



HAL
open science

Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency

Baptiste Andrieu, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, François Verzier

► To cite this version:

Baptiste Andrieu, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, François Verzier. Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency. *Environmental Science and Technology*, 2022, 56 (19), pp.13909-13919. 10.1021/acs.est.2c03462 . hal-03787921

HAL Id: hal-03787921

<https://hal.science/hal-03787921>

Submitted on 26 Sep 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

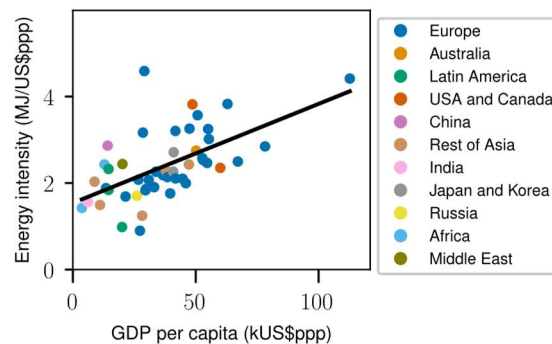
L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Energy intensity of final consumption: the richer, the poorer efficiency

Baptiste Andrieu*, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, François Verzier

Abstract

To maintain perpetual economic growth, most energy transition scenarios bet on a break in the historical relationship between energy use and gross domestic product (GDP). Practical limits to energy efficiency are overlooked by such scenarios, in particular the fact that high-income individuals tend to buy goods and services that are more energy intensive. Detailed assessments of the energy embodied in regional final consumption are needed to better understand the relationship between energy and GDP. Here, we calculate the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. We correct prices at the sector-level and account for the energy embodied in the whole value chain, including capital goods. We find that high-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.



Keywords

Energy efficiency, input-output, capital, gross domestic product (GDP), purchasing power parity (PPP)

Synopsis

This study uses a new approach to calculate regional energy intensities (energy per US\$ppp) and concludes that high-income regions are less energy-efficient than low-income ones.

1. INTRODUCTION

International treaties on climate change aim to hold global average temperature to well below 2°C above pre-industrial levels¹ while taking into account “the need to maintain strong and sustainable economic growth”², eluding the possibility of these imperatives being contradictory. Meeting climate mitigation targets requires to limit global energy demand, as the deployment of decarbonization technologies alone is not sufficient to reduce emissions at an adequate rate³. To allow continuous GDP (Gross Domestic Product) growth, scenarios thus rely on important energy intensity (energy use per unit of GDP) cuts. For the next decade, a yearly decrease of primary energy intensity from 2.4 to 6.8% is assumed³, breaking from historical trends of 1.5% for the 1990-2017 time period⁴. Not only does this hypothesis raise feasibility queries^{5,6}, but it also threatens some low-income regions to lack the energy required to maintain decent living standards⁶. In a context where resources of the global South are drained by the global North⁷ and environmental impacts are displaced through trade⁸, understanding precisely current differences in energy intensities is essential to assess the risks associated with scenarios.

Energy allows the production and exchange of services or goods. Its consumption increases together with income, which in turns provides wellbeing⁹, within certain limits (Easterlin paradox¹⁰). Although the emergence of ecological economics can be traced back to the 1970’s^{11,12}, most studies fail to consider energy as a central factor of production¹³. For example, most research on the energy-GDP interrelationship still do not account for energy embodied in trade^{13,14}. Many focus on the causality between both factors¹³ while some advocate that economic value will be decoupled from energy consumption. An edifying example is a study assuming the existence of a Kuznet’s curve between energy and GDP—an inverted U-shaped curve implying that total energy use tends to zero in an infinite economy—and predicting a peak of energy demand at US\$107,000 per capita¹⁵. Yet, to analyse energy intensities, it is essential to see energy neither as a cause or consequence of GDP, nor as an indicator independent of GDP, but as a provider of energy services¹⁶ which are subsequently estimated through the GDP prism. Energy intensity must therefore be understood as the ratio of all the energy necessary to produce a good or service divided by its associated value. This approach makes it necessary to study sector-level energy intensities as a function of affluence, to better pinpoint how different consumption patterns lead to unequal energy use^{17,18,19}.

So far, only three studies^{20,21,22} have carried out multi-sectoral and multi-regional comparisons of footprint energy intensities of goods and services. Oswald and colleagues¹⁹ have calculated sectoral final energy intensities and concluded that higher-income individuals tend to buy goods that are more energy intensive. Vita and colleagues²⁰ have established that energy footprints were mostly driven by durables (goods that are not purchased frequently). Chen and Wu have calculated energy intensities in 26 sectors of 186 regions and showed that intensities vary greatly between sectors.²² All three analyses account for the energy embodied in intermediate consumption but do not consider the capital goods used in the production process. If the footprint of a strawberry pie is thereby calculated, the energy embodied in the flour and in the strawberries will be accounted for, but not that necessary for the production of the bakery. It is significant because capital goods have a key role in footprint reallocation²³, representing up to two-thirds of the carbon footprint of specific sectors²⁴. Furthermore, as factories producing goods bought abroad are not accounted for, the footprints of regions that have delocalized their production are underestimated. Another limit to these studies is that they rely on country-level purchasing power parity (PPP)^{19,20} to eliminate national price level differences but not on sector-level PPP, hindering precise comparisons between product categories as different sectors in a given country have different PPPs²². For example, the PPP of the clothing sector in China is 77% above that of the Chinese average PPP, which in turn is 80% above that of the health sector²². Using the GDP-level PPP for China would thus underestimate the energy intensity of the clothing sector and overestimate that of the health sector. Finally, neither study reports the variations of energy intensity per category of product as a function of affluence (hereby defined as GDP per capita). This hampers to quantify the relationship between regional GDP and regional energy-intensity.

This study aims to calculate footprint energy intensities of households and governments' final consumption over 12 sectors in 49 world regions and compare them to affluence. To do so, we combine price level indexes with a multi-regional input-output (MRIO) database in which we endogenize capital.

2. MATERIALS AND METHODS

We calculate energy intensities according to three different definitions: production-based account, consumption-based account and final consumption account. We focus on final energy as it is closer to useful energy than primary energy^{14,26}. In the following, "energy" will thus refer to "final energy".

The production-based account (pba) energy intensity is the ratio of the energy used in a region by the households (E_{hh}) and by the local industries, (E_{pba}) divided by the GDP (Y) of that region calculated in \$PPP:

$$I_{pba} = \frac{E_{hh} + E_{pba}}{Y}$$

The consumption-based account (cba) energy use (E_{cba})^{27,28} is defined as the global energy used by industries to produce the GDP of a given region. The cba energy intensity (I_{cba}) is a better indicator of efficiency than (I_{pba}) as it accounts for the offshored energy use:

$$I_{cba} = \frac{E_{hh} + E_{cba}}{Y}$$

However, two limits are associated with I_{cba} 's calculation convention. First, in the classic input-output formalism, the energy used to produce capital goods is not imputed to the footprint of final consumption but to the gross fixed capital formation (GFCF), a measure of investment (Fig. 1a). If a factory is built in China to produce goods bought in the United States, the embodied energy of the factory is allocated to China's investments and not to the United-Sates. It follows that the energy necessary to produce the factory is omitted in the US footprint of final consumption expenditures. Second, E_{hh} is included in the calculation process of I_{cba} . However, E_{hh} is not in the input-output value chain and may have a different dynamic than E_{cba} .

To overcome these limits, we define the final consumption energy intensity (I_{fc}^K) as the ratio of the energy footprint of final consumption with capital endogenized (E_{fc}^K)—without accounting for E_{hh} — and the final consumption expenditures corrected for purchasing power parity (Y_{fc}):

$$I_{fc}^K = \frac{E_{fc}^K}{Y_{fc}}$$

The superscript K means that capital is endogenized. Capital endogenization consists in adding the consumption of fixed capital (CFC)—investments to replace end-of-life capital goods—to the input-output framework (Fig. 1b-c), thereby allocating the energy necessary to produce infrastructures to final consumption.

