Nexus

Research article

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IN BRIEF

This study quantifies household energy footprints across 201 expenditure groups in each of 116 countries, revealing large inequalities in both direct and indirect energy use. The top 1% consume 14% of global energy, while the bottom 50% use only 13%, exposing stark disparities both within and across countries.

Global energy inequality across energy types, expenditure groups, and consumption items

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BROADER CONTEXT

Understanding how household energy use varies across income levels—and addressing energy inequality—is central to achieving just and equitable development. Yet, most existing studies focus on national averages or direct household energy use, overlooking the energy embodied in consumed goods and services. This study addresses that gap by combining a global multi-regional input-output framework with energy consumption data and detailed household expenditure data for 201 income groups in each of 116 countries. Results reveal that indirect energy use dominates household energy footprints and contributes more to inequality than direct use in most countries. The top 1% of households account for 14% of global energy use, while the bottom 50% consume only 13%. Energy intensity declines with rising income but remains high in poorer regions. Differences in energy intensity across consumption items and countries underscore the need for targeted efficiency standards, improved infrastructure, and broader technology adoption. These findings highlight the importance of addressing consumption patterns and supply chains to support a more equitable energy future.

ABSTRACT

Understanding the relationship between household expenditure and energy use from a consumption and supply chain perspective is crucial to capturing direct household energy use and indirect energy use linked to various consumption items—often overlooked by studies focusing solely on direct energy—and to revealing the underlying patterns of global energy inequality across households. This study assesses the energy footprints across 201 household expenditure groups, seven final-use energy types, and 65 consumption items in each of 116 countries using a global energy- and expenditure-extended multi-regional input-output model for 2017. The Gini index for global energy footprints is 0.59, indicating a high level of energy inequality: the top 1% of households in 116 countries account for 14% of energy footprints, while the bottom 50% consumed only 13%. Substantial energy inequality is revealed both between and within countries. Less developed countries and regions generally exhibit greater inequality in per capita energy footprints between households compared to developed countries and regions. Energy intensity declines with higher expenditure, remaining higher in poorer regions and households. In richer regions, energy intensity is more evenly distributed across expenditure groups and overall lower than in developing regions. Accurately measuring global household energy footprints can help understand current energy inequality and guide future poverty and inequality reduction to promote a more just and equitable global society.

INTRODUCTION

As stated in the Sustainable Development Goals (SDG7), our everyday life relies on reliable and affordable energy.[1] From a final consumption perspective, households are one of the main energy consumers. This includes both direct energy such as coal and natural gas for cooking, oil for transport, electricity, heat, and biomass for heating, and indirect energy used in the production (often referred to as embodied, embedded, or virtual energy) for goods and services that households consume through global supply chains.[2–4] Many existing studies focus only on direct energy use,[5,6] while the consumption perspective accounting for energy use along the entire supply chain receives less attention.[7,8] Indirect energy consumption, driven by household demand for goods and services, provides insights into upstream energy use across supply chains.[9] Without considering indirect energy consumption embodied in products and services, the full extent of energy use linked to various household consumption items, such as food and transport, cannot be comprehensively assessed. Therefore, a

consumption-based analysis is essential to gain a holistic view of household energy consumption and energy inequality.

The energy footprint in consumption-based analysis refers to the sum of direct energy use—such as energy consumed directly by households for activities such as heating, cooling, and private transportation—occurring during household consumption activities and indirect energy consumption embodied in the production of goods and services for household final demand. The gap in energy consumption between the rich and poor in terms of energy footprints varies largely due to the inequality in household consumption, both between and within countries,[10–15] as all the products and services for human needs and living standards are sustained by different energy quantities and carriers.[16–18] Household consumption drives production along the entire global supply chain and plays a determinant role in energy consumption.[19–22] The large global inequality reflects great risks to those households and individuals in poverty, making them less able to achieve development and decent living, especially faced with the
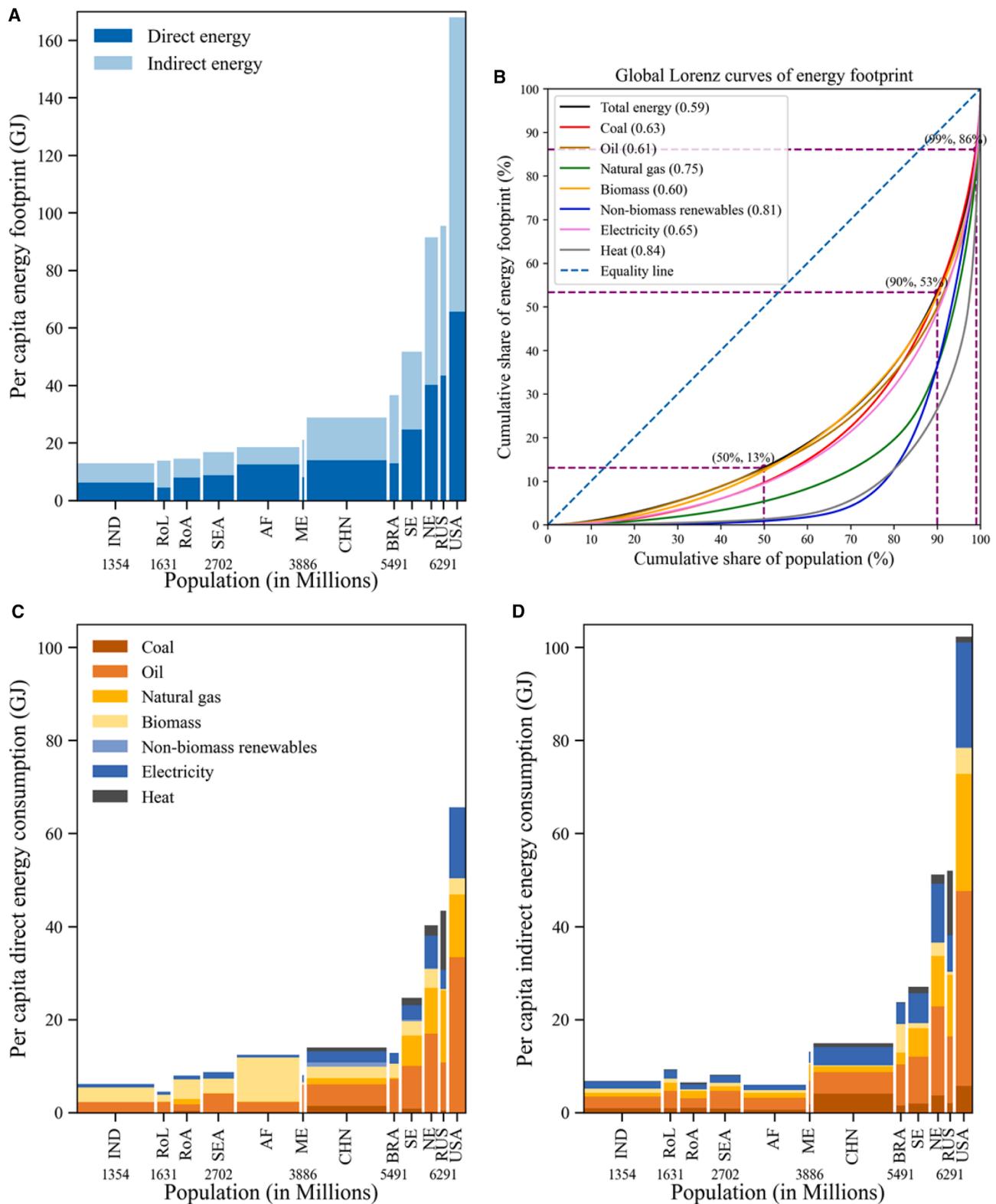
Figure 1. Energy inequality across regions, countries, and energy types

(A) Per capita energy footprint in the 12 aggregated regions and countries is depicted in the stacked bar chart, with dark-blue bars representing direct energy used in the households and light-blue bars representing indirect energy use for household consumption items. The width of each column represents the population in the 12 aggregated regions and countries. Values on the *x* axis indicate the cumulative population in millions. The height of each bar indicates the per capita energy footprint in each region, measured in gigajoules (GJ). Thus, the area of the bar reflects the total energy footprints of the region.

