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Review article

A review on buildings energy information: Trends, end-uses, fuels and drivers

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ABSTRACT

Buildings are a major contributor to climate change, accounting for one third of global energy consumption and one quarter of CO_2 emissions. However, comprehensive information is lacking for the development, evaluation and monitoring of mitigation policies. This paper discusses the remaining challenges in terms of reliability and consistency of the available data. A review of energy use in buildings is presented to analyse its evolution by building types, energy services and fuel sources. Residential buildings are the most consuming, although tertiary expansion requires further analysis to develop sound specific indicators. Heating Ventilation and Air Conditioning (HVAC) systems concentrate *38%* of buildings consumption, calling for strengthened standards and incentives for retrofitting. Electrification is rapidly increasing, representing a potential tool for climate change mitigation, if renewable power was promoted. However, energy use in buildings will only curb if global cooperation enables developing nations to break the link between economic growth, urbanisation and consumption. To this aim, efficiency gains both in construction and equipment, decarbonisation of the energy mix and a global awareness on energy conservation are all needed.

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1. Introduction

Despite the current urgency to halt climate change, the world energy use and its related CO_2 emissions keep on growing (Jackson et al., 2018). Population and wealth have boosted their increases, as globalisation improves living standards worldwide. On the contrary, efficiency gains have partially offset those effects, allowing wealth to grow above consumption. Meanwhile, energy and emissions have risen at similar rates, thus failing in decarbonisation in the last two decades (Jackson et al., 2019). However, their stabilisation seems to be close, as growth rates have halved since 2013 and the COVID-19 pandemic has radically altered emissions trajectory (Le Quéré et al., 2021).

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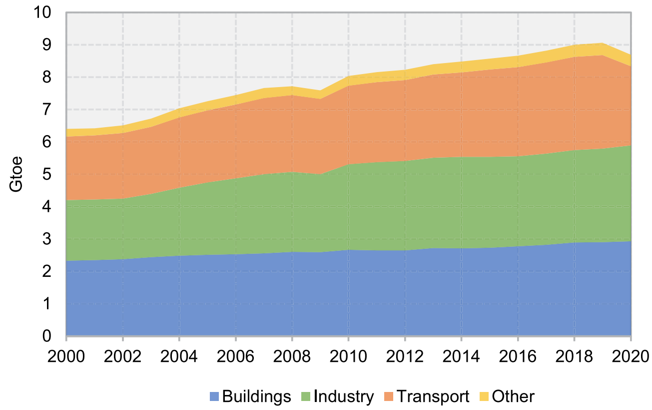

Fig. 1. Final global energy consumption by sector.
Source: Based on IEA data (IEA, 2021e,d,b)

Regional disparities show a world split in half. In 2019, developing nations (non-OECD) represented *82%* of the world population, generated about *53%* of global activity (World Bank, 2021) and were responsible for about two thirds of consumption and emissions (IEA, 2021e). However, people in developed countries (OECD) are still *4* times richer and roughly *3* times more consumers and emitters per capita. The gap is narrowing as economic expansion enables greater comfort in emerging nations, albeit increasing energy demand. Fortunately, drops in consumption and emissions in the developed region are about to cancel out rises in developing countries as they seek to reduce inequality (González-Torres et al., 2021a).

Nevertheless, emissions stabilisation will not be sufficient to limit the global temperature increase to *1.5* °C (IPCC, 2018). To face the environmental crisis, most climate policies focus on decarbonisation by shifting from emissive fossil fuels to clean renewable sources and by developing Carbon Capture and Storage techniques. However, these solutions are likely to be constrained on a global scale in the short term (Peters et al., 2017). Urgent changes are required, not only in the way energy is supplied, but also in the way it is consumed (Allouhi et al., 2015). Thus, a thorough analysis of consumption trends is crucial for addressing climate change mitigation.

Globally, main consuming sectors are buildings, transport, industry and others, which clusters minor activities such as agriculture, forestry and fishing (Fig. 1). Consumption in every sector has increased to *9.1 Gtoe* in 2019, whereas their shares in final consumption have remained slightly constant. Buildings were the most consuming sector, followed by industry and transport. Population growth, built area increase, higher buildings services and comfort levels, together with the rise in time spent inside buildings have raised buildings consumption by *1.2%/yr* since 2000. This upward trend has persisted even in periods of crisis such as the economic recession of 2008 or the COVID-19. Projections show that, without more stringent policies, the use of energy in buildings will continue to grow in the future, as consumption in developing countries gains importance (Levesque et al., 2018).

Contributions of each consuming sector to global CO_2 emissions allow the assessment of their environmental impact (Table 1). To this aim, direct emissions from fuel combustion as well as indirect emissions from the energy sector must be addressed. In 2019, industry remained the most emissive sector (*38%*), followed by buildings and transport (*28%*) to total *33.6* Gton (IEA, 2021c). Buildings are the most affected by indirect emissions from the energy sector, resulting in total emissions nearly three times above the direct flow. In contrast, direct emissions represented

Table 1
Share of direct and indirect CO_2 emissions by sector in 2019.
Source: Based on IEA data IEA (2021c).

Sector	*Direct*	*Indirect*	*Total*
Industry	19%	19%	38%
Buildings	9%	19%	28%
Transport	25%	3%	28%
Other	2%	4%	6%

97.5% of total emissions in transport and *50%* in the industrial sector.

In summary, buildings are responsible for about a third of global energy consumption and a quarter of CO_2 emissions. They even represent larger shares of consumption in some of the most consuming nations (*42%* in Russia, *41%* in the EU, *37%* in Japan and *34%* in the US (IEA, 2021e)). Their significant impact has placed them at the forefront of climate policies, due to their high potential for improving energy efficiency and generating renewable energy (Mavromatidis et al., 2016). However, the development, evaluation and monitoring of these policies could only succeed if energy information is available, not only for the whole sector, but also for building types and energy services. Unfortunately, gathering buildings information among the existing sources is a major challenge. Problems regarding data collection and elaboration have resulted in few studies on this sector, compared to industry and transport.

Several authors have reviewed the energy use in buildings despite data limitations. Pérez-Lombard et al. (2008) highlighted this sector as a major contributor to energy consumption in 2008. They summarised information for main building typologies and end-uses for some countries and criticised the unavailability of data. Ürge-Vorsatz et al. (2015) presented a simplified global and regional picture of the 2010 situation in residential and commercial buildings, before discussing the main drivers of the demand for energy heating and cooling. Berardi (2017) provided historical buildings trends up to 2010 and future estimates for US, EU and BRIC countries, and called for efficiency policies, which were almost non-existing in emerging nations and insufficient in developed ones. Similarly, Allouhi et al. (2015) actualised the 2011 status of buildings energy use in US, Australia, China and EU as a basis for setting and monitoring energy saving policies. In 2016, Cao et al. (2016) made a comparison of energy efficiency, end-uses and fuel mixes in 2012 for the top three consumers (US, EU, China) and focused on Zero Energy Buildings (ZEBs) to address the increasing energy demand. In 2019, Lu and Lai (2019) discussed the evolution of energy in residential and non-residential buildings up to 2015 in US, China, Australia and UK, their energy policies, rating schemes and efficiency standards. They suggested the need for different policies in developed and developing countries, the former to promote renewable energy and the latter to reduce commercial consumption. Finally, Guo et al. (2020) studied energy and emissions in 2017 for some countries and proposed a clustering according to the policies they require. They also analysed how these figures were related to energy mixes, population, floor area, wealth and the happiness score.