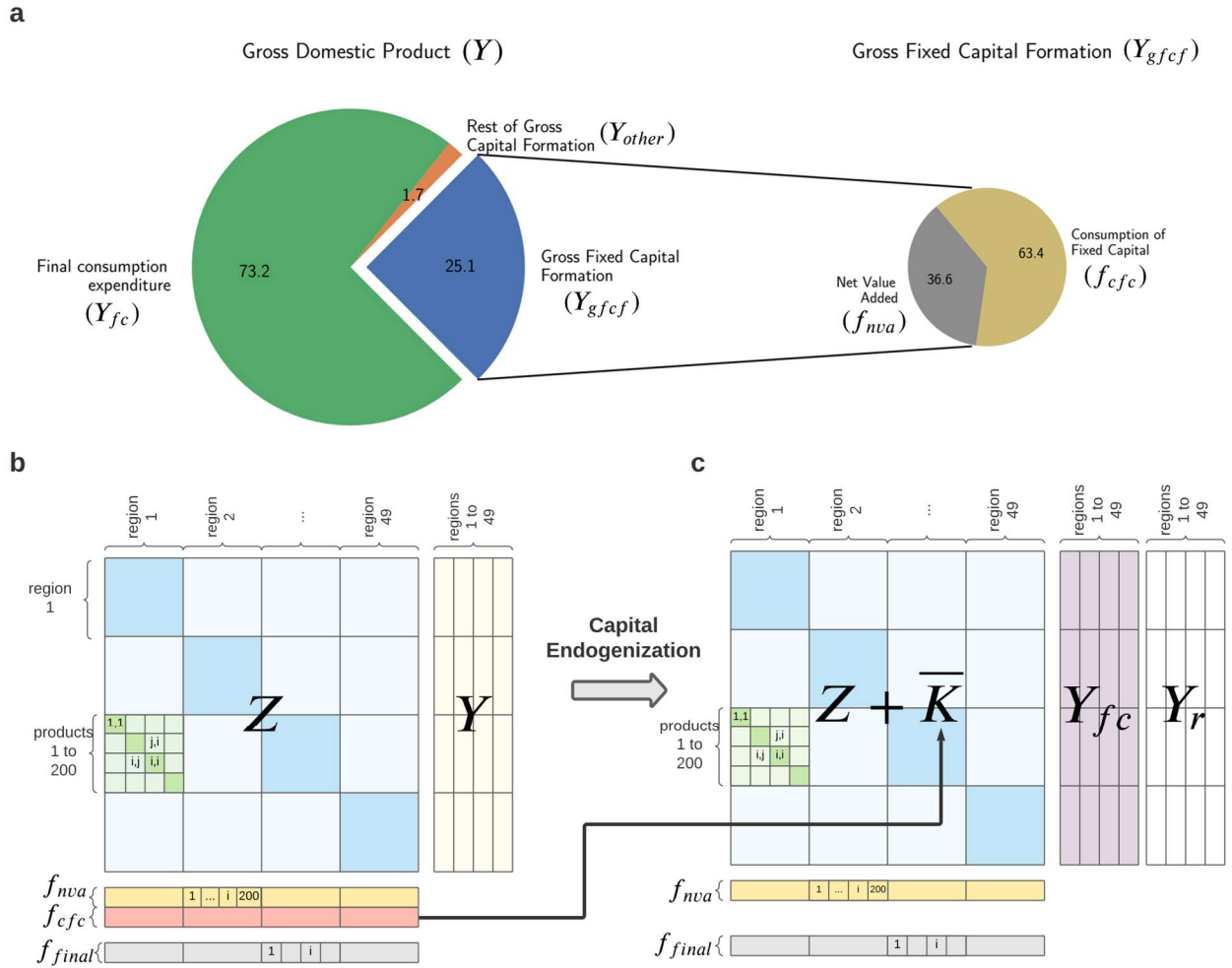


Figure 1. Input-output framework. **a**, GDP and GFCF decomposition. **b**, Input-output framework. Z is the transaction matrix, Y the final demand matrix, f_{nva} the net value-added vector, f_{cfc} the consumption of fixed capital vector and f_{final} the final energy extension. **c**, Input-output with capital endogenized. The consumption of fixed capital (f_{cfc}) is transformed into matrix \bar{K} and added to matrix Z . Y_{fc} is the final consumption by households and governments, Y_r is the residual final demand.

As a case example, results for these three types of energy intensities are compared for the two regions with extreme levels of affluence in EXIOBASE (Luxembourg and “Rest of Africa”, defined as the African continent without South Africa and Egypt). The choice to include or exclude E_{hh} in the calculation is then discussed based on regressions of E_{hh} per capita as a function of affluence and the share of E_{hh} in I_{cba} as a function of affluence.

We then test the results for correlations between energy intensities and affluence at an aggregated level (GDP level for I_{pba} and aggregated final consumption for I_{fc}^K). If there is a correlation, it can be explained either by a sector-level energy intensity and affluence correlation or by a change in final consumption composition with affluence. We evaluate how much each of the 12 sectors studied contribute to the change in energy intensity by calculating elasticities. Finally, we combine the dynamics of E_{hh} and I_{fc}^K as a function of affluence to estimate how much energy is associated with 1% of economic growth in each of the 49 regions.

Input-output

Input-output modelling allows to calculate the total industrial output (x) necessary to produce final demand Y . Z is the transaction matrix, representing the inter-industry transactions between sectors

and regions (for a detailed explanation of how Z is compiled, see Ref.²⁷ and supplementary information of Ref.²⁹). Z can be subdivided into 49*49 submatrices of dimensions 200*200 representing the flows of intermediate products between each pair of regions (Fig. 1b). Y contains vectors of final demand for each region. This final demand is disaggregated by sector and region of origin. The sum of a row of Z and Y gives the total output for a given sector in a given region. x thus writes:

$$x = Ze + Ye$$

with e a summation vector of appropriate dimension.

The direct requirement matrix A is defined as:

$$A = Z\hat{x}^{-1}$$

with $\hat{}$ meaning that the vector is diagonalized

We therefore have:

$$x = Ax + Ye$$

The Leontief inverse (L) is the inverse of matrix $(I - A)$, obtained when solving for x :

$$x = LYe$$

The production-based factors of production are given by matrix F . A row of F , called an extension, represents a given environmental or social impact associated with production. EXIOBASE3 provides several types of energy extensions. We build a final energy extension (f_{final}) by subtracting the extension "Energy Carrier Net LOSS" to the extension "Energy Carrier Net Total". For a discussion of the implications of different energy extension choices, see Ref.²⁵. The regional aggregation of f_{final} gives us E_{pba} .

The associated coefficients of production are given by:

$$s_{\text{final}} = f_{\text{final}}\hat{x}^{-1}$$

To obtain a region's consumption-based energy use ($E_{\text{cba,region}}$), we trace the total output associated to that region's GDP (Y_{region}) and multiply it by the coefficients of production. From the last two equations:

$$E_{\text{cba,region}} = s_{\text{final}}LY_{\text{region}}e$$

Capital endogenization

E_{fc}^K must be calculated using an input-output table with capital endogenized. Capital endogenization consists in allocating a share of the production of capital goods to final consumption expenditures. This share must be representative of how much capital goods are depreciated a given year due to the production of intermediate consumption. To do so, we choose to endogenize the consumption of fixed capital (CFC), defined as the decline in value of the capital stock due to normal wear and tear and obsolescence or normal accident damage²⁷.

Ref.²¹ built a capital transaction matrix \bar{K}_{15} with the same dimensions as Z , from the vector f_{cfc} of year 2015. Once added to Z , this matrix allows to consider CFC not as a sub-share of Y_{gfcf} (Fig. 1) but as intermediate consumption. A column total of \bar{K}_{15} equals CFC_{15} . To nowcast \bar{K}_{15} to 2017 using CFC_{17} , we transform it into a matrix of coefficients \bar{K}'_{15} with:

$$\bar{k}'_{i,j,15} = \frac{\bar{k}_{i,j,15}}{\sum_i \bar{k}_{i,j,15}}$$

where i is a row index and j a column index. \bar{K}_{17} is obtained by multiplying \bar{K}'_{15} by the f_{cfc} vector of year 2017 ($f_{cfc,17}$). EXIOBASE provides this extension. However, as pointed out by Ref.²⁸, inconsistencies exist between EXIOBASE and World Bank data for the ratio f_{cfc}/Y_{gfcf} . The World Bank gives an aggregate value per region of CFC (cfc^{WB}) and GFCF ($gfcf^{WB}$) which is deemed more reliable than EXIOBASE data²⁹. We therefore scale up $f_{cfc,17}$ by a scalar β for every region so that:

$$\frac{\sum_{products} Y_{gfcf,region}}{\beta_{region} \sum_{products} f_{cfc,region}} = \frac{gfcf_{region}^{WB}}{cfc_{region}^{WB}}$$

We thus obtain \bar{K}_{17} is the from coefficients $\bar{k}_{17,i,j}$:

$$\bar{k}_{17,i,j} = \bar{k}'_{15,i,j} \beta_j f_{cfc,17,j}$$

The mean of β values obtained is 0.99 but regional values range from 0.31 to 2.2, confirming the inconsistencies between both sources. \bar{K} is added to Z to have a total transaction matrix with capital endogenized. The direct requirement matrix with capital endogenized (A^K) is thus:

$$A^K = (Z + \bar{K})\hat{x}^{-1}$$

And the Leontief inverse with capital endogenized becomes:

$$L^K = (I - A^K)^{-1}$$

The total energy necessary to produce final consumption in a given region is thus:

$$E_{fc}^K = s_{final} L^K Y_{fc}$$

Purchasing power parities

Energy intensities are calculated using E_{pba} , E_{cba} , E_{fc}^K and economic data corrected for purchasing power parity. As I_{pba} and I_{cba} are calculated at an aggregated regional-level and not at the sector level, we directly use GDP data from Ref.²². For the EXIOBASE rest of the world regions, country-level data is aggregated using the python module `country_converter`³⁰.

However, I_{fc}^K is calculated at the sector level. We aggregate the 200 EXIOBASE products into the 12 sectors of the Classification of Individual Consumption According to Purpose (COICOP) as they are the ones used by the ICP. To do so, we modified the table of concordance built in Ref.³¹ in order to include all 200 EXIOBASE products. As differences exist between data in current dollars from EXIOBASE and ICP, we do not directly use ICP data in constant dollars but apply ICP price index to the EXIOBASE data. This prevents outliers to appear due to different sector allocations between EXIOBASE and ICP.

