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Higher total energy costs strain the elderly, especially low-income, across 31 developed countries

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Addressing the total energy cost burden of elderly people is essential for designing equitable and effective energy policies, especially in responding to energy crisis in an aging society. It is due to the double impact of energy price hikes on households—through direct impact on fuel bills and indirect impact on the prices of goods and services consumed. However, while examining the household energy cost burden of the elderly, their indirect energy consumption and associated cost burden remain poorly understood. This study quantifies and compares the direct and indirect energy footprints and associated total energy cost burdens for different age groups across 31 developed countries. It reveals that the elderly have larger per capita energy footprints, resulting from higher levels of both direct and indirect energy consumption compared with the younger age groups. More importantly, the elderly, especially the low-income elderly, have a higher total energy cost burden rate. As the share of elderly in the total population rapidly grows in these countries, the larger per capita energy footprint and associated cost burden rate of elderly people would make these aging countries more vulnerable in times of energy crises. It is therefore crucial to develop policies that aim to reduce energy consumption and costs, improve energy efficiency, and support low-income elderly populations. Such policies are necessary to reduce the vulnerability of these aging countries to the energy crisis.

aging society | energy footprint | energy cost burden | energy crisis | low-income elderly

Significance

Energy price hikes impact households directly through fuel bills and indirectly through increasing prices of goods and services consumed. Existing studies on the energy cost burden of the elderly only focused on the fuel bills of the elderly, especially low-income elderly's, but ignored their cost burden of indirect energy consumption. This study finds that the elderly in 31 developed countries have larger per capita direct and indirect energy footprints and bear higher total energy cost burdens, thus being more vulnerable to energy price hikes than younger groups. Our analysis provides quantitative assessments and insights into the links between energy cost burden and age, arguing that the elderly, especially the low-income elderly in developed countries, are more vulnerable to energy crisis.

Energy crisis, such as the recent one triggered by the Russia–Ukraine conflict, imposes a notable increase in the cost of living for everyone (1, 2), particularly the elderly, who are generally considered to be among the most vulnerable groups due to their declining physical and mental faculties (3, 4). The elderly population in Europe and North America exceeded 200 million in 2019 (5), and this number is projected to be double by 2050 (6, 7). Considering the two kinds of cost burden associated with energy prices—direct effects on household fuel bills and indirect effects on the prices of goods and services that households consume—and understanding the patterns of direct and indirect energy consumption and associated total cost burden for the elderly is a critical issue for energy policy design and effective response to the energy crisis in aging countries (2, 8).

As people age, their financial conditions as well as lifestyles related to direct and indirect energy consumption change substantially. They tend to face physical, legal, and social barriers to employment (9). Thus, the elderly rely on limited income sources such as pensions, savings, and investments (10–12), and may face higher risks of poverty (13). Turning to the lifestyle, the elderly tend to stay longer at home because of their health-related needs, and thus tend to have a higher level of household energy consumption (7, 14, 15). The elderly also have consumption patterns shaped by generational and habitual factors. For example, some studies found that the baby boom generation tends to have a higher fuel demand due to their car-based mobility preferences (16, 17). The elderly may be more conservative and habit-persistent, thus are more likely to dwell in older houses and use old equipment and products with low energy efficiency (18–20). In terms of socio-economic characteristics, there usually are diseconomies of scale for elderly households with smaller household size, which may result in more energy consumption per capita (15, 18, 21, 22).

Previous studies have usually linked aging to direct energy consumption, showing contradictory conclusions (15, 17, 23, 24). Some studies found that population aging has an inhibitory effect on energy consumption (25, 26), while others argue that elderly households usually have higher direct energy consumption (27). While direct energy consumption (e.g., heating, cooling, and mobility) is indispensable, so does the indirect energy consumption because energy is used in the supply chain to produce and distribute final goods and services that households consume (28, 29). Although many studies have investigated household's indirect energy consumption, most of them focused on the national scale or households with different levels of income or expenditure (2, 7, 29–33). Few paid attention to the indirect energy consumption of the elderly (34, 35). The

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literature on the energy cost burden of the elderly's indirect household energy consumption is largely missing. Considering the ways energy price hikes affect household expenditures—through direct impact on fuel bills and indirect impact on the prices of goods and services consumed (2, 36–38), it is important to investigate the total (direct and indirect) energy cost burden of the elderly, especially the low-income elderly, because such an investigation can fully reveal the overall energy cost burden and the vulnerability of elderly in times of energy price hikes.

To bridge the above research gap, we quantify the total energy footprint and compared the total energy cost burdens of younger (age < 30, age 30 to 44, age 45 to 59) and elderly groups (age > 60) in 31 developed countries (including 27 EU countries, the United Kingdom, Japan, the United States, and Australia). We use a global multi-regional input–output model combined with national-level household expenditure survey (HES) data to estimate the direct and indirect energy consumption and assess the total energy cost burden rate by age group (*Materials and Methods*). In this study, we first quantify the direct and indirect energy footprints across different age groups from 2005 to 2015 and explore the factors driving their variations. We then estimate and compare the total energy cost burden rate of different age groups. Finally, we consider the United States, the United Kingdom, and Japan as examples of different lifestyles of the elderly in North America, Europe, and East Asia to run the above analysis across income-age groups. The results provide a comprehensive representation of the energy consumption footprints for each age group and the associated total cost burden, offering valuable insights for designing just and effective energy policy and responding to the energy crisis in aging countries.

Results

Larger Per Capita Energy Footprint of the Elderly and the Rising Share of the Elderly's Energy Footprints. Although per capita energy footprints vary substantially across these 31 countries, we found that the elderly group had the largest per capita energy footprint (direct and indirect) (red bar in Fig. 1 *A*–*O*). For example, the per capita energy footprint of the elderly in the United States was 0.29 TJ in 2015, almost 60% higher than that of the youngest group (0.17 TJ). A similar pattern could be also observed in other countries/regions as the elderly's footprints (0.13, 0.10, and 0.16 TJ) were 30%, 42%, and 45% higher than the youngest group (0.10, 0.07, and 0.11 TJ) in EU, Japan, and the United Kingdom for the year of 2015, respectively. The energy footprints of all age groups were dominated by indirect energy use. However, the age pattern of energy consumption was observed in both direct and indirect energy consumption, i.e., both per capita direct and indirect energy footprints of the elderly were larger than that of younger groups in most of these 31 countries in 2005, 2010, and 2015 (*SI Appendix*, Figs. S1–S3).