Thus, there are some time gaps in buildings consumption trends over the present century. The global picture of the sector is often overlooked to focus either on residential or tertiary buildings, or on those countries where data are available. Moreover, the trajectories of the main factors driving changes in the whole sector are lacking in the literature. Furthermore, the main difficulties for data collection have not been criticised, so that the necessary changes in energy statistics to establish the most appropriate way to report buildings information remain unclear and

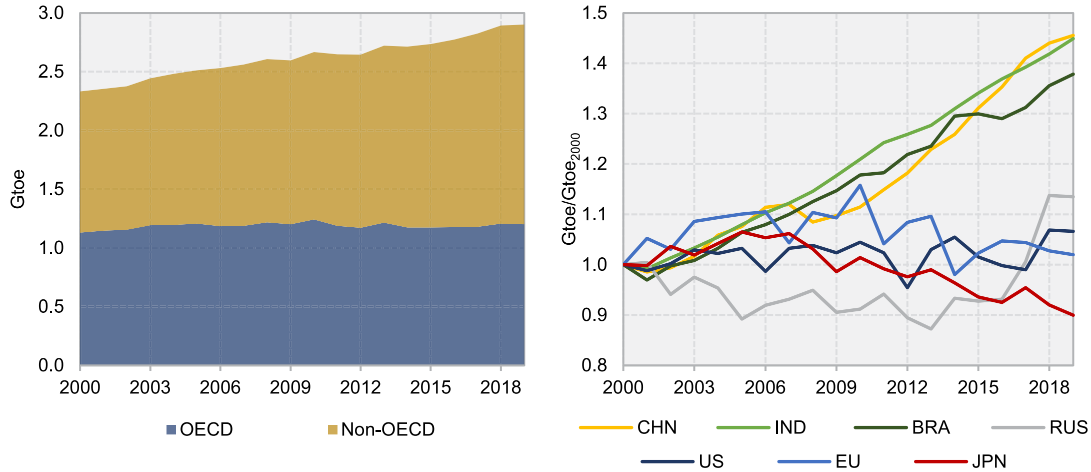

Fig. 2. Final energy consumption in buildings: OECD and the non-OECD (left), China, India, Brazil, Russia, US, EU, Japan (right). *Source:* Based on IEA (2021e) and Odyssee (2021) data.

unresolved. Consequently, this paper provides a deep analysis of buildings energy use for the world, the developed and developing regions and most consuming nations in the 21st century. Progress on data availability and main research challenges are discussed to propose coherent solutions. Are there comprehensive databases for buildings energy consumption? How do the main accounting methods differ? Which is the most consistent breakdown by building types and energy services? Thus, the paper is intended to reveal data collection requirements to enable proper monitoring of the sector, and to explain trends based on the analysis of main drivers of energy use in buildings.

To achieve these goals, the paper starts with a description of energy use in buildings, its evolution and its disaggregation in residential and tertiary sectors. Then, it analyses buildings energy services and fuel mixes. Lastly, it relates consumption to several drivers, among which population, wealth, efficiency, floor area and climate are further examined.

2. Energy use in buildings

As the main consuming sector worldwide, analysing energy use in buildings is of high interest. However, gathering data for this purpose remains a major challenge. First, buildings are usually not recognised as an independent sector. Traditionally, they have been hidden within a large ‘Other’ sector, despite being responsible for the largest share of consumption. Some sources have evolved to disaggregate ‘Other’ into different subsectors, of which ‘Residential’ and ‘Services’ can be added to obtain buildings data. However, this addition is still a proxy, since it may sometimes include some activities which do not occur in buildings (*non-building energy use*), such as street lighting, water supply, postal courier, etc., which could together represent up to *10%* of buildings consumption (France, 2018). Despite decomposing into subsectors is of interest, the buildings sector should first be accounted for independently and then broken down in residential and non-residential buildings.

Secondly, sources differ in the activities included in each consuming sector, making the comparison difficult. In their attempt to standardise definitions, data collection institutions normally define sectors according to the United Nations International Standard Industrial Classification (ISIC) (United Nations, 2008). Discrepancies are found regarding water supply, sewerage, waste management and remediation activities which are either considered as Services or ‘Other’ sector; repair and installation of machinery and equipment, which are included in Industry or in Services; or postal and courier activities, as part of Transport or Services. These definitions may vary even within databases from the same source: buildings data in the IEA World Energy Outlook (IEA, 2021g) include *non-specified consumption*, while it is accounted for within ‘Other’ in the IEA World Energy Balances (IEA, 2021e), resulting in discontinuities between past and future trends.

Thirdly, buildings sector definition is heterogeneous, not only due to the activities it comprises, but also in terms of the energy flow measured. Some sources account for final energy use (also referred to as site or delivered energy (U.S. Energy Information Administration (EIA), 2021) or final energy consumption (IEA, 2021f; Eurostat, 2021; Odyssee, 2021)), while others also add the indirect consumption related to the energy losses from the energy sector (total energy consumption (U.S. Energy Information Administration (EIA), 2021)). Similarly, most data sources limit their accounting to direct emissions from buildings, i.e., emissions from the combustion of fossil fuels on-site. The impact of the buildings sector on the environment is then underestimated since indirect emissions due to electricity and heat generation must also be considered. This adds uncertainty to buildings emissions due to the assumptions required for their calculation in the absence of data. Moreover, the buildings sector could be analysed from the life cycle perspective. Thus, other indirect energy and emissions could also be assessed, such as those embedded in food, equipment and building materials and their transport to the construction site (Ürge-Vorsatz et al., 2012). However, these indirect flows are already accounted for in other sectors, and their inclusion within the building sector requires complex accounting methods and assumptions. As a result, a life cycle approach could divert the focus and hinder the effectiveness of energy policy in buildings.

These issues could only be solved if a standard definition of the buildings sector and a universal energy conversion method are proposed. International organisations and national energy agencies should cooperate to harmonise their accounting, collection, and reporting methodologies on energy use in buildings. There is already some international cooperation on standard harmonisation, such as ISO 12655:2013, which focuses on the presentation of measured energy use of buildings (ISO, 2013).