Elasticities

Elasticity is defined as the percentage change of a variable due to a percentage change of another variable. It can be calculated as the slope of a log-log regression, see Ref.²⁰ for proof. We consider an elasticity only if the coefficient of regression is higher than 0.2. In this section we give the equations used to calculate the contribution of each of the 12 sectors studied to the change in I_{fc}^K , both due to the change of I_{sect}^K (I_{fc}^K for a given sector) and to the change of this sector's share in final consumption expenditures (θ_{sect}).

Let ε_{sect}^I be the elasticity of I_{sect}^K as a function of affluence. It is obtained by the following regression, with a constant:

$$\log(I_{sect}^K) = \varepsilon_{sect}^I \log\left(\frac{Y}{pop}\right) + a$$

A variation of I_{sect}^K implies a variation of I_{fc}^K . We define η_{sect}^I as the percentage change of I_{fc}^K resulting from the variation of I_{sect}^K due to an increase of 1% of affluence. By definition of ε_{sect}^I and θ_{sect} :

$$\eta_{sect}^I = \frac{\varepsilon_{sect}^I I_{sect}^K \theta_{sect}}{I_{fc}^K}$$

Let $\varepsilon_{sect}^\theta$ be the elasticity of θ_{sect} as a function of affluence. It is obtained by the following regression, with b constant:

$$\log(\theta_{sect}) = \varepsilon_{sect}^\theta \log\left(\frac{Y}{pop}\right) + b$$

A variation of θ_{sect} also implies a variation of I_{fc}^K . We define η_{sect}^θ as the percentage change of I_{fc}^K resulting from the variation of θ_{sect} due to an increase of 1% of affluence. By definition of $\varepsilon_{sect}^\theta$ and θ_{sect} :

$$\eta_{sect}^\theta = \frac{\varepsilon_{sect}^\theta \theta_{sect} (I_{sect}^K - I_{fc}^K)}{I_{fc}^K}$$

Changes in I_{sect}^K for the 12 ICP sectors could be explained by changes of consumption patters in sub-sectors or changes in energy intensities in sub-sectors. To find out is such is the case, we apply the consumer price indexes to the 255 sub-sectors of the ICP sectors (some of the 200 exiobase sectors are disaggregated between several ICP sectors). We then look for correlations between sub sectors' share of expenditures and energy intensities as a function of GDP.

Energy associated with economic growth

Energy per capita (E_{cap}) is obtained by combining the regressions of E_{hh} and I_{fc}^K as a function of affluence multiplied by final consumption expenditures per capita:

$$E_{cap} = \exp\left(a \log\frac{Y}{pop} + b\right) + \frac{Y_{fc}}{pop} \left(c \frac{Y}{pop} + d\right)$$

With a, b, c and d, the coefficients obtained from the regressions. To calculate the impact of economic growth, we modify the intercepts of the regressions of the previous equation for each region. Otherwise, the results would not account for the dispersion of the data around the regression line. For each given region, we define b' and d' the modified intercepts of the regressions of E_{hh} and I_{fc}^K so that the lines with slopes a and c pass by that region's data point. Solving for the increase of E_{cap} due to 1% increase of Y and Y_{fc} gives:

$$\Delta E_{cap} = (1.01^a - 1)e^{b'} \left(\frac{Y}{pop}\right)^a + 0.01 \frac{Y_{fc}}{pop} \left(2.01c \frac{Y}{pop} + d'\right)$$

Data

Our calculations are based on EXIOBASE v3.8.2²⁹, an open-access MRIO database which represents the world economy divided between 200 products in 44 countries and 5 rest of the world regions. It contains many environmental extensions, including primary energy and energy loss, which allows to calculate a final energy environmental extension. As of this version, the energy data for year 2017 is a nowcast based on 2015 International Energy Agency (IEA) world energy balances³⁵. The trade and macroeconomic data for year 2017 has been estimated by EXIOBASE authors based on the original EXIOBASE3 data series for year 2011 and United Nations macroeconomic data for year 2017²⁹. The

data for capital endogenization is based on matrixes built by Södersten and colleagues²⁴ for year 2015 and was nowcasted to year 2017 using World Bank data³⁶. The sectoral PPPs come from the International Comparison Panel (ICP) 2017 cycle²⁵.

Limitations

The main limitations to this study are those inherent to input-output calculation³⁷. We chose EXIOBASE3 for this study in order to endogenize capital using existing matrixes. Existing input-output databases have been extensively compared and differ in their methodology, thus yielding differences in the results³⁸. However, these differences are limited—1-3% of difference for most regions and up to 20% for outlier countries—when comparing carbon emission accounts for the same base year³⁹. Uncertainties are also associated with the year of reference of our data. ICP data is compiled for year 2017 but EXIOBASE tables were compiled for year 2011 and updated using macro-economic data for year 2017. The reference year for the inter-industry capital requirement matrix is 2015³² and we updated it using World Bank and EXIOBASE data for year 2017. Important differences existed between EXIOBASE and World Bank CFC data (β values). Energy data is a now-cast from 2015 IEA data³⁵. Uncertainties are also associated with sector aggregation in input-output^{40,41}. However, we aggregate sectors only after calculating the footprint so matrix L is not impacted. Uncertainties do exist due to the conversion of EXIOBASE sectors to COICOP sectors as it is not possible to have an exact correspondence.

3. RESULTS AND DISCUSSION

3.1. Choosing the right indicator

Differences in energy intensities calculation methods are illustrated in figure 2 for the two EXIOBASE regions with extreme levels of affluence: Luxembourg and “Rest of Africa” (Africa excluding Egypt and South Africa). I_{pba} (Fig. 2a), I_{cba} (Fig. 2b) and I_{fc}^K (Fig. 2c) have respective values of 2.3, 2.4 and 4.4 MJ/US\$ppp in Luxembourg and 4.3, 4.9 and 1.4 MJ/US\$ppp in “Rest of Africa”. For these regions, the consumption-based and production-based approaches yield similar results, with the energy intensity of “Rest of Africa” being twice higher than that of Luxembourg. However, I_{fc}^K is two times higher than I_{cba} in Luxembourg and three times lower than I_{cba} in “Rest of Africa”. This difference is mostly due to E_{hh} which is accounted for in I_{cba} but not in I_{fc}^K —another difference being the share of final consumption in GDP—. E_{hh} represents 65% of I_{cba} in “Rest of Africa” but only 17% in Luxembourg, although E_{hh} per capita is four times lower in “Rest of Africa” than in Luxembourg.