(B) Global Lorenz curves of energy footprint of total energy and seven final-use energy types: coal products (coal and coal products), oil products (crude oil, NGL, and feedstocks; oil products), natural gas, biomass (biofuels and waste), non-biomass renewables (geothermal; solar/wind/other), electricity, and heat. The *x* axis represents the cumulative share of the global population, and the *y* axis represents the cumulative share of energy consumption, with households ranked from lowest to highest per capita energy consumption. The 45-degree blue dashed diagonal line represents perfect equality. Gini indices shown in parentheses in the legend

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planet's increasingly strained resources and the urgent need to meet climate goals.[23,24] In line with SDG 10, which calls for reducing inequalities within and among countries, it is paramount to quantify the energy consumption of households across different income and consumption groups and to explore the intricate connections between household consumption and energy use across the world to promote a more just and equitable energy consumption.

A large body of literature about the inequality of household energy use either overlooks the supply chain or indirect consumption perspective[5,25] or is often geographically constrained to the national or subnational[26,27] or multinational levels.[28,29] A global perspective with country-level detail is needed to capture variations across countries with different income levels, energy systems, and development pathways. The few existing global studies on household energy footprint inequality[16,30,31] often neglect the wide range of energy types, including biomass and other renewables, and are confined to a limited number of household consumption groups and thus cannot provide a comprehensive understanding of direct and indirect energy consumption associated with a wide range of different consumption patterns by capturing the entire global value chain. The most detailed study so far by Oswald et al. covered 86 countries, representing 78% of the global population, but did not account for different energy types. They used a mixed dataset with four income groups, quintile-level income granularity, and reduced sectoral granularity to 26 industries, focusing primarily on global-level analysis with limited exploration of global, regional and national variations.

Aiming at the above research gap, this study assesses global energy footprints across 201 household expenditure groups, seven final-use energy types, and 65 consumption items in each of 116 countries for the year 2017 using a global energy- and expenditure-extended multi-regional input-output (MRIO) approach based on the global MRIO database[32] and an updated version of the World Bank's Global Consumption Database (WBGCD).[13,33] It is currently the most comprehensive dataset, covering 116 countries, representing 90% of the global population, and including the most detailed household consumption groups and consumption items. Accurately measuring global household energy footprints can provide a consumption and supply chain perspective in understanding current energy inequality and can help guide future poverty and inequality reduction to promote a more just and equitable global society.

RESULTS

Energy inequality across countries, regions, and energy types

Energy footprints per capita differ largely among countries. The per capita energy footprints of countries in 2017 range from 1.30 to 216.95 GJ (gigajoules) (Figure S2). The mean per capita energy footprint across 116 countries is 33.46 GJ. Generally, high-income countries have a higher per capita energy footprint than that of low-income countries. To highlight regional differences on the global scale, countries are classified into 12 aggregated regions and countries (Figure S1; Table S2). The inequality between regions is substantial when looking at the average per capita energy footprints. As Figure 1A shows, the United States, Russia, Northern and Western Europe, and Southern and Eastern Europe have the highest per capita energy footprints, with values of 168.04, 95.47, 91.46, and 51.75 GJ per person, respectively, while India has the lowest of 12.96 GJ per person.

When examining direct household energy use and indirect energy use embodied in consumption items through supply chains separately, countries with high direct energy consumption typically also exhibit high indirect energy consumption, both in total and per capita (Figures S2 and S3). The global total indirect energy consumption embodied in the supply chains in 2017 was 118.15 exajoules (EJ), which is larger than the household direct household consumption of 103.18 EJ. 59 out of 116 countries covered in this study have higher indirect than direct energy consumption. From Figure 1A, it can be seen that nearly all regions have a higher per capita indirect energy consumption than per capita direct energy consumption, with the exception of Africa and the rest of Asia. Africa has the lowest indirect energy consumption per capita among all regions with only 6.03 GJ, which is less than half of its direct energy consumption per capita (12.47 GJ). The rest of Asia also has low indirect and direct energy consumption per capita with 6.45 and 8.01 GJ, respectively. A higher direct than indirect energy consumption per capita reflects the high direct energy consumption from fossil fuels and biomass for household cooking and heating, as well as low consumption demand for goods, services, and imports in Africa and the rest of Asia. In contrast, the United States has an indirect per capita energy consumption of 102.39 GJ, almost double its direct per capita energy consumption of 65.65 GJ. Russia (52.06, 43.41 GJ) and Northern and Western Europe (51.20, 40.26 GJ) also have higher indirect than direct consumption. Developed countries on average have larger indirect than direct per capita energy consumption, reflecting high consumption levels and large impacts of production and supply chains on energy footprint (Figure S4; Table S2).

Considering different final-use energy types, as shown in Figures 1C and 1D, oil has the largest share in indirect per capita energy consumption among all regions, while the energy type having the largest share in household direct energy consumption differs. Indirect energy consumption shows energy use in domestic and international production processes such as transportation and manufacturing, which are heavily dependent on oil. Household direct energy consumption is mainly from private transport, heating, and cooking, which is more related to local energy resource endowment and climate conditions. Oil has a substantial role in the United States, accounting for 51% and 41% of per capita direct and indirect energy consumption of 33.45 and 41.95 GJ, respectively. As Figure 1B shows, oil has a lower energy inequality compared with other energy sources with a Gini index of 0.61. Final use of heat and natural gas have the largest energy footprint inequality, with Gini coefficients of 0.84 and 0.75. Heat is primarily used in colder, developed regions and is less accessible to poorer households globally. Natural gas is mainly used for heating, industry, and electricity generation, often consumed disproportionately by countries with more extensive natural gas infrastructure. Russia has the highest household direct natural gas use among all regions with a value of 15.56 GJ per person, and the share of natural gas in Russia's household direct energy consumption was also the highest (36%). Biomass has the lowest energy footprint inequality with a Gini coefficient of 0.60 as biomass is easily available and directly used by poorer households (Figure 1B). Africa has the highest per capita direct final use of biomass with a value of 9.53 GJ. Besides in Africa, biomass also sees the largest share of household final energy consumption in India and the rest of Asia. This underscores the challenge of limited energy access in these economically disadvantaged regions, forcing them to predominantly rely on biomass for essential cooking and heating needs. Non-biomass-based renewables (Gini: 0.81) such as wind and solar are mostly