At the country/regional level, the share of the elderly's energy footprint in the national/regional total shows an increase from 2005 to 2015 in all countries/regions (Fig. 1 *P*–*T* and *SI Appendix*, Fig. S4). The share of the energy footprint for the elderly group in Japan had the largest growth, reaching 53% in 2015. It is worth noting that the elderly group overtook the young and middle-aged group, and became the second-largest contributor to energy consumption in most countries, except Japan, Italy, and Bulgaria, where the elderly group was the main contributor during the study period (*SI Appendix*, Fig. S5). Following the current trend of transition to an aging society, it can be expected that the share of the elderly group in the national energy footprint will exceed the middle-aged group and become the largest contributor to the total household energy footprint in the near future.

The Elderly Group as a Major Contributor to the Rise in Household Energy Footprints. Energy footprints of the elderly group increased, whereas the average household energy footprint declined in many countries during the study period (Fig. 2). The share of the elderly's energy footprint in the total household energy footprints increased by about 2.3% during both 2005 to 2010 and 2010 to 2015 in the "all countries" figure, while the corresponding shares of the younger group decreased by 7.6% (2005 to 2010) and 5.7% (2010 to 2015), respectively. This contrast held true in Australia, the EU, and Japan, where the elderly group contributed 10.2%, 4.0%, and 4.4% of the changes in the household energy footprint during 2005 to 2015, respectively. We found that the elderly group was the lead contributor to the increase in household energy footprints during the study period.

We further investigated the socioeconomic factors which drive the changes in the household energy footprint by age group from 2005 to 2015 (Fig. 2). We found that the household effect of the elderly group, including changes in both household numbers and household size was the major contributor to the increasing energy footprint in most countries. Although the family size effect varied across age groups and countries, the household proliferation effect (mainly the increase in household numbers) drove a +3.9% and +5.6% increase in total energy footprint for all 31 countries. As the country with the largest share of aging population, the household effect of the elderly contributed to a 12.8% increase in total energy footprints in Japan during 2005 to 2015, exceeding the extent of decline caused by the household effect of the younger group (−10.6%).

The expenditure effect, including per capita expenditure and expenditure structure, worked differently in the two subperiods. In the first subperiod (2005 to 2010), the expenditure effect increased the energy footprint at the all countries aggregation, and led to a +7.9% and +4.6% increase in the total household energy footprint in the EU and Japan, respectively. However, in the second subperiod (2010 to 2015), it led to a −4.1% and -1.7% change at the all-countries aggregation for the younger and elderly groups, respectively, which was mainly contributed by the United States and Australia. This is because of the rapid increase in the expenditure shares of sectors with low energy intensity, such as services in these two countries, which exceed the growth effect of per capita expenditure.

The efficiency effect (energy intensity: footprint/expenditure) was the primary factor contributing to the footprint reduction in the first period (2005 to 2010). This is largely due to the energy efficiency improvement in these countries. We also found that the efficiency effect of the younger group played a more important role in the reduction of household energy footprints than the elderly group, i.e., the efficiency effect of the younger and elderly group contributed a −8.1% and −2.9% change in the total household energy footprint in this period, respectively. This indicates that the elderly group lagged behind the younger group in pursuing energy efficiency improvement in this period. This may be related to the lifestyle of the elderly. For example, the household size of the elderly is relatively small compared with that of the younger group (*SI Appendix*, Fig. S6). Meanwhile, they are more likely to live in larger and older houses far from the main towns (7), which usually results in a lower energy efficiency. Moreover, the sense of nostalgia and conservative shopping patterns also prevents the elderly from adopting emerging products with higher efficiency (39). However, the efficiency effects in the United States and Australia led to an increase in energy footprint during the second period (2010 to 2015), which was sharply different from the cases of other studied countries. It might be related to the significant deflation of energy prices in the United States (−16.7%) and Australia (−7.2%) in 2015 (7, 40). Cheaper energy in combination

