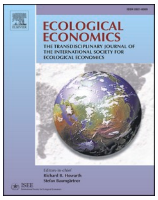
Ecological Economics 202 (2022) 107590

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon



Implications of shrinking household sizes for meeting the 1.5 °C climate targets

Diana Ivanova, Milena Büchs [*]

University of Leeds, Leeds LS2 9JT, United Kingdom

ARTICLE INFO

Keywords:
Household size
Household dynamics
Climate change
Carbon footprint
Degrowth

ABSTRACT

Understanding social trends such as shrinking household sizes plays an important role for designing effective policies to limit global warming to 1.5 °C and reach net-zero by 2050. Prior, cross-sectional work shows that larger households tend to have lower per capita carbon footprints and energy use due to sharing of living space and resources. However, we lack longitudinal studies that examine whether dwindling household sizes globally increase carbon footprints and create additional pressure for mitigation efforts in the future. We use data from 43 countries between 1995 and 2015, representative of 63% of the population and 80% of the carbon footprint globally in 2015. If household sizes had stayed at their 1995-levels, cumulative emissions between 1995 and 2015 would have been about 11.3 $GtCO_2eq$ lower. We project per capita total carbon footprints for 2030, showing that more household sharing could make a contribution to curbing emissions. This contribution, along other sustainable degrowth interventions, can produce substantial emission reductions necessary for achieving 1.5 °C compatible reduction targets for 2030. We further quantify some of the key socio-economic influences behind the household dynamics to discuss policy options for increased inter- and intra-household sharing.

1. Introduction

Urgent greenhouse gas (GHG) emission reductions are needed to limit global warming to 1.5 °C and reach net-zero by 2050 (Masson-Delmotte et al., 2018). Committed emissions from existing and proposed infrastructure exceed the entire 1.5 °C budget, suggesting that efforts to target early retirement of fossil fuel energy and industry infrastructure are needed to stay within the budget and the goals of the Paris Agreement (Tong et al., 2019). Beyond focus on industry and infrastructure, there is a need for a thorough understanding of socio-economic and cultural processes that influence GHG emission trajectories in order to design effective mitigation policies. This article makes an important contribution towards better understanding how shrinking household sizes worldwide affect the likelihood of meeting climate targets up to 2030.

According to a projection of household sizes (Jennings et al., 2000), the average global household size may fall from an average of 4.0 in 1990 to 2.5–3.0 in 2030 and 2.0–2.8 in 2050. The ratio of single-person households has grown over nine times between 1990 and 2050 (Jennings et al., 2000) and one-person households are expected to become the most prevalent of all household types by 2030. These decreases in household sizes vary substantially across countries, which also reflects huge differences in average household sizes around the world (*United Nations Population Division,* 2017). The decline in household sizes worldwide brings about increases in environmental impacts, and therefore has implications for efforts to mitigate climate change. However, a quantification of past and possible future impacts of shrinking household sizes is lacking so far, a gap that this paper addresses.

A range of previous papers have examined the influence of factors such as income, household size, age, education status, urbanity, labour market participation, increasing domestic floor area on per capita or household consumption-based GHG emissions (Büchs and Schnepf, 2013; Ellsworth-Krebs, 2019; Ivanova et al., 2018; Ivanova and Büchs, 2020; Lenzen et al., 2006; Lévay et al., 2021; Wiedmann et al., 2020). Most of these studies show that, holding other factors constant, larger household sizes tend to reduce per capita emissions due to sharing resources within households (Ivanova and Büchs, 2020), an effect known as *household economies of scale*. Prior research highlights the relationship between smaller average household sizes and higher per capita GHG emissions (Büchs and Schnepf, 2013; Fremstad et al., 2018; Ivanova et al., 2018; Ivanova et al., 2017; Ivanova and Büchs, 2020; Lévay et al., 2021; Zhang et al., 2015) and energy use (Ivanova and Büchs, 2020;

---

[*] Corresponding author.
E-mail addresses: d.ivanova@leeds.ac.uk (D. Ivanova), M.M.Buchs@leeds.ac.uk (M. Büchs).

https://doi.org/10.1016/j.ecolecon.2022.107590
Received 16 June 2021; Received in revised form 10 August 2022; Accepted 11 August 2022

Lenzen et al., 2004). However, these studies use cross-sectional, not longitudinal data, even though the latter are more suitable for controlling for observed and unobserved time-constant characteristics (Berrington et al., 2006). Advantages of panel data include more accurate inference of model parameters, greater capacity to capture the complexity of human behaviour, and simpler computation and statistical reference compared to cross-sectional data (Hsiao, 2007). Furthermore, the practice of extrapolating future trends based on cross-sectional patterns, which only reflect a snapshot of one point in time, has been called into question (Lesthaeghe, 2020). Notable exceptions include studies aiming to capture the long-term dynamics of household size on environmental impacts (Bradbury et al., 2014; Liu et al., 2003; Underwood and Zahran, 2015).

Finally, reducing GHG emissions and energy use through interventions that encourage larger household sizes requires a good understanding of the drivers behind the changes in household demographics. Various drivers have been discussed including changes in: (a) family and household formation, such as declining fertility rates (Bongaarts, 2001; Ivanova and Büchs, 2020; Underwood and Zahran, 2015), delayed fertility and changes in marriage and divorce rates (Ellsworth-Krebs, 2019; Lesthaeghe, 2014; Yu and Liu, 2007); (b) gender equality, such as shifts in female labour market participation, reproductive rights as well as trends in education, employment opportunities (Smith, 1981); (c) age, health and longevity; (d) increased material living standards (Keilman, 2003); (e) cultural preferences around cohabiting and intergenerational living, such as increased individual freedoms, economic aspirations and residential autonomy (Keilman, 2003); and (f) more general infrastructural, institutional and social influences such as housing prices (Keilman, 2003; *United Nations Population Division,* 2017), rigidity of the dwelling stock (Wulff et al., 2004) and net-migration (*United Nations Population Division,* 2017). Yet, quantitative evidence on the driving forces behind shrinking household sizes worldwide is largely missing.

To date there is limited research that connects the temporal and regional dynamics of household sizes and carbon footprints, amounting to a failure to recognize the potential of GHG emission savings through household sharing. Furthermore, the sharing agenda is often disconnected from a wider policy context necessary for transforming societies to meet climate targets. Here we quantify the GHG emission increase associated with the shrinking of average household sizes between 1995 and 2015 in a panel data analysis of 43 countries. We also project carbon footprints in 2030 at various household sizes and quantify the extent to which declining household sizes limit the potential for emission reductions while also taking factors such as population size, affluence and technology into account. Here, we compare the impact of shrinking household sizes in a scenario at past rates of economic growth and technological development with household size impacts in a degrowth context in which GDP declines by 4% per year by 2030 (Keyßer and Lenzen, 2021). Sustainable degrowth is a process of political and social transformation that reduces a society's material throughput while improving the quality of life (Kallis et al., 2018). Even though in a degrowth context GDP may increase in some economic sectors and shrink in others, an economy-wide reduction of material throughput will likely result in an overall reduction of GDP (Kallis, 2011). Here we refer to a planned and democratic reduction of material throughput in the context of our sample, which consists of primarily high and upper middle income countries.

While we find that future increases in household sizes have a smaller potential to reduce emissions compared to reductions in GDP, increased sharing of resources within and across households remains important. Household sharing supports a wider conservation of resources including energy, materials, living space, and opportunities to reduce waste. Enhancing sharing practices in household and communal contexts may further support key social foundations and foster cooperation, care and responsibility. Evidence presented in this paper is vital to inform adequate mitigation strategies within the 1.5 °C carbon budget. Finally, while prior literature highlights the role of household sizes and identifies potential factors for reduction, it has not yet quantified the emission saving potential of greater sharing within households and the effects of different drivers on changing household sizes.

2. Methods

2.1. Country sample

EXIOBASE provides global coverage of detailed trade relations of 43 countries (Table S1) and 5 rest-of-the-world regions. We discuss both global trends and sample trends – focusing specifically on the 43 countries for which we have data. The country sample comprises 67% of the world population in 1995 and 63% in 2015 and 2016. The countries also make up 80% of global GDP (PPP) in 1995 and 78% in 2015 and 2016. In terms of consumption-based GHG emissions, the 43 countries account for 81% of the global carbon footprint in 1995 and 2010, and 80% in 2015 and 2016.