Despite such difficulties, the most reliable data are chosen to compare regional and national trends for buildings energy use (Fig. 2). To this aim, the buildings sector is defined as the sum of residential and commercial figures, thus including non-buildings energy use and excluding losses from the power sector

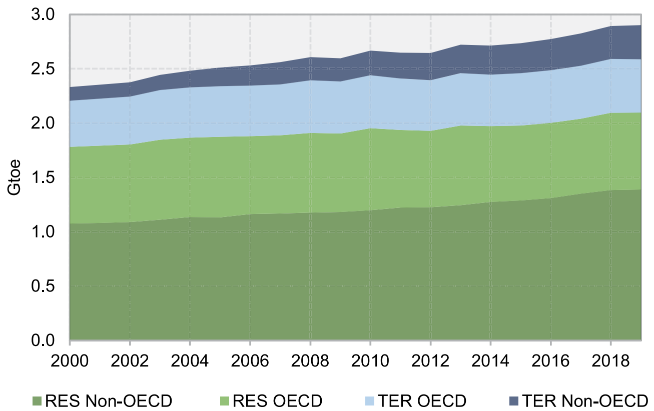

Fig. 3. Residential (RES) and tertiary (TER) energy consumption for the OECD and the non-OECD.
Source: Based on IEA data (IEA, 2021e).

and embodied energy from the life cycle perspective. Global increase on energy use in buildings is driven by *42%* rise in non-OECD since 2000, while consumption in the OECD decreases since 2010 (*3%*). Most consuming nations strongly influence trends in both regions. Consumption in Chinese and Indian buildings rose sharply after their economic expansion and industrialisation to some *45%*. Similarly, trends in other major emerging nations (BRIC members), namely Brazil, have followed impressive growths to some *40%*, except for Russia, which has only experienced a significant increase after 2016. In contrast, US and EU stopped their upward tendency around 2010. Since then, energy consumption in US buildings has only risen by *2%*, while it has dropped by *12%* in EU, because of efficiency gains from building's envelopes and equipment.

The buildings sector clusters many typologies which differ in their physical (age, size, geometry and construction) and operational (activities, internal loads, ventilation ratios, schedules, etc.) features, influencing the demand for energy services. Thus, the classification of building types is basic for understanding how energy is used and developing sound energy policies. At least, they should be broken down into residential (domestic) and non-residential (tertiary or services) buildings, as most sources have already done.

The residential sector accounts for the energy use in dwellings. However, there are difficulties in identifying and separating some activities that should be allocated to other sectors due to their purposes. For instance, the charging of electric vehicles in home garages should be assigned to the transport sector, while home professional activities should be part of non-residential consumption. This problem has been highlighted with the expansion of telework during COVID lockdown, since it is not clear how to measure this energy flow and who should be responsible for its costs. In addition, there are different typologies within the residential sector: single-family (which can be split in detached, semidetached and attached), multi-family (which can be broken down according to the number of units) and mobile homes.

The tertiary sector covers commercial and public activities within many different building types (offices, retail, educational, sanitary, hosting, leisure, etc.). Unfortunately, there are few consistent and reliable studies for this sector due to the heterogeneity of these typologies and the lack of information owing to the difficulties in collecting data, as tertiary buildings are usually multi-tenanted and share different activities. Moreover, data sources do not always agree on the activities included in this sector. For instance, repair and installation of machinery are sometimes included in industry, while warehousing for transportation is part of transport. Lastly, data for the tertiary sector normally include non-building consumption (such as street lighting), which is inconsistent with its definition.

Trends for the residential and services sectors by region are shown in Fig. 3. Residential consumption accounts for around three quarters of energy in buildings at global level. In the non-OECD region, an almost five times larger population results in twice the residential energy use of the OECD, despite their lower wealth. The rapid demographic and economic growths in the developing region have raised residential consumption by *29%*, in contrast to the flat trend of the developed region. On the other side, *61%* of global tertiary energy is still consumed in the OECD, where economy shifts from industry towards services have raised non-domestic consumption by *16%*. Tertiary consumption in developing countries will continue its impressive growth as they increase their living standards and, consequently, their demand for education, health, leisure and entertainment activities. Although both drivers influence both sectors, population has a greater impact on residential consumption, while wealth more significantly affects non-residential energy use.

The distribution among buildings subsectors varies across countries (Fig. 4), mainly due to different income levels, climatic conditions, economic structure, etc. National figures confirm the expansion of the tertiary sector, whose shares are higher in OECD countries (Japan, US, EU) than in non-OECD nations (Brazil, Russia, China, India), reinforcing the link between services and wealth. The highest tertiary shares correspond to the Japan (*54%*)

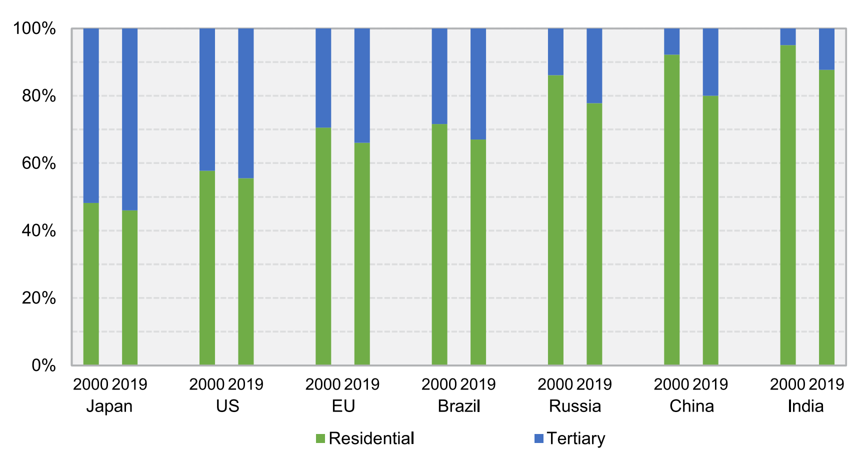

Fig. 4. Residential and tertiary shares for Japan, US, EU, Brazil, Russia, China and India.
Source: Based on IEA (2021e) and Odyssee (2021) data.

and US (*44%*), where the consumption is roughly equally distributed between residential and commercial buildings. Among the emerging nations, the importance of each subsector is determined by the balance between population density and per capita income. For instance, India presents the highest residential share (*88%*) for being the most populous (*460* cap/km^2) and poorest (*6.7* k$/cap) country. On the contrary, Brazil has a high tertiary share (*33%*) due to low population density (*25.3* cap/km^2) despite low per capita incomes (*14.7* k$/cap) (World Bank, 2021).

3. Buildings energy services

Disaggregating buildings consumption by energy services (also referred to as end-uses) allows users and owners to better understand their consumption patterns to identify cost-effective saving measures (Froehlich et al., 2011). Moreover, it would help policymakers to develop instruments targeting the most intensive services and devices.

However, energy disaggregation at this level is hardly available, as utility meters are unable to distinguish the energy consumed for each particular use (U.S. Energy Information Administration (EIA), 2017). Several methods have been developed to compile these data. *Direct metering* using distributed sensors (Glasgo et al., 2017) provides the most accurate information, whereas the installation and maintenance costs and the lack of a regulatory framework prevent its widespread use. Other methods involve *non-intrusive load monitoring* (Zoha et al., 2012), which estimates consumption by classifying measurements from a single sensing point through a pattern recognition algorithm. Thus, despite fewer installation costs, calibration and training sensors are required. Finally, *engineering and statistical methods,* such as regression models or neural network modelling, are also used (Swan and Ugursal, 2009). They need detailed information on the characteristics of buildings and equipment performance and stock, which must be gathered through comprehensive surveys. The US Residential Energy Consumption Survey (RECS) (U.S. Energy Information Administration (EIA), 2015) and the Commercial Buildings Energy Consumption Survey (CBECS) (U.S. Energy Information Administration (EIA), 2012) are the main reference in this regard. However, they cannot be released on a yearly basis due to their high preparation, collection and processing time and cost. In Europe, energy services information is still insufficient, though the Odyssee–Mure project (Bosseboeuf et al., 2015) is working on harmonising and centralising national data from National Statistical Offices and surveys carried out by governments, utilities or equipment manufacturers. Similarly, the IEA Energy Efficiency Indicators (EEI) database (IEA, 2020) has collected available energy services information for these and four additional nations (Canada, Korea, Morocco and Japan). In China, Tsinghua University has continuously collected information on residential energy and behaviour through large-scale surveys since 2008 (Zhang et al., 2010; Hu et al., 2017). For the rest of the world, with some exceptions, energy information by end-use is almost non-existent.

