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# Aging alone: a twin threat to decarbonisation and energy vulnerability in Japan and UK

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ABSTRACT

Demographic trends have attracted attention in the energy and climate change literature, where there is widespread concern about the potential for population level effects on both carbon emissions and energy vulnerability. Here, we offer a summary of the existing evidence associated with aging populations and reducing household sizes, and build on this to argue that 'aging alone' needs additional consideration. To that end, we present a novel cross-national comparison of the domestic energy effects of aging alone in Japan and the UK, to understand how these might shape broader societal goals of reducing energy vulnerability and decarbonisation. Older single-person households in both nations have lower incomes, but higher domestic energy use, related carbon emissions, and home energy costs per capita. There is a risk that more people aging alone could lead to more energy vulnerability, as well as a threat to decarbonisation targets. We conclude by encouraging scholars and policymakers to explore this issue in more detail in further research, and in designing housing and energy policy for this specific intersection.

## 1. Introduction

Nations across the globe face the challenge of an aging population (World Health Organisation, 2024). Specific concerns in global North nations, associated with long life expectancies and low birth rates, include the provision and costs of care, and cost of pensions. To date, there has been limited discussion of the links between aging populations and energy consumption trends, and the associated effects on carbon emissions and energy vulnerability (Muttarak, 2021).

Japan and the UK are characterised by relatively similar approaches to energy policy: both nations have high carbon footprints and are committed to reducing these under international agreements, both also recognise the presence of vulnerability to energy poverty. Japan and UK also have aging populations and shrinking household sizes, as well as a linked increase of single-person older households ('aging alone') (see Box 1). However, the connections between these demographic and household changes, and energy use and decarbonisation in the home have yet to be articulated in the public conversation in either nation, or indeed in research. Here we ask: what effect do the demographic and household changes associated with an increase in aging alone have on domestic energy consumption?

In this analysis, we begin by marshalling the interdisciplinary evidence to outline what is already known about the links between carbon emissions, energy vulnerability, aging populations and living alone. Then, drawing on quantitative government data from Japan and the UK, we profile contemporary trends in aging alone, revealing the carbon emissions and energy burdens associated with older single-person households in comparison to multi-person and younger households. The empirical contribution here is to demonstrate the intersectional effect of aging and household size on energy consumption, both in relation to carbon emissions and to energy poverty. We mean to draw attention to the energy-related risks associated with this demographic pattern, mainly by showing how aging alone shapes both carbon emissions and energy poverty in the present. In doing so we hope to stimulate a broader conversation about policy associated with energy and aging.

We find remarkable similarities between the two nations with

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regards to both energy vulnerability and domestic energy footprints. Older single person households in both nations have higher domestic carbon emissions per capita, higher home energy costs per capita and lower incomes. These effects increase with age, with those over 75 having the highest domestic carbon emissions and home energy costs per capita. In both countries, there is a risk that an increase in aging alone could lead to an increase in energy poverty and a failure to progress towards climate change targets. We finish by calling for further research in the area, as well as greater attention to this demographic in the context of decarbonisation and energy poverty policy.

## 2. Existing evidence

Pertinent evidence here comes from three interdisciplinary interest areas: research that explores how carbon emissions and related energy use are distributed through the population; research on energy poverty and vulnerability, specifically that which also takes an interest in aging; and research on social isolation in old age. We profile each of these in turn and conclude by identifying the missing evidence base on aging alone and domestic energy use.

### *2.1. Carbon emissions, aging and living alone*

Household carbon emissions arise from direct and indirect fossil fuel energy use. International studies have found that total (direct and supply chain) emissions or energy use tend to increase with age and fall with very old age (75-80+) (Büchs and Schnepf, 2013; Christis et al., 2019; Haq et al., 2007; Lévay et al., 2021a; Liu et al., 2022). This overarching pattern is not consistent across consumption items. Due to reduced mobility and spending more time at home in the day, older people tend to have higher home energy emissions (Büchs et al., 2018; Büchs and Schnepf, 2013; Christis et al., 2019; Lévay et al., 2021a). In contrast, younger people have higher emissions from air travel and the number of flights taken declines with age (Büchs and Mattioli, 2021, 2024; Mattioli et al., 2023). Private car use is more complex: younger people are less likely to own a car, middle aged and older households produce higher emissions from car travel, then the very old return to lower car usage (Büchs et al., 2018; Mattioli et al., 2023).