The geographic coverage of the sample includes the EU27 plus the United Kingdom, seven high-income countries (the United States, Canada, Japan, South Korea, Australia, Switzerland, and Norway), six upper middle income countries (China, Brazil, Mexico, Russia, Turkey, and South Africa) and two lower income countries (India and Indonesia). Throughout the analysis, we present country-specific results for those countries that have contributed to the largest increases in total carbon footprints due to shrinking household sizes.

2.2. Carbon footprints

In this study, we quantify total carbon footprints (including emissions from households, non-profit institutions serving households, governments, gross capital formation and changes in inventories) based on EXIOBASE 3. EXIOBASE is a multiregional input-output (MRIO) database designed particularly for the purpose of environmental analysis across countries and time. Consumption-based carbon footprints were calculated using the Global Warming Potential 100 (GWP100) metric (Solomon et al., 2007) communicating the amount of CO_2, CH_4, N_2O (from combustion and non-combustion) and SF_6 in kgCO_2-equivalents per year. EXIOBASE was developed and continuously updated in the European projects EXIOPOL (Framework Programme 6 (FP6)), CREEA (FP7) and DESIRE (FP7). The carbon footprints include direct emissions (associated with fuel combustion at home for cooking or heating as well as tailpipe emissions from private transport) and indirect emissions embodied in the global supply chains (associated with various consumption domains of food, transport, housing, clothing and other manufactured products and services).

While prior cross-sectional analysis that captures the household size effect on carbon footprints tends to focus on the household consumption component based on consumer expenditure surveys (Ala-Mantila et al., 2017; Büchs and Schnepf, 2013; Ivanova and Büchs, 2020), here we base our analysis on total carbon footprints for two reasons. First, while we indeed expect that household size influences household consumption through household economies of scale, we also expect additional impacts of household sizes on corporate investments and government spending. Household size is relevant for these additional final demand sources through the infrastructures and services serving households beyond household purchases: the more household sizes decline, leading to an increase in the number of households, the greater are the resources required to provide services to households, for instance for the provision of energy, water, communication, etc. Second, it is the total GHG emissions that matter for temperature response and other climate impacts in the context of emission projections.

2.3. Household size and other social factors

Table 1 describes the hypothesized effects of the independent variables in our models. The supplementary dataset includes a full account of data sources for all independent variables, including from the Organisation for Economic Cooperation and Development (OECD), Eurostat, the World Bank, International Energy Agency (IEA) and many others.

2.4. Multivariate panel data analysis

We examine the relationship between changing average household size and per capita total emissions, controlling for other important factors from 1995 to 2016. The years of 1995, 2000, 2005, 2010 and 2015 offer more complete data across countries, so we used these years to explore household dynamics over time. We depict a descriptive analysis of trends over time in GHG emissions, average household sizes and additional factors in the model.

Panel data is known to be superior to cross-sectional data due to the possibility of unobserved variable bias, endogeneity bias and the indeterminacy over the sequencing of the causal mechanism (Berrington et al., 2006). Fixed-effects panel models enable testing of variable relationships in situations where carrying out randomized experiments is not possible (Antonakis et al., 2010). By explicitly modelling the fixed effects, we control for any possible unobserved heterogeneity in GHG emissions at the country level, which would otherwise cause omitted variable bias (Antonakis et al., 2010). We estimate a fixed-effects model using the xtreg command in Stata IC 14.2. As the number of households in the sample weight variable is not allowed to vary within each country when using the xtreg command, we apply sample weights reflecting the number of households by country in 2015. We used weights to account for the substantial differences in the number of households (and population sizes) across the countries in our model. That way, for example, China exerts a greater influence on our total estimates and projections compared to Luxembourg.

We estimate emission increases between 1995 and 2015 from the

Table 1
Background on the independent variables.

Per capita total carbon footprint model

Variable	Direction	Description of the effect and sources
Household size	−	Household members share electrical appliances, tools and equipment, cook together, cool and heat common living spaces and require less individual living space (Ivanova and Büchs, 2020; Lenzen et al., 2006; Underwood and Zahran, 2015). These acts of sharing reduce per capita energy use, which further translates into lower emissions. While there is potential for household economies of scale for transport, the benefits of shared travel are not necessarily realised and there may be tendency to own multiple or bigger cars or using cars more intensely (Ivanova and Büchs, 2020; ONS, 2010). The number of households is also used as a weighting variable in the descriptive statistics analysis and regressions.
Year	+/−	Continuous time trend
Income and GDP	+	Rising income increases purchasing power, consumption and associated carbon footprints. Income has been discussed as a main driver behind increasing carbon footprints (the A in the IPAT equation) (Ivanova et al., 2017; Wiedmann et al., 2020). While higher income levels may allow for reduced carbon intensity, examples of absolute long-term decoupling between GDP and carbon footprints are rare (Haberl et al., 2020).
Population	−	Population may have a negative effect on per capita carbon footprints if more people use the same infrastructure (roads) and services (public transport). While population has a positive effect on impact according to the IPAT equation (Chertow, 2000), the impact refers to the overall carbon footprint, not per capita carbon footprints.
Rural share of the population	−/+	Urban typology is associated with more compact form, efficient dwelling types, and lower commuting and home energy use; yet, there is also evidence for higher consumption of food, leisure travel, manufactured products and services (Ivanova et al., 2017; Ottelin et al., 2015; Wiedenhofer et al., 2013).
Fossil share of energy consumption	+	An important physical driver of GHG emissions reflecting the displacement of fossil fuels by renewable and nuclear sources (Le Quéré et al., 2019).
Energy intensity per unit of GDP	+	Reflecting changes in energy efficiency and energy consumed or lost in energy extraction, conversion and transmission (Le Quéré et al., 2019). Also affected in the transition of countries providing more services and fewer manufactured goods.
CO_2 intensity of the energy mix	+	In addition to the fossil fuel share, the CO_2 intensity of the energy mix reflecting changes in the carbon intensity of energy fuels, reflecting the quality of fuels in the overall energy mix (Le Quéré et al., 2019).

Average household size model

Variable	Variable	Variable
Year	+/−	Continuous time trend
Fertility rate	(+)	Falling birth rates reduce the population size, but not necessarily the number of households; growing share of households without children (Keilman, 2003; OECD, 2011).
Average age at first marriage	+/−	As the age of first marriage increases, there is an increasing number of people who start living alone, cohabiting or having children before they marry (Lesthaeghe, 2014; OECD, 2011). The postponement of marriage may have a variable effect depending on the degree of cohabiting and the number of children before marriage.
Divorce rate	−	Increased divorce rates contribute to an increase in sole parenthood (OECD, 2011). Divorced households tend to be smaller compared to married households (Yu and Liu, 2007).
Female employment and education	−	Women having greater economic independence and thus freedom to live separately from extended family and undesired relationships (Keilman, 2003).
Life expectancy and population aging	+/−	Increased longevity increases the time when children live separately from their parents and widows/widowers living alone (Keilman, 2003); at the same time, increased longevity will positively affect household size if older people are living in bigger households (e.g. in care homes or with their family).
Income/ GDP per capita	−	Living in smaller households (not relying on extended family) is more affordable (Keilman, 2003).
Social contribution	−	Social security systems provide assurance against social risks, formerly covered by the extended family (Keilman, 2003), e.g. sole parents may live with their parents to pool resources and gain better access to child care when universal or affordable childcare is not available (OECD, 2011). Strong financial support following divorce and separation may also enable a higher proportion of divorces when children are involved (OECD, 2011) and unemployment and income support schemes can support people living alone.

The variables are included in the per capita total carbon footprint and average household size regression models presented in Tables 2 and 3; 1 provides the reasoning behind the inclusion of these independent variables in the models.