correspond to the areas between each Lorenz curve and the line of perfect equality. These global-level Gini coefficients are calculated based on 23,316 household expenditure groups (201 bins × 116 countries). Country-level Gini coefficients of energy footprints and expenditures are provided in Table S4.
(C and D) Per capita direct (C) and indirect (D) energy consumption considering seven final-use energy types. The width of each column represents the population in the 12 aggregated regions and countries. Values on the x axis indicate the cumulative population in millions. The height of each bar indicates direct and indirect per capita energy consumption in each region, measured in gigajoules (GJ). Thus, the area of the bar reflects the total direct and indirect energy consumption of the region. Energy data are from the International Energy Agency (IEA) energy balance table of 2017. Countries are ordered by per capita energy footprint: IND (India), RoL (the rest of Latin America and the Caribbean), RoA (the rest of Asia), SEA (South-East Asia and the Pacific), AF (Africa), ME (Middle East), CHN (China), BRA (Brazil), SE (Southern and Eastern Europe), NE (Northern and Western Europe), RUS (Russia), and USA (United States).
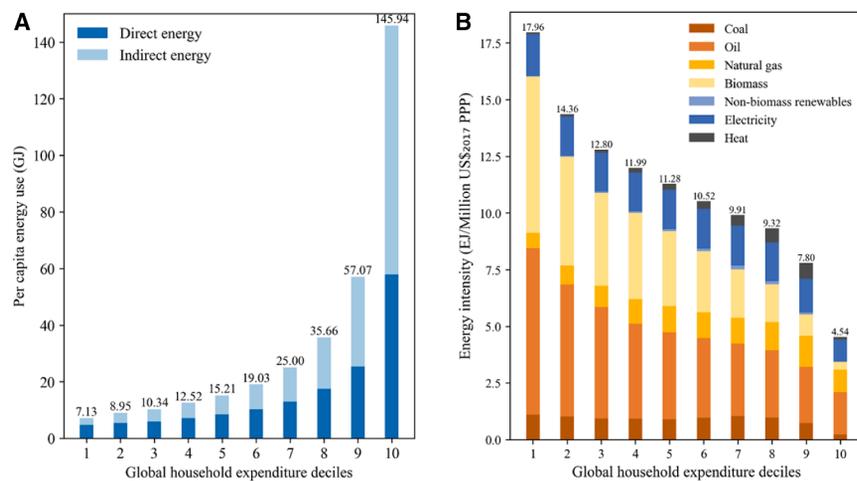
Figure 2. Energy inequality across house-holds

(A) Per capita energy use for global household expenditure deciles considering household direct and indirect energy use in 2017. Direct energy use is depicted in the dark-blue bars, which refer to the energy directly used in households, including private transport, and residential energy use for cooking, heating, and cooling, etc. Indirect energy use is depicted in the light-blue bars, which represent the indirect energy use in the supply chains for consuming goods and services. Unit: gigajoule (GJ).

(B) Energy intensity (energy footprints per dollar in 2017 PPP, unit: exajoule/million US$_{2017} PPP) of global household expenditure deciles considering seven final-use energy types: coal products (coal and coal products), oil products (crude oil, NGL, and feedstocks; oil products), natural gas, biomass (biofuels and waste), non-biomass renewables (geothermal; solar/wind/ other), electricity, and heat.

deployed in richer regions and are often capital-intensive, leading to higher inequality.

From poor to rich: How energy inequality manifests across households

The results show large energy inequality between households world-wide, both within and between countries. As seen in Figure 1B, the Gini index for global energy footprints is 0.59. The top 1% of all households covered in this study account for 14% of energy consumed directly and indirectly by households: the top 10% consume 47%, and the bottom 50% consume only 13%. To have a clearer picture of global and regional energy inequality, the global and regional households are grouped into 10 expenditure groups. Richer households tend to have higher levels of both direct energy use and indirect use, especially in regions such as Africa, the United States, Europe, and Russia (see Figures 2A and S6). However, in Brazil and the rest of Latin America and the Caribbean, only indirect energy use increases notably with higher expenditure, while direct energy use does not show a rise. Direct energy accounts for a larger portion of total energy use for poorer households and countries, while indirect energy use dominates in richer households, particularly in developed regions. This pattern suggests that addressing energy inequality will require a focus on reducing the indirect energy consumption of richer households.

Globally, rich households have larger per capita energy footprints but smaller energy intensity of expenditure than poor households. The richest 10% of the analyzed population have 145.94 GJ of per capita energy footprint and 4.54 EJ/million US$_{2017} PPP of energy intensity, while the poorest 10% have a per capita energy footprint of only 7.13 GJ and a high energy intensity of 17.96 EJ/million US$_{2017} PPP, as shown in Figures 2A and 2B. The final use of oil and biomass sees a clear decline in energy intensity with expenditure increases. Energy intensity from oil decreases from 7.35 EJ/million US$_{2017} PPP in the poorest 10% to 1.88 EJ/million US$_{2017} PPP in the richest 10%. Biomass energy intensity starts at 6.90 for the poorest households and drops to just 0.34 EJ/million US$_{2017} PPP for the richest 10%. This reflects the heavy reliance on traditional fuels such as biomass and transportation fuels such as oil in poorer households. Natural gas and heat even see higher intensity in the richest 10% than in the poorest 10% of analyzed population, both increasing from the poorest to the richest deciles, peaking in decile 9 (richest 10%−20%), before dropping sharply in the richest 10%, indicating higher energy needs of natural gas and heat for richer households. The energy intensity of electricity remains relatively stable across deciles, with only a slight decline from 1.85 EJ/million US$_{2017} PPP in the poorest 10% decile to 0.97 EJ/million US$_{2017} PPP in the richest 10%, showing electricity's role as an essential and universal energy service globally.

Households with high per capita energy footprints do not only exist in developed regions. It can be seen from Figure 3A that the top energy-

consuming households come from all world regions, which shows the population distribution of per capita energy footprint among household expenditure groups in 12 aggregated regions and countries. The vertical line represents the mean energy footprint per capita in the 116 analyzed countries, which is 33.45 GJ/capita. The United States has the largest proportion of households with the highest energy footprints. Africa has the largest proportion of households with the lowest energy footprints, with an average energy footprint of 18.50 GJ per person. Almost all of the population with higher than 200 GJ per person is in the United States, while less than 2 GJ per person is in Africa. However, it is noteworthy that the top 10% in Africa have a per capita energy footprint as high as 66.75 GJ per person. This reflects the wide inequality in per capita energy footprints within Africa. China sees the broadest distribution of per capita energy footprints among 12 regions, with the top 10% richest Chinese households' per capita energy footprint surpassing that of 93.7% of the population in 116 countries, whereas the poorest 10% have an energy footprint ranking at only 5.5% among the analyzed countries, as shown in Figure 3B. In contrast, India has a lower average per capita energy footprint and a more concentrated distribution of energy-consuming households. The inequality in per capita energy footprints among expenditure groups in India (Gini: 0.28, Table S3) is smaller than in China (Gini: 0.43). The richest top 10% in India have a per capita energy footprint exceeding 74.0% of the analyzed population, while the poorest 10% in India rank at 8.3%.