Aging clearly shapes energy use and carbon emission patterns, but these patterns are also changing over time, and it is unclear what the future holds. One would expect an aging population to result in lower carbon emissions associated with car travel, and higher emissions for residential energy (Bardazzi and Pazienza, 2023). However, the pattern of increasing emissions through middle and early old age may not hold for future generations (Bardazzi and Pazienza, 2023; Chancel, 2014; Owen and Büchs, 2024). Indeed, Generation X and Millennial households in the UK have smaller carbon footprints compared to Baby Boomers at a similar life stage after controlling for decarbonisation and inflation (Owen and Büchs, 2024). It is possible that specific generational constraints, associated with housing and heating type, lock people into higher emission profiles (Chancel, 2014).

Trends in emissions from domestic energy use in aging societies are also partly linked to falling household sizes. Household sizes are declining globally, a trend which started in the late 19th century in richer countries and includes poorer countries since the late 1980s (Bradbury et al., 2014; Ivanova and Büchs, 2022). At the same time, living space per person has been increasing in many countries due to larger dwellings and falling household sizes (Ellsworth-Krebs, 2020).

Several studies provide evidence that smaller and reducing household sizes are associated with higher per capita energy use and related emissions. For instance, in a sample of 43 countries, decreasing household size by one person increases per capita carbon footprints by 6% (Ivanova and Büchs, 2022); and smaller household sizes are linked to higher per capita emissions in Belgium (Lévay et al., 2021a) and China (Zhang et al., 2023). In Denmark, one-person households now make up 40% of all households and are responsible for 42% of Denmark's carbon footprint, the largest share of any household size (Jack and Ivanova, 2021). However, it should be noted that these average trends mask some areas in which smaller households can have lower than average energy use or emissions. For instance, one-person households are less likely to have a tumble drier than multiple-person households in the UK (Yates, 2018), smaller households are more likely to participate in environmentally-friendly behaviours in Belgium (Bartiaux and Reategui Salmon, 2014).

Existing evidence on the distribution of carbon emissions in the population to date, does not make clear how the intersection of increased numbers of older people living alone will affect energy use and related carbon emissions. While older households have lower emissions associated with travel, and single-person households have higher emissions overall, it is not clear if there is a difference in carbon emissions between younger and older households living alone, or how we would expect that to change over time.

### *2.2. Energy vulnerability and aging*

There is a growing body of research addressing energy vulnerability and older people. Energy vulnerability is understood as a failure to meet energy needs and one focus of research in this field has been the impacts of excessively low or high temperatures in the home on health, specifically cardio-vascular health (Marmot Review Team, 2011; Oliveras et al., 2020; Rudge and Gilchrist, 2005). Understanding and addressing older people's experiences tend to be a high priority in energy poverty and health research (Ballesteros-Arjona et al., 2022; Oliveras et al., 2020; Rudge and Gilchrist, 2005; Wilkinson et al., 2004). Age is not always the predominant factor determining energy vulnerability, however: while it plays a role in the level of vulnerability of individual members of the household, income and household composition are more prominent (Ballesteros-Arjona et al., 2022; Wilkinson et al., 2004). Vulnerability to energy poverty varies by place and by household type. Notably, the climate plays a role, with warmer countries affected by both summer heat and winter cold, and more extreme winter temperatures in cooler countries. The income of other family members, specifically head of household, and the number of incomes compared to number of family members living under the same roof also play a role in older people's vulnerability (Ballesteros-Arjona et al., 2022; Oliveras et al., 2020). In Japan, energy poverty prevalence among adults living alone is already known to be particularly high (Okushima, 2016, 2017).

Some studies have focussed on older people's experience of energy

**Box 1**
Demographic changes in age and household composition in Japan and UK

- Japan has the world's fastest aging population. In Japan, people who are both older (65+) and living alone are expected to reach 20+% of households by 2050 (from 13.2% in 2020) (National Institute of Population and Social Security Research, 2024)
- The UK saw an absolute increase in its older population, with 10.4 million people over 65 in the 2021 Census, in comparison to 8.7 million in the 2011 census (Centre for Aging Better, 2025). During this period, the UK has also seen absolute increases in men living alone (from 0.8 to 1.1 million, ibid.); and women living alone (1.9 to 2 million, ibid.). An anticipated 4.5 million older people will be living alone by 2043 (ibid.).

vulnerability, using qualitative interviews. Older Australians experiencing energy poverty were more likely to lack the means to afford adequate health care and food, while also less likely than other age groups to apply for complementary governmental support in relation to their energy needs (Porto Valente et al., 2022). In Japan, older people were seen to have emotional attachment to old and inefficient home appliances and were reluctant to engage in more substantial home renovations to improve thermal efficiency (Yagita and Iwafune, 2021). In England, studies have shown that older people face specific challenges in keeping warm, experience stigma associated to their age, and therefore require distinctive government support to combat vulnerability (Chard and Walker, 2016; Day and Hitchings, 2011; O'Neill et al., 2006). Studies in all locations agreed that older people experiencing energy vulnerability were often making choices between heating and eating, jeopardizing their health, and that current policies were not tackling the problem.