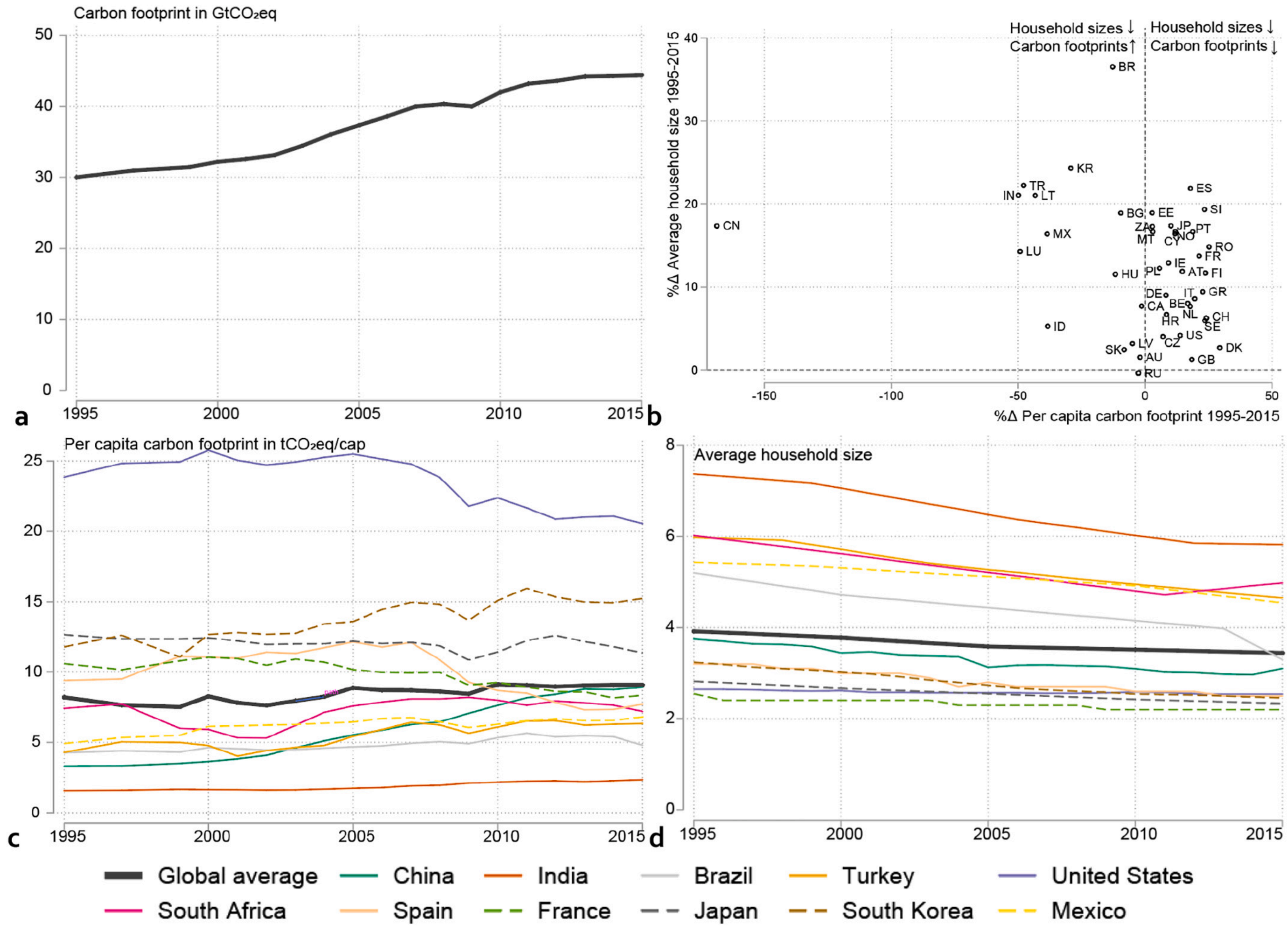


Fig. 1. Total carbon footprints and average household sizes of the total sample and selected countries between 1995 and 2015. a Global annual total carbon footprint measured in $GtCO_2eq$. b 1995–2015%-change in average household sizes (y-axis) and per capita carbon footprints (x-axis). Positive %-changes reflect absolute decreases in value between 1995 and 2015 and negative %-changes reflect absolute increases in value between 1995 and 2015. c Per capita total carbon footprint measured in tCO_2eq/cap including the global average and selected countries. d Average household size in persons per household including the sample (based on EXIOBASE's 43 countries) and selected countries. See Table S1 in the Supplementary Information for country codes and names.

predictions of the previously fit model at fixed values of household size and time covariates. The estimator is consistent as long as the independent variables are exogenous (Antonakis et al., 2010).

We then use our fixed effects model to predict mean carbon footprints for the sample of 43 countries in 2030. We apply the regression coefficients from our model and adopt projections of household sizes and per capita GDP. We depict the impact of household size on per capita carbon footprints using two scenarios for 2030: (1) assuming an increase in per capita GDP, where we adopt income projections based on historical trends (IMF, 2020; UN, 2020); and (2) assuming a 4% annual decrease in per capita GDP starting from 2016 (Keyßer and Lenzen, 2021) (see the supplementary dataset for more detail). The 4% annual GDP reduction is compatible with global energy estimates necessary to provide decent material living and offers a higher chance to stay within 1.5° of warming, given that emissions and GDP growth remain coupled while evidence of absolute decoupling at the global level is lacking (Haberl et al., 2020; Keyßer and Lenzen, 2021; Millward-Hopkins et al., 2020). Finally, in both scenarios we estimate per capita carbon footprints, keeping all other independent variables at their means.

We further refer to an estimate of the planetary boundary of climate change (O'Neill et al., 2018; Steffen et al., 2015), which is downscaled to per-capita equivalents. Estimates of per capita 2030-emission targets for limiting global warming to 1.5 °C tend to vary between 2.1 and 2.5 tCO_2eq/cap (Institute for Global Environmental Strategies Aalto University and D-mat ltd., 2019; Ivanova et al., 2020; OXFAM, 2020). We compare this target to the carbon footprint estimates at various household size levels.

Finally, we develop a fixed effects model to quantify the importance of various socio-economic factors for the change in average household sizes in the 43 countries between 1995 and 2015. We consult results from the Hausman (He et al., 2014) test for the choice of panel data method regarding the carbon footprint and household size models. Rejecting the null hypothesis with a highly significant statistic of 53.7 and 162.3 in the per capita carbon footprint and average household size models, respectively, favours the use of a fixed effects model. Finally, we test for multicollinearity in terms of 2015-values in the regression models through variance inflation factors (VIF) and tolerance values (Vita et al., 2020). Results shown in Table S2 present no strong evidence for multicollinearity with VIF values substantially below the threshold of 10 and tolerance values above 0.1.

2.5. *Limitations*

As there was a substantial variation in the methods and estimates for household sizes across different data sources, we avoided combining different datasets for the same country; that way, differences across

Table 2
Fixed effects multivariate regression with dependent variable: per capita total carbon footprints in logarithmic form.

Dependent variable: Per capita carbon footprint in logarithmic form	Total sample	Selected countries
Average household size	−0.06** (0.03)	−0.08*** (0.02)
Year	−0.01*** (0.00)	−0.01*** (0.00)
GDP per capita (constant USD 2011 PPP in logarithmic form)	0.87*** (0.06)	0.87*** (0.10)
Population (billions)	−0.83*** (0.19)	−0.95*** (0.23)
Rural population (%)	−0.00 (0.00)	−0.00 (0.01)
Fossil fuel energy consumption (% of total energy supply)	0.01*** (0.00)	0.01** (0.00)
CO_2 intensity of energy mix (tCO_2/toe)	0.04* (0.02)	0.04 (0.03)
Energy intensity per GDP (MJ/USD 2011 PPP)	0.05*** (0.01)	0.04*** (0.01)
Country fixed effects	Yes	Yes
N	777	203
N countries	43	11
Within R-sq	0.98	0.99
Between R-sq	0.83	0.80

Table 2 presents the regression coefficients and clustered standard errors in brackets with significance levels: * $p < .1$, ** $p < .05$, *** $p < .01$. Household weights are applied. See Methods and Fig. S3 in the Supplementary Information for more background on the model specification. The sample of selected countries refers to the eleven countries contributing to the highest GHG emission increases between 1995 and 2015 coupled with shrinking household sizes (see Fig. 2c).

years were more likely to be associated with actual changes in household sizes rather than the change in sources. The panel dataset is not strongly balanced due to missing values in household sizes (see the supplementary dataset for more information and list of sources). Furthermore, household definitions may vary across data sources, for instance based on a unit of people with a joint economy or based on a household-dwelling concept, which may be an additional source of measurement error. Where we did combine different sources for the same country, we checked that they matched well for the overlapping years.

