Energy & Buildings 273 (2022) 112428

Contents lists available at ScienceDirect

Energy & Buildings

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

Activity and efficiency trends for the residential sector across countries

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ARTICLE INFO

Article history:
Received 13 July 2022
Revised 10 August 2022
Accepted 23 August 2022
Available online 29 August 2022

Keywords:
Residential energy use
Residential end-uses
HVAC consumption
Fuel sources
Energy drivers
Urbanisation
Housing typology

ABSTRACT

The residential sector is a major contributor to climate change, accounting for almost a quarter of global energy consumption and a fifth of CO_2 emissions in 2019. Since 2000, residential consumption has grown at a sustained rate of 1%/year, driven by the development of emerging economies, despite stagnation in developed countries. The increasing demand for living space, energy services and comfort levels seems difficult to curb, especially in the developing world on its fair attempt to reduce inequality. To understand these trends, this paper analyses the trajectories of key indicators of activity and efficiency in this sector, for emerging and developed regions, as well as for major consuming nations, mainly China, United States, European Union, Russia, India, Japan and Brazil. Despite data limitations, meaningful cross-country comparisons are presented for fuel mixes, energy services and dwelling types. Heating, ventilation and air conditioning (HVAC) systems account for a third of residential consumption and will grow rapidly as increasing wealth in emerging economies allows for satisfying the thermal comfort demand. Economic development will naturally increase housing size and equipment level and reduce household size, and could close the per capita consumption gap between developing and developed regions. Efficiency improvements could reduce the energy use intensity to around 10 koe/m^2 but will not be enough to curb residential consumption. International cooperation, policy support and funding are essential to accelerate development and efficiency gains in developing countries without compromising environmental targets. In the meantime, politicians should focus on decarbonising the energy mix and promoting energy efficiency, while citizens focus on energy conservation to avoid irreversible environmental damage.

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https://doi.org/10.1016/j.enbuild.2022.112428
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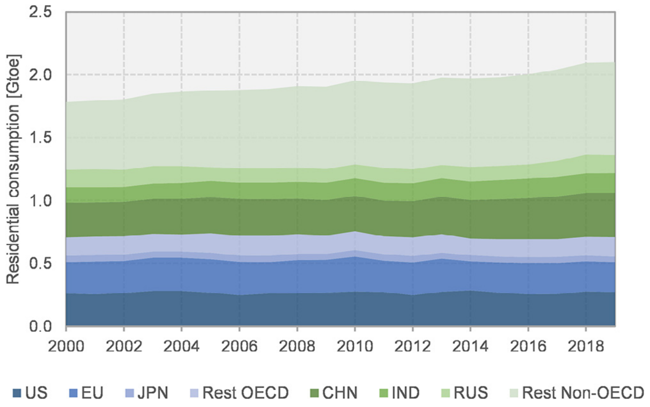

Fig. 1. Residential energy consumption [Gtoe] in the period 2000–2019. Based on IEA data [4].

1. Introduction

Despite the urgency to halt climate change [1], global energy use and CO_2 emissions continue increasing [2]. Consequently, they are further from safe levels and irreversible damages will take place unless immediate actions are taken [3]. In order to implement policies to reverse the current situation, consumption patterns need to be examined in depth to define appropriate mitigation policies.

From 2000 to 2019, global energy use and CO_2 emissions grew at an average rate of 2 %/yr, driven by activity increases in the industry, transport and buildings sectors [4,5]. However, the pandemic altered these trends, decreasing consumption in industry, transport and tertiary buildings, due to contingency measures restricting mobility and social gatherings. Consequently, activity shifted to residential buildings, changing patterns of household energy use, which are likely to continue and be integrated into new lifestyles (teleworking, online learning, etc.) [6].

Thus, residential sector during this century has gained more importance and requires specific analysis. In 2019, it represented 18 % (6 Gton) of global CO_2 emissions [5], 23 % (2.1 Gtoe) of total final consumption and 72 % of energy use in buildings [4]. Fig. 1 shows the evolution of residential consumption over the present century, which has grown by 0.9 %/yr due to increases in developing countries and economies in transition (non-OECD) despite the flat trend of the developed region (OECD). An almost five times larger population in the non-OECD resulted in twice the consumption of the OECD in 2019 and this difference will further widen as economic growth allows for improved living standards. The largest and fastest growing region is the rest of the non-OECD, which despite excluding top consuming developing nations (China, India and Russia), still accounts for 35 % of residential energy use (0.73 Gtoe). While some thriving economies, such as China, seem to be capping their upward trends (0.5 % growth 2018–2019), there is still much room for the enhancement of living conditions in most of developing countries. Developed nations should offset increases in emerging nations by exploiting the high potential of this sector for energy savings from reduced inefficiency [7], while equity in terms of residential energy use per capita is achieved worldwide.

Studies on residential consumption are abundant in the literature and much research have focused on analysing the drivers of residential energy use. Haas [8] was pioneer in setting out the methodological issues for identifying drivers for the whole sector and for different end-uses. Others have used decomposition analyses to explain changes in national consumption. For instance, Pachauri and Jiang [9] identified urbanisation levels, income, energy prices, energy access and local fuel availability as key drivers of the residential energy transition in China and India. Hojjati [10] decomposed the US household consumption in the period 1980–2005 according to the number of dwellings, the housing size, the housing typology, the geographical distribution, energy intensity and the weather effect. Xu and Ang [11] proposed a hybrid model to decompose consumption of various residential energy services in population, house occupancy, housing size, appliance ownership and energy intensity, and applied it to Singapore trends between 2000 and 2010. Other national decompositions of residential energy consumption have been carried out in China for the periods 1998–2007 [12] and 2001–2012 [13], in the US for the period 1990–2015 [14] and in EU for the period 2000–2016 [15]. However, there are few studies focusing on the heterogeneity of this sector across the world [16].

At national level works by Healy [17] on residential stock in the EU, by Moura et al. [18] for the USA over the period 1891–2010, by Sandberg et al. [19] on residential energy mix and efficiency in Norway and by Cuce [20] on UK household consumption by fuels and end-uses should be highlighted. However, a cross-country analysis of fuel mixes, energy services and housing stock is lacking, despite being essential for understanding energy trends, defining key indicators and proposing effective policies. The only exception is Nejat [21] who reviewed energy use, CO_2 emissions and energy policies in the residential sector up to 2011, both globally and in ten top emitter countries. Therefore, there is a lack of up-to-date cross-country analysis for this sector over the last two decades.

In the last decade, given the importance of the residential sector and its large savings potential, many international and national organisations have made efforts to collect reliable information for many nations, not only in terms of more detailed energy data, but also in terms of stock description (floor area, dwelling type, household size, income level, etc.). However, this new valuable information has not been sufficiently analysed in the literature.