Further literature investigates the efficacy of energy vulnerability interventions in targeting older people (Eisfeld and Seebauer, 2022; Romero et al., 2018; Thomson et al., 2019; Tonn et al., 2021; Wright, 2004). These studies agree that older people have specific needs and face specific challenges. For example, an Austrian study shows that self-restriction in energy use, specifically in older households makes vulnerable households almost impossible to identify, and, as such, current metrics underestimate the energy vulnerability of older people (Eisfeld and Seebauer, 2022). Such self-restriction is also commonly reported in other nations (Middlemiss and Gillard, 2015). Similarly, when measuring energy poverty among older people in Japan, authors called for an appropriate assessment of under-consumption of energy (Okushima, 2019, 2021). In Europe, cooling needs are frequently disregarded in energy poverty policies (Thomson et al., 2019), despite being important for older people (Oliveras et al., 2020). In Japan, cooling needs were also hard to meet for older people in summer, partly because of the preference in this age group not to use air-conditioning (Yagita and Iwafune, 2021).

The existing evidence on energy vulnerability and aging shows older people to be an important population of concern, in need of targeted policy. It does not tell us whether people aging and living alone have specific additional vulnerabilities in relation to energy. We now turn to the literature on the social impacts of aging alone to consider the potential additional risks.

### 2.3. Aging alone in social context

Given the demographic shift associated with an aging population, the increased number of single person households in the global North and their carbon footprint, as well as the presence of energy vulnerability within these household types, there are clearly some issues of concern related to the risks facing aging-alone households. There are two important additional risks of social exclusion for households that are aging alone which relate to their access to energy services: the risk of loneliness and isolation, and the risk of poverty.

An international scoping review finds that older people are often socially excluded due to their inability to access important services and social opportunities, and being dependent on local amenities and mobility options (Walsh et al., 2017). Social exclusion can also be a function of loneliness, which is both dependent on local opportunities, but also on how welcome older people are made associated with ageism (ibid.). In Japan and elsewhere, older people are often digitally excluded leading to isolation and reduced life fulfilment (Cabinet Office, 2022). As in other age categories, women and LGBTQ + people are at additional risk of exclusion (Walsh et al., 2017).

An awareness of the importance of social inclusion, has also arisen in recent energy social science research. Research in the UK on the importance of social relations in shaping people's experience of energy vulnerability (Hargreaves and Middlemiss, 2020; Middlemiss et al., 2019), suggests that people depend considerably on their intimate relations to help them navigate the energy market (Ambrosio Albala et al., 2020), to implement energy renovations (Bolton et al., 2023; Brown et al., 2025) and for other kinds of informal and emotional support. In a study on Japan, older people took more heed of advice from an intimate relation than from energy experts in deciding to renovate (Yagita and Iwafune, 2021). Compared to other global North countries, older people in Japan also have much weaker relationships outside the family (Cabinet Office, 2021). Given Japan's aging population, such weak social ties, coupled with insufficient public assistance, will pose serious risks to high energy vulnerability in future.

Older people have diverse experiences, and thriving depends on a range of factors. Policy facing older people tends to cater badly for this diversity (Rolls et al., 2011). In the UK, policy aims to promote independence which can be problematic, especially for those living alone. Much of the literature emphasises the importance of being able to control one's own life (Dale et al., 2012). In a Spanish study, authors point to physical and mental health, the family environment and financial stability being important in older people thriving (Bosch-Farré et al., 2020). People's standard of living in retirement, both financially and in relation to wellbeing, is shaped by their work history and health behaviours, as well as more exogenous factors such as disability or age-related disease (Kanabar, 2017). This can result in intersectional effects for older people. Women aging alone, for example, are more likely to be poorer (linked to lower earnings, and lower pensions) and in poor health (due principally to being older when living alone) (Forward et al., 2022).