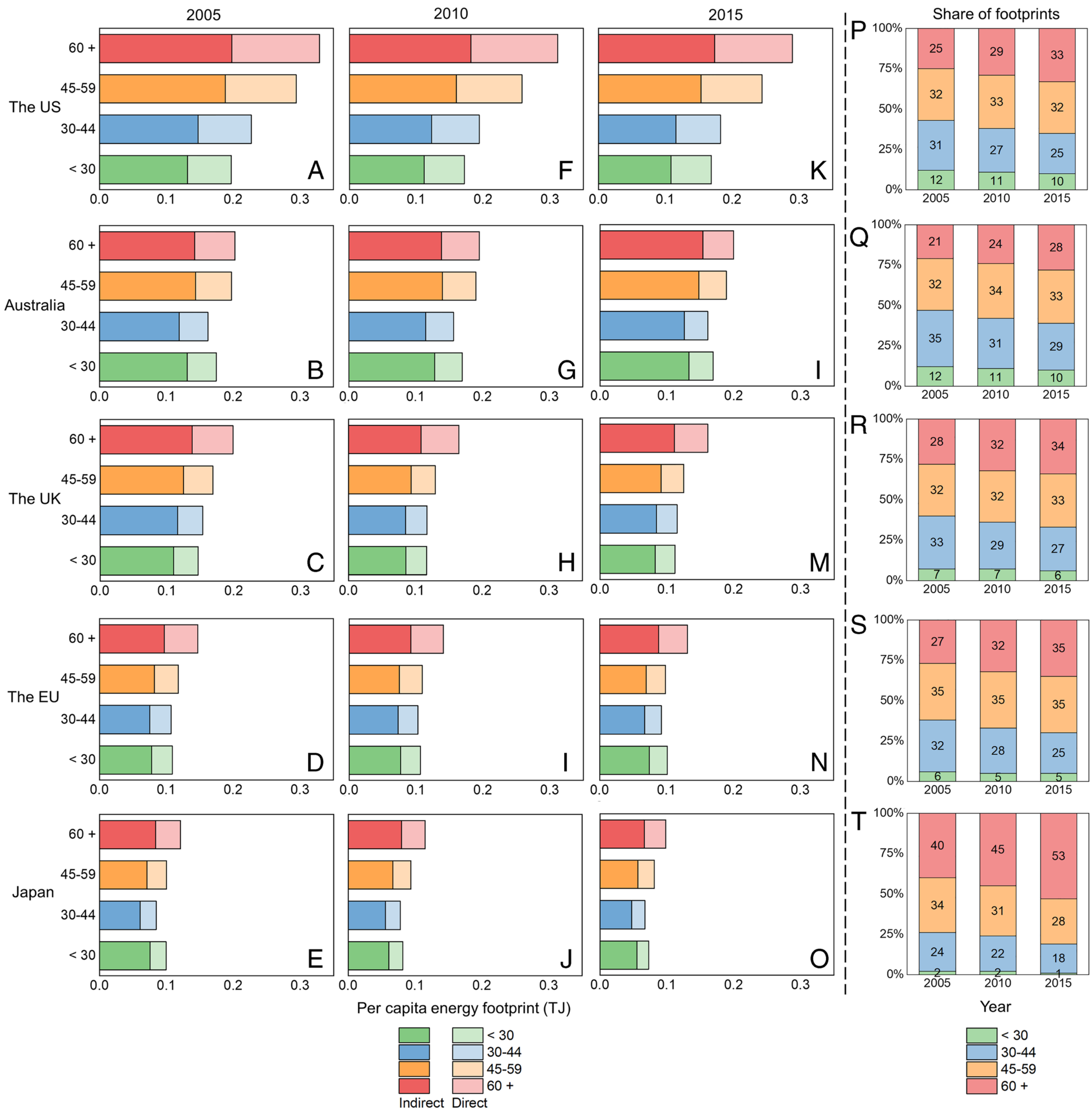

Fig. 1. Per capita and share of energy footprints of four age groups in 31 countries. (*A–O*) Per capita energy footprints of four age groups for the years of 2005, 2010, and 2015. (*P–T*) The share of the elderly's energy footprint in the national/regional total during 2005 to 2015. Note: The results of 27 EU countries are displayed as a whole. Countries/Regions are ranked by per capita energy footprint of the elderly group in 2015.

with reduced household income usually leads to an increase in energy intensity of households.

Higher Total Energy Cost Burden Rate of the Elderly. To quantify the total energy cost burden of different age groups, we used the total energy cost burden rate, i.e., the share of the total energy expenditure to total expenditure of the household, to assess this burden (41). Notably, the total energy expenditure is the sum of expenditure on both direct and indirect energy consumption, the latter of which refers to energy use in the supply chain to produce and distribute final goods and services that a household consumes (*Materials and Methods*).

We found that the elderly group had a higher energy cost burden rate than the younger age groups (red dots in Fig. 3*A*). For instance, the energy cost burden rate of the elderly in Japan was 15.0%, whereas that for the other three younger groups was 12.7%. 12.4%, and 9.3%, respectively. This skewed effect on the elderly groups can be observed in almost all 31 countries, despite people in wealthy countries usually having a lower energy cost burden rate. More importantly, we found that the low-income elderly group had a higher energy cost burden than the low-income younger group despite the energy cost burden presenting a regressive distribution in the United States, the United Kingdom, and Japan (Fig. 3 *B–D*). For example, the total energy cost burden rate