Consequently, the authors have prepared an update review on residential consumption trends and their driving factors from 2000 to 2019. The paper aims to explain the evolution of residential energy use, to analyse key activity and efficiency indicators, and to propose a possible way forward to keep consumption within the limits of the Paris agreement. Despite data limitations, meaningful cross-country comparisons are presented for fuel mixes, energy services and residential typologies, with a special focus on activity drivers. Thus, the paper fills the information gap on residential sector consumption in this century by (1) conducting a global, regional and cross-country analysis for most consuming nations, (2) reporting reliable and up-to-date information from the best available sources and (3) mapping and discussing activity and efficiency trends around the world.

Accordingly, the paper is structured in seven sections. Terminology, methods and data sources are presented in section 2. Sections 3 and 4 describe the residential fuel mix and the consumption by end uses, respectively. Section 5 analyses the residential stock by housing type (single-family vs multifamily) and degree of urbanisation (rural vs urban). The core of the paper is found in section 6, where main activity drivers (population, wealth, urbanisation, housing and household size, and climate) and efficiency energy trends (per capita consumption, energy intensity, energy use intensity and energy use per household) are discussed. Finally, main conclusions are presented and policy implications highlighted.

2. Methods and data sources

The paper aims to provide an updated report of residential energy use over the past two decades, giving a clear indication of the differences between the developed and the developing regions.

Table 1
Structural, activity and efficiency indicators of the residential energy use.

Type	*Indicator*	*Methodological issues*	*Unit*	*Data sources*
Structure	Final consumption by fuel	Electricity Natural gas Oil (crude and oil products) Coal Biofuels (including waste) Other renewables[1] Heat	*Mtoe* *(%)*	[4,24] *(EU)*
	Per capita final consumption by end-use	Space heating Space cooling Water heating Cooking Lighting Appliances[2]	*toe/cap*	*Consumption:* [48] *(world, China, India and Russia),* [49] *(Japan),* [27] *(US),* [24] *(EU)* *Population:* [28]
	Dwelling stock by housing type	Single family[3] Multi-family	*Number of dwellings (%)*	[29] *(India),* [30] *(Brazil)* [31] *(Russia),* [32] *(Japan)* [24] *(EU),* [27] *(US)*
	Dwelling stock by degree of urbanisation	Rural Urban[4]	*Number of dwellings (%)*	[33] *(Brazil),* [27] *(US),* [34] *(EU),* [31] *(Russia),* [35] *(China),* [32] *(Japan)* [36] *(India)*
Activity	Population	–	*cap*	*World Bank* [28]
	Wealth	Gross Domestic Product (GDP) / Population	*k$/cap*	*World Bank* [28]
	Urbanisation	Floor area / Population	*m^2/cap*	*Floor area:* [49,24] *(EU),* [35] *(China),* [37] *(India),* [31] *(Russia)* *Population: World Bank* [28]
	Housing size	Floor area/Number of households	*m^2/hh*	*Floor area:* [49,24] *(EU),* [35] *(China),* [37] *(India),* [31] *(Russia),* *Households:* [49,24] *(EU),* [35] *(China)*
	Household size	Population/Number of households	*cap/hh*	*Population:* [28] *Households:* [49,24] *(EU),* [35] *(China)*
	Heating Degree Days	If $Tm \leq Tref$ Then $[HDD = \sum_i(Tref - Tm^i)]$ Else $[HDD = 0]$[5]	*°C days*	[24,49,85]
Efficiency	Per capita energy consumption	Residential consumption / population	*toe/cap*	*Consumption:* [4,24] *(EU)* *Population: World Bank* [28]
	Energy intensity	Residential consumption / GDP	*toe/M$*	*Consumption:* [4,24] *(EU)* *GDP: World Bank* [28]
	Energy use intensity	Residential consumption/Floor area	*koe/m^2*	*Consumption:* [4,24] *(EU)* *Floor area:* [49,24] *(EU),* [35] *(China),* [37] *(India),* [31] *(Russia)*
	Energy consumption per household	Residential consumption / Number of households	*toe/hh*	*Consumption:* [4,24] *(EU),* *Households:* [49,24] *(EU),* [35] *(China)*

Notes: 1. Solar PV, solar thermal, tide, wind and heat pumps. 2. Including small cooking devices and consumption from other categories when disaggregated data are not available. 3. Including mobile houses in US. 4. Note that the definition of urban area might change according to the source. 5. Tm^i is the mean air temperature of day i and Tref is 18 °C (16 °C for Japan).

It distinguishes between OECD and non-OECD trends, and then focuses on those nations with the highest consumption figures: the United States (US), the European Union (EU) and Japan (JPN), as OECD members, and China (CHN), India (IND), Russia (RUS) and Brazil (BRA), as non-OECD members. However, where data limitations preclude the analysis of the chosen countries, the geographical scope is expanded to include nations with different wealth and climate to capture other significant patterns, such as New Zealand (NZL), Spain (ESP), France (FRA), Germany (DEU) and Sweden (SWE).

The analysis examines the structural characteristics of residential consumption as well as the activity and efficiency indicators, based on the results of energy reports and on micro or macro data from official databases. Table 1 defines main indicators, their nomenclature, units, data sources and key methodological aspects.

The paper compiles and harmonises data from different official sources to provide a comprehensive picture of regional and national residential consumption. It then discusses the limitations of the data, the strengths and weaknesses of the data sources and key methodological issues. Finally, the results are presented to explain current trends to make fair and viable decisions for the future.

As in any research, it is important to note the limitations of this work. First, national energy consumption figures for large countries may mask different trends and behaviours occurring at a more disaggregated level. However, our choice of geographic scope is intended to guide energy and climate targets at national or federal level, rather than to point out differences between regions that should be addressed by state or local policies. Secondly, the relationship between each driver and residential energy use has only been examined independently, so their joint influence is not considered. Future research could apply detailed econometric and statistical techniques to confirm these results at a more disaggregated level and to unravel the hidden trends and the mutual, combined and causal relationship between the factors. Lastly, despite the great effort made to harmonise data, the results are subject to

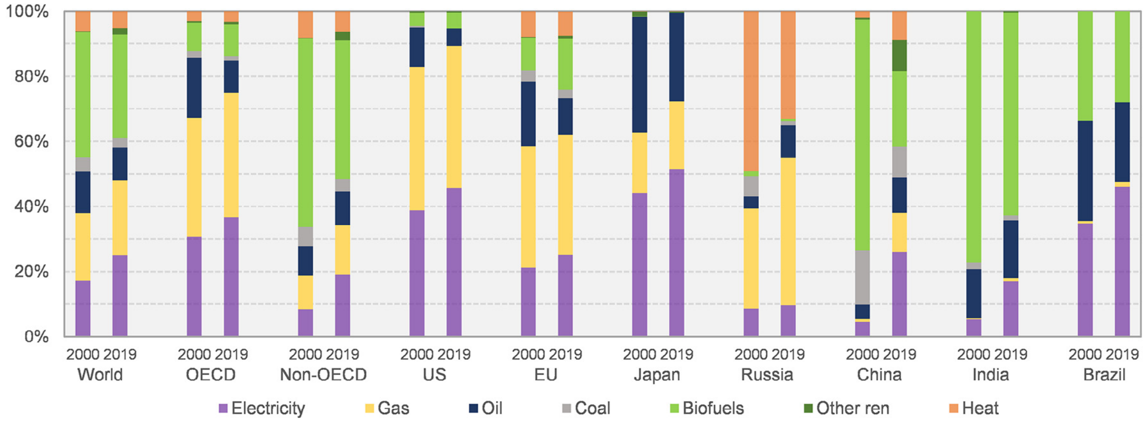

Fig. 2. Changes in residential fuel mix (2000–2019) for the world, the OECD and the non-OECD regions and US, EU, Japan, Russia, China, India and Brazil. Data based on IEA [4] and Odyssee [24] data.

uncertainty due to the reliability of the sources and the lack of a homogeneous methodology for data collection and processing.