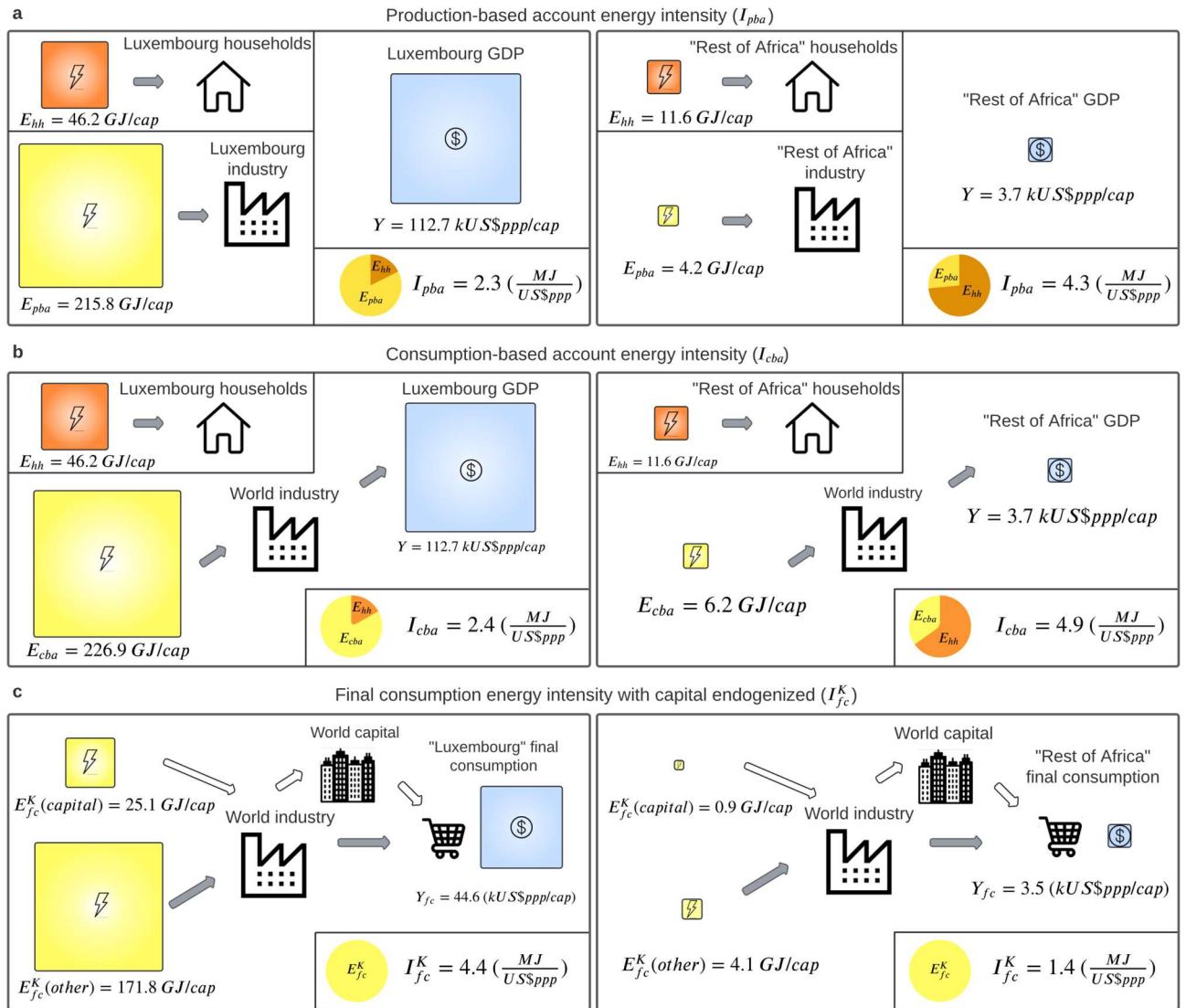


Figure 2. Energy intensity scopes. **a**, Production-based energy intensity (I_{pba}). **b**, Consumption-based energy intensity (I_{cba}). **c**, Final consumption energy intensity with capital endogenized (I_{fc}^K). **a-c**, Comparisons between richest and poorest EXIOBASE regions. "Rest of Africa" is the African continent less South Africa and Egypt. Open access pictograms from svgrepo.com.

This finding can be generalized to all EXIOBASE regions. Even though E_{hh} increases with affluence (Fig. 3a), its share in the total footprint of regions decreases with affluence (Fig. 3b). This change is due to the fact that even at very low levels of affluence (thus very low levels of final consumption energy footprint), direct energy is still used by individuals for survival or every day needs.

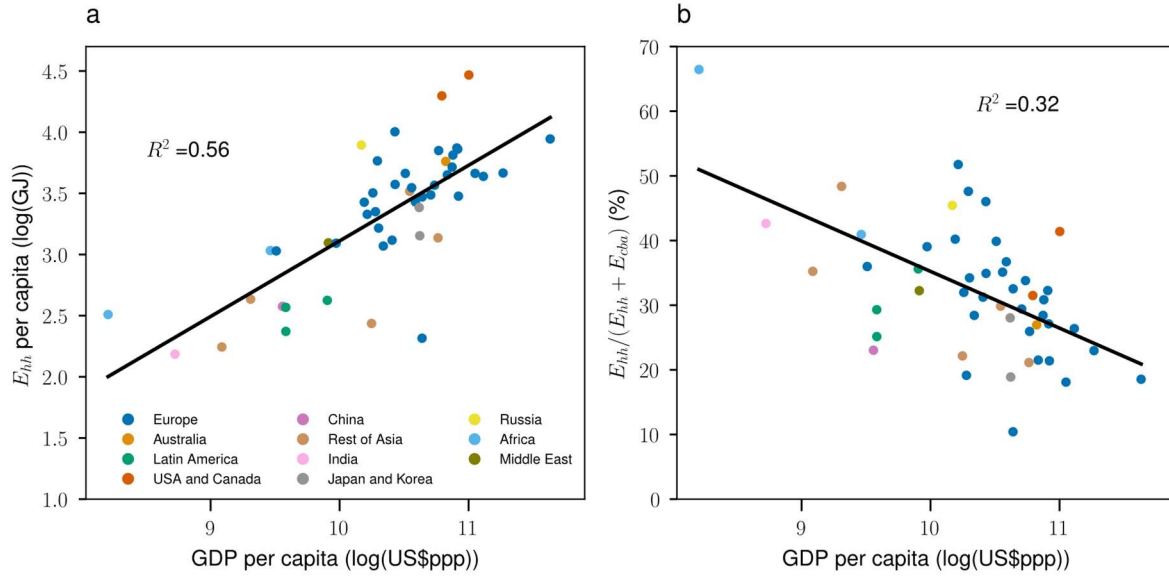


Figure 3. Households direct energy use (E_{hh}). **a**, Households direct energy use per capita (E_{hh} per capita). **b**, Share of households' direct energy use in consumption-based footprint ($\frac{E_{hh}}{E_{hh}+E_{cba}}$). **a-b**, Richer regions have higher per capita E_{hh} but the share of E_{hh} in the footprint decreases with affluence.

We argue that E_{hh} must be calculated separately from the energy intensity of GDP because it has a different dynamic. Oswald and colleagues²⁰ also found that “Heat and electricity”, the direct energy sector with the highest energy intensity, behaved fundamentally differently from others. Including E_{hh} in energy intensity calculation biases the results by inflating the energy intensity of poor regions more than that of wealthy ones. Energy intensities should therefore be analysed using I_{fc}^K and not I_{cba} . Using I_{cba} instead of I_{fc}^K could lead to major misinterpretations, such as concluding that Luxembourg is two times more efficient than “Rest of Africa” (Fig. 2b) whereas it is actually three times less efficient (Fig. 2c).

3.2. International energy intensity disparities

Regional values of I_{pba} are scattered but no trend is observed as a function of affluence ($R^2 < 0.2$) (Fig. 4a,d). In contrast, I_{fc}^K is higher in wealthier regions, with an elasticity of 0.27 (I_{fc}^K increases by 0.27% for every 1% increase of affluence) (Fig 4c,e). I_{pba} and I_{fc}^K are disaggregated for regions with extreme levels of affluence on figure 4b. I_{pba} is made of household direct energy use (in orange) and domestic production energy (in blue) whereas I_{fc}^K is only made of the footprint of final consumption (in grey).

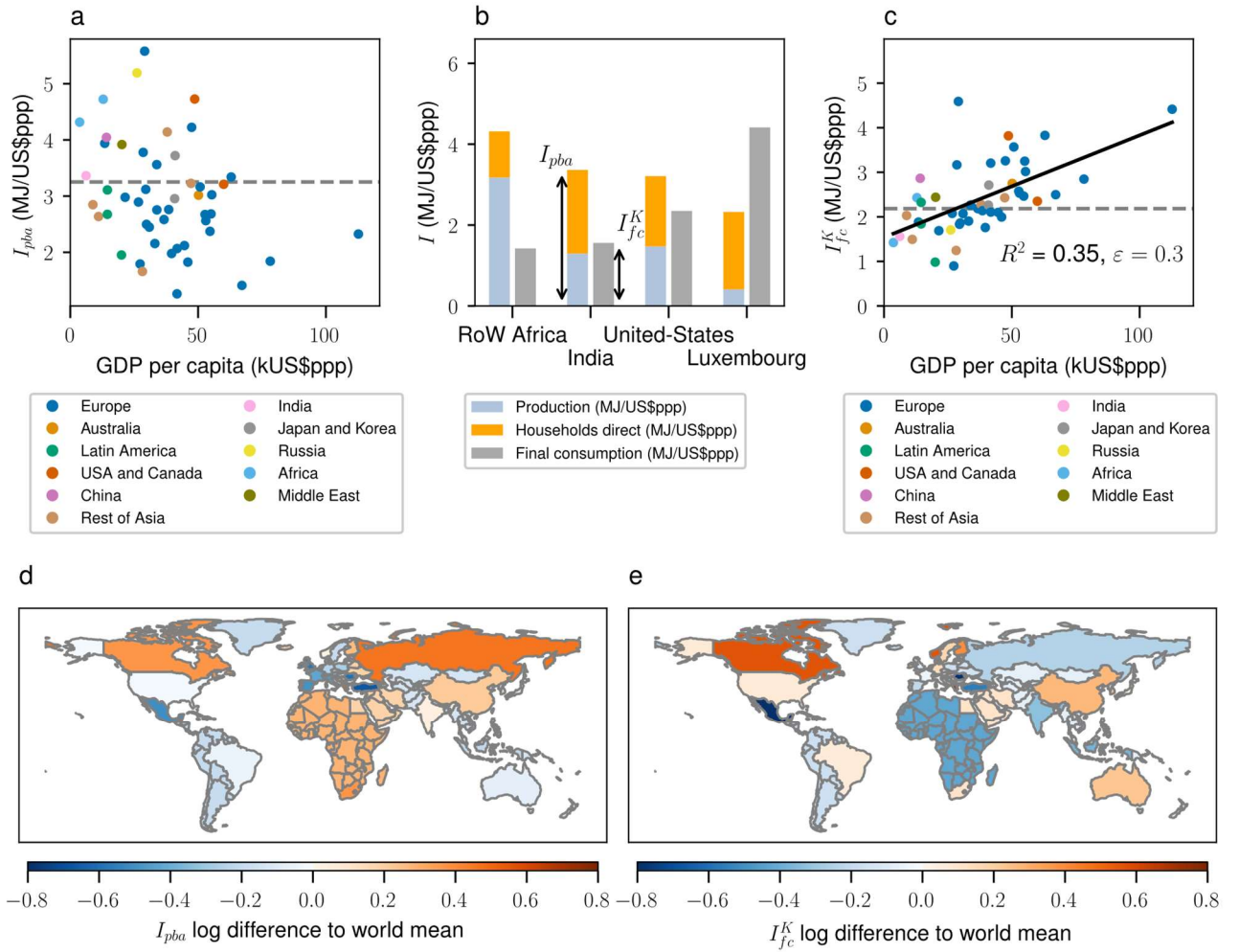


Figure 4. Energy intensity disparities. **a**, Production-based account energy intensity (I_{pba}) as a function of affluence. The dashed gray line represents the world value. Regional data (scattered dots) do not fit affluence ($R^2 < 0.2$). **b**, Energy intensity examples (I_{pba} and I_{fc}^K). **c**, Final consumption energy intensity with capital endogenized (I_{fc}^K) as a function of affluence. The dashed gray line represents the world value and the black line the linear fit. An elasticity (ϵ) of 0.27 is calculated. **d**, Log difference of I_{pba} to the world mean. **e**, Log difference of I_{fc}^K to the world mean. 20 of the 49 regions switch colors between the two maps.