Despite energy services classification varies among sources, this paper classifies them in Heating, Ventilation and Air Conditioning (HVAC), Domestic Hot Water (DHW), lighting, cooking and other equipment, mainly appliances and other plug-in devices. Their shares for the world and the most consuming countries are presented in Fig. 5, according to the latest available and reliable data for each region.

HVAC systems are the most consuming service worldwide (*38%*), both in residential (*32%*) and tertiary (*47%*) sectors. They have become almost essential in parallel with the spread of the demand for thermal comfort, considered a luxury not long ago. It is the largest end-use in every country except India, where

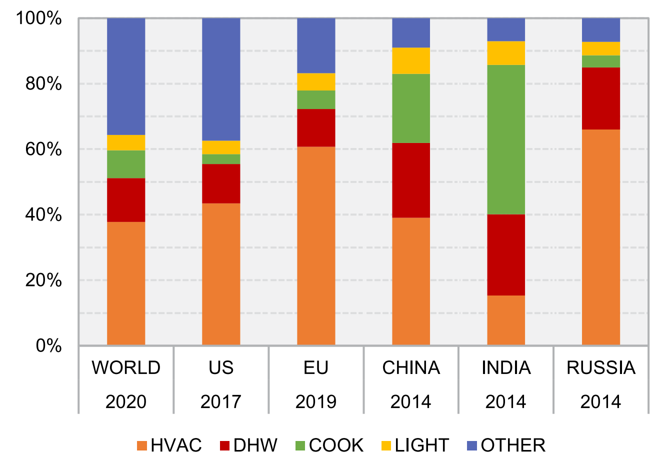

Fig. 5. Buildings consumption by end-uses for the world, US, EU, China, India and Russia.
Source: Based on IEA (2021d, 2017), U.S. Energy Information Administration (EIA) (2019) *and* Odyssee (2021) *data.*

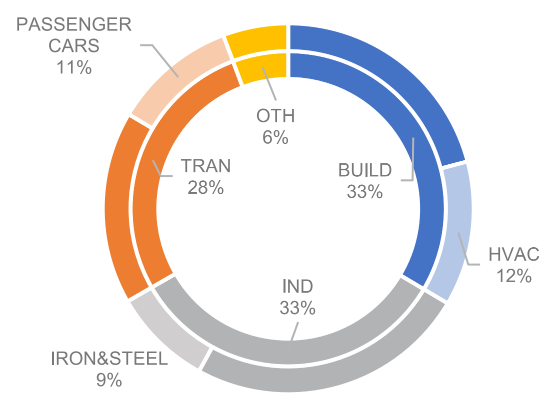

Fig. 6. Main end-uses by consuming sector. World, 2020.
Source: Based on IEA data (IEA, 2021d).

warmer weather and a lower income level push consumption towards basic ceiling fans and more indispensable end-uses, mainly cooking. Thus, HVAC's contribution to buildings energy consumption depends to a large extent on climate and wealth. Richest countries (US, EU) have higher shares than emerging ones (China, India), while the largest fraction is found in Russia because of the coldest climate. In summary, HVAC consumption represents about *12%* of final energy use worldwide and up to some *25%* in rich or cold regions such as the UE or Russia. Their weight in consumption is even comparable to main end-uses from other sectors, such as passenger cars in transport (Fig. 6). Consequently, policies should address this highly consuming end-use, namely in the developed region, by improving and retrofitting buildings' envelopes and HVAC systems (Pérez-Lombard et al., 2012).

DHW is the second buildings energy service at global level (*13%*), followed by cooking (*8%*) whose large shares in less developed countries contrast with the small figures in developed nations. Lighting represents the lowest share (*5%*) and continues to decrease as LEDs replace less efficient traditional bulbs. Finally, other equipment gathers *36%* of consumption, being more important in countries with higher access to electricity (*37%* in US vs. *7%* in India). Progress has made electric devices more affordable and widespread, whereas technology efficiency gains have offset their increasing demand in US and EU over the last years. Their important share would require further disaggregation to reveal which types of equipment are responsible for such a large impact on consumption. However, energy estimates for plug-in devices are particularly difficult to disentangle and there is no consensus on the sub-categories to be defined, as it consists of a miscellaneous mix of devices with minor energy shares.

4. Energy fuels in buildings

Building's energy mix strongly impacts on primary energy and CO_2 emissions. Buildings mainly use electricity, biofuels (biomass, liquid biofuels and biogases), natural gas, oil products (LPG, gasoil and fuel-oil), coal, district heating and 'other renewables'. Among these fuels, there is huge uncertainty in renewable information for biomass and other renewables. On the one hand, non-marketed biomass cannot be measured, so the weight of biofuels depends to a large extent on the reliability of the assumptions made for its estimation, especially in developing economies, where it represents a significant share of the energy use. On the other hand, 'other renewables' should include not only on-site generation of electricity and heat, but also other technologies that take renewable energy from the building's environment. However, they are usually not measured (solar thermal, photovoltaics and heat pumps) or not even measurable, such as daylighting, natural ventilation, free-cooling, and passive cooling and heating systems.

Due to the importance of their share, heating and cooling fuels play a dominant role in buildings energy mix. Fossil fuels are the most frequent heat source, although the proliferation of heat pumps has increased heating electrical consumption in recent years. For cooling generation, electricity is almost the only source, given the limited market for gas engine driven chillers, gas-driven air conditioners and absorption refrigerating machines (Pérez-Lombard et al., 2011b).

The evolution of the fuel mix in buildings (Fig. 7) shows that consumption growth has been supplied mainly by electricity and gas, accounting for *55%* of the energy use in 2020. Electricity (*33%*) has replaced biomass (*24%*) as the main energy source. The higher access to electricity in the developing region (Nejat et al., 2015) has driven shifts towards electric technologies, like the substitution of biomass for cooking. The expansion of the market of electrical equipment, such as small appliances and electronics, is also a driver for buildings electrification. Moreover, HVAC systems have become widespread, driving the use of electricity mainly for space cooling, but also for heating (Hojjati and Wade, 2012) with the use of heat pumps in mild climates.

Fossil fuels consumption has decreased thanks to the reduction of the use of oil products (*10%*) in favour of less emissive natural gas (*22%*), while the use of coal is marginal and constant

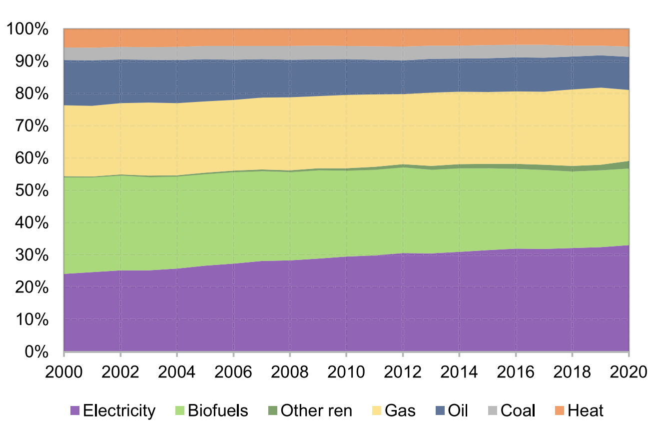

Fig. 7. Buildings fuel mix evolution for the world.
Source: Based on IEA data (IEA, 2021e,d).