3. Energy fuels in residential buildings

The energy mix of residential buildings has a strong impact on primary energy and CO_2 emissions. Dwellings use electricity, biofuels (biomass, liquid biofuels and biogases), natural gas, oil products (LPG, diesel and fuel oil), coal, district heating and other renewables.[1] Among these fuels, there is a large uncertainty in the information on renewables for biomass and other renewables. On the one hand, non-marketed biomass cannot be measured, so the weight of biofuels depends largely on the reliability of the assumptions made for its estimation, especially in developing economies where it represents a significant share of energy use. On the other hand, other renewables should include not only on-site generation of electricity and heat (mainly solar thermal and photovoltaic), but also other technologies that take renewable energy from the environment, such as heat pumps, daylighting, natural lighting, natural ventilation, free-cooling and passive cooling systems. However, they are usually not measured or cannot even be measured [22].

Heating and cooling fuels play a dominant role in the energy mix of dwellings, due to the high share of HVAC systems energy use. Fossil fuels are the most frequent heat source, although the proliferation of heat pumps has increased electricity consumption for heating in recent years. For cold generation, electricity is almost the only source, given the limited market for gas-powered chillers, gas air conditioners and absorption chillers [23].

The evolution of the fuel mix in residential buildings (Fig. 2) shows that, although consumption growth has been mainly supplied by electricity and gas, which account for half of energy use in 2019, biofuels remain the main energy source (32 %). Electrification is increasing at a high rate of 2.8 %/year, but its share is still far from that of commercial buildings (25 % vs 52 %). In contrast, fossil fuels have decreased thanks to a reduction in the use of oil products (10 %) in favour of less pollutant natural gas (23 %), while coal use is marginal and declining (3 %). Finally, the share of district heating has remained almost constant (5 %), and on-site renewables have appeared at up to 2 % with impressive growing rates.

In the OECD, natural gas was already the main source in 2000, followed by electricity, and electrification has increased while replacing the supply of coal and oil products. For example, in the US, the residential energy mix was almost equally distributed between electricity (46 %) and gas (44 %) in 2019. In the EU, the share of electricity is limited to a quarter of household energy consumption due to a lower consumption of space cooling compared to the US, and they rely mainly on gas (37 %), with more significant figures for biofuels (16 %), oil (11 %) and heat (8 %). Japanese households are the most electrified (51 %) and stand out for their high share of oil (27 %) over gas (21 %).

In contrast, fuel availability and access to electricity limit the use of marketed energy carriers in non-OECD countries, mainly in rural areas [39]. Consequently, electricity was a minor source in 2000, while it has doubled its share to 19 % in 2019 due to economic development and urbanisation. In developing economies, the large consumption of biofuels (43 %) is due to traditional biomass, and their consumption of fossil fuels has increased due to the rise of gas (15 %). Data from India in 2000 illustrate the energy mix of less developed countries, where residential energy demand was mainly supplied by non-commercial biomass (wood), fossil fuels accounted for 17 % and electricity for only 5 %. In 2019, they still have the highest share of biofuels among the countries under study (62 %), although electricity has tripled, and fossil fuels have increased to 20 %. Electricity shares in China (26 %) and Brazil (46 %) have also increased and are comparable to those of developed countries, while biofuels still contribute more than 20 %. China has the highest share of other renewables (10 %) due to public policies promoting the use of on-site solar energy, which contrasts with its high fossil fuel fraction (32 %), equally divided between gas, coal and oil. Russia differs from other non-OECD countries since the electrification accounts for only 10 %, while it relies mainly on gas, either directly consumed (45 %) or used to produce heat (33 %).

Policy efforts towards electrification could be a keystone for reducing the environmental impact of energy [40]. Electricity end-uses are more efficient and could therefore reduce energy consumption, while reducing CO_2 emissions if electricity is produced from low carbon sources. Unlike other consuming sectors, the full electrification of dwellings is feasible because every energy service can be electrified. The main barriers are found in space and water heating in colder climates, where electrification would require the use of ground or water source heat pumps, as low outdoor temperatures penalise the performance of air-to-water equipment. Nevertheless, promoting the use of heat pumps for space and water heating can quickly and cost-effectively reduce end-use consumption and emissions through electrification [41].

However, fossil electricity generation in 2019 still accounted for 63 % of total global emissions [42], adding 2.7 Gton to the 2.2 Gton emitted directly by households. Thus, the current electricity mix could turn electrification into a threat rather than an opportunity

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[1] The term ‘other renewables’ refers to the final consumption of renewable energy excluding biofuels and waste, i.e., solar PV, solar thermal, tide, wind and heat pumps.

to address climate change, by increasing emissions instead of achieving desirable reductions. Some developed nations have labelled nuclear and gas as "*transitional*" energy sources, since they are needed as an interim energy source to become climate-neutral by 2050 [43]. However, it is important to remark that it is only acceptable until sufficient renewable energy is available to meet the demand, so the promotion of renewable electricity should remain the priority for future sustainability [44].

4. Residential energy services

Disaggregating building consumption by energy services (also referred to as end-uses) allows users and owners to better understand their consumption patterns in order to identify cost-effective savings measures [45]. It would also help policymakers to identify the most intensive services so they can be targeted by instruments such as efficiency minimum requirements at equipment or service level [46]. However, energy disaggregation at this level is hardly available, as standard utility meters are unable to distinguish the energy consumed for each particular use [47].

Many studies have investigated consumption profiles by end-uses through direct measurements [48,49]. However, installing distributed sensors [50] or even single sensing points for non-intrusive load monitoring [51] in a sufficient number of dwellings to estimate national consumption is very costly, so the scope of these studies is normally limited to a few selected buildings whose results cannot be extrapolated. In this respect, progress has recently been made in developing national statistics based on field measurements to provide accurate data on household appliance consumption in France at a reasonable cost [52]. Nevertheless, the end-use disaggregation of a country is more often estimated using engineering and statistical methods [53], such as regression models or neural networks trained with data gathered through comprehensive surveys. The US Residential Energy Consumption Surveys (RECS) [54] are the main reference in this regard. However, their results cannot be published annually due to the high time and cost of preparation, collection and processing. Alternatively, results from these surveys can serve as inputs to accounting models that project consumption by end-use based on historical series of statistics such as, socio-economic indicators, equipment stock and housing characteristics. For instance, the US National Energy Modeling System (NEMS) Residential Demand Module (RDM) uses RECS data to elaborate their energy services projections for the Annual Energy Outlook [27], while the International Energy Agency (IEA) collects statistics on end-uses, efficiency and activity through annual questionnaires since 2009 as the basis of buildings-related energy assessment and modelling [55]. Additionally, valuable information on energy services in Europe is available through the Odyssee-Mure project [24], Eurostat [56] and the EU Building Stock Observatory [57], especially in the last years when their reporting started to be mandatory and regulated by the 1099/2008/EC. In non-OECD countries, data by energy use are rarely available and quite unreliable, with the exception of China, thanks to research by Tsinghua University [35].