It is clear then that living alone in old age carries risks of loneliness and poverty. Initial work on social relations and energy poverty suggests that living alone may result in some older people struggling to access energy services. The causal link here is somewhat unclear however: merely living alone does not necessarily result in people being socially isolated. Similarly, while older people living alone on low incomes are likely to be more exposed to energy vulnerability, the evidence for this is not yet clear cut.

### 2.4. Aging alone: the missing evidence base

In summary, older people are more vulnerable on average to energy poverty, as well as consuming more domestic energy per person than other households on average. Older people are also vulnerable to social exclusion, loneliness and isolation. While people face a diverse range of aging experiences, the intersection of 'aging alone' potentially poses risks for older people themselves, and for decarbonisation and energy vulnerability. What happens to both carbon emissions and energy vulnerability at the intersection of 'aging alone' is not yet clear, due to a lack of analysis for this specific population. Given the strong demographic trends towards aging alone in many richer countries, and the interdisciplinary evidence summarised here, this is a topic that is surely worthy of investigation.

The research gap here relates to the specific experiences of single-person older households and their impacts on energy consumption. In wealthy countries faced with an aging population and falling household sizes, there is a strong case to study the needs and impacts of older people aging alone. A failure to understand the energy implications of aging alone, poses risks associated with fair policy making and effectiveness of energy transition policy, which translate to health and social risks for the household.

In the following section, we begin to fill this gap, establishing a deeper understanding of the risks associated with aging alone, exposure to energy poverty and meeting decarbonisation targets in Japan and the UK. We do so by undertaking a comparative analysis of data on emissions from domestic energy use and energy vulnerability (underuse of domestic energy) from aging-alone households in the two nations.

 

## 3. Comparing aging alone in Japan and the UK

### 3.1. Methodological approach

This analysis provides a first impression of the effects of aging alone on energy poverty and domestic energy carbon footprints, presenting empirical results from an analysis of quantitative Japanese and UK datasets created using government data. These two countries make for a valuable comparison, given their geographical distance and cultural differences, and common challenges associated with shrinking household sizes, aging population, energy poverty and decarbonisation. We compare data from 2019: the latest possible year before the disruption caused by Covid-19, as well as a year in which data for both countries is available.

Our sample contains 9660 households in Japan and 5438 households in the UK. Data are disaggregated by household composition (single, couple, other) and age group (younger, 65+, 75+). In both the Japanese and the UK data, multi-person households in the 65+ age group contain at least one person aged 65-74, but no person aged 75+, while multi-person households in the 75+ age group contain at least one person aged 75+. Each group contains a substantial number of households (see Table 1), meaning our findings are sufficiently robust.

UK consumption-based emissions are calculated using data from the UK's multi-regional input-output model (Owen and Kilian, 2024) and the UK's official household expenditure survey, the Living Costs and Food Survey (LCFS) (ONS, 2023). These datasets allow us to calculate consumption-based emissions from home energy use for each household in the LCFS. For Japan, all the data needed for the below analysis, including CO2 emissions, are derived from anonymized information on 'the 2019 Survey on the Actual Conditions of Carbon Dioxide Emissions from Residential Sector', which was provided for this study by the Ministry of the Environment, Japan (see 'Appendix A: methods notes' for detailed information).

Notably, this analysis adopts a risk-based perspective on energy vulnerability linked to high energy costs and low incomes, rather than applying a formal threshold-based measure of energy poverty. A risk-based approach is preferable in the context of 'aging alone', as fixed-threshold energy poverty measures may fail to capture emerging forms of energy vulnerability associated with ongoing demographic change.

### 3.2. Key trends: a remarkably similar story in both nations

The trends in the UK and in Japan are remarkably similar.[i] The main feature is that both household shrinking and aging contribute to higher CO2 emissions per capita, as well as higher energy costs. As household size gets smaller, energy consumption per person increases, such that single-person households have the highest CO2 emissions per capita, as well as the highest energy costs. The same pattern applies to the aging of population: both CO2 emissions and energy costs also increase with household age.

The combined effects of household shrinking and aging are noteworthy. When household composition is combined with age, aged 75+ and living alone is the highest carbon emitting household type (Fig. 1), and this household type also has the highest energy burdens (Fig. 2).