(*3%*). The increase in natural gas, which is mostly used for space heating, has been partially offset by efficiency gains (condensing boilers, gas furnaces...). However, the long lifetime of heating equipment compared to other end-uses hinders the promotion of enhanced heating technologies, thus delaying their effect on energy consumption (Hojjati and Wade, 2011). Lastly, the share of district heating has remained roughly constant (*6%*), whereas on-site renewables have appeared in buildings up to *2%*.

Regional differences in fuel mixes are plotted in Fig. 8. In the OECD, electricity was already the major source in 2000, followed by natural gas, and their shares have increased while replacing the supply of coal and oil products. For instance, in US, buildings energy mix was almost equally distributed between electricity (*49%*) and gas (*41%*) in 2019. The electricity share in the EU is limited to a third of buildings energy consumption, as they mainly rely on gas (*35%*) and have more significant figures for biofuels (*11%*), oil (*10%*) and heat (*7%*). Japanese buildings are the most electrified (*53%*) and they stand out for their high oil share (*24%*) above that of gas (*19%*).

In contrast, fuel availability and access to electricity constrain the use of marketed energy carriers in the non-OECD, mainly in rural areas (Chaturvedi et al., 2014). Consequently, electricity was a minor source in 2000, whereas it has doubled its share to *25%* in 2019 due to economic development and urbanisation. In developing economies, the large consumption of biofuels (*36%*) is due to traditional biomass, and their fossil fuels consumption has risen due to gas increases. Data for India in 2000 illustrate the energy mix of the least developed countries, where buildings energy demand was mainly supplied by non-marketed biomass (wood), fossil fuels accounted for *19%* and electricity was below *7%*. In 2019, they still presented the highest biofuels share among the studied countries, although electricity has tripled, and fossil fuels have increased to *23%*. Electricity shares in China (*30%*) and Brazil (*61%*) have also risen and are comparable to those of developed countries, while biofuels still contribute by *18%*. China has the highest renewable fraction (*9%*) due to numerous policies promoting the use of on-site solar energy, which contrasts with their high fossil fuels fraction (*35%*), equally divided between gas, coal and oil. Russia differs from other non-OECD members since it relies mainly on gas (*38%*) and heat (*36%*) and electrification is only *15%* of buildings energy mix.

Policy intentions targeting electrification could be a keystone for reducing the energy environmental impact (Miller, 2018). Electric end-uses are more efficient, so they could reduce energy consumption, while lessening CO_2 emissions if electricity were produced from non-emitting sources (renewable and nuclear). In contrast to other consuming sectors, buildings electrification is feasible because all their services can be electrified. Main barriers are found for space heating and DHW in the coldest climates, where electrification would require the use of ground or water source heat pumps, since low outdoor temperatures penalise the performance of air-to-water equipment. With all, encouraging the use of heat pumps for space and water heating can quickly and cost-effectively reduce final consumption and emissions through electrification (Langevin et al., 2019).

However, fossil electricity generation in 2019 still represented *63%* worldwide (IEA, 2021a), adding *5.6* Gton to the *3* Gton directly emitted in buildings. Current electricity mix could make electrification a threat rather than an opportunity to tackle climate change, by increasing emissions instead of achieving desirable reductions (González-Torres et al., 2021b). Thus, renewable electricity promotion is a priority for future sustainability (Mai et al., 2018).

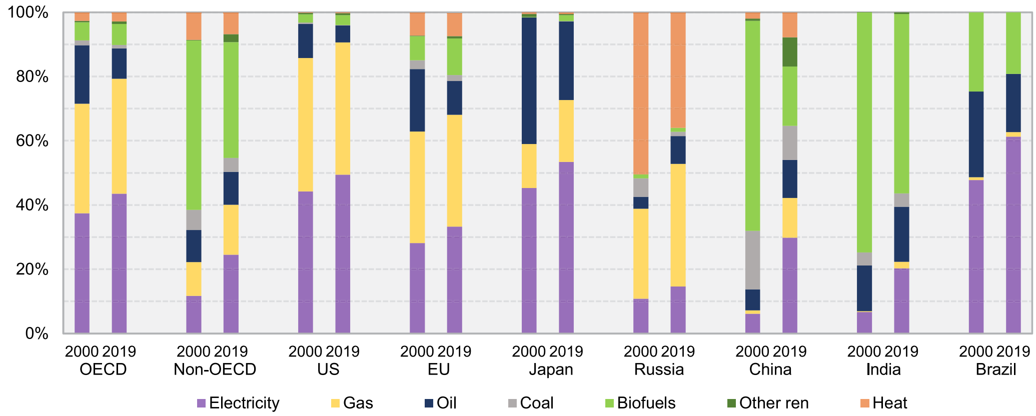

Fig. 8. Changes of buildings fuel mix (2000–2019) for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil.
Source: Based on IEA (2021e) and Odyssee (2021) data.

5. Energy drivers in buildings

Buildings are responsible for a significant share of world energy use and related CO_2 emissions, but which are the main factors driving their change? To answer this question, some activity indicators commonly available in datasets, such as population and wealth, could be analysed. However, other more specific indicators are harder to find and less reliable, since they are difficult to measure, especially in developing countries (Ürge-Vorsatz et al., 2015). Examples include urbanisation, floor areas, number of buildings, number of occupants, equipment stock, fuel prices, climate indicators and culture and human behaviours. To this extent, detailed information could only be obtained through comprehensive census, data collection from random samples and subsequent data processing and modelling (Haas, 1997), requiring huge work and investment. In this respect, US's surveys on residential (RECS) (U.S. Energy Information Administration (EIA), 2015) and commercial sectors (CBECS) (U.S. Energy Information Administration (EIA), 2012) remain as the most valuable references. Odyssee–Mure project (Bosseboeuf et al., 2015) and IEA EEI database (IEA, 2020) collect and publish meaningful information from European countries and IEA members, though they are subject to the national sources on which they are based. Data limitations prevent a quantitative analysis of the impact of these factors on buildings energy trends. However, they are briefly examined below to explain consumption patterns for the selected nations where information is available. Main drivers under the scope of this paper are population, wealth, efficiency, floor area and climate.

5.1. Population

Population is commonly chosen as a key activity indicator for energy use and related CO_2 emissions (Blanco et al., 2014). In this respect, Fig. 9 shows the relation between buildings energy consumption and population for different regions. As expected, population growth leads to energy consumption increases. However, there is an imbalance in per capita terms among nations. Most populated countries, such as China or India, have the lowest per capita consumption figures together with other emerging countries such as Brazil. Despite Indian population is four-fold the American's and over twice the European's, it still consumes half as much as developed countries. Thus, their per capita energy consumption in buildings (*0.13* toe/cap) is about ten times lower than in US (*1.5* toe/cap) and six times below the EU (*0.82* toe/cap). An early convergence in per capita terms is unlikely, due to their slow trends and the huge distance between their starting points. Note that buildings energy consumption increases in Russia and decreases in Japan despite constant population, revealing the importance of analysing additional drivers to explain such changes.