Although the classification of energy services varies among sources, this paper classifies them into Heating, Ventilation and Air Conditioning (HVAC), Domestic Hot Water (DHW), lighting, cooking and other equipment, mainly appliances and other plug-in devices. However, there are still some issues in the available statistics. Firstly, small cooking appliances, such as microwaves, ovens, toasters, etc., are included in appliances and not in cooking, due to the difficulty of separating their respective consumptions, and so, cooking category only covers stoves and hobs. This difficulty also affects other electric end-uses, for instance hindering the differentiation of lighting from other appliances in Japan. Similarly, it results in the underestimation of space cooling shares, which are only significant in US, where the most comprehensive surveys are carried out. Secondly, accounting for non-commercialised fuels, such as traditional biomass or on-site renewables, is particularly difficult and could therefore add uncertainties to the end-use figures, especially in developing countries where they are the main source of energy.

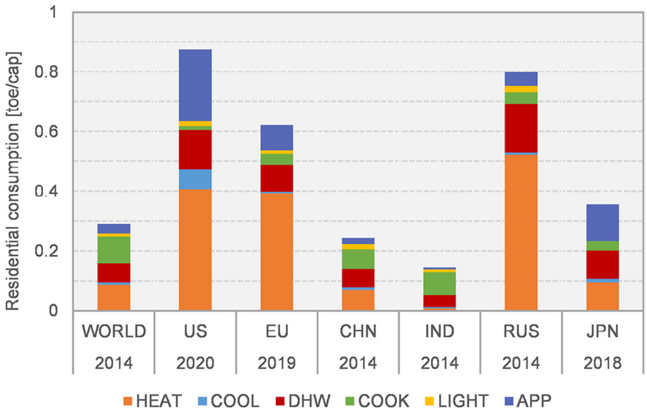

Fig. 3. Residential per capita consumption by end-uses for the world, US, EU, China, India, Russia and Japan. Based on IEA [25,26], EIA [27], Odyssee [24], World Bank [28] data.

Per capita consumption by end-use for the world and the main consuming countries is presented in Fig. 3, according to the latest available and most reliable sources for each region. At global level, the most consuming energy services are HVAC (32 %) and cooking (31 %), followed by DHW (22 %). Note that lighting is becoming residual (4 %) as LEDs replace less efficient traditional bulbs. In contrast, household appliances and other equipment (11 %) are gaining weight as electrification and technological advances make them more affordable. In addition, the pandemic has shifted consumption from tertiary buildings to dwellings, as it has forced people to spend more time at home, increasing residential demand for HVAC and cooking, but especially for small appliances due to the acquisition of new electronic appliances, computers and office equipment for entertainment and remote working or schooling [58]. Thus, energy efficiency becomes essential to offset higher appliance ownership, which can be promoted by setting minimum energy performance standards and incentives.

Wealth is a determining factor in the breakdown of consumption by energy services. The highest per capita consumption figures for HVAC and appliances are found in developed countries (about three quarters of consumption in the EU, US and Japan), where comfort requirements and equipment levels are well above those in poorer nations. Climate also plays an important role, increasing HVAC consumption in cold regions such as Russia by up to 66 %, or reducing it in warm areas as Japan [59] down to 0.12 toe/cap. Note that, HVAC consumption is mostly driven by space heating, with space cooling ranging from 3 % to 1 % of the residential consumption in the selected countries despite warm weather, except for US, whose consumption rises up to 8 %. On the contrary, energy use in developing countries is linked to essential services (cooking and DHW). China and India have the highest residential cooking consumption due to behavioural aspects (people in developed countries often eat out or reheat pre-cooked food in the microwave) and accounting issues (they consume mainly non-marketed fuels, adding uncertainty to the results). As they thrive, they are expected to increase their demand, especially for thermal comfort to approach developed country figures of around 0.4 toe/cap, resulting in five times the current HVAC energy use of China and over 30 times that of India.

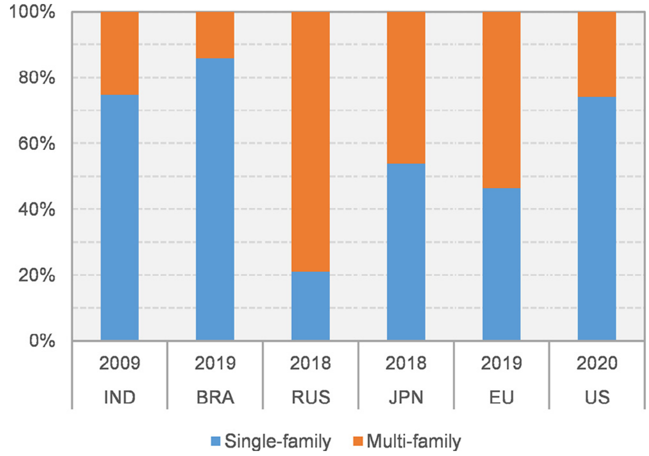

Fig. 4. Distribution of the dwelling stock by housing type (single-family and multi-family) based on the number of dwellings. Based on data from NSS [29], IBGE [30], ROSSTAT [31], SBJ [32], Odyssee [24], EIA [27]. Note that single-family in the US includes mobile homes.

5. Residential typologies

The residential sector clusters buildings with different characteristics (age, size, geometry, construction and location) that influence their energy demand and consumption [60]. Therefore, classification by housing type is essential to understand how energy is used and to develop sound energy policies. Although energy data are often not available at this level, it is useful to at least distinguish between housing type (single vs multi-family) and degree of urbanisation (rural vs urban).

5.1. Housing type

The distribution of residential stock by housing type differs greatly between nations (Fig. 4). While their proportion is very similar in the EU and Japan, single-family dwellings account for the largest share of the stock in the US (74 %), India (75 %) and Brazil (86 %), but only one fifth in Russia (21 %). Stock distribution is influenced by wealth in developed countries, as people move to larger and more independent single-family houses, and by cultural aspects, such as Soviet heritage determining the dominance of flats in Russia. Moreover, some developing countries have higher single-family shares than US despite their lower wealth, owing to the large population living in rural areas (70 % in India [28]) and in urban slums with small single-family dwellings and substandard housing (16 % in Brazil [28]). The proportion of multi-family dwellings is slowly increasing with urbanisation, as more buildings are concentrated in a given land area.