Our results show that when calculating the energy intensity with capital endogenized, the energy intensity is higher in richer regions while Oswald and colleagues²⁰ found that it decreases slightly in richer regions. Three factors explain these differences: we consider the footprint of capital goods and of government final consumption expenditures, we do not consider households direct energy use, we study year 2017 and not 2011. Our results challenge the belief that richer regions are more efficient. One explanation is that economy-wide rebound effects can cut half of the gains from improved energy efficiency⁵. Another explanation could be that the energy efficiency gains in a region affects other regions in a globalized world economy. Indeed, if technologies are transferred, they can improve energy intensity of all regions at the same time and not only that of the wealthy ones. This is consistent with the fact that absolute decoupling of energy consumption and GDP (growth of GDP and degrowth of energy consumption)—though experienced in a limited number of regions—has been observed in regions with extremely low HDI and not only in high-income regions⁴². Vita and colleagues²¹ also found that over the period 1995-2011, energy efficiency was observed in 47 out of 49 studied regions, with very different affluence levels.

3.3. Sector-level energy intensities

The fact that I_{fc}^K scales with affluence can either be explained by increases of sector-level energy intensities (I_{sect}^K) with affluence, or by a change of composition of final consumption across regions. Only the housing, education and health sectors—representing respectively 19%, 15% and 7% of world final consumption—show a correlation between I_{sect}^K and affluence ($R^2 > 0.2$) (Table 1, Fig. 5). Their elasticities, ϵ_{sect}^I , defined as the percentage change of I_{fc}^K due to a change of I_{sect}^K resulting from an increase of affluence by 1%, are respectively of 0.08%, 0.02% and 0.02%. The increase of the energy intensity of these three sectors thus explains 45% of the total elasticity of I_{fc}^K , equal to 0.27% (Fig4c).

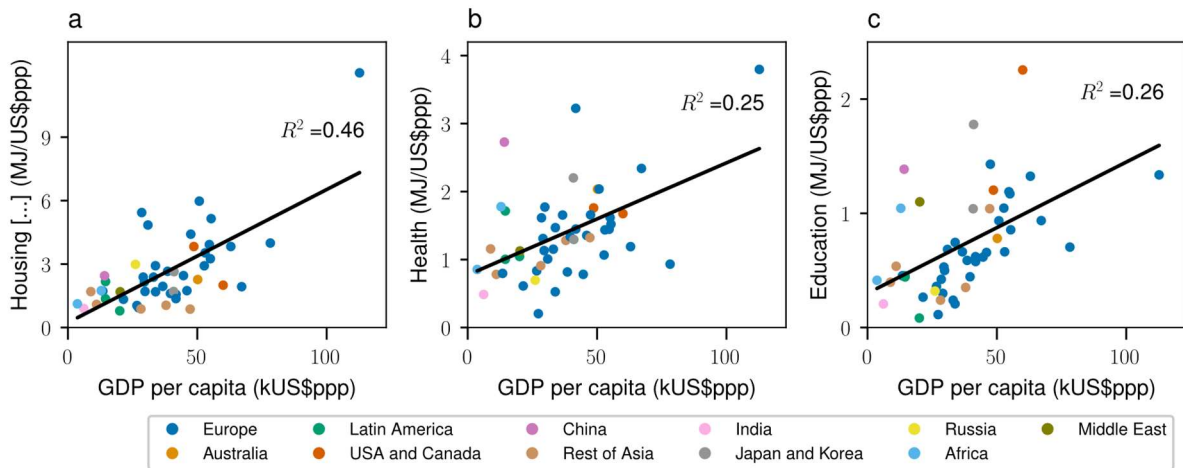


Figure 5. Sector level energy intensities. **a**, Housing, water, electricity, gas and other fuels sector. **b**, Health sector. **c**, Education sector. **a-c**, The black lines represent linear fits. The nine other sectors are not displayed as we obtained $R^2 < 0.2$.

The transport sector's share in final consumption ($\theta_{transport}$) is the only one correlated to affluence ($R^2 > 0.2$) (Extended Data Table 1, Fig. 6). For each 1% increase of affluence, $\theta_{transport}$ increases by 0.34%. As the energy intensity of the transport sector is higher than that of the world mean (Table 1, Fig. 4e), an increase in $\theta_{transport}$ translates by an increase of I_{fc}^K . The increase of I_{fc}^K due to an increase of $\theta_{transport}$ resulting from an increase of 1% of affluence is of 0.02%. This value represents 8% of the total elasticity of I_{fc}^K .

The four dynamics above-mentioned are significant as they explain 53% of the total elasticity, the twenty other dynamics (Table 1) explaining the 47 other % but with R^2 s under 0.2.

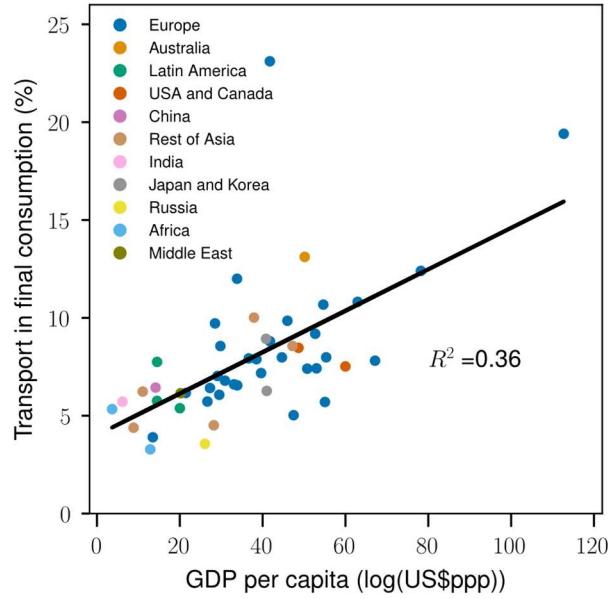


Figure 6. Share of transport sector in final consumption expenditures versus affluence. The black line represents the linear fit. The eleven other sectors are not displayed as we obtained $R^2 < 0.2$.

| | I_{sect}^K | | | | θ_{sect} | | | |
|--|--------------|-------|---------------------|-----------------|-----------------|-------|--------------------------|----------------------|
| | World value | R^2 | ϵ_{sect}^I | η_{sect}^I | World value | R^2 | ϵ_{sect}^θ | η_{sect}^θ |
| CPI: 01 - Food and non-Alcoholic beverages | 4 | 0,02 | 0,14 | 0,02 | 0,07 | 0,02 | -0,16 | -0,01 |
| CPI: 02 - Alcoholic beverages, tobacco and narcotics | 6,4 | 0,05 | -0,15 | 0 | 0,01 | 0,01 | -0,19 | 0 |
| CPI: 03 - Clothing and footwear | 5,2 | 0,08 | 0,19 | 0,01 | 0,02 | 0 | -0,19 | -0,01 |
| CPI: 04 - Housing, water, electricity, gas and other fuels | 1,8 | 0,46 | 0,48 | 0,08 | 0,19 | 0,17 | -0,17 | 0,01 |
| CPI: 05 - Furnishings, household equipment and routine household maintenance | 4,6 | 0,18 | 0,17 | 0,01 | 0,02 | 0,04 | -0,01 | 0 |
| CPI: 06 - Health | 1,5 | 0,25 | 0,3 | 0,02 | 0,07 | 0,07 | 0,15 | 0 |
| CPI: 07 - Transport | 4,6 | 0,02 | 0,27 | 0,04 | 0,07 | 0,36 | 0,34 | 0,02 |
| CPI: 08 - Communication | 1,4 | 0,01 | -0,02 | 0 | 0,04 | 0,08 | 0,41 | -0,01 |
| CPI: 09 - Recreation and culture | 3,1 | 0,04 | 0,09 | 0,01 | 0,06 | 0,01 | 0,1 | 0 |
| CPI: 10 - Education | 0,7 | 0,26 | 0,47 | 0,02 | 0,15 | 0,11 | -0,12 | 0,01 |
| CPI: 11 - Restaurants and hotels | 1,3 | 0,02 | 0,15 | 0,01 | 0,06 | 0 | -0,53 | 0,01 |
| CPI: 12 - Miscellaneous goods and services | 2 | 0,04 | 0,15 | 0,03 | 0,25 | 0,04 | 0,14 | 0 |

Table 1. Elasticities. R^2 refers to the coefficient of regression of I_{sect}^K and θ_{sect} as a function of affluence. The associated ϵ and η are used in the paper only if $R^2 > 0.2$ (colored lines).