Less developed countries and regions generally exhibit greater inequality in per capita energy footprints between households compared to developed countries and regions. Africa, the rest of Latin America and the Caribbean, the rest of Asia, and the United States have the largest energy footprint Gini, all larger than 0.44 (Table S3). Meanwhile, Northern and Western Europe and Russia have the lowest energy inequality between households, with a Gini index of less than 0.30. As Figure 3B shows, the per capita energy footprints in Russia and Northern and Western Europe are high. Among the top 10% richest households in Northern and Western Europe and Russia, the per capita energy footprints rank among the top 1%−2% in 116 analyzed countries. Even the poorest 10% of their populations have per capita energy footprints exceeding those of more than 70% of the population in the analyzed countries. Although the United States has a large energy inequality with a Gini coefficient of 0.47, the per capita energy footprint of the poorest 10% in the United States is larger than that of 66% of the analyzed population. In contrast, developing countries have larger energy inequality between households. African countries display large inequality in per capita energy footprints among household expenditure groups, reflecting severe energy inequality (Figure S5). Table S4 further shows the energy footprint Gini for 116 countries, ranging from 0.11 to 0.58. Countries with an energy footprint Gini higher than 0.50 are mostly African countries, where income inequality is large, and many households cannot meet basic needs. In contrast, countries with the
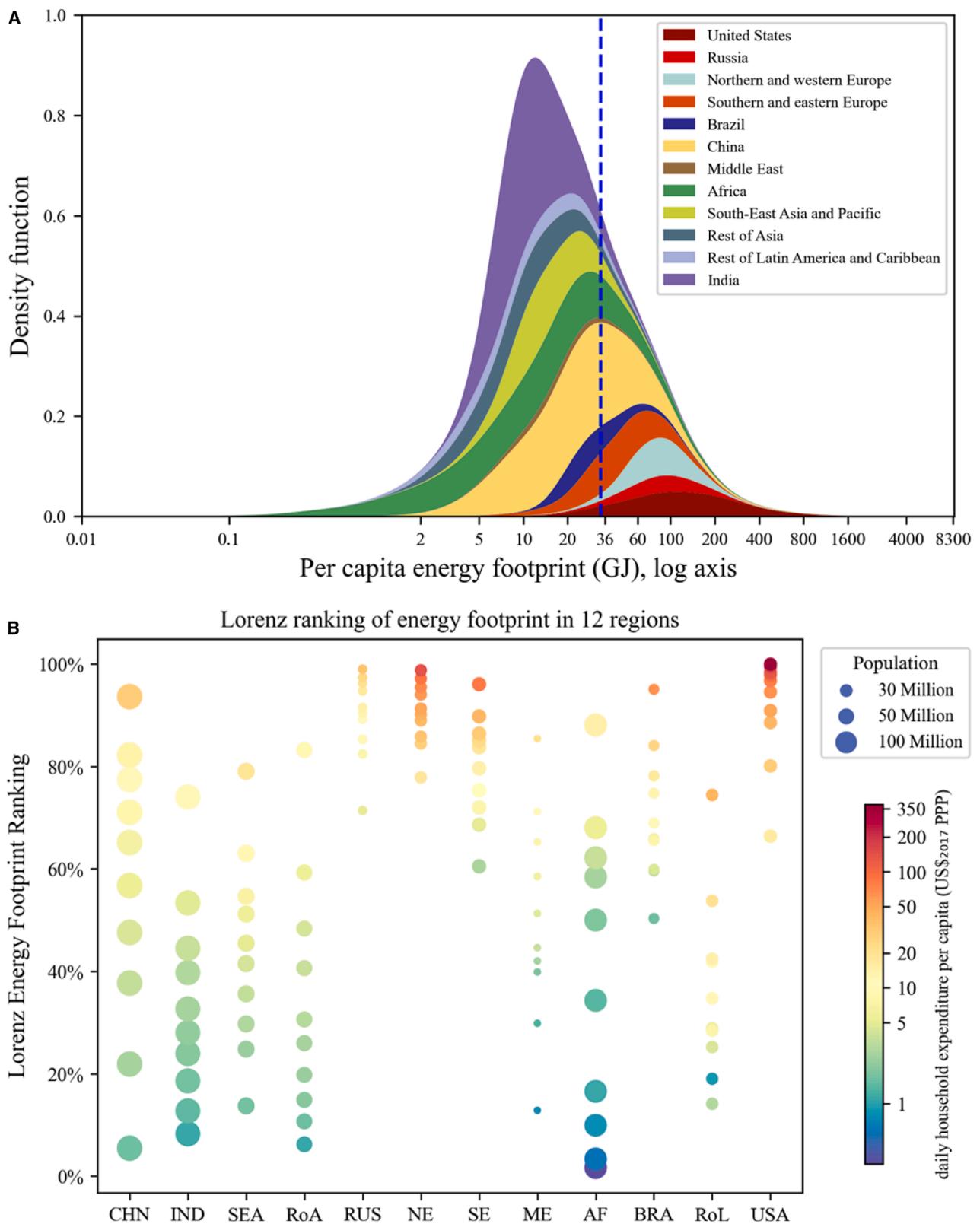
Figure 3. Energy inequality in 12 aggregated regions and countries

(A) The density function shows the cumulative probability distribution of the per capita energy footprint for different household expenditure groups of 12 aggregated regions and countries in 2017. The regions are arranged in descending order, with the highest mean energy footprint per capita at the bottom and the lowest at the top. The colored areas represent the population share of each region in the total population of 116 countries. The *x* axis represents the per capita energy footprint and is log-scaled. Unit: gigajoule (GJ). The vertical blue dashed line represents the mean energy footprint per capita of the 116 analyzed countries in 2017.

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lowest energy footprint Gini are mostly European, where income and consumption are more equal, and living standards are higher.

The role of consumption choices in driving energy inequality

Considering household energy use from 65 consumption items, both direct and indirect energy use are grouped into seven consumption categories and 13 sub-categories (Table S5). Globally, housing exhibited the lowest inequality, with a Gini coefficient of 0.52 (Table 1), followed by food and manufactured products, both with a Gini index of 0.60. In contrast, energy use from the consumption of services is the most unequal, with a Gini coefficient of 0.75, followed by water (0.72) and transport (0.67).

Expenditure elasticity is assessed to show how changes in expenditure may affect household spending patterns and, consequently, household energy footprints. Food (elasticity: 0.81) and housing (elasticity: 0.83) exhibit the lowest elasticity, showing a smaller increasing rate of per capita energy footprint than per capita expenditure, which is the property of necessities. Services display the highest expenditure elasticity of 1.10, followed by water (elasticity: 1.02). Among the 13 sub-categories (Table S6), transport vehicles and equipment, services and transport services have a high elasticity at 1.48 and 1.03, respectively, showing a larger increasing rate of household energy footprints from these dimensions than the increase of household expenditure. This can be attributed to the growing accessibility and availability of essential energy needs, as well as the rising demand for luxury items with increasing expenditure. As shown in Figures S7 and S8, while basic needs such as food contribute relatively evenly across all deciles, richer households allocate a much larger share of their energy use to transport and services, further enlarging energy inequality.