Area shares by housing type are rarely reported. However, the average size of single-family dwellings is larger than that of multi-family in the developed countries where data are available. This leads to higher shares of single-family area reaching 88 % in the US and 74 % in Japan, as they tend to be twice the size of multi-family dwellings [32,54].

Similarly, despite the lack of energy data by housing type prevents a more exhaustive analysis, significant conclusions can be drawn from data on occupied dwellings in the US [54] and Spain [61] (Table 2). Energy consumption per household in single-family dwellings (2.25 toe/hh in US, 1.3 toe/hh in Spain) more than doubles that of multi-family, as they usually have higher household incomes and sizes [62]. Such differences are not that noticeable in terms of energy use intensity, which is only 25 % higher in Spain (9.4 koe/m^2) and 15 % lower in US (10.2 koe/m^2) as much of the floor area of US single-family homes is often unoccupied. As for consumption by end uses, the importance of HVAC in single-family dwellings stands out (1.2 toe in US, 0.86 toe in Spain), which is approximately-three times higher than multi-family, due to their larger transfer and conditioned surface area. Finally, the dominance of heating in single-family houses is accompanied by higher shares of gas in their fuel mix.

5.2. Degree of urbanisation

Another way of classifying residential stock is by urbanisation rate, defined as the percentage of the population living in urban areas. However, available data must be examined with care as national statistics differ in the criteria to define urban and rural population. Some nations use the number of inhabitants or the population density (EU [63], US [64], Japan [65]), while others base their statistics on the predominance of people living from the primary sector (mainly agriculture and farming) [66]. But even for a population density approach, thresholds vary among nations. For instance, people living in an area above 2500 inhabitants could be accounted as urban people in the US, while they should be at least 5000 in EU. This could explain European higher share of rural dwellings compared to that of the US.

Leaving aside methodological differences, some interesting conclusions can be drawn from urbanisation figures (Fig. 5). Urban households outnumber rural, with percentages above 65 % in all nations except Japan (43 %) and India (35 %). Moreover, these percentages are increasing rapidly in developing countries, as people move from rural to urban areas [35] in their search for better jobs, education and services. On the opposite, in some developed countries, such as the US, rural population is increasing due to urban saturation and improved infrastructure and living conditions in rural areas.

Rural and urban dwellings can vary significantly in terms of design and construction, householders and energy supply, and so can their consumption patterns. Rural housings tend to be single-family (82 % in India [29], 97 % in US [54]) and have larger average dwelling sizes (100.1 vs 88.7 m^2 in EU [67] and 215 vs 179 m^2 in US [54]). Their householders have lower income levels, 21 % lower in the EU [68] and 66 % lower in Russia [69]. They also tend to have a higher proportion of older residents [32,34].

Detailed energy data for rural and urban dwellings are only available for the US (2012) [54] and China (2015) [35]. Rural dwellings tend to be higher consumers (2.1 vs 1.9 toe/hh in US, 1.4 vs 1 toe/hh in China). Rural consumption is also characterized by the inefficient use of non-marketed biomass [70] (mainly straw and wood) due to its availability and limited access to electricity. For instance, it accounts for 32 % of rural energy supply in China and 15.5 % of US rural households, contrasting with their low share in urban ones (2 %).

6. Drivers

A deep analysis of the main factors driving residential consumption could shed light on future trends as well as on where to focus efforts to reduce its environmental impact. However, this requires residential activity information which is not commonly available. Population and wealth (expressed as Gross Domestic Product per capita) are of interest, but other activity indicators are harder to find and less reliable, especially for developing countries [71]. This is the case of the scarce information regarding built-up area, number of dwellings, number of occupants, household income, equipment stock, fuel prices, climate indicators and human behaviour, even for most developed countries. Major efforts are needed worldwide, as this type of information can only

Table 2
Energy indicators by housing type for US (2015) and Spain (2011). Based on EIA [54] and IDAE [61] data.

	United States		*Spain*	
	SF	MF	SF	MF
Average dwelling size [m^2/hh]	217	83	140	87
Consumption per household [toe/hh]	2.25	1.01	1.3	0.65
Energy use intensity [koe/m^2]	10.2	11.8	9.4	7.5
HVAC consumption [toe/hh]	1.2	0.38	0.86	0.22

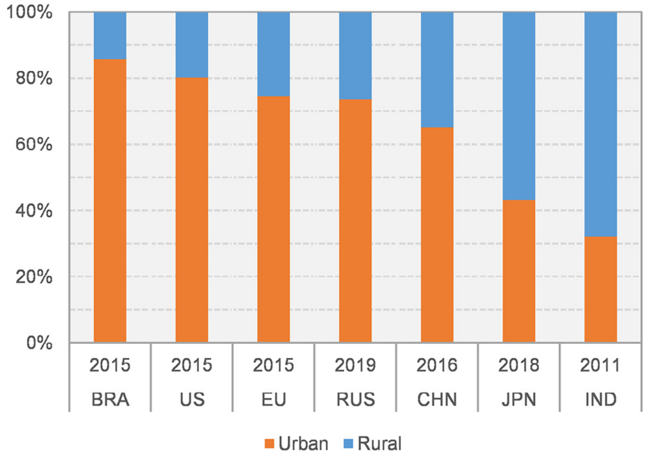

Fig. 5. Degree of urbanisation of the dwelling stock. Based on data from IBGE [33], EIA [27], Eurostat [34], ROSSTAT [31], Jiang et al. [35], SBJ [32] and NBO [36].

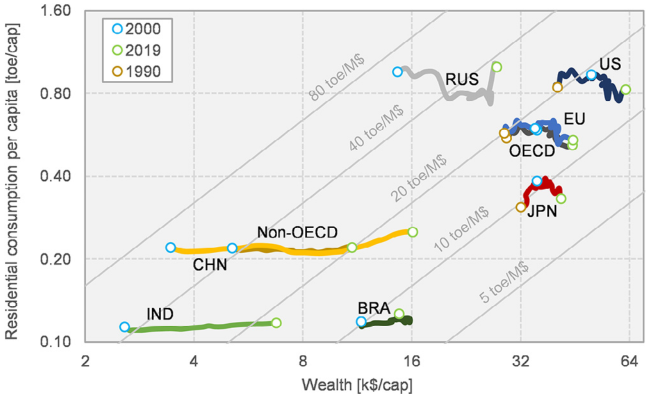

Fig. 7. Residential consumption per capita vs wealth (GDP per capita) for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil. Based on IEA [4], Odyssee [24] and World Bank [28] data.

