Doctoral Thesis
Energy, Chemical and Environmental Engineering

Methodology for analysing CO_2 emissions due to energy use: Pyramid approaches for activity, intensity and carbon drivers.

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A mi familia, amigos y Guille, quienes me han acompañado en esta etapa y han sido mi apoyo y fuente de energía.

A mi tutor, Luis, quien, además de indicarme el camino, me ha enseñado a disfrutarlo.

ABSTRACT

Global concern about climate change and environmental sustainability has become widespread, together with the awareness of holding the world temperature increase below 1.5ºC. However, the continued growth of energy use and energy-related CO_2 emissions remains an unsolved problem. Effective mitigation measures will only be possible if the drivers of emissions are analysed in depth in order to define future sustainable development pathways and improve governance in this area. This requires a thorough analysis of the impact of energy use on the environment at all stages of the energy chain. This thesis proposes three different approaches to this aim. First, the driving forces that make emissions change are assessed by the definition of an *Emissions Indicators Pyramid* that examines the energy system from a global perspective. Secondly, the focus moves to the *supply side* to analyse the effect of the energy sector on the overall efficiency. Finally, the demand-side approach focuses on the *final services in buildings*, which are examined to define and quantify main activity and efficiency drivers of consumption changes. The thesis is framed within a research line that could be called *Global energy analysis and diagnosis*, which studies the energy system, and identifies the causes of the problem by examining its stages and links to shed light on how to mitigate its impact.

RESUMEN

A pesar de que la preocupación por el cambio climático, la sostenibilidad medioambiental y la necesidad mantener el aumento de la temperatura global por debajo de 1.5ºC se han extendido en los últimos años, el continuo crecimiento del uso de la energía y de sus emisiones de CO_2 sigue siendo un problema sin resolver. La adopción de medidas de mitigación eficaces solo será posible si se analizan en profundidad los factores que impulsan las emisiones para definir futuras vías de desarrollo sostenible y mejorar la gobernanza en este campo. Para ello, es necesario analizar a fondo el impacto del uso de la energía en el medio ambiente en todos los eslabones de la cadena energética. Esta tesis propone tres enfoques diferentes para alcanzar este objetivo. En primer lugar, se evalúan los factores que hacen cambiar las emisiones mediante la definición de una *pirámide de indicadores de emisiones* que examina el sistema energético desde su perspectiva más global. En segundo lugar, el enfoque se traslada al lado de la oferta para analizar los efectos del sistema de producción de energía sobre la eficiencia. Por último, el análisis del lado de la demanda se centra en los edificios. El examen profundo de los servicios energéticos resulta imprescindible para definir y cuantificar los principales impulsores de la actividad y la eficiencia en este sector. La tesis se enmarca dentro de una línea de investigación que podría denominarse *Análisis y diagnóstico energético global*, que toma el sistema energético como un todo, y, a través del examen individual de sus componentes, identifica las causas del problema para arrojar luz sobre cómo mitigar su impacto.

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NOMENCLATURE

A	Floor area
a	Building size
A_s	Area of buildings subsector (tertiary or residential)
b	Buildings per capita
B	Number of buildings
BF	Backward flow
c	Climatic effect
CCS	Carbon Capture and Storage
CHN	China
c_s	Climatic factor of the energy consumption of the buildings subsector (tertiary or residential)
DCO	Direct carry over
e	Energy intensity
E	Energy consumption
E_B	Buildings energy consumption
e_B	Energy intensity of buildings (energy use intensity)
E_{Bc}	Weather corrected buildings energy consumption
e_{Bc}	Weather corrected energy use intensity
E_{Bcs}	Weather corrected energy consumption of buildings subsector (tertiary or residential)
e_{Bcs}	Weather corrected energy intensity of buildings subsector (tertiary or residential)
E_{Bs}	Actual energy consumption of buildings subsector (tertiary or residential)
E_F	Final energy
e_F	Final energy intensity
EHP	Electricity, Heat and combined heat and power Plants
E_I	Final energy consumption in industry
E_O	Final energy consumption in other sectors
E_P	Primary energy
$E_{P,fos}$	Primary energy consumption of fossil fuels
E_T	Final energy consumption in transport
e_T	Primary energy intensity of transformation T to GDP
e_{Tf}	Primary energy intensity of transformation T and fuel f to GDP
EU	European Union
F	CO_2 emissions
f	Carbon intensity
F_{CD}	Emissions from conversion devices
F_{CP}	Emissions from conversion plants

F_D	Emissions from distribution
F_{DEM}	Emissions from demand side
F_{ET}	Emissions from extraction and treatment
F_{PS}	Emissions from passive systems
F_{SUP}	Emissions from supply side
f_{fos}	Carbon intensity of fossil fuels
g	Wealth, Gross Domestic Product per capita
GDP, G	Gross Domestic Product
h	Carbon intensity of GDP
HDD	Heating Degree Days
HVAC	Heating Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
KI	Kaya Identity
L	Losses
L_{CD}	Energy losses from conversion devices
L_{CP}	Energy losses from conversion plants
L_D	Energy losses from distribution
L_{DEM}	Energy losses from demand side
L_{ET}	Energy losses from extraction and treatment
L_{PS}	Energy losses from passive systems
L_{SUP}	Energy losses from supply side
LMDI	Logarithmic Mean Divisia Index
OECD	Organisation for Economic
OT	Other transformations, including gas works, coal transformations, liquefication plants and others
OU	Energy industry own use
P	Population
PEF	Primary Energy Factor
PEF_T	Primary Energy Factor of transformation T
PEF_{Tf}	Primary Energy Factor of transformation T
REF	Oil refineries
s_{fos}	Share of fossil fuels in primary consumption
SPS	Stated Policies Scenario
s_s	Share of buildings subsector (tertiary or residential) in the total floor area
s_T	Structure of final energy by transformation type T
s_{Tf}	Structure of final energy by transformation type T and fuel f
u	Urbanisation, per capita floor area
US	United States

1. INTRODUCTION

This opening chapter aims to introduce the reader to this dissertation. It begins with the background and context that provide the framework for its motivation. Secondly, it sets out the objectives guiding the research and the questions it aims to address. It also discusses the scope, limitations and main assumptions made. Finally, the contents are summarised as a guide to the analysis of the main findings and contributions.