Four sectors play a specific role in this energy intensity evolution. A first contribution comes from the transport sector, whose share in final consumption expenditures increases with affluence. As the energy intensity of this sector is twice higher than that of total final consumption, a higher share of transport sector implies a higher energy intensity. The energy intensity elasticities of housing, education and health sectors are positive, meaning that richer regions use more energy per dollar of

final consumption. However, the contribution to the increase of I_{fc}^K due to the housing sector is four times higher than that of the education and health sectors.

These sectors can be further disaggregated into exiobase sub-sectors. Out of 255 possible exiobase sub-sectors, only 12 had their expenditure shares of the CPI sector total which fitted as a function of GDP with $R^2 > 0.2$. Among these, none represented more than 4% of a CPI sector's total expenditures.

Moreover, 40 sub-sectors had their energy intensity which fitted as a function of GDP with $R^2 > 0.2$. Among these, only 7 represented more than 4% of a CPI sector's total expenditures, all fitting positively as a function of GDP. These included vegetables, fruit, nuts (14% of CPI 01), wearing apparel; furs (18% of CPI 03 total), real estate services (55% of CPI 04 total), public administration and defense services; compulsory social security services (15% of CPI 06 total), air transport services (7% of CPI 07 total), education services (65% of CPI 10 total) and retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (15% of CPI 10 total).

3.4. Total energy footprint

The total footprint energy per capita (Fig. 7) is obtained by combining the regression of E_{hh} per capita (Fig. 3a) and the regression of I_{fc}^K (Fig. 4c), multiplied by final consumption per capita. The black line of Fig. 7 is not linear because regions have a different share of final consumption in their GDP. Together, these two dynamics explain the differences in total footprint per capita between regions with a R^2 of 0.88 (Fig. 7).

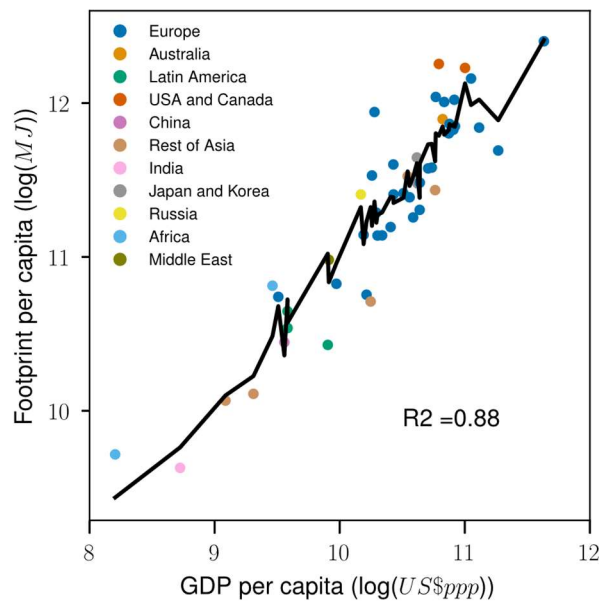


Figure 7. Total footprint energy per capita. Total footprint energy per capita scales with affluence ($R^2 = 0.88$). The black line is obtained by summing E_{hh} per capita from the regression of Fig. 3a and E_{fc}^K from the regression of Fig. 4e multiplied by final consumption expenditure per capita.

Economic growth is sometimes considered useful to reduce energy use as it could drive technological progress, thereby reducing overall energy use¹⁵. However, the first consequence of economic growth is to produce more goods and services. We quantify the regional increase in energy footprint per capita due to 1% of economic growth for year 2017, independently of technological progress (Fig. 8). In 2017, 9.2% of global population still lived in extreme poverty⁴³. We show that the energy associated with 1% of economic growth is 27 times higher in the richest region studied than in the poorest, meaning that supplementary energy use would have much more impact if used for the Global South than for the

Global North. This corroborates similar work on carbon emissions which has shown that eradicating world poverty would increase global carbon emissions by less than 2.1%⁴⁴ or that a re-composition of consumption could reduce by 16% overall emissions while allowing a rise in consumption for those earning the less⁴⁵. Equity in energy use would reduce poverty and shift energy use from luxury and transport to subsistence and necessities⁴⁶.

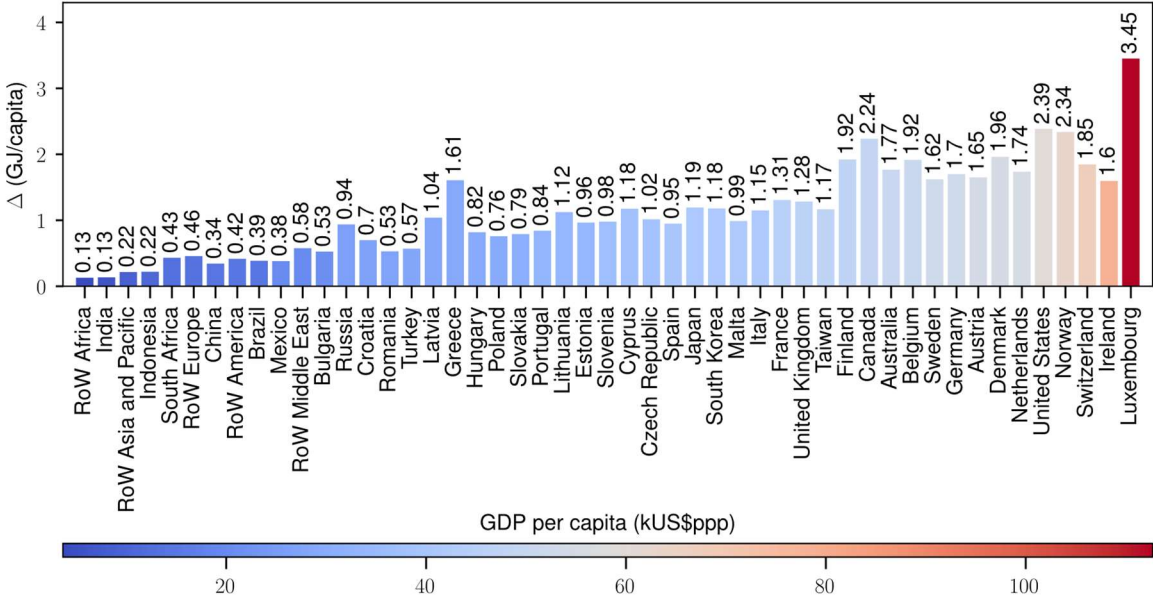


Figure 8. Energy per capita associated with 1% of economic growth. Bars represent the increase of energy footprint per capita if a region’s GDP increases by 1% for year 2017, that is without technological progress associated with time.

3.5. Implications for energy transition scenarios

Conceptually, the energy intensity of final consumption—calculated by using sectoral purchasing power parities and considering capital goods—is the most interesting definition of energy intensity as it is the closest to the thermodynamic meaning of embodied energy. This indicator increases with GDP per capita, meaning that richer regions are less efficient than poorer ones. This contradicts the common belief that a higher GDP is correlated with a better efficiency and corroborates existing research questioning the plausibility of a break in the historical energy intensity trend^{5,6,47}. Though potential of improvement is still considerable^{48,49}, economy-wide rebound effects^{5,50}, costly investments^{51,52,53} and adaptation to climate change⁵⁴ may limit our ability to reduce energy intensity as fast as it is planned in reference scenarios⁶.

We call for the authoritative scenario makers to stop speculating on energy intensity reduction and to produce prudential scenarios in which environmental and social targets are met no matter the energy intensity. Mathematically, it means that some regions must be prepared to limit their economic growth. Energy scenarios must focus on sufficiency⁵⁵ in order to meet everyone’s basic needs^{56,57}, even if this implies limiting the luxury consumption of a rich minority²⁰. The choice of the regions whose economic growth must be limited should take place in the context of common but differentiated responsibilities to tackle climate change² and within a specific framework of energy justice⁵⁸. A solution could be to achieve absolute convergence between Global South and Global North energy use per capita⁷. We go even further and argue that the Global South must temporarily have more access to

energy per capita to build the infrastructure already built in the Global North⁵⁹. If there is a break in the historical data due to breakthrough technologies, then growth in every region could become an option again but climate action would not have been jeopardized by exogenously-fixed economic growth.

ASSOCIATED CONTENT

The python code, correspondence tables and data used for the figures are available at: [baptiste-an/The-richer-the-poorer \(github.com\)](https://github.com/baptiste-an/The-richer-the-poorer)

AUTHOR INFORMATION

Corresponding author

Baptiste Andrieu – Institut de Sciences de la Terre (ISterre), CNRS-University of Grenoble, 1381 Rue de la Piscine, 38041 Grenoble, France; The Shift Project, 16-18, Rue de Budapest, 75009 Paris, France; <https://orcid.org/0000-0002-1485-3165>; Phone: +33 4 76 63 52 00; email: baptiste.andrieu@univ-grenoble-alpes.fr

Authors

Olivier Vidal – Institut de Sciences de la Terre (ISterre), CNRS-University of Grenoble, 1381 Rue de la Piscine, 38041 Grenoble, France

Hugo Le Boulzec – Institut de Sciences de la Terre (ISterre), CNRS-University of Grenoble, 1381 Rue de la Piscine, 38041 Grenoble, France; <https://orcid.org/0000-0003-3658-7715>

Louis Delannoy – Univ. Grenoble Alpes, CNRS, Inria, LJK, STEEP 38000 Grenoble, France; <https://orcid.org/0000-0002-5821-2597>

François Verzier – Institut de Sciences de la Terre (ISterre), CNRS-University of Grenoble, 1381 Rue de la Piscine, 38041 Grenoble, France ; [François Verzier \(0000-0003-1601-7301\) \(orcid.org\)](https://orcid.org/0000-0003-1601-7301)

Funding sources: The Shift Project, University Grenoble Alpes, CNRS.