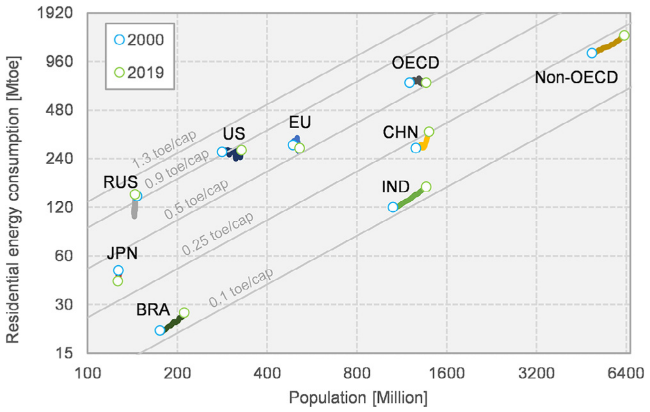

Fig. 6. Residential consumption vs population for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil. Based on IEA [4], Odyssee [24] and World Bank [28] data.

be obtained through comprehensive censuses, data collection from random samples and subsequent data processing and modelling [8,72] which require huge work and investment. For some nations, sufficient data exist to characterise the residential stock, but energy data limitations prevent a quantitative analysis of the impact of these factors on residential energy trends. This section examines the data available to explain the consumption patterns for those nations where information is available. The main factors discussed are population, wealth, floor area, climate and number of dwellings, deriving in the activity and efficiency indicators previously presented in the methods section (Table 1).

6.1. Population

Population is the key activity indicator for residential energy use, as shown in Fig. 6. The larger the population, the higher the residential consumption, although this relationship is less than proportional. Indeed, developing economies, with four times the population, have only twice the consumption of the developed region, resulting in half their per capita consumption in 2019 (0.22 vs 0.5 toe/cap). Energy trends in developing countries are strongly influenced by population growth and can be adjusted by a linear correlation in India, an exponential one in Brazil and a quadratic one in China, where wealth growth caused a turning point in 2010. In contrast, the US and the EU have achieved declining consumption trends despite an increasing population. Convergence between regions is unlikely to happen soon, due to the slowness of their trends and the huge distance between their starting points. Increases in energy use in Russia and decreases in Japan with a constant population reveal that there are other factors causing consumption change.

Regarding other demographical characteristics, age would also have an impact in residential consumption, since an ageing population tends to result in more single person households [73], more time spent at home and higher demands for comfort levels.

6.2. Wealth

In principle, wealth should be a natural driver of residential consumption, provided that per capita consumption in developed economies is twice as high as in developing ones. A detailed analysis of national trajectories for both variables (Fig. 7) can explain the extent to which per capita income translates into in residential consumption.

In developing countries such as India, income levels are not yet sufficient for national wealth growth to translate into increases in residential consumption. As a result, per capita consumption remains limited to essential services along with low appliances penetration levels [74] and their residential energy intensity (toe/M$) is high but rapidly declining. In other emerging economies, higher affluence levels allow citizens to increase their living space and improve the level of comfort and equipment in their homes [75], especially of cooling systems and electrical devices [76]. Increases in GDP translate into increases in residential consumption that slow down the decline of residential energy intensity. For instance, China shows growth in per capita consumption (2 %/yr) after a turning point in 2010, halving the rate of decline in energy intensity (from 9.4 to 4.5 %/yr).

Economic and technological development in OECD countries has shown since 2000 that breaking the link between wealth and consumption is possible in nations with efficient equipment and housing stock. The OECD has clearly demonstrated that sustained rates of wealth growth can be compatible with reductions in residential consumption, which will be further improved if citizens adopt more conservative lifestyles by curbing their demand for living space and services. Regional trends are indeed consistent with the theory of the Environmental Kuznets Curves, according to which the pressure of an economy on the environment is high during the early stage of development, but attenuates over time with the economic growth to the point of even improving environmental quality [77].

The OECD trajectory should serve as a roadmap for emerging countries to decouple their development and consumption trajectories. However, as long as their living standard remains far behind that of developed nations, it will not be possible to decrease their demand for space, comfort and equipment. Even implementing energy efficiency measures, they will not reduce their per capita consumption in their fair attempt to reduce global inequality.

Special cases are Russia, where the cold climate and poor thermal insulation of buildings [78] result in the highest residential energy intensity (37 toe/M$), and Brazil, whose low figure (8.5 toe/M$) raises doubts about the suitability of using GDP as an activity indicator for the residential sector. Instead, household income is better suited to this objective [79], although the lack of data prevents its use. This could explain the twofold differences in energy intensity between Brazil and China for similar levels of national wealth, as the average wage is about three times higher in China, allowing for higher household energy expenditure.

6.3. Floor area

One of the main consequences of increasing wealth is the demand for more living space per capita. Thus, it is useful to plot the impact of urbanisation (m^2/cap) on per capita consumption (toe/cap), drawing lines of constant energy use intensity (koe/m^2), the standard energy efficiency indicator for the building sector (Fig. 8, left). Note also that urbanisation growth can be driven by an increasing dwelling size (m^2/hh) and a decreasing household size (cap/hh) (Fig. 8, right).

For the non-OECD, only China can be analysed, due to the lack of information for floor space and stock in other nations. In the first decade of this century, the increase in wealth translated into an almost linear increase in living space per person, due to the rapid increase in the size of dwellings and the slower decline in the size of households. During this period, the demand for energy services did not increase, maintaining per capita consumption almost constant. Consequently, the energy use intensity declined, as the improvement in living standards induced a faster growth in area than in consumption. From 2010 onwards, the growth in the housing size slowed down as figures approached those of Europe. Then, the continuous increase in wealth pulled demand for energy services and increased energy use intensity. Thus, wealth remains the main driver of residential consumption, as it not only increases the demand for floor space, but also allows for higher levels of comfort and equipment.

Meanwhile, developed nations kept on increasing urbanisation mainly due to smaller household sizes. In the US, the dwelling size sharply declined due to population shifts towards smaller rented houses, coinciding with economic crisis in 2008, but it is again growing. However, efficiency improvements, thanks to technological enhancement and house renovations [80], and the saturation of the energy services [81] allowed slight consumption drops compatible with area growth, resulting in energy use intensity reductions.

In terms of absolute figures, countries with the highest per capita floor area, such as the US (70 m^2/cap), correspond to those with the largest per capita consumption (0.82 toe/cap). On the other side, India has the lowest per capita consumption (0.12 toe/cap) due to low services and urbanisation (11.5 m^2/cap). The energy use intensity in most developed countries (around 12 koe/m^2) contrasts with that of some emerging nations, such as China (7 koe/m^2), due to conservation habits rather than higher levels of efficiency [82]. The greater intensity in India (10 koe/m^2) can be explained by the high occupancy density of its housing stock, resulting in one third of the area and half of the consumption of China, for roughly the same population.

However, countries such as Germany and New Zealand show large differences in per capita consumption at similar levels of urbanisation and wealth, which can be explained by the effect of climate. The former's severe climate contrasts with the latter's mild weather. Climate could also explain the differences between Spain or Japan and the European Union. Similarly, the high energy use intensity in Russia is mainly due to its extremely cold climate driving heating demand up to 65 % of residential consumption [25].

6.4. Climate

Climate is also a key factor in the consumption of residential buildings. It obviously affects the energy demand for HVAC and DHW, but also other services and equipment (lighting, refrigerators, dryers, etc.) due to weather-dependent variables such as daylight, humidity and the number of indoor hours.