The top 10% of the population in the United States have the highest per capita energy footprint globally, reaching 609.51 GJ (Figure 4). In contrast, the bottom 10% of the population in Africa have the lowest per capita energy footprint globally of 3.67 GJ, which is only about 6% of the per capita energy footprint for transport alone among US households (57.01 GJ). Richer regions such as Northern and Western Europe and the United States show a large increase in energy consumption as household expenditure rises, especially driven by transport, housing, and services. In developing regions such as India and Africa, total energy consumption is much lower, and food and housing account for a larger share of energy use, particularly among lower expenditure deciles.

Energy intensity varies across regions and expenditure groups. As shown in Figure 5, in most developing regions—such as India, South-East Asia and the Pacific, the Middle East, Africa, Brazil, and the rest of Latin America and the Caribbean—the poorest 10% households exhibit the highest energy intensity, which tends to decline as expenditure increases. This pattern reflects the reliance of poor households on energy-intensive goods and services, often associated with inefficient energy use in subsistence-level activities. In contrast, richer households benefit from economies of scale and access to more efficient technologies, leading to lower relative energy intensity. In richer regions such as the United States and Northern and Western Europe, energy intensity remains more stable across expenditure groups, due to the broad availability of efficiency technologies, higher regulatory standards, and modern infrastructure. China shows a decrease in energy intensity after an initial increase, indicating a transitional phase for middle-income households, with increasing energy use on housing, transport, and appliances before eventually benefiting from improved energy efficiency as incomes rise further. This trend aligns with China's rapid urbanization and transition to a consumption-driven economy. Meanwhile, Russia and the United States do not show a clear

decreasing trend in energy intensity across expenditure groups. This pattern reflects overall high energy consumption across households due to colder climates and lower energy prices in the case of Russia[34] and energy-intensive lifestyles in the case of the United States.[35]

Energy intensity also differs by consumption items across regions, with varying patterns as expenditure increases. In Africa, housing dominates energy intensity in all expenditure groups, accounting for 84% in the poorest decile and 56% in the richest; this reflects a heavy reliance on biomass for cooking and heating. In regions such as Africa and India, poor and rich households all exhibit high housing-related energy intensity, partly due to inefficient infrastructure and widespread reliance on traditional fuels. Among the poor, this intensity is further amplified by subsistence-level housing-related energy use, such as biomass burning for cooking and heating, which aligns with the high biomass intensity observed in lower-income groups (Figure 2B). In contrast, in higher-income regions such as the United States and Europe, energy intensity is more evenly distributed across households, with richer households relying on cleaner and more efficient energy carriers such as electricity and gas across a wider range of consumption categories (e.g., transport, services). These patterns reveal how consumption types and energy carriers interact to reinforce inequality: poor households tend to have both higher energy intensity and lower per capita energy use, often due to reliance on inefficient energy types tied to essential consumption (e.g., biomass for housing). Rich households show lower energy intensity (due to efficiency and clean energy access) but much higher per capita energy use, driven by more diverse and energy-intensive consumption in transport and services.

DISCUSSION

The results based on 201 household expenditure groups in each country show larger energy inequality than previous studies.[16,36] Note that some high-income and high-energy-consuming countries, such as Canada, Australia, Qatar, Iceland, and Norway, are not included in the analyzed countries, so the global energy inequality may be even higher than what we estimated. At the national level, Figure S10 shows that energy footprint inequality is generally larger than expenditure inequality, consistent with findings by Oswald et al.. However, our results reveal that more countries show notable deviations from the best-fit line, particularly above it (indicating higher expenditure inequality than energy footprint inequality), while deviations below the line are less pronounced. At the regional level, most global regions exhibit a larger expenditure Gini than energy footprint Gini, except for Africa and the rest of Asia (Table S3). This pattern may reflect regional variations in how expenditure translates into energy consumption. Most developed countries have a larger expenditure Gini than energy footprint Gini (See Table S4). This occurs in countries with strong social policies that subsidize or ensure universal access to essential energy services, regardless of income disparities. In contrast, most African countries exhibit a much larger energy footprint Gini compared to expenditure Gini. This often reflects limited energy access or infrastructure disparities.

The results highlight the crucial role of supply chains and interconnected international trade in energy consumption and inequality among countries[37,38] by showing the larger indirect than direct energy consumption, and larger inequality in indirect than direct energy consumption in most regions and countries, especially in high-income countries, which is also supported by country-level studies.[3,39,40] Meanwhile, lower per capita energy footprints and greater energy inequality between households in developing than developed countries and regions exhibit highly unequal income distribution between households in developing countries. The energy demand of households can be considered as an outcome of household consumption choices. Richer households tend to

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(B) The global Lorenz ranking of per capita energy footprints for 12 aggregated regions and countries in 2017 involves arranging the per capita energy footprint of each region's household expenditure deciles in ascending order on a Lorenz curve. A larger proportion of the ranking indicates a higher per capita energy footprint, signifying that it surpasses a certain percentage of the population. The size of the bubbles indicates the population represented by the household expenditure decile, while the coloring indicates the daily household expenditure per capita of the region-specific decile (unit: US$_{2017} PPP). CHN, China; IND, India; SEA, South-East Asia and the Pacific; RoA, the rest of Asia; RUS, Russia; NE, Northern and Western Europe; SE, Southern and Eastern Europe; ME, Middle East; AF, Africa; BRA, Brazil; RoL, the rest of Latin America and the Caribbean; USA, United States.

Table 1. Global Gini coefficients and per capita energy footprint elasticity of seven consumption categories

Consumption items	Gini index	Elasticity (R-squared)
Food	0.60	0.81 (0.89)
Transport	0.67	0.97 (0.86)
Housing	0.52	0.83 (0.70)
Water	0.72	1.02 (0.80)
Clothing	0.64	0.96 (0.90)
Manufactured products	0.60	0.99 (0.91)
Services	0.75	1.10 (0.95)

Note: The Gini index indicates the inequality in energy footprints across households, while elasticity reflects the relationship between expenditure and energy use for each consumption category. A log-log model is applied to determine the global per capita energy footprint elasticity of expenditure for each consumption category. The values in parentheses represent the R-squared values of the calculated elasticity. See Table S6 for Gini coefficients and elasticity values for the more detailed 13 consumption categories.

consume more energy across all consumption items by allocating a larger portion of their expenditure toward transport and services, leading to substantial energy overconsumption, consistent with previous findings.[14,16] In contrast, poorer households focus more on basic needs such as food and housing, with much smaller energy demands per capita. Achieving decent living standards for all, including access to adequate shelter, mobility, and healthcare, will require increased energy use among poorer households.[41–44] While this can help reduce deprivation, it may also raise global energy use unless accompanied by reductions in excessive consumption among high-income groups or substantial gains in energy efficiency. Without such balancing, energy inequality may persist or even worsen, as the relative gap in per capita energy use remains wide. This study, based on detailed expenditure datasets of households, can help quantify these trade-offs between poverty alleviation, energy use, and inequality. It contributes to ongoing debates on decent living energy and energy justice[45–47] and supports the design of more inclusive and sustainable energy policies.