There is limited – especially quantitative – evidence regarding the driving forces behind the worldwide shrinking of household sizes. The social and cultural factors affecting household sizes and consumption patterns are interconnected, difficult to quantify and tightly linked to wider structural and economic issues (Klocker et al., 2012). As a result, omission of important factors – particularly cultural preferences around cohabiting and sharing, and more general infrastructural, institutional and social influences – may bring about omitted variable bias in our models, particularly in Table 3.

Other limitations regarding the choice of the MRIO database (e.g. regarding country detail, uncertainty, accounting principle) and projecting consumption-based emissions have been detailed elsewhere (Bjelle et al., 2021; Moran and Wood, 2014; Usubiaga and Acosta-Fernández, 2015; Wiebe, 2016; Wood et al., 2014).

Finally, our analysis cannot take longer-term demographic trends such as aging societies into account. Since additional children per household tend to reduce per capita emissions per household more than additional adults (Büchs and Schnepf, 2013), and since fertility is declining in many societies, the emission projections for different household sizes in this paper might slightly overestimate the emission saving potential of household sharing. However, older people tend to have much lower carbon footprints for travel and other consumption (Büchs and Schnepf, 2013), while these domains make up the majority of people's carbon footprints. Long-term demographic trends such as aging societies may thus involve mixed effects that are beyond the scope of this analysis.

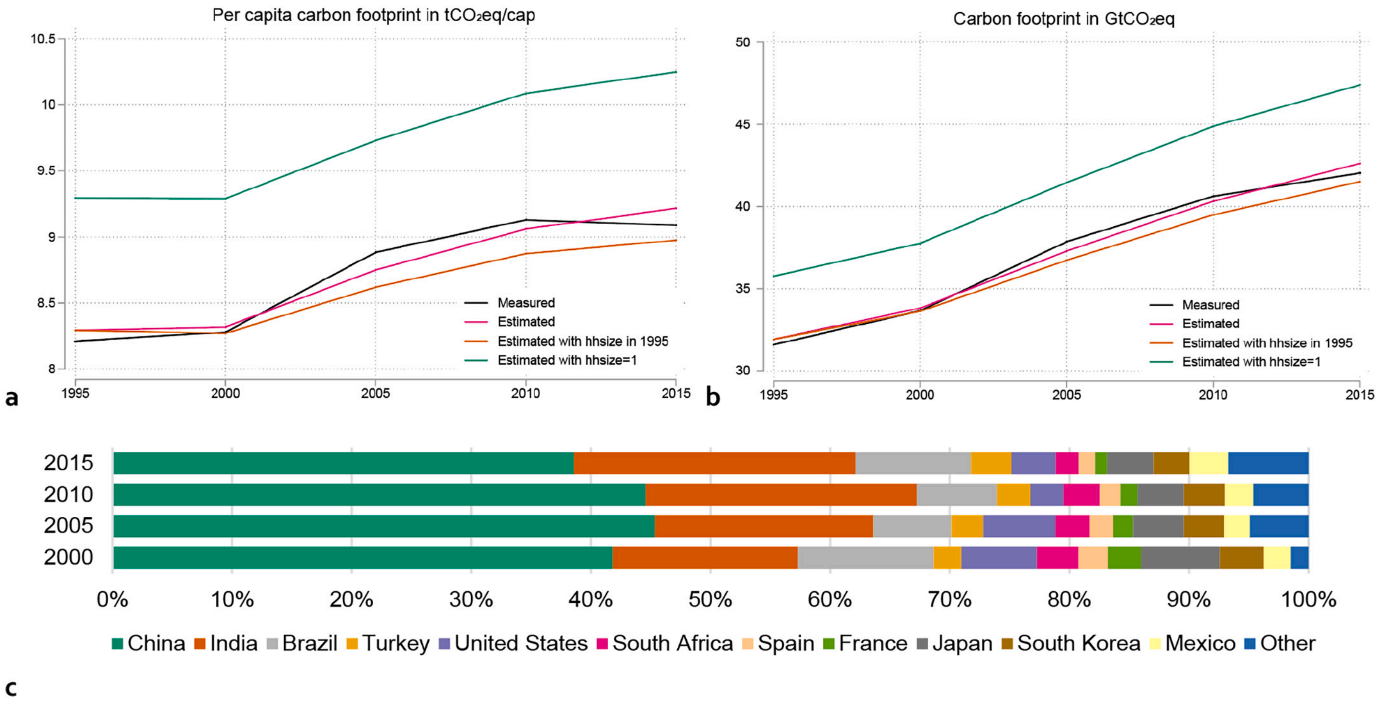


Fig. 2. Plots comparing the measured and estimated total carbon footprints of the sample in 1995, 2000, 2005, 2010 and 2015. The black lines represent measured footprints, while the pink lines represent footprints estimated by our model. The orange lines represent estimated footprints if the average household sizes remained at 1995-levels. The teal lines represent estimated footprints if the average household size had dropped to one person per household. a Annual average per capita footprints for total emissions measured in tCO_2eq/cap. b Annual average total carbon footprint of the sample measured in $GtCO_2eq$. Household weights are applied. Note that the y-axes start at non-zero values. c The sample carbon savings if the average household size had stayed at 1995-levels by country in 2000, 2005, 2010 and 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

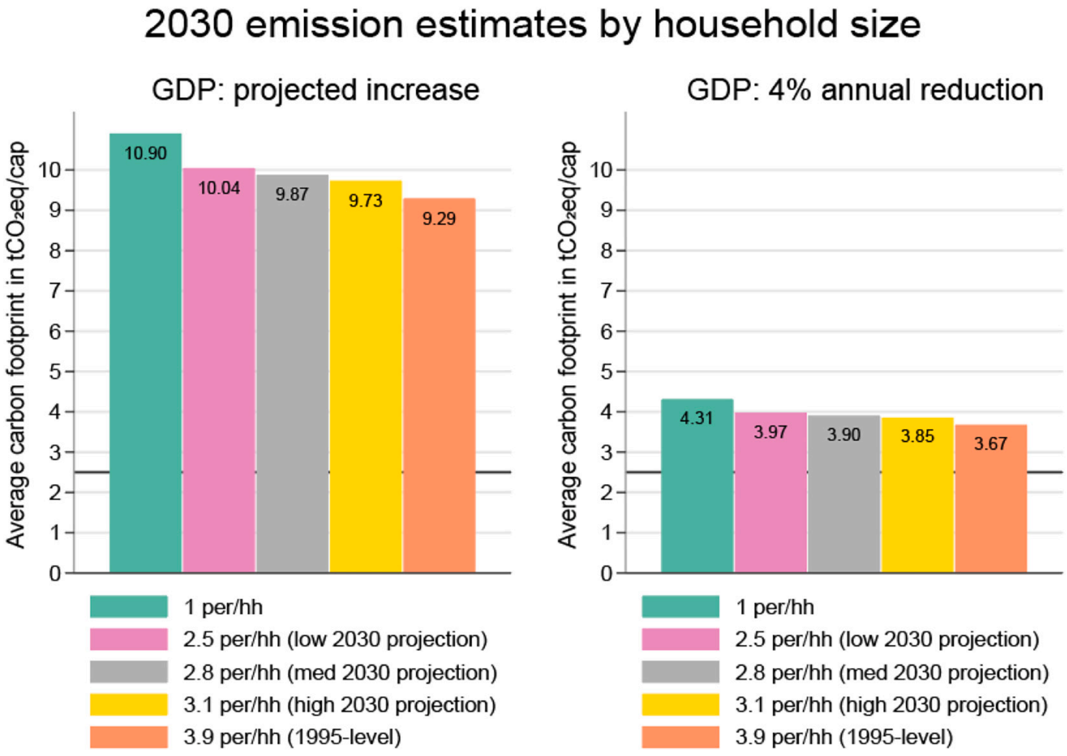


Fig. 3. 2030 total carbon footprint projections of the sample at various household sizes where 2.5, 2.8 and 3.1 are low, medium and high projections for average household sizes in 2030, and 3.9 is the average household size in 1995. The scenario on the left adopts current GDP and population projections to estimate per capita GDP (IMF, 2020; UN, 2020). We adopted per capita GDP projections for 2026 instead of 2030, the closest year available. The scenario on the right hand side assumes a 4% annual reduction in per capita GDP (Keyßer and Lenzen, 2021). Both scenarios apply the fixed effect model with regression coefficients depicted in Table 2, holding all other factors at mean values to estimate carbon footprints. The thick black line reflects the 2030 carbon target of 2.5 tCO_2eq/ cap.