In order to examine such dependence, the energy use intensity of selected countries is plotted vs their Heating Degree Days (HDD) (Fig. 9), which measure the severity of winter by accounting for the difference between the outdoor temperature and a base temperature, below which heating systems are assumed to turn on [83]. Residential consumption per floor area is obviously higher in colder areas, especially in low efficiency buildings, but there are still significant outliers. Swedish low consumption compared to Russian, reflects the priority on high performance envelopes and highly efficient district heating systems in Northern Europe [84], which results in energy use intensity figures even comparable to those in milder areas [85]. Twofold differences are found between China and US around 2000 °C days, due to the reduced stock of heating systems and lower comfort levels and to big shares of non-climate dependent energy services, such as cooking, in the former.

Climate could also be responsible for short-term fluctuations in energy consumption, as milder than usual weather could decrease annual energy demand, while severe winter or hot summer seasons could cause consumption peaks. In principle, better monitoring of energy use in dwellings can be achieved by correcting consumption to neutralise the effects of weather, commonly assuming a linear regression with heating degree-days [86]. However, this does not work and may even lead to unrealistic fluctuations in developing countries, where the response to weather variations does not necessarily translate into increased energy use, but rather into decreased thermal comfort, as low income levels restrict energy expenditure [22].

6.5. Household size

The household size might be also a driver of per capita residential consumption, as bigger households could consume less as a

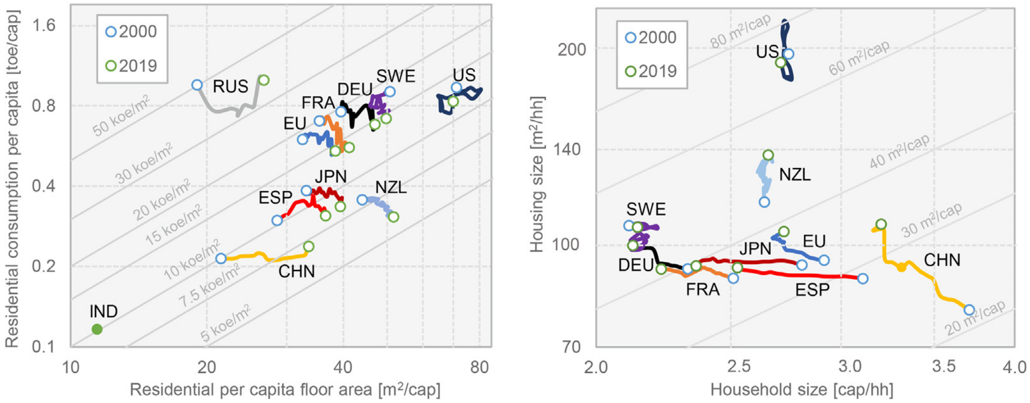

Fig. 8. Residential consumption per capita vs per capita floor area (left) and housing size vs household size (right) in selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24], Jiang et al. [35], AEEE [37], ROSSTAT [31] and World Bank [28]. Indian value is only available for 2017, Chinese data from 2001 to 2016, US, New Zealand and Japan only up to 2018.

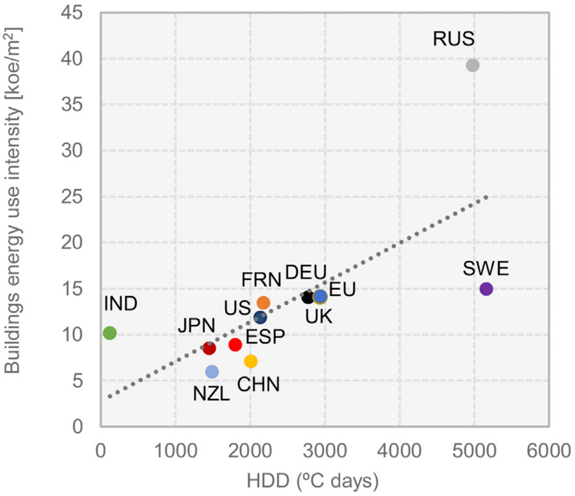

Fig. 9. Residential energy use intensity vs Heating Degree Days (HDD) in selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26,38], Odyssee [24], Jiang et al. [35], AEEE [37], ROSSTAT [31] and World Bank [28]. Year 2018, except for India (2017) and China (2016).

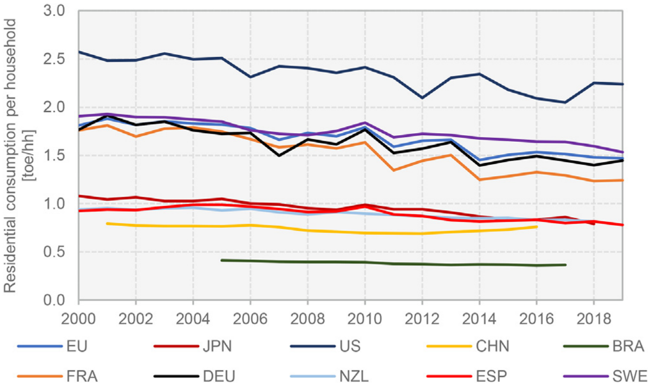

Fig. 11. Residential energy use per household in selected countries: US, EU, Japan, China, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24] and Jiang et al. [35].

result of sharing energy services and equipment (mainly HVAC) [79]. However, the results in Fig. 10 show poor or even inverse correlation between these indicators. In fact, Germany, France and the global EU have reduced their per capita consumption despite decreasing household sizes thanks to efficiency gains, promoted by energy and climate policies in buildings [87]. In contrast, Brazil and China increased per capita consumption while lessening household sizes due to the higher demand for floor area and energy services. In countries such as US, Sweden and New Zealand, the per capita energy consumption decreased with constant household sizes, and it experienced little change in Spain and Japan while their household size decreased by roughly 20 %. Among countries, those with the lowest consumption figures correspond to those with largest households, but as a matter of the poor living standards, rather than of the dwelling's occupancy.

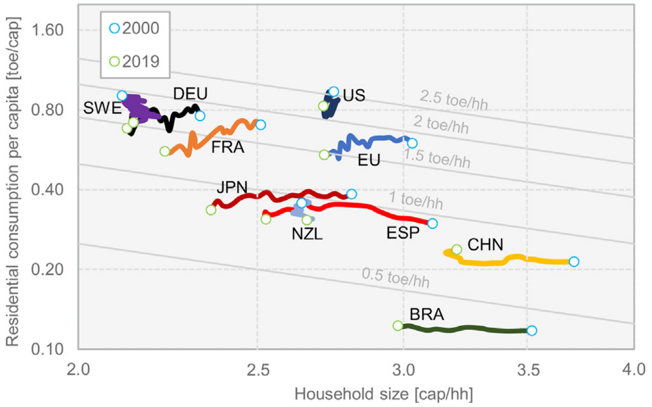

Fig. 10. Residential consumption per capita vs household size in selected countries: US, EU, Japan, China, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24], Jiang et al. [35] and World Bank [28]. Chinese data from 2001 to 2016, New Zealand and Japan only up to 2018.