Consumption-based policies offer avenues to reduce energy inequality by addressing the disproportionate energy use of high-income households, especially in luxury consumption such as excessive private transport and high-end services. Progressive energy taxation or carbon pricing that reflects indirect energy embodied in goods and services can address energy inequality by internalizing the environmental cost of luxury consumption, thereby reducing the disparity in energy footprints across household groups.[48,49] More broadly, addressing indirect energy inequality requires shaping consumption patterns through mandatory product labeling for embodied energy, public campaigns promoting sustainable lifestyles, and regulations to limit advertising and overconsumption of energy-intensive products.[50] At the same time, redistributive policies—such as energy subsidies for energy-efficient appliances—can support low-income households and help narrow the gap in energy access and quality. Public investment in energy-efficient infrastructure and services—such as affordable public transport and low-energy housing—can reduce reliance on inefficient forms of energy, especially in low-income communities. Targeted subsidies[51] and cash transfers[52,53] for the poorest groups can improve access to clean energy without increasing their energy burdens, further contributing to a more equal energy distribution.

While energy intensity generally declines with rising income—suggesting more efficient energy use among wealthier households—the poorest still rely on traditional, inefficient energy sources such as biomass, particularly in regions such as Africa and South Asia. Regional differences in energy intensity highlight the importance of energy efficiency standards, energy infrastructure development, and advanced technology adoption in shaping energy use patterns. In richer regions, such as Northern and Western Europe, stringent building codes, energy labels for buildings, energy standards for appliances, and strong incentives for renewable energy use contribute to relatively uniform and lower energy intensity across income groups. As countries develop and global energy systems evolve, energy intensity patterns are likely to converge among household expenditure groups through technology transfer and knowledge spillovers.[54,55] Developing countries can leverage such transitions to reduce energy inequality and improve efficiency, though temporary rises in energy intensity may occur during shifts in consumption patterns, as seen in China.

Lack of access to clean and affordable energy combined with a heavy reliance on the inefficient and unsustainable use of traditional biomass fuels can be both the manifestations and causes of poverty.[56] Many poor households struggle to meet basic energy needs, leading to health risks and perpetuating the cycle of poverty. As proposed in SDG 7.2, the share of renewable energy is aimed to increase substantially in the global energy mix by 2030.[57] As renewable energy capacity experiences a rapid rise, coupled with the adoption of advanced technologies to enhance energy efficiency, and the utilization of cleaner energy in developing countries with higher energy intensities,[58] future research can consider the evolving energy structure by using a projected input-output table to analyze the impact of the energy transition on addressing energy inequality and future renewable energy demand. Moreover, a more nuanced exploration of the roles of disabled people, older individuals, and women could help contribute to a more inclusive and just energy transition.[59,60]

METHODS

Direct energy consumption of households

Direct energy is energy consumed directly in households, including private transport, and residential energy use for cooking, heating, and cooling. Country-specific final energy is used as it is closer than primary energy to the services that can satisfy human needs, and renewable energy sources can also be considered as they have no primary energy equivalent.[16,45] Since transformation is not considered in final energy, the final uses of coal and electricity do not overlap. Direct country- and expenditure-specific energy consumption is collected from the International Energy Agency (IEA) for 2017, and expenditure shares of relative economic sectors in each country from the WBGCD. Following the approach used in Guan et al.,[61] coal and oil are allocated using the expenditure share from the petroleum and coal products sector, and natural gas using the share from the gas manufacture and distribution sector. The expenditure share of the electricity sector is used to distribute electricity, heat, and non-biomass renewables across 201 household expenditure groups in each country, as these energy types are primarily related to electricity generation. Biomass use is allocated based on the overall household consumption level, assuming that lower-income households use more biomass. This assumption is supported by empirical evidence showing that traditional biomass is predominantly used by poorer populations, mainly for cooking and heating purposes.[62,63] Given biomass's relatively small share in total energy use, national-level impacts are relatively small, though distributional estimates—especially for low-income groups—may be affected. Biomass use among the poorest households may be
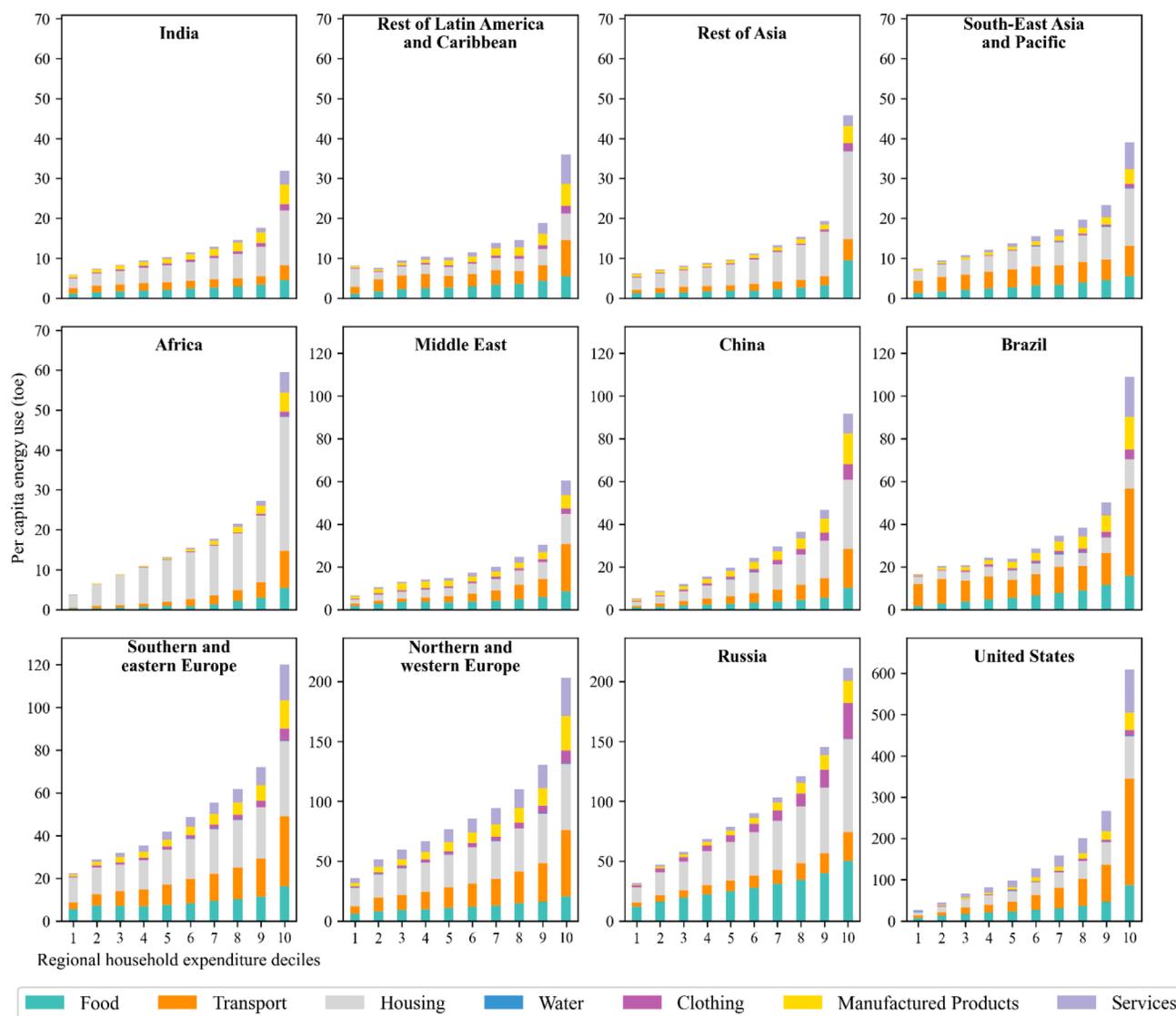
Figure 4. Energy use per capita of household expenditure deciles across seven consumption categories in 12 aggregated regions and countries in 2017