Which features might explain these common trends in such different countries? As discussed in the literature on economies of scale in residential energy demand, domestic energy use increases less than proportionally with household size, reflecting the shared nature of housing space and energy services, particularly space heating (Longhi, 2015; Matsumoto, 2025; Schröder et al., 2015). And these scale effects are especially relevant for older households, which often experience household downsizing without a proportional reduction in house size. House size per person therefore plays an important role (Ellsworth-Krebs, 2020; Okushima, 2024). This shows up in the analysis, where we see that single-person, older households live in larger homes (measured by floor space per capita in Japan; by number of rooms per capita in the UK) ( Fig. 3).[ii]

The fact that aging-alone households have both higher per capita CO2 emissions associated with domestic energy use and higher per capita energy costs raises serious concerns about future decarbonisation and energy vulnerability. Aging-alone households are more likely to be on low incomes (Fig. 4), which will reduce their capacity to adapt to change under decarbonisation policy, and increase the risk of energy vulnerability.

These empirical findings point to likely future risks in both countries, as well as potentially in other global north nations. Older households typically have greater domestic energy demands, leading to higher energy expenditure and higher CO2 emissions per capita, alongside financial constraints due to lower incomes. An increase in aging-alone households is likely to exacerbate energy vulnerability, and to make meeting international climate targets more challenging.

**Table 1**
Number of households in sample.

| | | Japan | UK |
|---|---|---|---|
| Single | younger | 1108 | 772 |
| | 65+ | 478 | 366 |
| | 75+ | 304 | 372 |
| Couple | younger | 1250 | 828 |
| | 65+ | 1060 | 532 |
| | 75+ | 544 | 378 |
| Other | younger | 2871 | 1978 |
| | 65+ | 833 | 136 |
| | 75+ | 1212 | 76 |
| Total | | 9660 | 5438 |

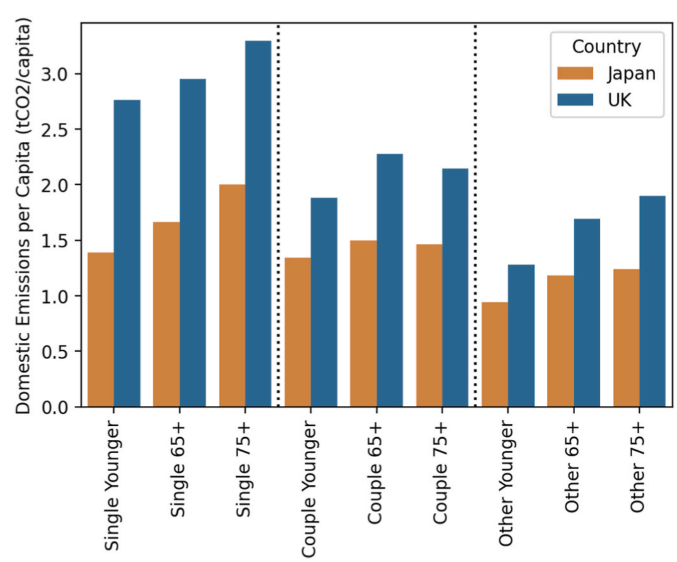


**Fig. 1.** CO2 emissions from domestic energy services use per person.

[i] This despite the fact that, as is well known, households in Japan use less home energy, particularly for heating, than Europeans (Kahouli and Okushima, 2021).

[ii] In Japan, older people often live in large, old, detached houses that are not well (or not) insulated (Castaño-Rosa and Okushima, 2021).