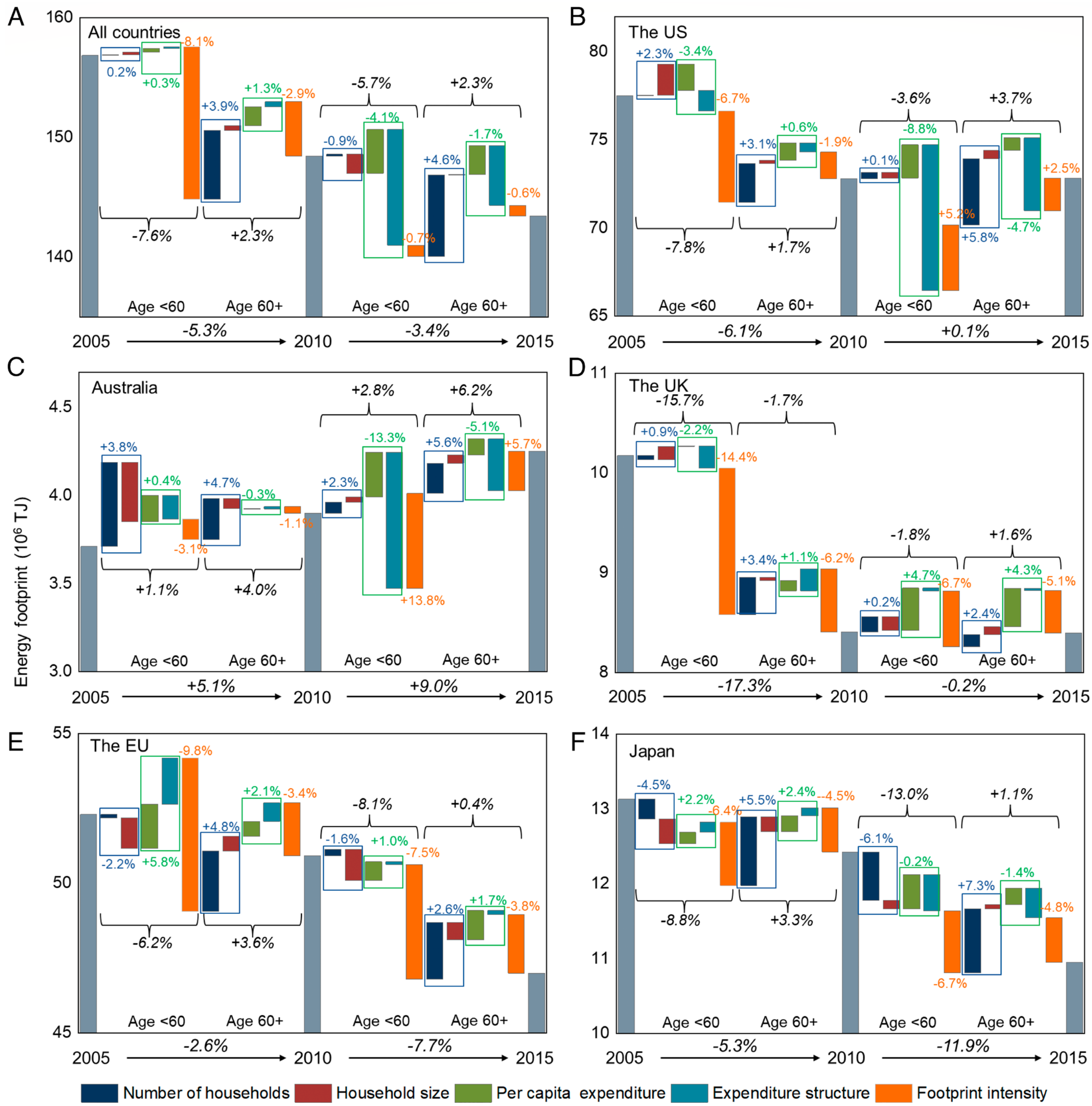

Fig. 2. Contributions of different factors to the changes in household energy footprint by age group from 2005 to 2015, for the United States, Australia, the United Kingdom, the EU, and Japan. (*A*) All of the 31 countries, (*B*) the United States, (*C*) Australia, (*D*) the United Kingdom, (*E*) the EU, and (*F*) Japan. The gray bars refer to the total household energy footprint in different years, while the colored bars refer to different socioeconomic factors driving changes in household energy footprints, presented by younger and elderly groups. Five socioeconomic driving factors were considered in this study. Number of households and household size were combined and referred to as household effect (blue box), per capita expenditure and expenditure structure factors are referred to as expenditure effect (green box), and footprint intensity is referred to as the efficiency effect (orange bar).

of the lowest-income elderly group were 16.9%, 22.9%, and 17.1% in the United States, the United Kingdom, and Japan, respectively, while the corresponding numbers were 14.4%, 18.1%, and 15.0% for the lowest-income younger group, respectively. The low-income elderly tend to spend higher share of expenditure on their direct and indirect energy consumption than their younger low-income group.

Given the higher share of their energy expenditure in total household expenditure, the elderly, particularly the low-income elderly, would be more vulnerable to energy price hikes (1, 2, 42). This inference was confirmed by our model simulation (*SI Appendix*, Fig. S7), in which we set the level of energy price hikes to the level of September 2022 during the Russia–Ukraine conflict, as done in reference (2). We found that the elderly, especially the low-income elderly, had the higher additional expenditure burden rate under energy price hikes (*SI Appendix*, Fig. S7), which can be observed in almost all studied countries. In addition, we found that the relative gap in the additional expenditure burden