Regional household deciles are sorted based on the household expenditure per capita within each region. 65 consumption items are grouped into seven consumption categories: food, transport, housing, water, clothing, manufactured products, and services. Transport and housing include both indirect energy use along global supply chains induced by household consumption of goods and services, and direct energy use for private transport and residential energy use for cooking, heating, and cooling. The energy use per capita of household expenditure deciles across 13 consumption categories can be found in Figure S9. Correspondence from GTAP-MRIO sectors to seven consumption categories and 13 sub-categories can be found in Table S5.

underestimated if their actual reliance on traditional biomass exceeds their overall consumption share.

Indirect energy consumption of households

Indirect energy is the energy consumption across economic sectors that is indirectly induced by household consumption through global supply chains. Environmentally extended multi-regional input-output (EEMRIO) analysis is conducted to assess country-, sector-, and fuel-specific energy use embodied in all upstream production stages of 201 household expenditure groups in each of the 116 countries. We mapped the 2017 IEA energy data to the 2017 Global Trade Analysis Project (GTAP)-MRIO table and matched and bridged the modified 2011 WBGCD household expenditure data to the household final demand vector of the GTAP-MRIO table following previous studies.[13,61] To align the 160-region GTAP-MRIO with the 116-country WBGCD dataset, we downscaled regional data to the national level by matching country classifications and allocating household demand to each country based on its population share, assuming similar consumption

patterns within aggregated regions. The 2011 expenditure structure from WBGCD is used to disaggregate the total household final demand in the 2017 GTAP-MRIO table. 33 sectors (WBGCD) are mapped to 65 sectors (GTAP) using a correspondence matrix (see Tables S1, S7, and S8). The matched and bridged matrix consists of 10,400 rows by 23,316 columns, containing household final demand for 201 expenditure groups in each of 116 WBGCD countries and trade data between 65 economic sectors in 160 GTAP countries and regions.

By applying the 2011 distribution of expenditure shares across household groups to the 2017 household final demand in the GTAP-MRIO table, both the relative expenditure shares between poor and rich households and the consumption structure within each expenditure group are assumed to have remained stable during this period. Meanwhile, both the total household final demand and its sectoral composition are based on the GTAP-MRIO 2017 data, which reflect actual economic growth and structural changes in production and consumption at the national level. This assumption may not hold in countries that implemented strong redistributive policies or experienced rapid shifts in
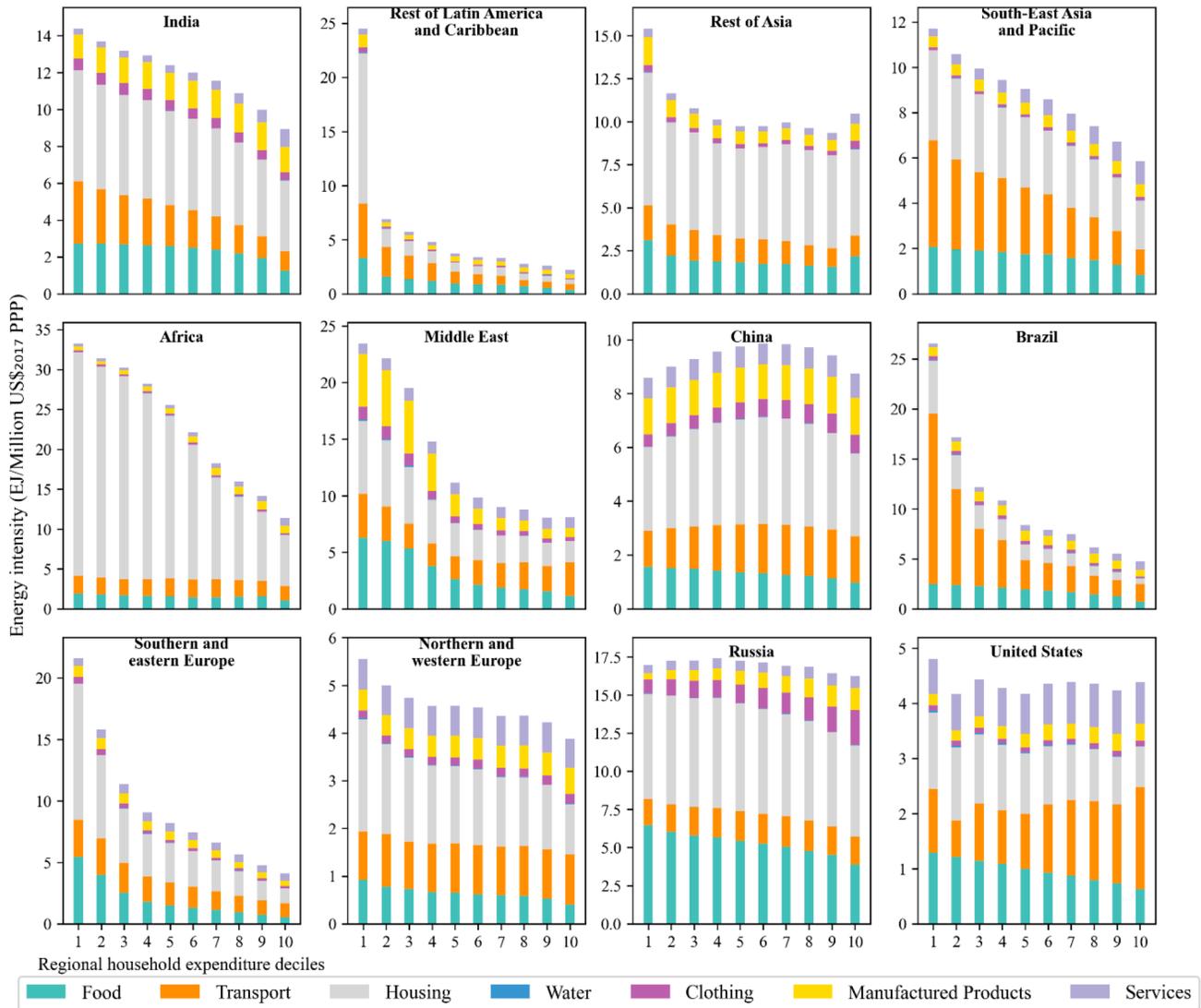
Figure 5. Energy intensity of expenditure of seven consumption categories across 12 aggregated regions and countries

65 consumption items are grouped into seven consumption categories: food, transport, housing, water, clothing, manufactured products, and services. Energy intensity refers to the energy footprint per unit of household expenditure. The *y* axis represents energy intensity, while the *x* axis is divided into household expenditure deciles, with the first decile representing the lowest income group and the tenth decile representing the highest. Unit: exajoule/million US$_{2017} PPP.