ACKNOWLEDGMENTS

B.A. is grateful for the The Shift Project for the funding and fruitful exchanges, especially with Maxime Efoui-Hess. B.A. also thanks Anne-Laure Tournier for her fruitful comments. Finally, the authors are grateful for the time spent by the three anonymous reviewers to review this paper.

REFERENCES

- (1) UNFCCC. *Paris Agreement*; 2015.
- (2) UNFCCC. *United Nations Framework Convention on Climate Change*; 1992; p 33.
- (3) Gambhir, A.; Drouet, L.; McCollum, D.; Napp, T.; Bernie, D.; Hawkes, A.; Fricko, O.; Havlik, P.; Riahi, K.; Bosetti, V.; Lowe, J. Assessing the Feasibility of Global Long-Term Mitigation Scenarios. *Energies* **2017**, *10* (1), 89. <https://doi.org/10.3390/en10010089>.
- (4) Ahmad, T.; Zhang, D. A Critical Review of Comparative Global Historical Energy Consumption and Future Demand: The Story Told so Far. *Energy Reports* **2020**, *6*, 1973–1991. <https://doi.org/10.1016/j.egyr.2020.07.020>.
- (5) Brockway, P. E.; Sorrell, S.; Semieniuk, G.; Heun, M. K.; Court, V. Energy Efficiency and Economy-Wide Rebound Effects: A Review of the Evidence and Its Implications. *Renewable and Sustainable Energy Reviews* **2021**, *141*, 110781. <https://doi.org/10.1016/j.rser.2021.110781>.
- (6) Semieniuk, G.; Taylor, L.; Rezai, A.; Foley, D. K. Plausible Energy Demand Patterns in a Growing Global Economy with Climate Policy. *Nat. Clim. Chang.* **2021**, *11* (4), 313–318. <https://doi.org/10.1038/s41558-020-00975-7>.
- (7) Hickel, J.; Dorninger, C.; Wieland, H.; Suwandi, I. Imperialist Appropriation in the World Economy: Drain from the Global South through Unequal Exchange, 1990–2015.

- Global Environmental Change* **2022**, 73, 102467.
<https://doi.org/10.1016/j.gloenvcha.2022.102467>.
- (8) Wood, R.; Stadler, K.; Simas, M.; Bulavskaya, T.; Giljum, S.; Lutter, S.; Tukker, A. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3: Growth in Environmental Impacts Embodied in Trade. *Journal of Industrial Ecology* **2018**, 22 (3), 553–564.
<https://doi.org/10.1111/jiec.12735>.
 - (9) Kalt, G.; Wiedenhofer, D.; Görg, C.; Haberl, H. Conceptualizing Energy Services: A Review of Energy and Well-Being along the Energy Service Cascade. *Energy Research & Social Science* **2019**, 53, 47–58. <https://doi.org/10.1016/j.erss.2019.02.026>.
 - (10) Easterlin, R. A. Does Economic Growth Improve the Human Lot? Some Empirical Evidence. In *Nations and Households in Economic Growth*; David, P. A., Reder, M. W., Eds.; Academic Press, 1974; pp 89–125. <https://doi.org/10.1016/B978-0-12-205050-3.50008-7>.
 - (11) Georgescu-Roegen, N. *The Entropy Law and the Economic Process*; Harvard University Press, 2013. <https://doi.org/10.4159/harvard.9780674281653>.
 - (12) Cleveland, C. J. Biophysical Economics: Historical Perspective and Current Research Trends. *Ecological Modelling* **1987**, 38 (1–2), 47–73. [https://doi.org/10.1016/0304-3800\(87\)90044-5](https://doi.org/10.1016/0304-3800(87)90044-5).
 - (13) Wiedenhofer, D.; Virág, D.; Kalt, G.; Plank, B.; Streeck, J.; Pichler, M.; Mayer, A.; Krausmann, F.; Brockway, P.; Schaffartzik, A.; Fishman, T.; Hausknost, D.; Leon-Gruchalski, B.; Sousa, T.; Creutzig, F.; Haberl, H. A Systematic Review of the Evidence on Decoupling of GDP, Resource Use and GHG Emissions, Part I: Bibliometric and Conceptual Mapping. *Environ. Res. Lett.* **2020**, 15 (6), 063002.
<https://doi.org/10.1088/1748-9326/ab8429>.
 - (14) Haberl, H.; Wiedenhofer, D.; Virág, D.; Kalt, G.; Plank, B.; Brockway, P.; Fishman, T.; Hausknost, D.; Krausmann, F.; Leon-Gruchalski, B.; Mayer, A.; Pichler, M.; Schaffartzik, A.; Sousa, T.; Streeck, J.; Creutzig, F. A Systematic Review of the Evidence on Decoupling of GDP, Resource Use and GHG Emissions, Part II: Synthesizing the Insights. *Environ. Res. Lett.* **2020**, 15 (6), 065003.
<https://doi.org/10.1088/1748-9326/ab842a>.
 - (15) Bogmans, C.; Kiyasseh, L.; Matsumoto, A.; Pescatori, A.; Ferretti, G. M. M. Energy, Efficiency Gains and Economic Development: When Will Global Energy Demand Saturate? *IMF Working Papers* **2020**, 2020 (253).
<https://doi.org/10.5089/9781513561240.001.A001>.
 - (16) Fell, M. J. Energy Services: A Conceptual Review. *Energy Research & Social Science* **2017**, 27, 129–140. <https://doi.org/10.1016/j.erss.2017.02.010>.
 - (17) Galvin, R.; Sunikka-Blank, M. Economic Inequality and Household Energy Consumption in High-Income Countries: A Challenge for Social Science Based Energy Research. *Ecological Economics* **2018**, 153, 78–88.
<https://doi.org/10.1016/j.ecolecon.2018.07.003>.
 - (18) Shove, E.; Walker, G. What Is Energy For? Social Practice and Energy Demand. *Theory, Culture & Society* **2014**, 31 (5), 41–58.
<https://doi.org/10.1177/0263276414536746>.
 - (19) Chen, G. Q.; Wu, X. D.; Guo, J.; Meng, J.; Li, C. Global Overview for Energy Use of the World Economy: Household-Consumption-Based Accounting Based on the World Input-Output Database (WIOD). *Energy Economics* **2019**, 81, 835–847.
<https://doi.org/10.1016/j.eneco.2019.05.019>.
 - (20) Oswald, Y.; Owen, A.; Steinberger, J. K. Large Inequality in International and Intranational Energy Footprints between Income Groups and across Consumption

- Categories. *Nat Energy* **2020**, 5 (3), 231–239. <https://doi.org/10.1038/s41560-020-0579-8>.
- (21) Vita, G.; Rao, N. D.; Usubiaga-Liaño, A.; Min, J.; Wood, R. Durable Goods Drive Two-Thirds of Global Households' Final Energy Footprints. *Environ. Sci. Technol.* **2021**, 55 (5), 3175–3187. <https://doi.org/10.1021/acs.est.0c03890>.
 - (22) Chen, G. Q.; Wu, X. F. Energy Overview for Globalized World Economy: Source, Supply Chain and Sink. *Renewable and Sustainable Energy Reviews* **2017**, 69, 735–749. <https://doi.org/10.1016/j.rser.2016.11.151>.
 - (23) Wu, X.; Li, C.; Guo, J.; Wu, X.; Meng, J.; Chen, G. Extended Carbon Footprint and Emission Transfer of World Regions: With Both Primary and Intermediate Inputs into Account. *Science of The Total Environment* **2021**, 775, 145578. <https://doi.org/10.1016/j.scitotenv.2021.145578>.
 - (24) Södersten, C.-J. H.; Wood, R.; Hertwich, E. G. Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting. *Environ. Sci. Technol.* **2018**, 52 (22), 13250–13259. <https://doi.org/10.1021/acs.est.8b02791>.
 - (25) World Bank. *Purchasing Power Parities and the Size of World Economies: Results from the 2017 International Comparison Program*; World Bank: Washington, DC, 2020. <https://doi.org/10.1596/978-1-4648-1530-0>.
 - (26) Mastrucci, A.; Min, J.; Usubiaga-Liaño, A.; Rao, N. D. A Framework for Modelling Consumption-Based Energy Demand and Emission Pathways. *Environ. Sci. Technol.* **2020**, 54 (3), 1799–1807. <https://doi.org/10.1021/acs.est.9b05968>.
 - (27) Miller, R. E.; Blair, P. D. *Input-Output Analysis: Foundations and Extensions*; Cambridge University Press, 2009.
 - (28) Owen, A.; Brockway, P.; Brand-Correa, L.; Bunse, L.; Sakai, M.; Barrett, J. Energy Consumption-Based Accounts: A Comparison of Results Using Different Energy Extension Vectors. *Applied Energy* **2017**, 190, 464–473. <https://doi.org/10.1016/j.apenergy.2016.12.089>.
 - (29) Stadler, K.; Wood, R.; Bulavskaya, T.; Södersten, C.-J.; Simas, M.; Schmidt, S.; Usubiaga, A.; Acosta-Fernández, J.; Kuenen, J.; Bruckner, M.; Giljum, S.; Lutter, S.; Merciai, S.; Schmidt, J. H.; Theurl, M. C.; Plutzar, C.; Kastner, T.; Eisenmenger, N.; Erb, K.-H.; de Koning, A.; Tukker, A. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3. *Journal of Industrial Ecology* **2018**, 22 (3), 502–515. <https://doi.org/10.1111/jiec.12715>.
 - (30) *Glossary | DataBank*. <https://databank.worldbank.org/metadataglossary/world-development-indicators/series/NE.EXP.GNFS.CD> (accessed 2022-02-24).
 - (31) Södersten, C.-J.; Wood, R.; Wiedmann, T. The Capital Load of Global Material Footprints. *Resources, Conservation and Recycling* **2020**, 158, 104811. <https://doi.org/10.1016/j.resconrec.2020.104811>.
 - (32) Södersten, C.-J. Capital Use Matrices, 2020. <https://doi.org/10.5281/zenodo.3874309>.
 - (33) Stadler, K. The Country Converter Coco - a Python Package for Converting Country Names between Different Classification Schemes. *Journal of Open Source Software* **2017**, 2 (16), 332. <https://doi.org/10.21105/joss.00332>.
 - (34) Castellani, V.; Beylot, A.; Sala, S. Environmental Impacts of Household Consumption in Europe: Comparing Process-Based LCA and Environmentally Extended Input-Output Analysis. *J Clean Prod* **2019**, 240, 117966. <https://doi.org/10.1016/j.jclepro.2019.117966>.
 - (35) *World Energy Balances – Analysis*. IEA. <https://www.iea.org/reports/world-energy-balances-overview> (accessed 2022-03-10).