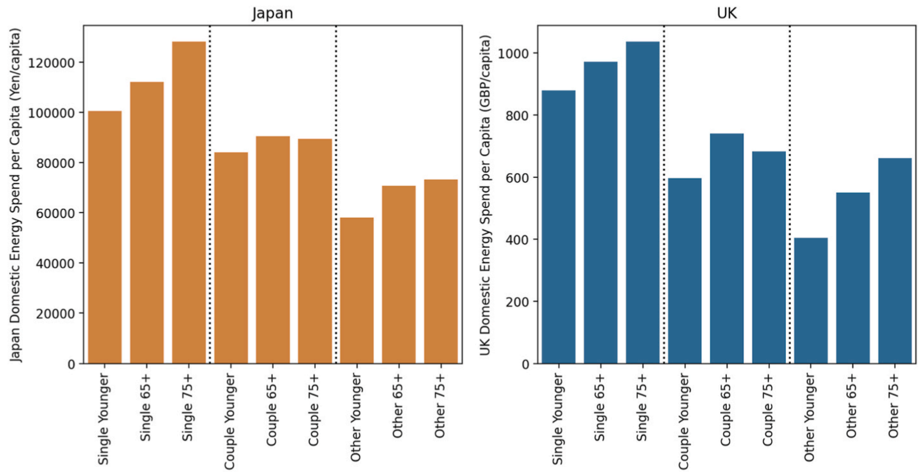


**Fig. 2.** Domestic energy expenditure (energy costs) per person.

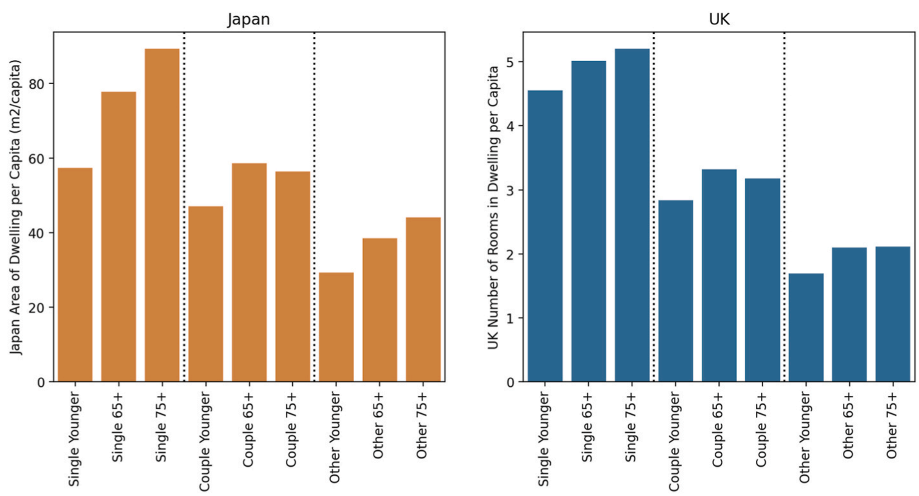


**Fig. 3.** Characteristics of housing – size of dwelling in Japan (m2 per capita) and the UK (number of rooms in dwelling per capita).

## 4. Conclusion and policy implications

Our initial analysis of existing evidence, including the comparison between Japan and the UK, suggests that this is an important line of enquiry. We hope that it will stimulate further research on this topic, looking at this problem in more detail within nations, and using evidence to think more creatively about how policy can address the condition of 'aging alone'. It also suggests the need to be alert to the intersecting effects of age and household size on both carbon footprint and energy vulnerability related to domestic energy consumption, and the possibility for similar effects at other intersections (Rainard et al., 2025). Further research should integrate both age and household size into wider research questions, but there is also plenty of scope for exploring the risks associated with aging alone in particular.

The most straightforward policy response to this evidence is to address aging-alone households explicitly and distinctively. This might mean offering additional support for aging-alone households to address high energy costs, as well as more substantive measures including energy renovation and retrofit for buildings inhabited by 'aging-alone' households. Longer term aspirations in both countries to improve the energy efficiency of the housing stock will have gradual positive impacts on these households, but a more targeted approach offers opportunities for more substantial carbon reductions, as well as likely reductions of energy vulnerability and associated health effects.

Given the broader evidence we profile above, there is also likely to be a need for more creative policy approaches to living a good life in old age. There are opportunities here to address loneliness, high carbon footprints and energy vulnerability through joined-up policy approaches. Existing studies have profiled means of reducing high-carbon single living (Ivanova and Büchs, 2022) which include relocating older people to smaller well-insulated dwellings in Japan (Yagita and Iwafune, 2021), preferably in areas where public transport is effective (Okushima and Simcock, 2024); or promoting and facilitating intergenerational co-housing in the UK, which reduces energy use (Williams, 2005) by both ensuring a smaller dwelling footprint, and by sharing energy-using facilities (Chatterton, 2013). Such policy options have cultural and social sensitivities, and require a cautious approach. A more low-key solution could be to help older people in underoccupied dwellings to rent space to younger people, with the resultant potential for reduction in both loneliness and energy costs. Further, the opportunity for sharing energy services in public spaces could also alleviate these issues. In Japan we see the promotion of the use of public baths to alleviate loneliness and reduce energy consumption (Yagita and Iwafune, 2021). We would encourage policy-makers and practitioners to draw on emerging evidence about aging alone, and to address this creatively given that it seems to be an intersectional issue worthy of attention, as well as an opportunity for addressing a range of social issues simultaneously.

