sommer M, Kratena K. The Carbon Footprint of European Households and Income Distribution. Ecological Economics. 2017;136(C):62–72.

20. Többen J. Regional Net Impacts and Social Distribution Effects of Promoting Renewable Energies in Germany. Ecological Economics [Internet]. 2017 May [cited 2021 Feb 26];135:195–208. Available from: https://www.sciencedirect.com/science/article/pii/S0921800916302178

21. Hubacek K, Baiocchi G, Feng K, Muñoz Castillo R, Sun L, Xue J. Global carbon inequality. Energy, Ecology and Environment. 2017 Dec;2(6):361–9.

22. Berthe A, Elie L. Mechanisms explaining the impact of economic inequality on environmental deterioration. Ecological Economics. 2015;116(Complete):191–200.

23. Scruggs L. Political and economic inequality and the environment. Ecological Economics. 1998;26(3):259–75.

24. Weber CL, Matthews HS. Quantifying the global and distributional aspects of American household carbon footprint. Ecological Economics. 2008 Jun;66(2–3):379–91.

25. Bianco V, Cascetta F, Marino A, Nardini S. Understanding energy consumption and carbon emissions in Europe: A focus on inequality issues. Energy. 2019 Mar;170:120–30.

26. Kerkhof AC, Benders RMJ, Moll HC. Determinants of variation in household CO2 emissions between and within countries. Energy Policy. 2009;37(4):1509–17.

27. Eurostat. Eurostat - Data Explorer - Production of electricity and derived heat by type of fuel [Internet]. 2021 [cited 2020 Oct 1]. Available from: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_peh&lang=en

28. Werner S. International review of district heating and cooling. Energy. 2017 Oct;137:617–31.

29. Sovacool BK. Reviewing, Reforming, and Rethinking Global Energy Subsidies: Towards a Political Economy Research Agenda. Ecological Economics. 2017 May;135:150–63.

30. Rao ND, Ruijven BJ van, Riahi K, Bosetti V. Improving poverty and inequality modelling in climate research. Nature Climate Change. 2017 Dec;7(12):857–62.

31. European Commission. The European Green Deal Investment Plan and JTM explained [Internet]. European Commission - European Commission. 2020 [cited 2020 Aug 7]. Available from: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_24

32. Eurostat. Living conditions in Europe - material deprivation and economic strain - Statistics Explained [Internet]. 2020 [cited 2021 Jan 23]. Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Living_conditions_in_Europe_-_material_deprivation_and_economic_strain

33. IEA. CCUS in Clean Energy Transitions [Internet]. IEA, Paris; 2020. Available from: https://www.iea.org/reports/ccus-in-clean-energy-transitions

34. Mac Dowell N, Fennell PS, Shah N, Maitland GC. The role of CO 2 capture and utilization in mitigating climate change. Nature Climate Change [Internet]. 2017 Apr [cited 2021 Apr 14];7(4):243–9. Available from: https://www.nature.com/articles/nclimate3231

35. IEA. Five keys to unlock CCS investment [Internet]. IEA, Paris; 2018. Available from: https://www.iea.org/reports/five-keys-to-unlock-ccs-investment

36. Cuéllar-Franca RM, Azapagic A. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO2 Utilization [Internet]. 2015 Mar [cited 2021 Apr 13];9:82–102. Available from: https://www.sciencedirect.com/science/article/pii/S2212982014000626

37. Alcalde J, Flude S, Wilkinson M, Johnson G, Edlmann K, Bond CE, et al. Estimating geological CO 2 storage security to deliver on climate mitigation. Nature Communications [Internet]. 2018 Jun [cited 2021 Apr 13];9(1):2201. Available from: https://www.nature.com/articles/s41467-018-04423-1

38. European Parliament. The ECB’s Mandate: Perspectives on General Economic Policies, Study for the Committee on Economic and Monetary Affairs, Policy Department for Economic, Scientific and Quality of Life Policies. Luxembourg: European Parliament; 2020.

39. Lagarde C. Climate change and central banking [Speech]. 2021 Jan [cited 2021 Feb 23]; Available from: https://www.ecb.europa.eu/press/key/date/2021/html/ecb.sp210125 f87e826ca5.en.html

40. Klenert D, Mattauch L, Combet E, Edenhofer O, Hepburn C, Rafaty R, et al. Making carbon pricing work for citizens. Nature Climate Change. 2018 Aug;8(8):669–77.

41. Lamb WF, Antal M, Bohnenberger K, Brand-Correa LI, Müller-Hansen F, Jakob M, et al. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. Environmental Research Letters. 2020;

42. Gough I. Recomposing consumption: Defining necessities for sustainable and equitable well-being. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2017 Jun;375(2095):20160379.

43. Chancel L, Piketty, Thomas. Carbon and inequality: From Kyoto to Paris. Paris School of Economics. 2015;

44. Haberl H, Wiedenhofer D, Virág D, Kalt G, Plank B, Brockway P, et al. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: Synthesizing the insights. Environmental Research Letters. 2020;

681 45. D’Alessandro S, Cieplinski A, Distefano T, Dittmer K. Feasible
682 alternatives to green growth. Nature Sustainability. 2020 Apr;3(4):329–35.