3. Results

3.1. The role of shrinking household sizes for total carbon footprints

Global emissions need to decline by about 45% between 2010 and 2030 in order to increase the chance of no or limited overshoot of 1.5 °C (Masson-Delmotte et al., 2018). Yet, globally there was no decline in overall emissions, but rather an increase of 5.7% in 2015 (and 7.3% in 2016) compared to 2010 (Fig. 1a). Overall and per capita carbon footprints between 1995 and 2015 share trends in most countries (Fig. S1).

Countries show distinct patterns in terms of their carbon footprints and household dynamics (Fig. 1b-d), although average household sizes shrink in our sample (Fig. S2) and almost everywhere in the world in the observed period (United Nations, 2018). The average household size in the sample falls from 3.9 in 1995 to 3.4 in 2015. Brazil, South Korea, Turkey, Spain and India note some of the steepest declines in average household sizes between 1995 and 2015, with reductions of over 20%. In some countries, per capita carbon footprints and household sizes trend in the opposite direction. For example, India, Turkey and Mexico experience steep reductions in their average household sizes between 1995 and 2015, while their overall and per capita carbon footprints increase (Fig. 1b). The United States and France, on the other hand, report reductions in per capita carbon footprints and decreasing average household sizes.

Increasing the average household size by one member reduces the per capita total carbon footprint by 6% (Table 2). Among the eleven countries that contribute most to rising GHG between 1995 and 2015, an increase in the household size by one member reduces per capita total carbon footprints by 8%. This is comparable to prior cross-sectional estimates of the household size effect (Ivanova and Büchs, 2020). It is worth noting that the most substantial household size reductions took place before 1990s (Bradbury et al., 2014; United Nations, 2018).

Based on the fixed-effects model over time (Table 2), we estimate that if the average household size remained at its 1995-value, cumulative GHG emissions from 1995 to 2015 would have been 11.3 $GtCO_2eq$ lower (the total area between the pink and orange lines in Fig. 2a). When we only focus on the single year of 2015, estimated total annual emissions with household sizes at 1995-values are 1.1 $GtCO_2eq$ lower than measured (Fig. 2b). That is, total annual GHG emissions in 2015 increased by 3.1% due to the fall in household sizes since 1995 according to our model, with expected further future emission increases. Dwindling household sizes in China, from an average of 3.8 in 1995 to an average of 3.1 in 2015, contribute to the largest emission increase in the sample (Fig. 2c). In 2015, shrinking household sizes in China make up about 39% of the total emission increase, followed by households in India (24%), Brazil (10%), the United States and Japan (4%), Turkey, Mexico and South Korea (3%).

Beyond falling household sizes, several factors contribute to per capita GHG emission increases between 1995 and 2015 (Table 2). Most importantly, per capita GDP increased by 53% in our sample (from 14.6 to 22.4 thousand USD). Indeed, increases in global affluence and consumption have cancelled out any technological gains aimed at reducing environmental impacts (Wiedmann et al., 2020). In the same period, the fossil fuel energy share increased from 77.1% in 1995 to 81.4 in 2015, and so did the CO_2 intensity of the electricity mix.

We estimate per capita total carbon footprints at various household sizes, while keeping all independent variables besides per capita GDP and year at mean levels. At projected values of mean household sizes between 2.5 and 3.1 persons per household (Jennings et al., 2000) and increased GDP, the 2030 per capita total carbon footprint of our sample varies between 9.7 and 10.0 tCO_2eq/cap (Fig. 3). Assuming consistent reductions in per capita GDP, the carbon footprint goes down to 3.9 tCO_2eq/cap at an average household size of 3.1 (equivalent to the high 2030 projection) and 3.7 tCO_2eq/cap at an average household size of 3.9

Table 3
Fixed effects multivariate regression with dependent variable: average household size.

Dependent variable: Average household size	Total sample	Selected countries
Year	−0.01**	−0.01*
	(0.01)	(0.00)
Fertility rate (births per woman)	0.26***	−0.09
	(0.09)	(0.22)
Age at first marriage, females (average age)	0.01**	0.01**
	(0.01)	(0.00)
Crude divorce rate (per 1000 inhabitants)	−0.12***	−0.08*
	(0.03)	(0.04)
Female employment (% of female population aged 15+)	−0.02***	−0.03***
	(0.01)	(0.01)
School enrolment, primary and secondary (gross), gender parity index (ratio of girls to boys)	0.18	0.32
	(0.92)	(0.98)
Life expectancy at birth (total years)	0.02*	0.02**
	(0.01)	(0.01)
Population aged 14 and under (%)	0.01	0.08**
	(0.03)	(0.03)
Population aged 65 and over (%)	−0.02	−0.02**
	(0.01)	(0.01)
GDP per capita (constant USD 2011 PPP in logarithmic form)	−0.26	−0.19
	(0.19)	(0.22)
Social contribution (% of revenue)	−0.01	0.01
	(0.00)	(0.00)
Country fixed effects	Yes	Yes
N	188	38
N countries	42	10
Within R-sq	0.76	0.95
Between R-sq	0.69	0.88

The sample of selected countries refers to the eleven countries contributing to the highest GHG emission increases between 1995 and 2015 coupled with shrinking household sizes (see Fig. 2c), except for India for which we found no divorce statistics. The regression model depicts the regression coefficients and clustered standard errors in brackets with significance levels: * $p < .1$, ** $p < .05$, *** $p < .01$. Household weights are applied. The regressions are based on data from 1995, 2000, 2005, 2010 and 2015, hence the difference in sample sizes compared to the annual model presented in Table 2. See Methods for hypothesized effects and sources across the independent variables.

(equivalent to our sample's 1995-level). Thus, carbon footprints in the context of reduced GDP are more than 60% lower compared to the growth scenario.

The scenarios reflect the role of household size and GDP for meeting carbon reductions. As there is a great urgency in reducing global CO_2 emissions, it is important to note that carbon footprints are not predetermined by a set of demographic and technical trends; instead, climate policy and broader societal context may bring about dramatic changes. Changes in the extent of sharing within and across households has a smaller effect than changes in income levels, but more sharing can still make an important contribution to emission reductions overall.

3.2. Drivers behind shrinking household sizes

Table 3 sheds light on the factors that contribute to the shrinking of household sizes worldwide and the slowing down of this trend in certain countries. The results for the total sample suggest that the main contributors include changing family and household formation trends (e.g. fertility rate, age at first marriage and divorce rates) and gender equality trends (e.g. female employment). In addition, there is a negative and significant time trend suggesting that we are likely not capturing additional drivers that vary over time such as religious, cultural, political and social shifts (Keilman, 2003). In addition to the aforementioned factors, longevity trends (e.g. life expectancy, population shares by age) play a key role for household dynamics among the countries with the steepest reductions in household sizes. Political factors (welfare spending) and per capita income have insignificant effects on household sizes.

We further find that the increasing average age at first marriage (Fig. 4b) has a positive effect on household sizes (indicating that it has a positive effect on cohabitation and childbearing before marriage, see Table 1). Similarly, reversing trends in divorce rates (Fig. 4c) may encourage an increase in household sizes. This is consistent with accumulating evidence of a surprising degree of family stability preference and a return to "more family" as gender equality norms become more established (Esping-Andersen and Billari, 2015).

Gender equality has a negative effect on household sizes with a 10% increase in female labour market participation reducing the average household size by 0.2 persons, an effect particularly present where work and family are less compatible. However, female participation in the labour force actually decreased in the countries with shrinking household sizes, particularly driven by China, India and Brazil in recent years. These reductions in female labour market participation contrast earlier developments in these countries and have been linked to diminution of childcare provision and social security reducing options for working mothers (Wang and Klugman, 2020).

4. Discussion and policy implications

Reversing the trends around household sizes and economic growth, alongside other interventions to stay within 1.5 °C of global warming (Ivanova et al., 2020; Keyßer and Lenzen, 2021; Le Quéré et al., 2019; Millward-Hopkins et al., 2020; O'Neill et al., 2018; Wiedmann et al., 2020), can make a contribution to reduce GHG emissions, particularly in rich countries. Increases in average global household sizes from 2.5 to 3.1 persons and income reductions (4% annual decrease of GDP assumed in this study) by 2030 result in substantial decreases in per capita carbon footprints, from 10.0 to 3.9 tCO$_2$eq/cap, holding other factors constant. While in this article we focus on enhancing household sharing as a strategy to reduce emissions, increased sharing clearly needs to be combined with wider policy efforts to transform societies towards ensuring a good life at low ecological impact.