income distribution. In many cases, however, income inequality increased during this period.[15] In such contexts, richer households may have expanded their consumption of luxury and energy-intensive goods and services, potentially leading to a slight underestimation of energy inequality. Nevertheless, assuming stable consumption structures over six years is a common and reasonable practice in empirical research, as studies show consumption patterns remain stable, especially among low-income households.[64,65]

Input-output analysis is based on the interconnections between production activities through trade links in the economic system and can be reflected in the input-output models. MRIO tables can show economic flows in various regions and economic sectors, distinguish technological and economic differences between regions, and are widely used in studies on regional economic linkages, production chains and supply chains, pollutant emissions, greenhouse gas emissions, resource use, and the impact of air pollution on the health of residents.[66–68]

The MRIO model measures the driving effect of increases in final demand on the growth of output in whole economy. The row equilibrium in the MRIO table is that total output equals the sum of intermediate use and final demand, which can be represented by the following equation:

$$x_i^f = \sum_{s=1}^{n}\sum_{j=1}^{m} z_{i,j}^{f,s} + \sum_{s=1}^{n} y_i^{f,s} = \sum_{s=1}^{n}\sum_{j=1}^{m} a_{i,j}^{f,s} x_i^f + \sum_{s=1}^{n} y_i^{f,s} \quad \text{(Equation 1)}$$

x_i^f represents the total output of sector *i* in region *f*, which is the sum of intermediate use and final demand. $z_{i,j}^{f,s}$ represents intermediate products supplied by sector *i* in region *f* to sector *j* in region *s*. $y_i^{f,s}$ is the final demand of region s from sector *i* in region *f*. Final demand can be divided into three components: household consumption, government consumption, and investment. $a_{i,j}^{f,s}$ refers to the technological coefficient, which is calculated by $z_{i,j}^{f,s} / x_i^f$. *n* denotes the number of regions, and *m* denotes the number of sectors. The basic equation of MRIO model can be expressed in simplified matrix form as follows:

$$X = Z + Y = AX + Y \quad \text{(Equation 2)}$$

$$\mathbf{X} = (I - A)^{-1}\mathbf{Y} = L\mathbf{Y} \quad \text{(Equation 3)}$$

X is the total output vector with the element of x_i^f. A is the technological coefficient matrix with the element of $a_{i,j}^{f,s}$. Z matrix represents the intersectoral economic linkages between the regions with the element of $z_{i,j}^{f,s}$. **Y** denotes the final demand vector, which only covers household consumption in this study as we focus on the energy requirements and energy inequality of households. I is an identity matrix with the same size of A. $(I - A)^{-1}$ or L is the Leontief inverse matrix or total requirements matrix with the element $l_{i,j}^{f,s}$ showing the total inputs of sector i in region f required to satisfy one unit of final demand in sector j in region s.

Household consumption is a part of final demand that drives the production of all economic sectors throughout the economic network. By linking with energy and environmental satellites, the EEMRIO model allows us to estimate the energy embodied in the production and consumption of goods and services in different countries and sectors from a consumption and supply chain perspective. The basic equation of the EEMRIO model can be expressed in matrix form as follows:

$$\mathbf{E} = \mathbf{e}(I - A)^{-1} * \widehat{\mathbf{Y}} = \mathbf{e}L\widehat{\mathbf{Y}} \qquad \text{(Equation 4)}$$

E is the indirect energy consumption vector, with the element $E_i^{g,k,f}$ representing the indirect energy consumption induced by the final demand of household expenditure group g for fuel k in sector i in region f. **e** represents the energy intensity (that is, energy consumption per unit of total output) vector, with the element $e_i^{k,f}$ referring to the energy intensity of fuel k in sector i in region f. $\widehat{\mathbf{Y}}$ is the diagonalized final demand vector, with the element $Y_i^{g,f}$ representing the final demand of household expenditure group g in sector i in region f.

The use of the MRIO approach enables to analyze household energy use from a consumption perspective, but different prices for the poor and rich when consuming the same products, as well as the dynamic changes in prices with changes in household consumption, cannot be considered due to the innate limitation of homogeneous aggregation of economic sectors and the static nature of the MRIO approach. Further uncertainties in household energy footprint modeling arise from the household expenditure dataset and the processes of matching and bridging to the MRIO table.[16,69]

Energy inequality of households

To examine the inequality of global household energy consumption both between and within countries, the most widely used measures of inequality, Gini coefficients and Lorenz curves, are adopted.[70] In this study, Gini coefficients are calculated separately for each of the 116 countries, based on the distribution of energy footprints across 201 household expenditure groups in each country. For each country, households are ranked from the poorest to the richest based on per capita expenditure. The cumulative share of energy consumption is then plotted against the cumulative share of the population to generate the Lorenz curve, and the Gini coefficient is calculated as the ratio of the area between the Lorenz curve and the line of perfect equality (the 45-degree line) to the total area under the line of perfect equality. At the global level, the Gini coefficient is calculated by pooling all 23,316 household expenditure groups (201 bins × 116 countries), ranking them from lowest to highest per capita expenditure, and applying the same Lorenz-based method using their corresponding cumulative energy footprints and population shares.

Data sources

Country-specific final-use energy data for households and industries are obtained from the 2017 energy balance table of IEA,[71] which reflects national differences in energy structures. Final-use energy is grouped into seven energy types, namely, coal products (coal and coal products), oil products (crude oil, NGL, and feedstocks; oil products), natural gas, biomass (biofuels and waste), non-biomass renewables (geothermal; solar/wind/other), electricity, and heat.

The MRIO table is obtained from the GTAP 11 database (the 4th pre-release version) for 2017.[32] It includes detailed information on interindustry relationships and trade flows among 160 countries and 65 economic sectors.

Household expenditure data are based on the WBGCD,[33,72,73] which provides survey-based expenditure information for 116 countries in 2011, covering nearly 90% of the global population and offering a good representation of developing countries. In the modified WBGCD, each country's household consumption is disaggregated into 201 expenditure bins across 33 economic sectors. While the WBGCD is based on 2011 data, it remains the latest and most detailed dataset available.

Population data of countries in 2017 are from the World Bank.[74] Population data are used to downscale household final demand from aggregated regions in GTAP to the national level, allowing for matching and linking with expenditure data from WBGCD.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Yuli Shan (y.shan@bham.ac.uk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Global multi-regional input-output (MRIO) table was obtained from Global Trade Analysis Project (GTAP) 11 database (the 4th pre-release version).[32]
- Energy consumption data were retrieved from IEA.[71]
- The global expenditure data and population data were obtained from the World Bank.[33,74]
- All data generated and analyzed in this study are available within the article and Supplemental information.
- Programming code for MRIO analysis and any additional information required to reanalyze the data reported in this paper are available from the lead contact upon request.

AUTHOR CONTRIBUTIONS

Y.W., Y.G., Y.S., and K.H. designed the research. Y.W. and Y.G. developed the model and performed the research. Y.W. led the analysis, visualized the results, and drafted the manuscript. Y.L. provided the data sources (global multi-regional input-output tables). Y.S. and K.H. supervised and coordinated the overall research. All authors participated in the writing of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.ynexs.2025.100086.

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