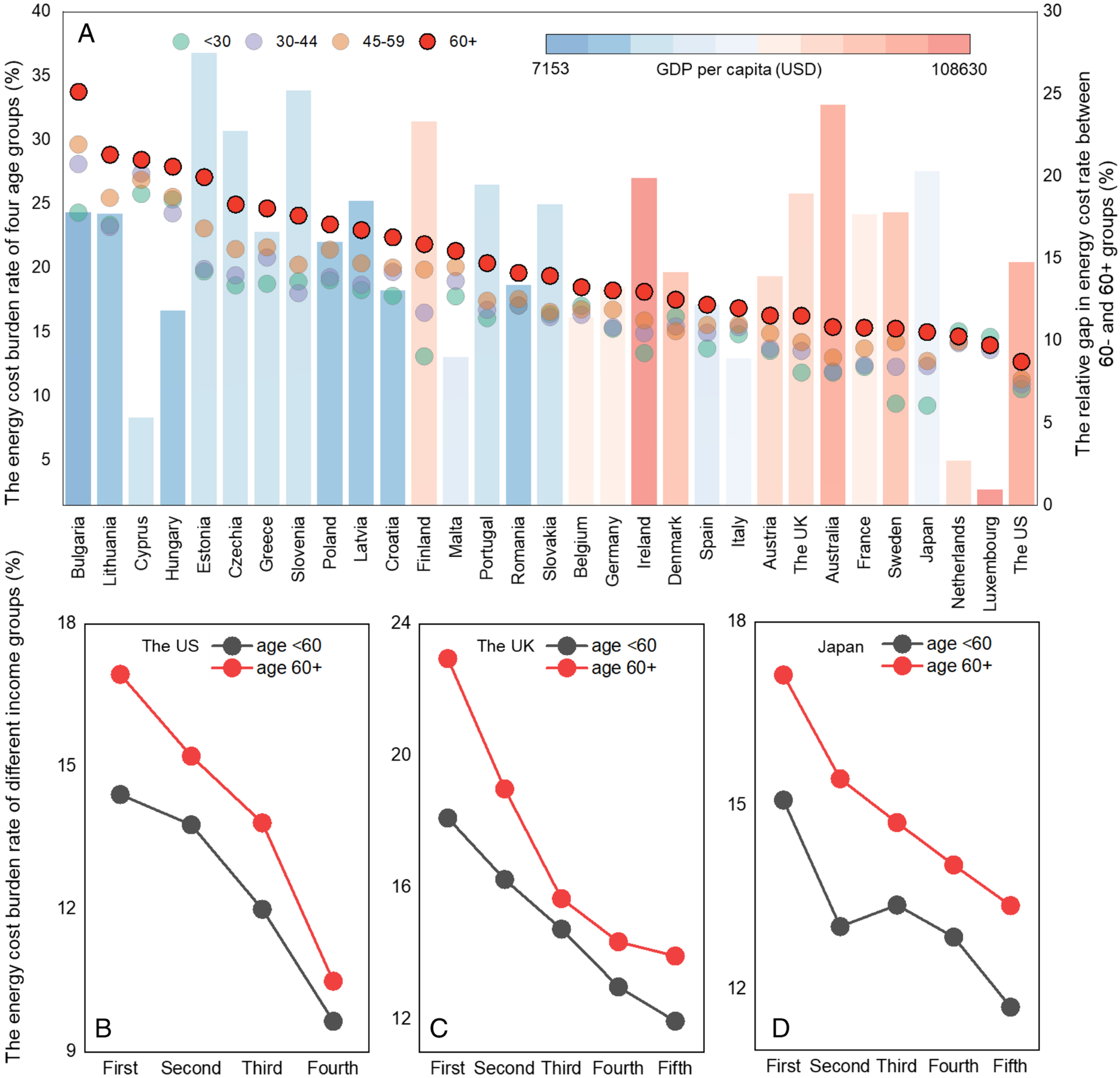

Fig. 3. The total energy cost burden rate among different age and income groups in 2015. (*A*) The energy cost burden rates of four age groups by country in 2015. Dots refer to the total (direct and indirect) energy cost burden rate by age group (left coordinate scale). Bars refer to the relative gap of the energy cost burden rates between age <60 and age 60+ groups (right coordinate scale). The color of the bars corresponds to the national per capita GDP. (*B*, *C*, and *D*) The energy cost burden rates of different income and age groups in the United States, the United Kingdom, and Japan, respectively. Labels on the *x*-axis show an increasing income from the first to the fifth group.

rate between the elderly and younger groups in less affluent countries (e.g., Poland and Czechia) were much larger than those in relatively affluent countries (e.g., Luxembourg and Sweden) (*SI Appendix*, Fig. S8), which implies that the low-income elderly and elderly in less affluent countries are more vulnerable to the energy price hikes.

The different distributions of the energy cost burden rate between the elderly and younger groups are largely determined by structural differences in their consumption and corresponding supply chains. We further investigated the sectoral structure of the energy cost burden among different age and income groups (Fig. 4*A*). We found that direct energy cost was the major component of the total energy cost burden for all age groups, despite the direct energy use was only one-third of indirect energy consumption in most of the studied countries. This is because household energy prices are much higher than industrial energy prices in most of these 31 countries. Compared with other age groups, elderly usually have a higher share of direct energy cost, and lowest-income elderly typically have the highest share of direct energy cost. This may be related to their longer stay at home, higher demand for cooling and heating, and the lower purchasing power of low-income elderly (24, 43). However, fewer outdoor activities may not necessarily mean lower transport fuel (Fig. 4*A*). The elderly may use more private transport because they usually live in distant

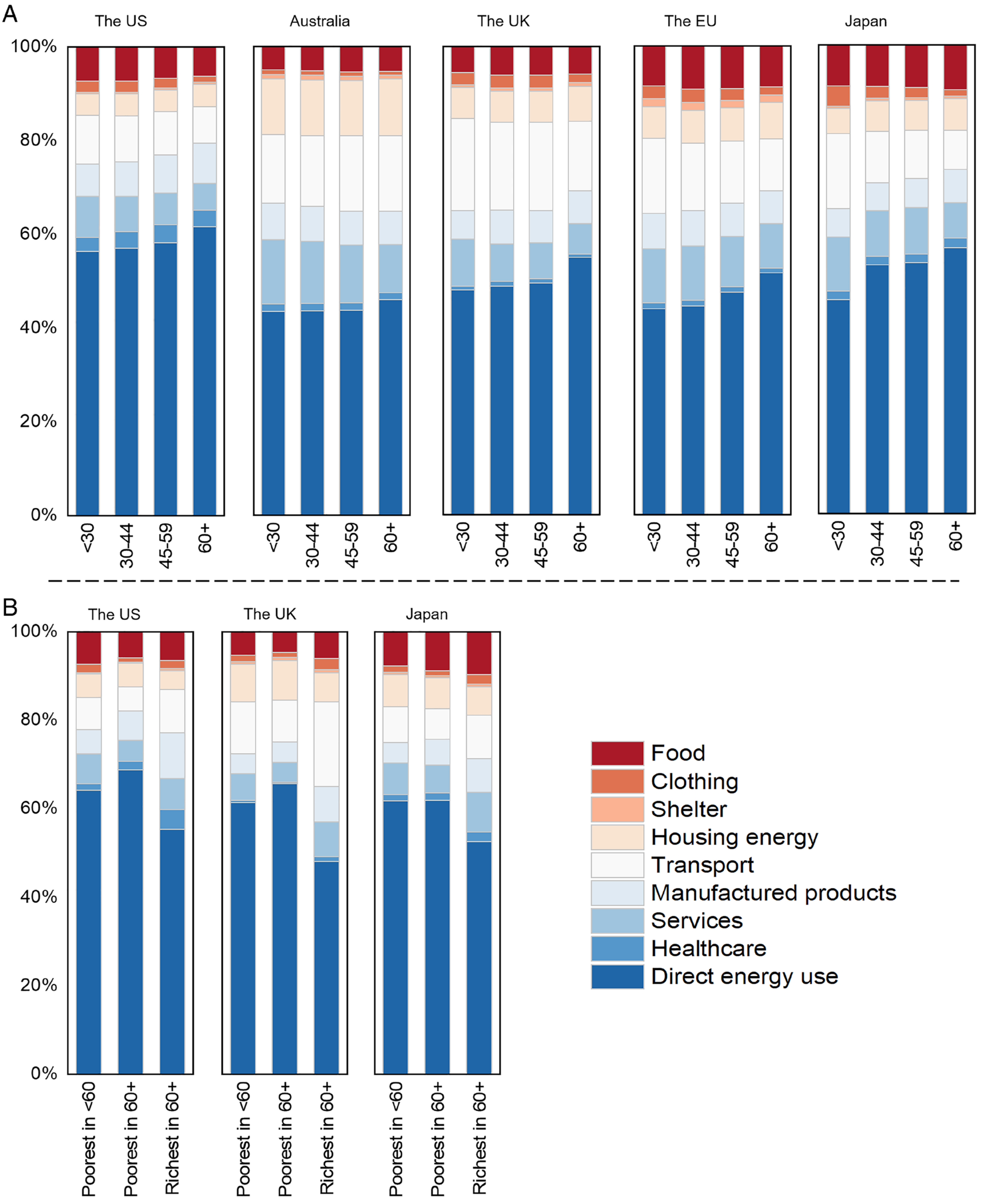

Fig. 4. Composition of per capita energy burden for different age and income groups in 2015. (*A*) Sectoral structure of energy cost burden for four age groups in the United States, Australia, the United Kingdom, the EU, and Japan. (*B*) The comparison of sectoral structure of total energy cost burden for three selected income-age groups in the United States, the United Kingdom, and Japan. The results of 163 sectors in EXIOBASE are aggregated into 8 merged sectors. Energy use for resident and private transport is included in "Direct energy use", which follows the classification of Exiobase 3.

suburbs (44), which leads to a high share of direct energy use costs and a lower share of commercial and public transport costs. Compared with the low-income younger group, the low-income elderly have higher (indirect) energy costs for manufactured products and housing energy, while high-income elderly groups tend to have higher (indirect) energy costs for services (38).