Clearly, an annual reduction of GDP of 4% would have a far more substantial effect on emission reductions that an increase of household size alone: at the medium projected household size of 2.8 in 2030, emissions would be 6 tCO$_2$eq/cap lower compared to the scenario of currently projected GDP increases (Fig. 3). While indeed addressing affluence is key to mitigating climate change (Wiedmann et al., 2020), the effect of sharing initiatives on GHG emissions, though smaller, should not be neglected. Interventions to increase household sizes can be particularly effective in reducing housing-related energy (Ivanova and Büchs, 2020) in the first stages of the low-carbon transition at available technologies and relatively low cost, when buildings are less efficient and energy is primarily sourced from fossil fuels. While a range of barriers exist to encourage housing sharing, it might be a more readily available strategy given that current economies and policy-making are built around economic growth. Finally, encouraging household sharing has implications for resource conservation (e.g. energy, materials, living space) and social wellbeing (e.g. care, cooperation and solidarity) beyond GHG emissions.

It is important to note that even the scenario at the highest household size of 3.9 persons per household at reduced incomes overshoots the 2030 carbon target of 2.5 tCO2eq/cap to stay below 1.5 °C of global warming by around 1.7 tCO2eq/cap. Furthermore, GDP would need to shrink much more than 4% per year in richer countries to enable poorer countries in our sample to increase living standards. Decarbonising the energy system and other sustainable degrowth interventions would still have to play a major role to meet this climate target. Given the enormous challenge to achieve targets that are compatible with staying within planetary boundaries, any contribution counts, including the contribution that greater sharing of resources within households can make.

4.1. Household dynamics

There is an obvious value in reversing trends of shrinking household

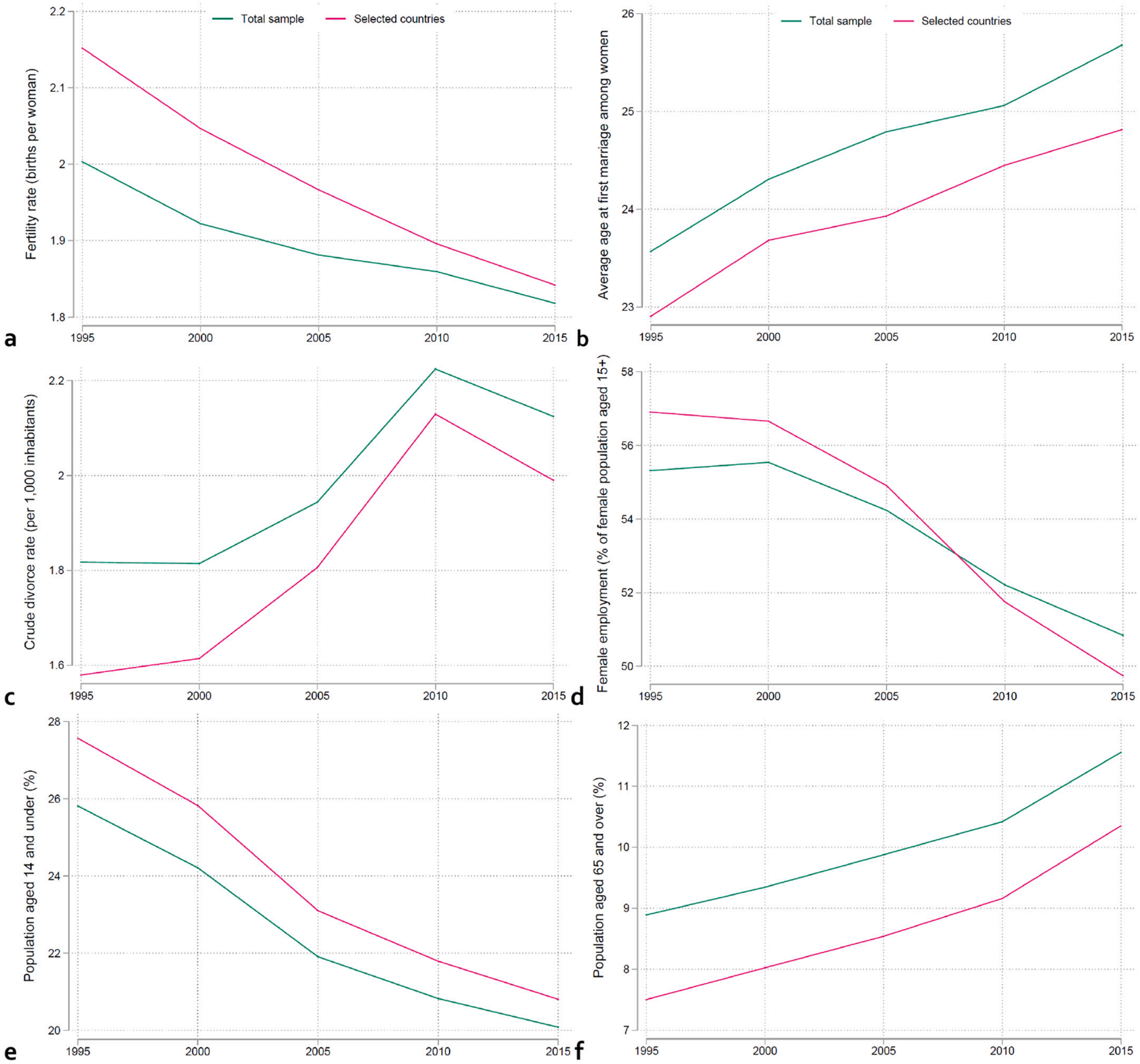


Fig. 4. Differences in various socio-economic factors that influence household size in the total sample and selected countries. The data are from 1995, 2000, 2005, 2010 and 2015. Trends in: a Fertility rates (births per woman). b Average age at first marriage, females. c Crude divorce rates (per 1000 inhabitants). d Female employment (% of female population aged over 15). e Population aged 14 and under (%). f Population aged 65 and over (%).

sizes, while encouraging and preserving gender equality, social security and individual freedom. The Sustainable Development Goals (SDG) include preserving achievements of good health and well-being (SDG3), quality education (SDG4), gender equality (SDG5), decent work (SDG8) and reduced inequalities (SDG10), all of which may have implications for household dynamics. Clearly, policies need to adopt a synergistic approach when addressing consumption and sharing practices (SDG12), act on climate change (SDG13) and avoid undermining progress made in other areas. Furthermore, recent developments suggest that the relationship between fertility and gender equality is reversing in several countries at the forefront of the second demographic transition, following a U-shaped curve (Esping-Andersen and Billari, 2015). That is, beyond a certain threshold, an increase in gender equality has a positive effect on fertility and, thus, household size. In order to enable this reversing trend, institutions and partnerships are key to allow for affordable, high-quality child care, mother-friendly labor markets and opportunities for part-time employment, thus, enhancing the compatibility between career and family (Esping-Andersen and Billari, 2015).

Prior demographic studies argue that distinct country clusters emerge, broadly corresponding to welfare regime typology (Sobotka, 2008a), values and attitudes, social institutions, and family and reproductive patterns (Lesthaeghe, 2020; Lesthaeghe, 2014; Sobotka, 2008a). These studies define a cluster of countries (e.g. Northern and Western Europe, Australia, Canada and the United States) with changing demographic trends through greater postponement of first birth and marriage, lower rates of teenage fertility, higher rates of non-marital births and divorce rates, compared to other countries (Lesthaeghe, 2020; Sobotka, 2008b). Broadly, our analysis of household dynamics is coherent with such clustering; yet, some differences remain. For example, France and the United States appear to have contributed substantially to GHG emission increases through household size shrinkages, even though they emerge as frontrunners in the second demographic transition in terms of their relationships between fertility rates and social indicators such as human development and gender equality (Lesthaeghe, 2020; Sobotka, 2008b).