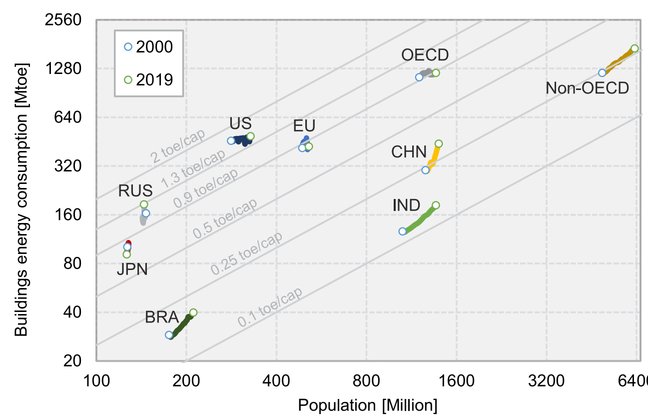

Fig. 9. Buildings consumption vs. population for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil.
Source: Based on IEA (2021e), Odyssee (2021) and World Bank (2021) data.

5.2. Income level

Differences in per capita consumption can be partially explained by wealth figures, which are positively correlated (Fig. 10). Indeed, higher affluence allows for better comfort levels and entertainment activities, as citizens can afford energy and equipment, as well as larger living and leisure space (Santamouris et al., 2007). Moreover, as an economy thrives, it tends to shift from industry to tertiary activities, also leading to higher consumption in buildings. However, this correlation should be broken, as developed nations have already achieved. US, EU and Japan have increased wealth while decreasing per capita consumption due to more efficient buildings and equipment and the saturation of energy services (Haas et al., 2008). This trend was also followed by Russia, though it deviated due to a noticeable increase in the built-up area since 2013 (ISI Emerging Markets Group Company, 2021). The OECD path should serve as a roadmap for emerging countries to decouple development trajectories from consumption as soon as possible. Note also that nations have evolved to converge in terms of buildings energy intensity of *GDP* (*20* toe/M$), after the impressive rise in wealth in developing countries. In other words, their buildings consume roughly the same by unit of *GDP*, reinforcing the link between energy use in buildings and activity generation. Thus, every nation would

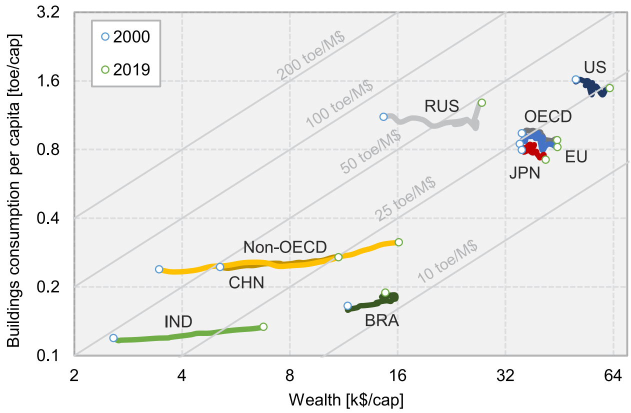

Fig. 10. Buildings consumption per capita vs. wealth for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil. *Source:* Based on IEA (2021e), Odyssee (2021) and World Bank (2021) data.

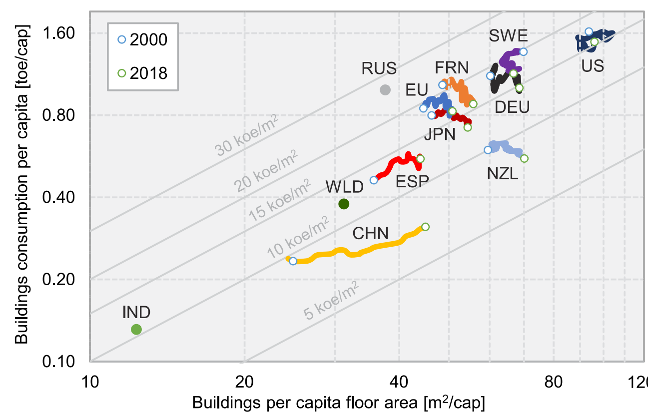

Fig. 11. Buildings per capita energy consumption vs. per capita floor area selected countries: World, US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Indian and Russian values are only available for 2017 and 2013, respectively. World figures correspond to 2019. *Source:* IEA (2021e, 2020), Odyssee (2021), Jiang et al. (2018), Alliance for an Energy Efficient Economy (AEEE) (2018), Bashmakov (2016) and World Bank (2021).

consume the same energy in buildings, if they had the same *GDP*. The only exception is Russia, where the cold climate and the poor thermal insulation of buildings (Lychuk et al., 2012) resulted in higher consumption figures for its wealth level (*47* toe/M$).

5.3. Efficiency

Efficiency is postulated as the basic instrument to decouple energy use and economic growth, as it allows energy savings with no detriment to the welfare of buildings occupants (De Rosa et al., 2014). In developed countries, wealth has enabled the spread of efficient but expensive equipment. They have also benefited from electricity access which allows the use of electrical devices, less consuming than those supplied by other sources. Moreover, they can afford buildings designs which lessen heating and cooling demand by implementing energy conservation measures, both for building envelope and mechanical equipment. Hopefully, globalisation is playing an important role in reducing efficiency differences between regions by transferring the latest technological achievements across borders.

Regulatory bodies have three basic instruments to promote energy efficiency in buildings: regulations, auditing and certification. Energy regulations, also referred to as 'building energy codes', set minimum efficiency requirements at component (prescriptive approach) or global levels (performance approach) for the design, construction and retrofitting of buildings (Pérez-Lombard et al., 2011a). Energy auditing are investigations to identify areas with potential retrofit opportunities in existing buildings and propose efficiency measures accordingly (Ma et al., 2012). Finally, certification schemes encompass any procedure (benchmarking, rating and labelling) allowing the comparative determination of the quality of new or existing buildings in terms of their energy use (Pérez-Lombard et al., 2009). These instruments require improved calculation methodologies and the definition of efficiency indicators (Wong et al., 2020). This way, users could better understand their consumption patterns and adopt conservative behaviours, while decision-makers could design more stringent and effective energy policies.

However, measuring energy efficiency in buildings is a complex issue. Energy intensity, defined as the ratio of energy consumption (input) to an activity indicator (output) (Pérez-Lombard et al., 2013), is the most common efficiency metric. Main difficulties for its assessment lie in the suitability and availability of activity data. General purposes of other consuming sectors are clear: industry aims to generate products and wealth, while transport aims to move goods and passengers. Thus, *tonnes of product* or *Gross Value Added*, and *passenger-kilometres* or *ton-km* are proper activity indicators to evaluate industry and transport efficiency, respectively. In contrast, energy is used in buildings to provide different services: comfort, lighting, hot water, cooking, etc. Therefore, the activity indicator should vary among end-uses (Xu and Ang, 2014) and the construction of efficiency indicators requires highly disaggregated data.