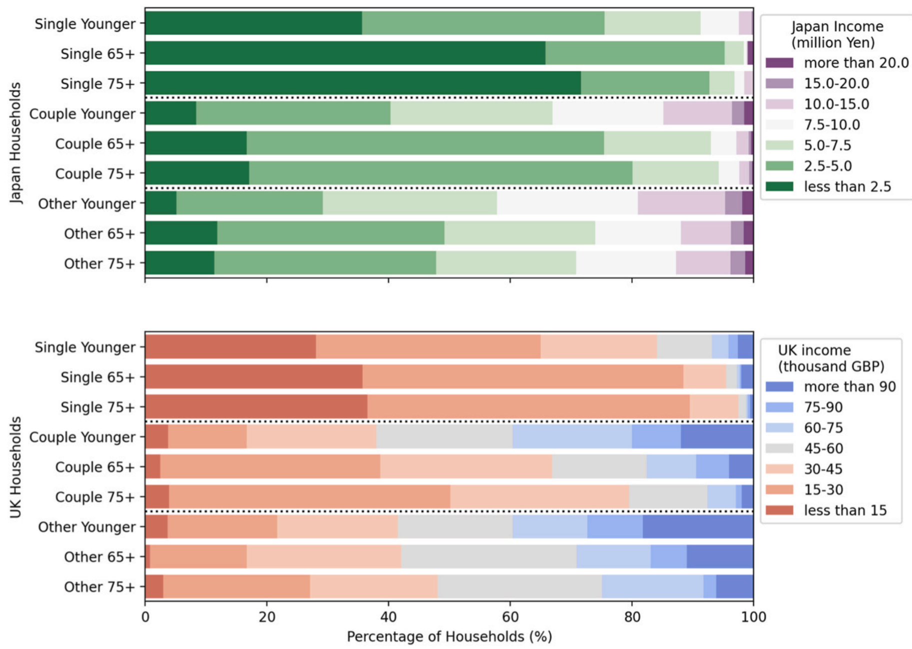


**Fig. 4.** Annual household income for Japan (top) in million Japanese Yen and UK (bottom) in thousand GBP; note, no adjustment for household size is done.

## CRediT authorship contribution statement

**Lucie Middlemiss:** Writing – original draft, Supervision, Investigation, Conceptualization. **Shinichiro Okushima:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Lena Kilian:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Mathilde Rainard:** Writing – original draft, Investigation, Conceptualization. **Milena Büchs:** Writing – original draft, Investigation, Conceptualization. **Anne Owen:** Writing – review & editing, Investigation, Conceptualization.

## Data statement

UK data is open source and freely available for research use. Japanese data used is anonymized information derived from ‘the 2019 Survey on the Actual Conditions of Carbon Dioxide Emissions from Residential Sector’. Microdata is not publicly available but was offered to us privately for this research by the Ministry of the Environment, of the Japanese government.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. methods notes

### *A.1 Japan Emissions*

Regarding Japan's $CO_2$ emissions data, this study employs anonymized information derived from ‘the 2019 Survey on the Actual Conditions of Carbon Dioxide Emissions from Residential Sector’. The summary statistics of this survey are published (Ministry of Environment, 2025), but its microdata is not publicly available and was offered to us privately for this research by the Ministry of the Environment, of the Japanese government. This anonymized information includes all the data necessary for the above analysis, such as household-level energy consumption, carbon dioxide emissions, and a comprehensive set of household characteristics, including household composition, dwelling information, and income brackets.

### *A.2 UK Emissions*

Households act as both producers of energy-related emissions released on-site and consumers of energy-related emissions that are emitted elsewhere. The former includes scope 1 emissions from households burning gas, liquid and solid fuel to heat the home. The latter include both emissions associated with supplying and making fuel and the scope 2 emissions associated with producing and supplying electricity to the home. The total emissions associated with households burning onsite are recorded in the UK's Environmental Accounts (Office for National Statistics, 2024). However, to calculate the emissions associated with supplying and making fuel and electricity (known as ‘supply chain emissions’ henceforth) we need to use a consumption-based accounting methodology whereby we can reallocate emissions from industry (i.e. the electricity or gas manufacturing sectors) to the point of consumption by the household.

To calculate the supply chain emissions of households, we need household expenditure data and supply chain carbon multipliers of energy products (in $tCO_2e/£$). We do this using the UK's multi-regional input-output model (UKMRIO)(Owen and Kilian, 2024) and the environmentally extended Leontief equation ($\mathbf{f} = eLy$), with $\mathbf{y}$ representing final demand by UK households, $\mathbf{e}$ is a measure of emissions intensity of industrial sectors and $\mathbf{L}$ is the Leontief inverse matrix which serves to reallocate emissions from industries to products. This calculates the emissions associated with demand for all goods and services by all UK households and it is possible to isolate the impact of consuming energy sectors from this calculation (Miller and Blair, 2022; Wood et al., 2019). After the supply chain emissions are calculated, we can add the direct household emissions to the products associated with fuel burning.