- (36) *World Development Indicators | DataBank*.
<https://databank.worldbank.org/reports.aspx?source=2&series=NY.ADJ.DKAP.CD&country=> (accessed 2022-03-10).
- (37) Rodrigues, J. F. D.; Moran, D.; Wood, R.; Behrens, P. Uncertainty of Consumption-Based Carbon Accounts. *Environ. Sci. Technol.* **2018**, *52* (13), 7577–7586.
<https://doi.org/10.1021/acs.est.8b00632>.
- (38) Owen, A. Discussion. In *Techniques for Evaluating the Differences in Multiregional Input-Output Databases: A Comparative Evaluation of CO₂ Consumption-Based Accounts Calculated Using Eora, GTAP and WIOD*; Owen, A., Ed.; Springer International Publishing: Cham, 2017; pp 167–184. https://doi.org/10.1007/978-3-319-51556-4_6.
- (39) Wood, R.; Moran, D. D.; Rodrigues, J. F. D.; Stadler, K. Variation in Trends of Consumption Based Carbon Accounts. *Sci Data* **2019**, *6* (1), 99.
<https://doi.org/10.1038/s41597-019-0102-x>.
- (40) de Koning, A.; Bruckner, M.; Lutter, S.; Wood, R.; Stadler, K.; Tukker, A. Effect of Aggregation and Disaggregation on Embodied Material Use of Products in Input–Output Analysis. *Ecological Economics* **2015**, *116*, 289–299.
<https://doi.org/10.1016/j.ecolecon.2015.05.008>.
- (41) Steen-Olsen, K.; Owen, A.; Hertwich, E. G.; Lenzen, M. Effects of Sector Aggregation on Co₂ Multipliers in Multiregional Input–Output Analyses. *Economic Systems Research* **2014**, *26* (3), 284–302. <https://doi.org/10.1080/09535314.2014.934325>.
- (42) Akizu-Gardoki, O.; Bueno, G.; Wiedmann, T.; Lopez-Guede, J. M.; Arto, I.; Hernandez, P.; Moran, D. Decoupling between Human Development and Energy Consumption within Footprint Accounts. *Journal of Cleaner Production* **2018**, *202*, 1145–1157. <https://doi.org/10.1016/j.jclepro.2018.08.235>.
- (43) World Bank. *Poverty and Shared Prosperity 2020 : Reversals of Fortune*; Washington, DC: World Bank, 2020. <https://doi.org/10.1596/978-1-4648-1602-4>.
- (44) Bruckner, B.; Hubacek, K.; Shan, Y.; Zhong, H.; Feng, K. Impacts of Poverty Alleviation on National and Global Carbon Emissions. *Nat Sustain* **2022**.
<https://doi.org/10.1038/s41893-021-00842-z>.
- (45) Millward-Hopkins, J.; Oswald, Y. ‘Fair’ Inequality, Consumption and Climate Mitigation. *Environ. Res. Lett.* **2021**, *16* (3), 034007. <https://doi.org/10.1088/1748-9326/abe14f>.
- (46) Oswald, Y.; Steinberger, J. K.; Ivanova, D.; Millward-Hopkins, J. Global Redistribution of Income and Household Energy Footprints: A Computational Thought Experiment. *Glob. Sustain.* **2021**, *4*, e4. <https://doi.org/10.1017/sus.2021.1>.
- (47) Andrieu, B.; Marraud, L.; Vidal, O.; Egnell, M.; Boyer, L.; Fond, G. The Exponential Relationship between Healthcare Systems’ Resource Footprints and Their Access and Quality: A Study of 49 Regions between 1995 and 2015. Rochester, NY August 8, 2022. <https://doi.org/10.2139/ssrn.4182423>.
- (48) Nakićenović, N.; Gilli, P. V.; Kurz, R. Regional and Global Exergy and Energy Efficiencies. *Energy* **1996**, *21* (3), 223–237. [https://doi.org/10.1016/0360-5442\(96\)00001-1](https://doi.org/10.1016/0360-5442(96)00001-1).
- (49) Cullen, J. M.; Allwood, J. M.; Borgstein, E. H. Reducing Energy Demand: What Are the Practical Limits? *Environ. Sci. Technol.* **2011**, *45* (4), 1711–1718.
<https://doi.org/10.1021/es102641n>.
- (50) Sorrell, S.; Dimitropoulos, J. The Rebound Effect: Microeconomic Definitions, Limitations and Extensions. *Ecological Economics* **2008**, *65* (3), 636–649.
<https://doi.org/10.1016/j.ecolecon.2007.08.013>.

- (51) Fowlie, M.; Greenstone, M.; Wolfram, C. Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program*. *The Quarterly Journal of Economics* **2018**, *133* (3), 1597–1644. <https://doi.org/10.1093/qje/qjy005>.
- (52) Gillingham, K.; Stock, J. H. The Cost of Reducing Greenhouse Gas Emissions. *Journal of Economic Perspectives* **2018**, *32* (4), 53–72. <https://doi.org/10.1257/jep.32.4.53>.
- (53) Jacques, P.; Delannoy, L.; Andrieu, B.; Yilmaz, D.; Jeanmart, H.; Godin, A. Assessing the Economic Consequences of an Energy Transition Through a Biophysical Stock-Flow Consistent Model. Rochester, NY July 28, 2022. <https://doi.org/10.2139/ssrn.4174917>.
- (54) van Ruijven, B. J.; De Cian, E.; Sue Wing, I. Amplification of Future Energy Demand Growth Due to Climate Change. *Nat Commun* **2019**, *10* (1), 2762. <https://doi.org/10.1038/s41467-019-10399-3>.
- (55) Millward-Hopkins, J.; Steinberger, J. K.; Rao, N. D.; Oswald, Y. Providing Decent Living with Minimum Energy: A Global Scenario. *Global Environmental Change* **2020**, *65*, 102168. <https://doi.org/10.1016/j.gloenvcha.2020.102168>.
- (56) Rao, N. D.; Min, J.; Mastrucci, A. Energy Requirements for Decent Living in India, Brazil and South Africa. *Nat Energy* **2019**, *4* (12), 1025–1032. <https://doi.org/10.1038/s41560-019-0497-9>.
- (57) Grubler, A.; Wilson, C.; Bento, N.; Boza-Kiss, B.; Krey, V.; McCollum, D. L.; Rao, N. D.; Riahi, K.; Rogelj, J.; De Stercke, S.; Cullen, J.; Frank, S.; Fricko, O.; Guo, F.; Gidden, M.; Havlík, P.; Huppmann, D.; Kiesewetter, G.; Rafaj, P.; Schoepp, W.; Valin, H. A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies. *Nat Energy* **2018**, *3* (6), 515–527. <https://doi.org/10.1038/s41560-018-0172-6>.
- (58) Sovacool, B. K.; Heffron, R. J.; McCauley, D.; Goldthau, A. Energy Decisions Reframed as Justice and Ethical Concerns. *Nat Energy* **2016**, *1* (5), 16024. <https://doi.org/10.1038/nenergy.2016.24>.
- (59) Vidal, O.; Le Boulzec, H.; Andrieu, B.; Verzier, F. Modelling the Demand and Access of Mineral Resources in a Changing World. *Sustainability* **2022**, *14* (1), 11. <https://doi.org/10.3390/su14010011>.