Most prevalent activity indicator is building floor area, though it correlates better with space heating and cooling than with other end-uses, such as water heating, equipment or cooking (Belzer, 2014). Thus, urbanisation, in terms of per capita floor area, is a meaningful metric to assess space requirements for living, working, health, education and entertainment. Fig. 11 shows the relation between per capita energy consumption and per capita floor area in buildings for the world and some countries. Constant lines of energy consumption per square metre (referred to as *energy use intensity*) could serve as an efficiency indicator. Countries with the largest per capita floor area (above *50* m^2/cap) correspond to those with higher per capita consumption (above *0.6* toe/cap). On the other side, India has the lowest per capita consumption (*0.13* toe/cap) due to its low urbanisation (*12* m^2/cap). China stands out for its impressive area growth as a result of the continuous shift from rural to urban areas, which leads to lifestyles changes and increases personal living space (Jiang et al., 2018). However, in per capita terms, Chinese lower income keeps consumption low, despite building areas approaching those of developed countries (*45* m^2/cap).

Three different patterns are found among the studied countries: (a) efficiency improvements in most developed nations, which have achieved area growth compatible with consumption drop, thanks to successful energy policies; (b) efficiency improvements with rises in consumption in China, where improved living standards have induced area growth above energy demand; (c) constant efficiency in Spain, where the construction boom and the growth of the economy have boosted the floor area and the energy use at the same pace. Regarding absolute figures, energy use intensity in most developed countries (around *15* koe/m^2) contrasts with that of some emerging nations, such as China (*7* koe/m^2), thanks to energy conservation habits rather than to higher efficiency levels. A higher intensity in India (*11* koe/m^2) is explained by the large occupancy density of their buildings, resulting in a quarter the area and half the consumption of China, for roughly the same population.

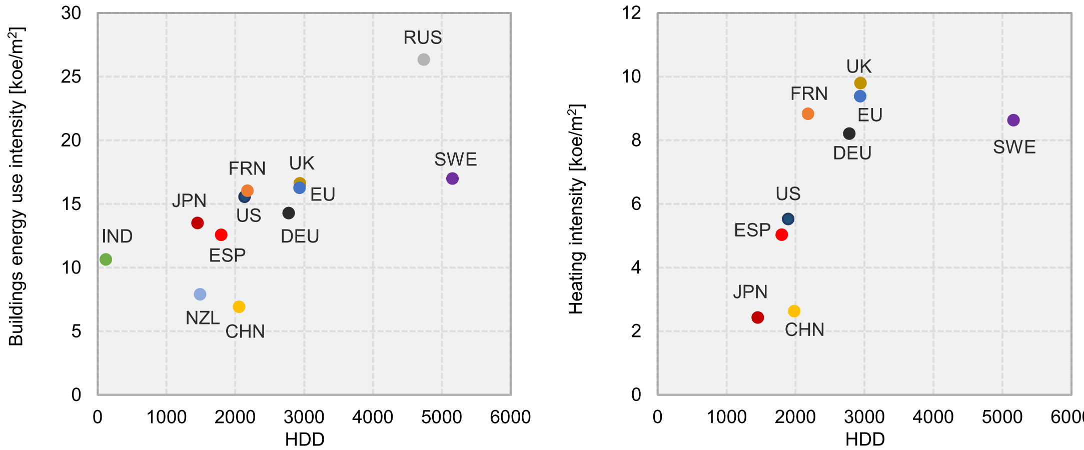

Fig. 12. Buildings energy use intensity (left) and heating energy intensity (right) vs. Heating Degree Days for selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Figures correspond to 2018, except for India (2017) and Russia (2013) (left) and US (2017) and China (2014) (right).
Source: IEA (2021e, 2020), IEA and CMCC (2021), Odyssee (2021), Jiang et al. (2018), Alliance for an Energy Efficient Economy (AEEE) (2018) and Bashmakov (2016).

Note also that 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 climate. The severe climate in the former contrasts with the mild climate in the latter. Similarly, the high Russian energy use intensity is mainly driven by the extremely cold weather surging the demand for space heating, which is above *62%* of buildings consumption (IEA, 2017).

5.4. Climate

Weather is also considered as a key driver for buildings consumption since it obviously affects HVAC and DHW energy demand. Furthermore, other weather dependent conditions, such as daylight, temperature and humidity have a great impact on the use of certain equipment (lamps, refrigerators, dryers, etc.) and on the number of hours indoors.

Heating Degree Days (HDD) are commonly used to correlate energy consumption and climate. They measure the cold weather intensity over a certain period by accounting for the difference between the outdoor temperature and a base temperature, below which heating systems are presumed to turn on. However, discrepancies among datasets are found in the choice of the base temperature, which may vary depending on the inhabitants' tolerance to cold temperatures, building type, building envelope, occupancy density, etc. Moreover, HDD can be corrected to address the potential effects of additional climatic parameters, such as humidity and solar radiation, by using the Heat Index, Humidex or Environmental Stress Index as input parameters (Atalla et al., 2018).

Energy use intensity is plotted vs. HDD for some nations in Fig. 12 (left). Buildings consumption per floor area is clearly higher in colder areas. Swedish low consumption compared to Russian, reflects the priority on high performance envelopes and highly efficient district heating systems in Northern Europe (Berardi, 2017). Again, China stands out for the reduced stock of heating systems and lower comfort levels. However, energy use intensity does not correlate well with HDD, since two-fold differences are found for countries around 2000 degree-days. A better correlation results if only consumption figures for heating purposes are considered Fig. 12 (right). However, it requires HVAC consumption disaggregation, which is not always available. Also, the quality of the correlation highly depends on the uncertainties added by the extended use of non-marketed wood for heating, as well as on the size of the country, which could cluster different climate regions (e.g., US).

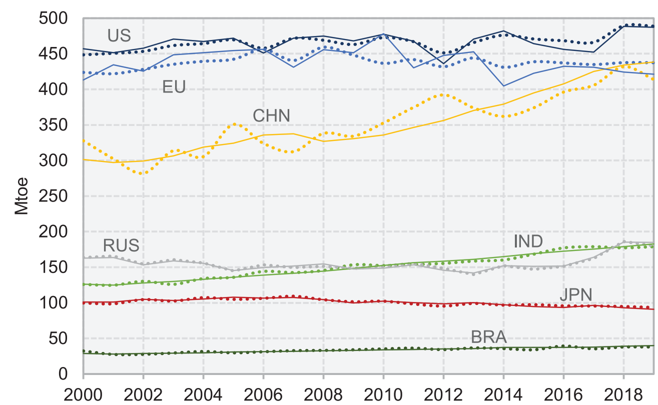

Fig. 13. Weather-adjusted (dashed lines) and real (solid lines) buildings energy use in US, EU, China, India, Japan and Russia.

Climate could also be responsible for short-term fluctuations in energy consumption, as milder-than-usual weather could lessen annual energy demand, while the severity of winter or hot summer seasons could cause occasional consumption peaks. In principle, a better monitoring of energy use in buildings can be achieved if consumption is corrected to neutralise weather effects, commonly assuming a linear regression with heating degree days (Makhmalbaf et al., 2013). Fig. 13 plots trends with and without weather adjustment for the most consuming nations. The method succeeds in removing main annual fluctuations only in US and EU, allowing a better understanding of the evolution of the buildings sector. However, for the rest of the countries, climate is a negligible driver for energy use in buildings, especially in developing nations, where the response to weather variations does not result in increased energy use, but in decreased thermal comfort, as low-income levels restrict energy expenditure. Therefore, there is no reason for climate adjustment in these cases since it could lead to unreal fluctuations (China).