Using this analysis, we calculate total UK household emissions. To disaggregate these by household type, we divide total emissions by total household spend at a product-level to calculate the product-based multipliers (in $tCO_2e/£$). We then multiply these by household spends by type of household from the UK's annual consumption and expenditure survey, the Living Costs and Food Survey (LCFS) (ONS, 2023). In addition to detailed expenditure, the LCFS also contains information on household composition, income, dwelling size and age of residents. This means we can produce spend profiles by the nine household types shown in Table 1.

### *A.3 Variable differences between Japan and the UK*

Cross-country comparisons necessarily involve several sources of measurement heterogeneity regarding data sources and indicators. While both datasets contain domestic energy carbon emissions, UK emissions rely on expenditure data and MRIO to infer embodied carbon emissions, whereas Japan emissions use information on physical quantities of energy consumption derived from survey-based data. In addition, dwelling size is measured using total floor area in the Japanese dataset and number of rooms in the UK dataset. Finally, income and expenditure are in Japanese Yen and income is measured as categorical bands in the Japanese dataset, while in the UK dataset they are in British Pounds and income is measured as a continuous variable. However, this study does not compare absolute levels across countries and instead examines within-country relationships, so these measurement differences do not affect our analysis. Moreover, when comparing income groups, we use categories in accordance with comparable income ranges across both countries.

## Appendix B. Regression Analysis

To assess robustness of differences associated with aging alone a linear regression analysis is done. This uses household composition (as defined in Table 1), income, and dwelling size (dwelling area for Japan and number of rooms in accommodation for the UK) to predict per capita domestic carbon emissions and energy spend. The results show that, across both Japan (Table B1) and the UK (Table B2), the estimated coefficients broadly align with the relationships discussed in the main text. While these results are not interpreted causally, single-person households, particularly at older ages, exhibit higher per-capita domestic emissions and energy expenditure relative to multi-person households, after controlling for income and dwelling size, consistent with the main findings.

**Table B1**
Japan Result

| | Domestic Emissions per Capita (tCO2/capita) | Domestic Energy Expenditure (Yen/capita) |
|---|---|---|
| Single Younger | 0.739*** (0.034) | 53065*** (1563) |
| Single 65+ | 1.042*** (0.063) | 67149*** (2936) |
| Single 75+ | 1.272*** (0.076) | 76885*** (3278) |
| Couple Younger | 0.463*** (0.024) | 28004*** (1072) |
| Couple 65+ | 0.529*** (0.028) | 30880*** (1210) |
| Couple 75+ | 0.503*** (0.036) | 30746*** (1610) |
| Other 65+ | 0.149*** (0.026) | 9720*** (1199) |
| Other 75+ | 0.125*** (0.025) | 9299*** (1115) |
| Dwelling area | Control: Yes | Control: Yes |
| Income | Control: Yes | Control: Yes |
| Observations | 9309 | 9309 |
| R-squared | 0.213 | 0.300 |

Note: OLS estimates with robust standard errors. The reference category is 'Other Younger' households. For the regression analysis reported here, observations with missing data on dwelling area (n = 351) were excluded. Standard errors are shown in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

**Table B2**
UK Result

| | Domestic Emissions per Capita (tCO2/capita) | Domestic Energy Expenditure (GBP/capita) |
|---|---|---|
| Single Younger | 1.691*** (0.080) | 551.7*** (23.5) |
| Single 65+ | 1.707*** (0.109) | 595.9*** (38.5) |
| Single 75+ | 1.990*** (0.125) | 660.1*** (34.3) |
| Couple Younger | 0.661*** (0.054) | 212.7*** (15.1) |
| Couple 65+ | 0.763*** (0.078) | 248.3*** (32.3) |
| Couple 75+ | 0.645*** (0.078) | 215.4*** (22.4) |
| Other 65+ | 0.269*** (0.089) | 113.2*** (33.0) |
| Other 75+ | 0.475** (0.200) | 274.6*** (69.1) |
| Number of Rooms | Control: Yes | Control: Yes |
| Income | Control: Yes | Control: Yes |
| Observations | 5438 | 5438 |
| R-squared | 0.183 | 0.204 |

Note: OLS estimates with robust standard errors. The reference category is 'Other Younger' households. Standard errors are shown in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

## Data availability

Japanese data is confidential and provided by government to Shinichiro Okushima, UK data is open source.

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