4.2. Policy intervention

Reversing trends of shrinking households holds potential to reduce consumption, energy use and associated emissions, in support of a wider effort to stay within planetary boundaries and 1.5 °C climate targets. To reach this potential, policies should tackle excessive consumption in the form of overly large homes and secondary residence of the wealthy (Wiedmann et al., 2020) as well as increases in dwelling size per person (Ellsworth-Krebs, 2019; Huebner and Shipworth, 2017). The highest carbon savings are to be expected when targeting one-person households and consumption domains of housing and home energy use (Ivanova and Büchs, 2020). Dwelling size per capita is by far the strongest predictor of residential energy consumption, highlighting the potential for downsizing (Huebner and Shipworth, 2017) and shared living.

Removing infrastructural, institutional and social barriers is critical for reversing the trend of increasing dwelling space per person. Infrastructural barriers include the rigidity of housing stock (Wulff et al., 2004), which implies a lack of adequately sized housing to move to for single residents and an increase in dwelling space per person (Ellsworth-Krebs, 2019; Huebner and Shipworth, 2017). The lack of affordable options and incentives for cohabiting, sharing and compact living independent of marriage (Underwood and Zahran, 2015) (e.g. housing cooperatives and co-housing) present a further institutional barrier. Furthermore, changes in metrics and regulations to incorporate the importance of scale are necessary; particularly, shifting towards measuring a house's total energy demand rather than energy efficiency per square metre will reduce the incentive to build larger homes (Ellsworth-Krebs, 2019).

Finally, other barriers to increased household sharing may include social preferences and privacy concerns (regarding increased living space, owning or renting, dwelling forms and location) (Klocker et al., 2012; Wulff et al., 2004), emotional attachment to a familiar home, community or way of living which reduces people's willingness to change (Ellsworth-Krebs, 2019; Wulff et al., 2004), challenge of dealing with conflicts among household members (Klocker et al., 2012) or aspirations to be able to accommodate visitors or expectation for repartnering (Ellsworth-Krebs et al., 2019; Wulff et al., 2004). Enabling material space that facilitates individual independence and privacy, e.g. through improving the standards of visual and acoustic privacy, may improve satisfaction with shared living arrangements (Ellsworth-Krebs, 2019; Klocker et al., 2012). Furthermore, challenging the notion that "bigger is better" and a shift towards *lagom* or enough-ness is key to achieve absolute reductions in energy demand. The literature on extended family living refers to financial imperatives and caring requirements as the main motives for shared living, while environmental sustainability is rarely recognized (Klocker et al., 2012). The full capacity to share resources, appliances and spaces is also rarely utilised, thus reducing sustainability benefits (Klocker et al., 2012).

The satisfaction of people's basic needs typically requires the use of *shared* resources and systems (Coote et al., 2019; Rao and Baer, 2012) for food provision, housing, transportation, tools and skill sharing among others. Building a social movement based on genuine practices of sharing and cooperation in the provisioning and consumption of goods and services – from the use of commons to household and community sharing – holds great potential for social (Bradbury et al., 2014) and environmental (Ivanova and Büchs, 2020) benefits. Unfolding that potential requires challenging the main institutional, infrastructural and social barriers and democratizing the governance of sharing practices.

Data availability

The data used in the regression analysis is made openly available in the supplementary dataset. The code for footprint calculations (in Python), descriptive statistics and regression analysis (in Stata) are available upon request.

Funding

The European Union's Horizon 2020 research and innovation program funded the research under Marie Sklodowska-Curie grant agreement 840454. The authors also received support from UK Research and Innovation, Centre for Research on Energy Demand Solutions [EPSRC award EP/R035288/1].

CRediT authorship contribution statement

Diana Ivanova: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Milena Büchs:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

The data on which this analysis is based can be downloaded from the supplementary material.

Acknowledgments

We thank the whole EXIOBASE team for the effort to build the database and make it available for other researchers to use. We also want to thank Dr. Tullia Jack for her valuable feedback on an early draft and Loup Suja-Thauvin for his on-call support with graphics.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107590.

References

Ala-Mantila, S., Ottelin, J., Heinonen, J., Junnila, S., 2017. To each their own? The greenhouse gas impacts of intra-household sharing in different urban zones. J. Clean. Prod. 163, S79–S90. https://doi.org/10.1016/j.jclepro.2017.05.138.
Antonakis, J., Bendahan, S., Jacquart, P., Lalive, R., 2010. On making causal claims: a review and recommendations. Leadersh. Q. 21, 1086–1120. https://doi.org/10.1016/j.leaqua.2010.10.010.
Berrington, A., Smith, P.W., Sturgis, P., 2006. An overview of methods for the analysis of panel data. ESRC Natl. Cent. Res. Methods Brief. Pap, 1–57.
Bjelle, E.L., Wiebe, K.S., Többen, J., Tisserant, A., Ivanova, D., Vita, G., Wood, R., 2021. Future changes in consumption: the income effect on greenhouse gas emissions. Energy Econ. 95 https://doi.org/10.1016/j.eneco.2021.105114.
Bongaarts, J., 2001. Household size and composition in the developing world in the 1990s. Popul. Stud. (NY). 55, 263–279. https://doi.org/10.1080/00324720127697.
Bradbury, M., Peterson, M.N., Liu, J., 2014. Long-term dynamics of household size and their environmental implications. Popul. Environ. 36, 73–84. https://doi.org/10.1007/s11111-014-0203-6.
Büchs, M., Schnepf, S.V., 2013. Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO2 emissions. Ecol. Econ. 90, 114–123. https://doi.org/10.1016/j.ecolecon.2013.03.007.
Chertow, M.R., 2000. The IPAT equation and its variants. J. Ind. Ecol. 4, 13–29. https://doi.org/10.1162/10881980052541927.
Coote, A., Kasliwal, P., Percy, A., 2019. Universal Basic Services: Theory and Practice.
Ellsworth-Krebs, K., 2019. Implications of declining household sizes and expectations of home comfort for domestic energy demand. Nat. Energy 1–6. https://doi.org/10.1038/s41560-019-0512-1.

Ellsworth-Krebs, K., Reid, L., Hunter, C.J., 2019. Home comfort and "peak household": implications for energy demand. Hous. Theory Soc. 00, 1–20. https://doi.org/10.1080/14036096.2019.1694579.

Esping-Andersen, G., Billari, F.C., 2015. Re-theorizing family demographics. Popul. Dev. Rev. 41, 1–31. https://doi.org/10.1111/j.1728-4457.2015.00024.x.

Fremstad, A., Underwood, A., Zahran, S., 2018. The environmental impact of sharing: household and urban economies in CO2 emissions. Ecol. Econ. 145, 137–147. https://doi.org/10.1016/j.ecolecon.2017.08.024.

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., Creutzig, F., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab842a.

He, Q., Bertness, M.D., Bruno, J.F., Li, B., Chen, G., Coverdale, T.C., Altieri, A.H., Bai, J., Sun, T., Pennings, S.C., Liu, J., Ehrlich, P.R., Cui, B., 2014. Economic development and coastal ecosystem change in China. Sci. Rep. 4, 1–9. https://doi.org/10.1038/srep05995.

Hsiao, C., 2007. Panel data analysis-advantages and challenges. Test 16, 1–22. https://doi.org/10.1007/s11749-007-0046-x.

Huebner, G.M., Shipworth, D., 2017. All about size? – the potential of downsizing in reducing energy demand. Appl. Energy 186, 226–233. https://doi.org/10.1016/j.apenergy.2016.02.066.

IMF, 2020. GDP, Current Prices [WWW Document]. World Econ. Outlook (October 2020). https://www.imf.org/external/datamapper/NGDPD@WEO/OEMDC/ADVEC/WEOWORLD (accessed 11.5.20).

Institute for Global Environmental Strategies Aalto University and D-mat ltd, 2019. 1.5-Degree Lifestyles: Targets and options for reducing lifestyle carbon footprints. In: Technical Report. Institute for Global Environmental Strategies, Hayama, Japan.

Ivanova, D., Büchs, M., 2020. Household sharing for carbon and energy reductions: the case of EU countries. Energies 13, 1–28. https://doi.org/10.3390/en13081909.

Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P.C., Wood, R., Hertwich, E.G., 2017. Mapping the carbon footprint of EU regions. Environ. Res. Lett. 12, 1–13. https://doi.org/10.1088/1748-9326/aa6da9.