In the long-term, climate change could modify buildings energy patterns, especially for HVAC systems. Energy demand will shift towards cooling (Roberts, 2008) while passive approaches will become less effective due to the temperature rise. This, along with more frequent extreme weather events, such as heat waves (De Wilde and Tian, 2011), could raise energy consumption. Consequently, the related emissions growth could intensify climate change, resulting in a dangerous vicious circle.

5.5. Other Drivers

Other factors also influence energy use in buildings, though they are more difficult to quantify than those analysed above. Some of them are briefly commented below and meaningful references are given to complete the discussion here provided.

The number of buildings (Berrill et al., 2021) can be introduced to decompose urbanisation (m^2/cap), which can be driven by an increase in building size (m^2/build) or by a growing demand for buildings per capita (build/cap). Smaller households or more commercial buildings per capita would lead to higher consumption levels, as their occupants do not share energy-consuming equipment (Bertoldi et al., 2018). US's figures from 2005 to 2015 show that residential urbanisation has decreased to *69* m^2/cap since the average home size has drop to *187* m^2 and the number of dwellings per person has decreased to *0.37* build/cap (average household size of *2.7* people) (U.S. Energy Information Administration (EIA), 2015, 2005). For tertiary sector over the period 2003–2018, urbanisation has risen to *28* m^2/cap due to the increases in buildings per capita (*18* buildings per *1000* citizens) and in the average building size (*1519* m^2) (U.S. Energy Information Administration (EIA), 2003, 2018).

Demography can also be a driver, as ageing population tends to result in more single person households (World Business Council for Sustainable Development, 2008), a minor energy use for entertainment activities and a higher residential energy consumption because they stay more time at home and demand higher comfort levels.

Buildings sector structure, also referred to as building type mix, is also a major driver. Higher shares of most intensive building types would rise sectoral energy consumption. For instance, tertiary buildings in the US are twice more intensive (*25* koe/m^2) than residential ones (*12* koe/m^2), while most intensive non-residential types could double (*47* koe/m^2 for health care) or even triple (*77* koe/m^2 for food services) average figures (U.S. Energy Information Administration (EIA), 2012).

Rises in electricity and fuel prices (Greening et al., 2001) could in principle drive consumption decline. However, rather than preventing energy use, they tend to widen the gap between high and low-income citizens. They may also lead to fuel switching to cheaper energy sources. Policy makers could take advantage of this strategy to promote the use of cleaner sources and reduce related CO_2 emissions.

Lastly, behavioural aspects, lifestyle and socio-cultural habits (Huebner et al., 2015) play an important role in determining the time spent indoors, and consequently equipment usage patterns. Also, they strongly influence choices of cooking and diet (Hager and Morawicki, 2013), as well as equipment stock, which would result in different consumption figures. Individual practices are essential for reducing wasteful behaviours, through a rational use of energy. Low-energy practices, encompassing new technology choices and new behaviours in their uses, could reduce buildings consumption by more than *10%* by 2100 (Levesque et al., 2019). However, these changes are hardly induced by policy measures, except by incentives for the adoption of efficient technologies and time-of-use tariffs. In this respect, Buildings Energy Management Systems (BEMS) could play an important role in two ways. On the one hand, metering would provide users with information to improve buildings' performance and to identify cost-cutting opportunities by detecting inefficiencies, benchmarking and planning load and energy usage (Ahmad et al., 2016). On the other hand, monitoring and control techniques would compensate unconscious occupant behaviours by scheduling controls, system optimisation, occupant detection control, and variable speed control (Cheng and Lee, 2018). In parallel, behavioural changes should be stimulated by increased awareness of energy conservation as a scarce and polluting resource (Wolske et al., 2020; Marghetis et al., 2019), which could be promoted by billing and metering feedback, education and advice.

6. Conclusions

Buildings currently account for a third of global consumption and a quarter of CO_2 emissions. Their significant impact has placed 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, evaluation and monitoring of sound policies requires meaningful information, not only for the whole sector, but also for building types and energy services. To this end, buildings should be treated as an independent sector in energy statistics. Key activity indicators such as floorspace, number of buildings and equipment stock should be collected and reported. Although surveying, metering and modelling fundamentals are well established, the lack of information is hindering the quantification of efficiency and carbon indicators. Further work and international consensus are needed for buildings information standardisation.

As for building types, energy use is commonly split into residential (*72%*) and non-residential (*28%*) buildings. They should be treated both together and separately, as their physical and operational differences require specific policies. Information is lacking, especially for the tertiary sector, due to harder data collection and the variety of their activities. This problem should not be overlooked as it already accounts for about half of buildings consumption in developed nations and is expanding impressively in emerging countries.

Regarding buildings services, HVAC systems have become almost essential in parallel with the spread of the demand for thermal comfort. They are the most consuming end-use worldwide, accounting for *38%* of buildings consumption, thus meaning about *12%* of global final energy. Consequently, incentives and standards should promote energy-efficient HVAC retrofitting, which will otherwise be delayed due to their long lifetime.

Population, urbanisation and wealth put pressure on buildings consumption, which has risen by *1.2%/yr* since 2000. Population boosts energy use, especially in emerging economies, due to their rising per capita consumption and access to electricity. Urbanisation grows dramatically in developing countries due to shifts from rural to urban areas and lifestyle changes. Higher affluence allows for better comfort levels, higher penetration of equipment and larger living and leisure floorspace.

Consumption growth has been mainly supplied by electricity and natural gas, accounting for *55%* of energy use. Electricity has already replaced biomass as the main energy source, mainly due to the increased accessibility in the developing region, the expansion of cooling demand and heat pumps for heating, and the growing market for electrical equipment, such as small appliances and electronics. However, in 2019, electricity only represented a third of the final energy consumption in buildings, and great efforts would be necessary for full electrification.

Energy use intensity is the principal efficiency indicator for buildings, whereas it is only available for the few countries where energy use and floor area information are collected. In developed countries, more efficient buildings and equipment, and the saturation of energy services, have allowed significant reductions in energy intensity to roughly *15* koe/m^2.

Reducing energy use in buildings will not be possible unless global cooperation enables developing nations to break the link between economic growth, urbanisation and consumption. Customised development approaches are needed for these nations to reduce the existing gap in terms of income, floor area and energy use per capita. Technicians and politicians must work together to implement and stimulate efficiency improvement and on-site renewable promotion as key demand-side instruments. Despite assuming that buildings could be fully electrified once the power grid is ready to satisfy their demand, the world should not solely rely on supply-side electricity decarbonisation in the short term for climate change mitigation. Moreover, buildings embodied energy and other GHG emissions cannot be disregarded due to their significant environmental impact. The synergistic effect among construction and buildings sectors is an important challenge to be addressed.

In summary, efficiency improvement and decarbonisation will hardly be able to reduce emissions to safe levels unless global awareness of energy as a scarce and polluting commodity drives real conservation habits. Buildings are constructed to serve human beings, so the quantity and quality of the service demanded is largely in our hands. It is time to move from words to actions.

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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