Discussion

In this study, we have quantified the direct and indirect energy footprints and associated total energy cost burdens for different age groups across 31 developed countries. By contrast, previous studies have focused on the direct energy use and cost of the elderly. Our results show that the elderly have larger per capita energy footprints, resulting from higher levels of both direct and indirect energy consumption compared with the younger age groups. More importantly, the elderly, especially the low-income elderly, have a higher total energy cost burden rate. As the share of elderly people in the total population is rapidly increasing in the studied countries, the greater per capita energy footprint and associated cost burden rate of the elderly make these countries more vulnerable during energy crises. Our simulation on price hikes further affirms that the elderly, especially the low-income elderly, face a heightened financial strain due to elevated energy costs, which pose challenges to energy policy design.

However, existing policies lack attention to the larger footprints of the elderly's energy consumption and the associated cost burden. People aged above 60 y are projected to be double between 2000 and 2050, and high-income region, such as Europe, is expected to remain the most aging society in this period (45). It can be anticipated that the enlarged share of the elderly in total population will drive up the shares of both direct and indirect energy consumption in the total expenditure in the future. It should be recognized that not all energy consumers have the same needs and same cost-bearing ability. The public sector needs to recognize and respond to such differences (46, 47). Although energy policy clearly needs to pay more attention to low-income groups (2, 48), our study suggests that the elderly group might need additional consideration even if they are not low-income so that their energy costs burden rate can be reduced. In addition, it should be noted that some climate or fiscal policies, such as carbon price and energy tax, would also drive up the prices of fossil energy, which may add disproportionate burden to the elderly (41). This requires the government to take appropriate protection schemes when implementing these policies.

Given that the low-income elderly with the highest energy cost burden is the most vulnerable group to energy price hikes, targeted policy protection and support are essential. Since 2021, European countries have enacted many measures, including subsidies of more than 600 billion euros and several policy measures, such as reducing energy tax, retail price regulation, cash transfer to vulnerable groups, and business support, to respond to the energy price spikes during an energy crisis (1, 49). However, targeted support for the elderly, particularly low-income elderly, is still limited. Although previous policies have included low-income groups in reducing the impacts of the energy price increase, the plight of the low-income elderly group has not received sufficient attention (50, 51). Compared to their younger counterpart, there are larger physical and social barriers preventing the low-income elderly group from coping with the energy crisis. For instance, there is significant age discrimination in the labor market. The United States has added 2.7 million jobs for workers under the age of 55 after COVID-19, and only a meager 28,000 for people over 55 y of age (52). Thus, low-income elderly people are more dependent on social and government aid. At the very least, it is imperative that response policies to an energy crisis are inclusive of the needs of the low-income elderly, who suffer great risks under the energy crisis. Crafting policies with this consideration is a crucial step toward achieving an equitable and effective response to the energy crises in an aging society.

Our research further underscores the importance of improving energy efficiency across the global supply chain in increasing the resilience of the elderly in developed countries against energy supply shocks. Although there are many measures that can help the elderly improve their energy efficiency, implementation of these measures requires substantial financial and social support. This is partly due to the need to change some long-standing habits and the generational preference of the elderly for less energy-efficient practices (15, 17, 19, 20). For example, implementing upgrades such as insulation and sealing drafts represents a good investment to improve household energy efficiency, considering that the elderly tends to live in bigger and older properties (53–55). Government support and community help are also necessary to encourage older adults to choose a more energy-efficient lifestyle. For instance, helping the elderly use newer, more efficient products (56) and providing better access to convenient public transport (53) can lead to significant improvement in energy efficiency. Nonetheless, intensified efforts from the public sector are imperative to drive this change.

Materials and Methods

Calculation of Energy Footprint with an Environmental Extended Multi-Regional Input–Output Approach. Environmental extend input–output (EEIO), which has been widely used to analyze the direct and indirect footprints of consumption and trade (29, 33, 57, 58), was used to estimate the energy footprints of different age and income groups in this study. The energy footprints of four age groups (<30, 30 to 44, 45 to 59, 60+) for 31 developed countries (including 27 EU countries, the United Kingdom, Japan, the United States, and Australia) were calculated for 2005, 2010, and 2015. The basic linear equation with the classic Leontief inverse is

$$x = (I - A)^{-1} y, \quad [1]$$

where x is total output, A is the technical coefficient matrix of the economy, y is the final demand vector by sector, and $(I - A)^{-1}$ is the Leontief inverse matrix, which shows the total production of each sector required to satisfy the final demand vector in the economy.

Energy footprints were calculated using the environmentally extended multi-regional input–output (EEMRIO). Due to that the MRIO database EXIOBASE, which this study uses, reports final energy use for industry and household separately, for each energy carrier (c), the energy footprint ($Ef_{i,q,c}$) of household group (q) in country (i) thus can be obtained by summing the indirect energy consumption ($Ef^{indir}_{i,q,c}$) embodied in the consumption of goods and services and the direct energy consumption ($Ef^{dir}_{i,q,c}$) by household group (q) (59–62). Mathematically:

$$Ef_{i,q,c} = Ef^{indir}_{i,q,c} + Ef^{dir}_{i,q,c}, \quad [2]$$

where the indirect energy footprint $Ef^{indir}_{i,q}$ can be expressed as the product of the energy intensity (K_c) of energy carrier (c), the Leontief inverse matrix ($(I - A)^{-1}$), and the vector of final demand ($y_{i,q}$) of household group (q) in country (i):

$$Ef^{indir}_{i,q.c} = K_c (I - A)^{-1} y_{i,q}, \quad [3]$$

wherein the energy intensity (K_c: TJ/10^6 euro) of energy carrier (c) is a row vector by industry sector (j) for each country (i), can be obtained by dividing energy consumption ($E_{i,j,c}$) of production industry sector (j) and country (i) by total input ($x_{i,j}$) of industry sector (j) and country (i): Mathematically:

$$K_{i,j} = E_{i,j,c} / x_{i,j}. \quad [4]$$

Due to the energy consumption account ($E_{i,j,c}$) in MRIO database only involves the energy consumption for the industrial production (59), the $Ef^{indir}_{i,q,c}$ thereby captured energy consumption along the supply chain of household, in other words, indirect energy consumption. The direct energy consumption of all household can be directly obtained from the household energy consumption account of the EXIOBASE database (*SI Appendix*, Fig. S10). Then, we split the direct energy consumption of all household based on the HES data and obtained the direct energy consumption of each age group ($Ef^{dir}_{i,q,c}$) (7).