Ivanova, D., Vita, G., Wood, R., Lausselet, C., Dumitru, A., Krause, K., Macsinga, I., Hertwich, E., 2018. Carbon mitigation in domains of high consumer lock-in. Glob. Environ. Chang. 52, 117–130. https://doi.org/10.1016/j.gloenvcha.2018.06.006.

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab8589.

Jennings, V., Lloyd-Smith, B., Ironmonger, D., 2000. Global projections of household numbers and size distributions using age ratios and the Poisson distribution. In: 10th Bienn. Conf. Aust. Popul. Assoc. Melbourne, Aust, 30.

Kallis, G., 2011. In defence of degrowth. Ecol. Econ. 70, 873–880. https://doi.org/10.1016/j.ecolecon.2010.12.007.

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., Schmelzer, M., 2018. Research on degrowth. Annu. Rev. Environ. Resour. 43, 291–316. https://doi.org/10.1146/annurev-environ-102017-025941.

Keilman, N., 2003. Biodiversity: the threat of small households. Nature 421, 489–490. https://doi.org/10.1038/nature01359.

Keyßer, L.T., Lenzen, M., 2021. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. 1–16. https://doi.org/10.1038/s41467-021-22884-9.

Klocker, N., Gibson, C., Borger, E., 2012. Living together but apart: material geographies of everyday sustainability in extended family households. Environ. Plan. A 44, 2240–2259. https://doi.org/10.1068/a44594.

Le Quéré, C., Korsbakken, J.I., Wilson, C., Tosun, J., Andrew, R., Andres, R.J., Canadell, J.G., Jordan, A., Peters, G.P., van Vuuren, D.P., 2019. Drivers of declining CO_2 emissions in 18 developed economies. Nat. Clim. Chang. 9, 213–217. https://doi.org/10.1038/s41558-019-0419-7.

Lenzen, M., Dey, C.J., Foran, B., 2004. Energy requirements of Sydney households. Ecol. Econ. 49, 375–399. https://doi.org/10.1016/j.ecolecon.2004.01.019.

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., Schaeffer, R., 2006. A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. Energy 31, 181–207. https://doi.org/10.1016/j.energy.2005.01.009.

Lesthaeghe, R., 2014. The second demographic transition: a concise overview of its development. Proc. Natl. Acad. Sci. U. S. A. 111, 18112–18115. https://doi.org/10.1073/pnas.1420441111.

Lesthaeghe, R., 2020. The second demographic transition, 1986–2020: sub-replacement fertility and rising cohabitation—a global update. Genus 76. https://doi.org/10.1186/s41118-020-00077-4.

Lévay, P.Z., Vanhille, J., Goedemé, T., Verbist, G., 2021. The association between the carbon footprint and the socio-economic characteristics of Belgian households. Ecol. Econ. 186, 107065.

Liu, J., Daily, G.C., Ehrlich, P.R., Luck, G.W., 2003. Effects of household dynamics on resource consumption and biodiversity. Nature 421, 530–533.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T., 2018. IPCC Special Report 1.5 - Summary for Policymakers.

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: a global scenario. Glob. Environ. Chang. 65, 102168 https://doi.org/10.1016/j.gloenvcha.2020.102168.

Moran, D., Wood, R., 2014. Convergence between the EORA, WIOD, EXIOBASE, and OPENEU'S consumption-based carbon accounts convergence between the EORA, WIOD, EXIOBASE, and OPENEU'S consumption-based carbon accounts. Econ. Syst. Res. 26, 245–261. https://doi.org/10.1080/09535314.2014.935298.

OECD, 2011. Doing Better for Families: United States. OECD Publishing. https://doi.org/10.1787/888932392457.

O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1, 88–95. https://doi.org/10.1038/s41893-018-0021-4.

ONS, 2010. National Travel Survey: 2010 [WWW Document]. Dep. Transp. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/8938/nts2010-07.pdf (accessed 2.13.20).

Ottelin, J., Heinonen, J., Junnila, S., 2015. New energy efficient housing has reduced carbon footprints in outer but not in inner urban areas. Environ. Sci. Technol. 49, 9574–9583. https://doi.org/10.1021/acs.est.5b02140.

OXFAM, 2020. Confronting Carbon Inequality.

Rao, N.D., Baer, P., 2012. "Decent living" emissions: a conceptual framework. Sustainability 4, 656–681. https://doi.org/10.3390/su4040656.

Smith, R.M., 1981. Fertility, economy, and household formation in England over three centuries. Popul. Dev. Rev. 7, 595–622.

Sobotka, T., 2008a. Overview chapter 6: the diverse faces of the second demographic transition in Europe. Demogr. Res. 19, 171–224. https://doi.org/10.4054/DemRes.2008.19.8.

Sobotka, T., 2008b. Does persistent low fertility threaten the future of European populations? In: Syrkyn, J., Deboosere, P., Van Bavel, J. (Eds.), Demographic Challenges for the 21st Century - a State of the Art in Demography. VUB Press.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M.M.B., LeRoy Miller, H., Chen, Z., 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Climate Change 2007 the Physical Science Basis. Cambridge, United Kingdom and New York, NY, USA.

Steffen, W., Richardson, K., Rockström, J., Cornell, E., Fetzer, I., Bennett, E.M., Biggs, R., Stephen, R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Linn, M., 2015. Planetary boundaries: guiding human development on a changing planet. Science (80-.) 1–18. https://doi.org/10.1177/0973408215600602a.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., Davis, S.J., 2019. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature. https://doi.org/10.1038/s41586-019-1364-3.

UN, 2020. World Population Prospects 2019 [WWW Document]. Dep. Econ. Soc. Aff. https://population.un.org/wpp/Download/Probabilistic/Population/ (accessed 11.4.20).

Underwood, A., Zahran, S., 2015. The carbon implications of declining household scale economies. Ecol. Econ. 116, 182–190. https://doi.org/10.1016/j.ecolecon.2015.04.028.

United Nations, 2018. Household Size and Composition.

Population Fact Sheet No. 2: Household Size and Composition around the World, 2017. United Nations Population Division.

Usubiaga, A., Acosta-Fernández, J., 2015. Carbon emission accounting in MRIO models: the territory vs. the residence principle. Econ. Syst. Res. 27, 458–477. https://doi.org/10.1080/09535314.2015.1049126.

Vita, G., Ivanova, D., Dumitru, A., García-mira, R., Carrus, G., Stadler, K., Krause, K., Wood, R., Hertwich, E.G., 2020. Happier with less? Members of European environmental grassroots initiatives reconcile lower carbon footprints with higher life satisfaction and income increases. Energy Res. Soc. Sci. 60, 1–11. https://doi.org/10.1016/j.erss.2019.101329.

Wang, L., Klugman, J., 2020. How women have fared in the labour market with China ' s rise as a global economic power. Asia Pac. Policy Stud. 7, 43–64. https://doi.org/10.1002/app5.293.

Wiebe, K.S., 2016. The impact of renewable energy diffusion on European consumption-based emissions†. Econ. Syst. Res. 28, 133–150. https://doi.org/10.1080/09535314.2015.1113936.

Wiedenhofer, D., Lenzen, M., Steinberger, J.K., 2013. Energy requirements of consumption: urban form, climatic and socio-economic factors, rebounds and their policy implications. Energy Policy 63, 696–707. https://doi.org/10.1016/j.enpol.2013.07.035.

Wiedmann, T., Steinberger, J.K., Lenzen, M., Keyßer, L.T., 2020. Scientists ' warning on affluence. Nat. Commun. 1–10 https://doi.org/10.1038/s41467-020-16941-y.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J., Merciai, S., Tukker, A., 2014. Global sustainability accounting—developing EXIOBASE for multi-regional footprint analysis. Sustainability 7, 138–163. https://doi.org/10.3390/su7010138.

Wulff, M., Healy, E., Reynolds, M., 2004. Why don't small households live in small dwellings? Disentangling a planning dilemma. People Place 12, 58–71.

Yu, E., Liu, J., 2007. Environmental impacts of divorce. Proc. Natl. Acad. Sci. U. S. A. 104, 20629–20634. https://doi.org/10.1073/pnas.0707267104.

Zhang, X., Luo, L., Skitmore, M., 2015. Household carbon emission research: an analytical review of measurement, influencing factors and mitigation prospects. J. Clean. Prod. 103, 873–883. https://doi.org/10.1016/j.jclepro.2015.04.024.