6.6. Consumption per household

Finally, trends in consumption per household, a common efficiency indicator in international comparisons, can be examined in the light of the previous analyses of the drivers (Fig. 11). Consumption per household has declined in all countries since 2000 thanks to efficiency improvement, except in China, where it started to rebound in 2012, as economic development led to improved living standards. It is expected that Brazil will soon follow this trend to approach the figures of developed countries. Within the OECD, nations are grouped into different clusters around 0.8 toe/hh and 1.5 toe/hh due to climate effects. The United States again stands out owing to the impressive size of its dwellings, which require twice as much as other developed countries (2.2 toe/hh). Consequently, it will be difficult to reduce consumption in the residential sector without curbing the demand for personal living space.

7. Conclusions

Residential buildings account for a quarter of final energy consumption and a fifth of CO_2 emissions. Their significant impact has put them at the forefront of climate policies, due to their high potential for electrification, energy efficiency improvement and on-site renewable generation. However, the development, implementation and monitoring of effective policies for limiting energy consumption growth must be based on relevant information, both for housing characteristics and energy consumption by fuel type and end-use.

The key principles of surveys, in situ measurements and models for assessing residential energy use are well established, but they are time-consuming and costly to prepare, collect and process. As a result, reliable data are only available for certain developed countries and a few emerging ones, such as China. This lack of information hampers the further development of effective policies for this sector. There is a need for a global call to collect and report key indicators of activity, such as floor area, number of dwellings, household size, income level and equipment stock, especially in developing countries. It is therefore essential to create consensus towards an international standard information on the sector and to provide the necessary funding for the whole data reporting process.

Regarding residential services, HVAC systems are becoming almost essential in parallel with the expanding demand for thermal comfort. HVAC systems are the most consuming end-use accounting for a third of residential consumption, which means about 8 % of the final energy use on the planet. Consequently, policies should focus not only on strengthening energy codes for new dwellings but also on promoting envelopes and HVAC retrofitting for existing buildings, which will otherwise be delayed due to their long lifetime.

Population, wealth and living space drive residential consumption, which has increased by 1 % per year since 2000. Population boosts energy use, especially in emerging economies, due to their rising per capita consumption. As income levels rise, citizens demand more living space, within better equipped dwellings and with a higher comfort level, which necessarily leads to consumption growth. Convergence between regions is unlikely to happen soon, but in the future each citizen could consume around 0.4 toe/cap at home, equivalent to 12 kWh/cap daily. Moreover, the demand for floor space will continue to grow and could converge with developed nations at around 40 m^2/cap, due to the increase in dwelling size (up to 100 m^2/hh) and the reduction in the household size (down to 2.5 cap/hh).

Energy use intensity is widely used in energy codes as an indicator to assess the quality of the building envelope and the efficiency of HVAC systems. However, household demand for all other residential services is directly dependent on the behaviour and number of residents. In other words, they are the individuals who consume energy and not the floor area of their dwellings. Therefore, cross-country comparisons for the residential sector should be based on per capita consumption figures rather than on per floor area, which could be misleading. In any case, energy use intensity is only available for the few countries where floor area information is collected. In the near future, more efficient buildings and equipment in developed nations, coupled with consumption per capita increases linked to wealth generation in emerging economies, could see energy use intensity converge to around 10 koe/m^2, being even lower in warm areas.

Table 3 shows the main energy efficiency indicators of the residential sector for the most consuming nations (United States, European Union, China and India), which also highlight differences between the OECD and the non-OECD. First, the growing per capita consumption in the developing region contrasts with the decreasing trends in the developed one in the last decade, while figures in India are still half those of China and about one fifth those of EU. Second, energy intensity has dropped in every nation, especially in China and India to approach values of developed countries. Third, the reduction of the energy use intensity shows efficiency improvements in EU and US, but it is also related to living space growing above the consumption in China. Finally, residential consumption per household in China is half that of the EU and one third that of the US, so both efficiency and sufficiency should be further promoted in the developed region to accelerate their drops and close the gap among regions. Table 3 also highlights the performance of the EU in achieving the fastest declining trends in all indicators, so its experience could be exported across borders, while further efforts are undertaken to reach sustainable goals.

Growth in residential consumption has been mainly supplied by electricity and gas, which together account for half of the energy use. However, biofuels remain the main source of energy due to the use of non-marketed biomass and the share of residential electricity globally is only a quarter. Thus, although electrification seems to be the panacea for decarbonisation, it could lead to a sharp increase in emissions in the short term, if residential electrification is faster than decarbonisation of the energy system. The substitution of biofuels and gas by electricity, especially for cooking and heating services, will increase primary energy factor and carbon intensity, unless the share of renewable power is greatly accelerated.

Moreover, the COVID pandemic has exacerbated the consumption growth in the residential sector, as it has forced people to spend more time at home, increasing their demand for HVAC and cooking, but especially for small appliances due to the acquisition of new electronic appliances, computers and office equipment for

Table 3
Energy efficiency indicators in the residential sector for the most consuming nations (2000–2019). The compound annual growth rates since 2010 are shown in brackets to highlight most recent trends.

Indicator	**Unit**	**US**	**EU**	**CHN**	**IND**
Per capita energy consumption	toe/cap	0.94–0.82 [-0.6 %]	0.6–0.54 [-1.8 %]	0.22–0.25 [2 %]	0.11–0.12 [0.4 %]
Energy intensity	toe/M$	19 – 13 [-2.2 %]	17 – 12 [-3.2 %]	64 – 16 [-4.5 %]	44 – 17 [-4.7 %]
Energy use intensity	koe/m^2	13–12* [-1.6 %]	18 – 14 [-2.3 %]	10–7** [-1%]	10***
Consumption per household	toe/hh	2.6–2.2 [-0.8 %]	1.7–1.5 [-1.8 %]	0.79–0.76** [1.5 %]	–

Available data (*) 2000–2018, (**) 2001–2016, (***) 2017.

entertainment and remote working or schooling. Thus, efforts must intensify to compensate the changes in the household energy use patterns, which are likely to continue and be integrated into new lifestyles.

Reducing energy use in residential buildings will not be possible unless global cooperation and effective policies enables the links between economic growth, urbanisation and consumption to be broken, including reducing the rebound effect. On the demand side, policy actions should be aimed at (1) motivating citizens to move to less intensive multi-family dwellings, (2) promoting energy efficiency in residential end-uses (through product-policies) and in the constructive characteristics of the buildings (through codes and retrofitting), and (3) stimulating behavioural changes towards conservation habits and sufficiency for living space, appliances ownership and energy services. Construction companies, manufacturers and policy makers must work together to implement residential efficiency and on-site renewables, while citizens must do their part to reduce any excessive and inefficient use of energy in order to meet the Paris Agreement goals.

Data availability

The authors do not have permission to share data.

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.

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