Finally, the total energy footprint ($Ef_{i,q}$) can be obtained by summing direct and indirect footprints of all energy carriers:

$$Ef_{i,q} = \sum_{c=1}^{8} (K_c (I-A)^{-1} y_{i,q} + Ef_{i,q,c}^{dir}). \quad [5]$$

All energy carries are merged into eight categories (coal, natural gas, gasoline, diesel oil, kerosene, fuel oil, electric, others) and are involved in the energy footprints calculation, thereby there are eight types of energy carrier (c).

Estimation of the Total Energy Cost Burden. We also use the MRIO to estimate the total energy cost burden on households (63, 64), given that it can capture both direct and indirect energy costs on households, including not just energy products, such as fuel, but also the energy cost embodied in the consumption of goods and services. Similarly, the energy cost $Ep_{i,q,c}^{tot}$ of energy carrier (c) was calculated using the environmentally extended MRIO. Based on the energy cost coefficient e_c (i.e., the production cost in each economic sector owing to the energy consumption, can be expressed as the product of energy prices (p_c) and energy intensity (K_c) (2, 41). Mathematically:

$$Ep_{i,q,c}^{tot} = p_c \times K_c (I-A)^{-1} y_{i,q} + p_c \times Ef_{i,q,c}^{dir}, \quad [6]$$

where p_c is the energy price of energy carrier (c), which is a vector by countries. $p_c \times K_c(I-A)^{-1} y_{i,q}$ captures indirect energy costs along the supply chain, and $p_c \times Ef_{i,q,c}^{dir}$ denotes the direct energy cost.

Last, as the absolute energy cost value is unable to reflect affordability, while different groups having varying financial capabilities. We used the total energy cost burden rate $I_{i,q}$, i.e., the share of total energy expenditure (direct plus indirect) to total household expenditure ($m_{i,q}$), to assess the full energy cost burden of different age and income groups. Mathematically:

$$I_{i,q} = \frac{\sum_{c=1}^{7} Ep_{i,q,c}^{tot}}{m_{i,q}}, \quad [7]$$

where $\sum_{c=1}^{7} Ep_{i,q,c}^{tot}$ is the energy cost for all energy carrier use of age or income or income-age group q and m_q is the total household expenditure for q. Notably, we consider seven energy carrier (c), excluding the category of "others" when calculating the energy cost burden and impacts of energy price hikes.

Similar to the calculation of energy cost burden, we also used the MRIO to estimate the impact of increased energy prices on households, given that it can capture both direct and indirect impacts of increased energy prices on households, including not just energy products, such as oil, but also the price increase of other consumption goods as triggered by energy prices rising. This method has been widely applied in impact studies of energy subsidies, energy/carbon tax, and carbon pricing (36, 38, 65, 66). Notably, the MRIO approach provides an upper-bound estimate of the short-term impact of an energy price rise as it cannot reflect the short-term substitutions of production factors in the economy. However, it is close to the intuition perceived by the public owing to its transparency, making it a good way for policymakers to focus on the social reaction to energy pricing hikes (66, 67).

Specifically, the energy price p_c hikes when energy crisis occurs. The additional expenditure ($\Delta Ep_{i,q,c}^{tot}$, direct plus indirect) of energy carrier (c) under energy price hikes can be expressed as:

$$\Delta Ep_{i,q,c}^{tot} = \Delta p_c \times K_c (I-A)^{-1} y_{i,q} + \Delta p_c \times Ef_{i,q,c}^{dir}, \quad [8]$$

where, Δp_c is the increase rate of energy price of energy carrier (c). And we also use the additional expenditure burden rate ($\Delta I_{i,q}$) to refer the impact of rising energy prices:

$$\Delta I_{i,q} = \frac{\sum_{c=1}^{7} \Delta Ep_{i,q,c}^{tot}}{m_{i,q}}. \quad [9]$$

Logarithmic Mean Divisia Index Decomposition. We used the logarithmic mean divisia index (LMDI) to investigate the socio-economic driving forces of energy footprint change in 31 countries. This method has been widely applied in studies on energy and carbon emissions (68–71). In this study, we decomposed energy footprints by country with age groups as five socioeconomic driving factors, i.e., number of households, household size, per capita expenditure, expenditure structure, and footprint intensity. The number of households and household size were combined and referred to as the household effect. Per capita expenditure and expenditure structure factors are referred to as expenditure effect. Footprint intensity is referred to as the efficiency effect. More information about LMDI can be found in *SI Appendix*.

Data Sources. We used detailed household expenditure by age/income groups and global MRIO tables as well as energy consumption extended accounts to assess energy footprints and capture the energy cost of different groups. The MRIO table and energy consumption extended accounts (energy consumption of production industry and household) were obtained from EXIOBASE, a global detailed environmentally extended MRIO database developed by harmonizing and detailing supply use tables for EU countries and their main global trade partners, including 44 countries and 5 rest of the world regions (61, 62, 72). It provides a detailed sectoral classification of 200 products (163 sectors) from 1995 to 2016, with more than 1,000 environmental and social satellite accounts. EXIOBASE (version 3.7), covering 2005, 2010, and 2015, was used in this study. The builders of EXIOBASE 3 have developed multiple energy accounts. We specifically chose the "Net energy use" account as it effectively addresses the prevalent "double accounting" problems encountered in energy footprint accounting (59).

The household expenditure survey (HES) data were derived from national statistics agencies of the EU (Eurostat), the United Kingdom (Office for National Statistics), the United States (Bureau of Labor Statistics), Japan (Statistics Bureau of Japan), and Australia (Australian Bureau of Statistics). HES data provide a comprehensive description of household consumption characteristics for different households, including family member parameters, consumption items, household size, and expenditure on items. Notably, because the sampling is based on households in HESs, the HES data by age groups published by these agencies are presented by the age of the reference person (usually called household head referring to the breadwinner) of a household, and the expenditures are presented by households (7, 61). Given the economic status of household heads, age has a significant impact on household expenditure patterns. Therefore, grouping households according to the age of the household head is a common practice in the literature. All HES data of all countries/regions used in this study are nationally averaged, rather than micro-data at the household level. The income-age paired group data were only available for the United States, the United Kingdom, and Japan. Therefore, the income-age paired analysis was suitable only for these three countries. Notably, for the income-age paired groups, the households were first divided into multiple income groups based on household income, and each income group was further divided into multiple age groups based on the age of the household head (*SI Appendix*, Fig. S11).

Seven energy carries (coal, natural gas, gasoline, diesel oil, kerosene, fuel oil, electric) were involved in the energy cost burden calculation. The yearly energy price of these energy carries was derived from the International Energy Agency (IEA) (73). Particularly, we have considered the end-use price difference between industrial and household energy. In most study countries, household end-use energy prices are much higher than industrial end-use energy prices.

To measure the fluctuations in energy prices since the Russia–Ukraine conflict, we also collected the actual energy prices from Newcastle coal futures, Brent futures, and US natural gas futures (1, 2). Compared to 2021, the futures prices of coal, crude oil, and natural gas increased by 176%, 51%, and 94% from February 2022 to September 2022, respectively. Considering that our research year is 2015, we applied this rate of change in energy prices to 2015. Finally, we designed the energy price hike scenario in this study: the prices of coal and coal products, oil and oil products, and natural gas increase by 176%, 51%, and 94%, respectively. Notably, due to the end-use, energy prices involve many other additional costs besides energy raw material costs, such as energy tax and profits of energy companies, the end-use energy prices are much higher than that of futures market prices (74). we assumed that the price hikes only occurred in the energy raw material price, which is the futures market prices. And the prices of coal and oil products follow the variation patterns of coal and oil, respectively (2).

Limitations. In this study, we quantified the direct and indirect energy footprints as well as the total energy cost burden rate of elderly groups. There are several uncertainties and limitations to our study. First, HES data are presented by the age of the reference person (breadwinner) of a household, as identified by national statistical agencies (27, 75, 76). It means that younger people will be counted as a member of their parental household if they cohabit with their parents, which may lead to uncertainties. However, the cases where children live with their parents aged 60+ could be very rare in these 31 developed countries (7, 22). Our data do show that elderly households usually have smaller household sizes in comparison with middle-aged households (*SI Appendix*, Fig. S6). Literature has shown that smaller households generally have higher per capita consumption and environmental footprint (21, 22). Therefore, household size and composition are important when translating the results to per capita. To some extent, using the per adult-equivalent (minors are converted into adults by a certain coefficient) measure helps alleviate the problem (77). We further calculated the results per adult-equivalent for 2015. We found that the elderly group still had the highest footprints and energy cost burden rate when the results were presented as adult-equivalent (*SI Appendix*, Fig. S9). Based on the above, we argue that the age group classified by breadwinner's age would not distort our major findings significantly. On the other hand, it is worth noting that micro-level data with higher resolution and wide coverage are needed for providing hierarchical results in the future.

Second, the published HES data is categorized into specific age groups, which prevents us from exploring the differences within the group. For example, the consumption patterns of elderly aged 75+ can markedly differ from those in their early 60 s. This also deserves attention in future work. Third, we used the energy footprint and yearly end-use energy prices to calculate the energy cost burden of household. The end-use energy prices may change within a year and our footprints calculations were based on the energy equivalent, rather than physical quantity, which have some uncertainties. But the conversion between energy equivalent and physical commodities is a common practice in the literatures and IEA reports (21). Fourth, as discussed in the method section, the MRIO model is linear. Thereby, the MRIO approach provides an upper-bound estimate of the short-term impact of an energy price hikes as it cannot reflect the short-term substitutions of production factors in the economy (38, 41, 67). The computable general equilibrium (CGE) model may be a good option for addressing this concern in the future (35). Finally, our study focuses on developed countries. The aging issue are more complex in developing countries, such as China and India, which usually experiencing rapid economic development and changes in lifestyle (27, 78). In addition, they have different cultures and habits compared with developed countries. For instance, many elderlies in China reside with their children, whereas the elderly in developed countries usually live independently (79). This may make it difficult to capture the consumption pattern of elderly households using HES data classified by reference person. Future research in southern countries can enrich the results of our study.

Data, Materials, and Software Availability. The EXIOBASE 3.7 is available at https://www.exiobase.eu/ (62) and https://zenodo.org/record/4588235#.YxoZS3bMKUk (80). End-use energy price data are available at https://www.iea.org/data-and-statistics/data-product/energy-prices (81). Futures market energy prices data are available at https://tradingeconomics.com/commodities (82). Household expenditures by aging groups are sourced from the household budget survey of the EU (https://ec.europa.eu/eurostat/web/household-budget-surveys/database) (83), consumer expenditure survey of the United States (https://www.bls.gov/cex/csxstnd.htm) (84), Family Income and Expenditure Survey of Japan (https://www.stat.go.jp/english/data/sousetai/1.html) (85), and Household budget survey of Australia (https://www.abs.gov.au/statistics/economy/finance/household-expenditure-survey-australia-summary-results) (86). Household expenditure by income-age paired groups is sourced from the Consumer Expenditure Survey of the United States (https://www.bls.gov/cex/csxstnd.htm) (84), Office for National Statistics of the United Kingdom (https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/expenditure) (87), and Family Income and Expenditure Survey of Japan (https://www.stat.go.jp/english/data/sousetai/1.html) (85). Data sources and code to calculate the energy footprints and energy cost burden of age groups is available at: https://github.com/PeipeiTian/Aging-society-and-energy-cost-burden (41, 88). All other data are included in the manuscript and/or *SI Appendix*.

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