1.1. Motivation

Global concern about climate change and environmental sustainability has become widespread, together with the awareness of holding the world temperature increase below 1.5ºC [1]. However, the continued growth of energy use and energy-related CO_2 emissions remains an unsolved problem, despite the implementation of efficiency and decarbonisation policies worldwide [2]. It seems clear that humanity is conscious of the serious environmental problem but is not providing the necessary means for its mitigation. Actions must be taken before the problem becomes an emergency, so urgent treatment is required to avoid irreversible damage [3].

Effective mitigation measures will only be possible if the drivers of emissions are analysed in depth in order to define future sustainable development pathways and improve governance in this area [4,5]. This requires a comprehensive analysis of the impact of energy use on the environment.

The global energy chain (Fig. 1) shows the map of the whole energy system [6]. Energy resources, also referred to as primary energy products (E_P), are extracted from nature and treated to be directly distributed to final sectors (Direct Carry Over, DCO) or transformed in *conversion plants*. After the distribution, the so-called final energy products (E_F) turn into different useful energy forms (E_U), mainly heat and motion, through *conversion devices*. Finally, useful energy is converted into final services within passive systems [7,8]. Then, the demand for energy services is met through a process that must be continuously adjusted to avoid supply difficulties, geopolitical stress and economic harms. Additionally, the energy chain has a threefold impact on the environment: the depletion of natural resources at the beginning of the sequence (*source exhaustion*), the energy degradation (*L, losses*) throughout the chain (*thermal pollution*) and gas emissions (mainly CO_2, *F*) derived from the extraction, conversion and transportation of energy (*greenhouse effect*). The last two effects contribute to the world energy imbalance and are raising the temperature at local or global level [9].

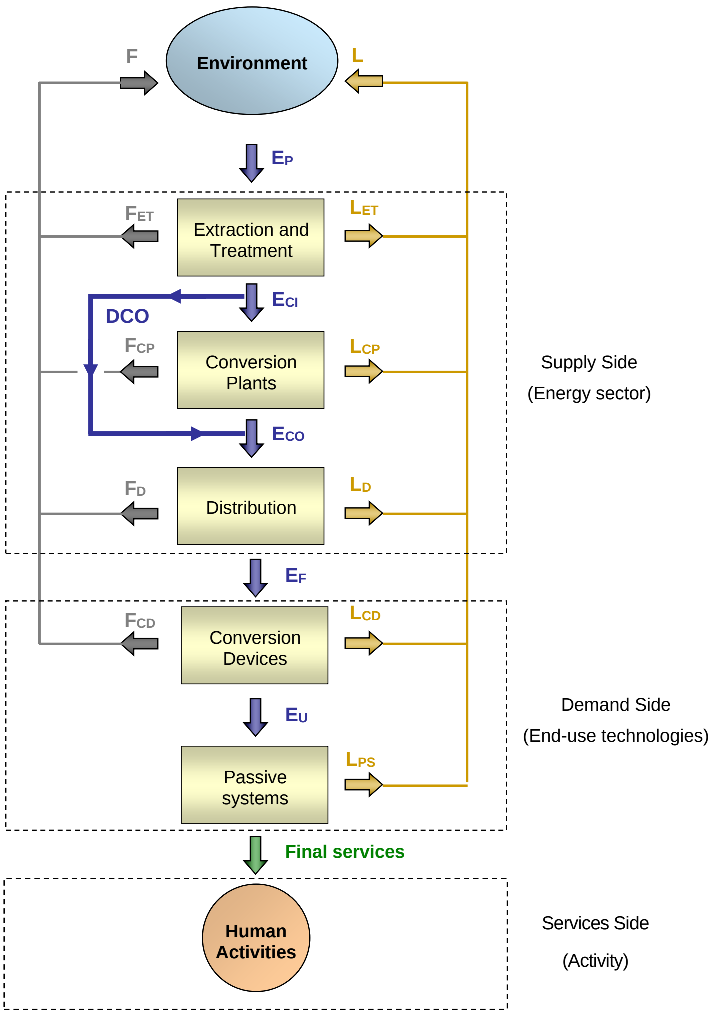

Fig. 1: Schematic of the global energy system. Emissions (*F*), energy products (*E*) and energy losses (*L*) are shown for each stage: extraction and treatment (ET), conversion plants (CP), distribution (D), conversion devices (CD) and passive systems (PS).

To reduce these impacts, it is necessary to analyse in depth all the links in the energy chain, in a research line that could be referred to as *Global Energy Analysis Diagnosis*. This holistic approach can be assessed using different versions of the Kaya Identity with the help of decomposition analysis. Furthermore, from the bottom to the top of the energy chain, three distinct blocks can be distinguished: *services*, *demand* and *supply sides*. They are briefly outlined below, in order to frame the research topics within the research line, justify its interest and highlight its main research questions.

Services-side focus

Human activity is primarily responsible for the planet's energy demand. Energy is an indispensable resource in our lives, to the extent that per capita consumption is used as an indicator of development level. Our way of life continuously requires final services (movement of people and goods, manufacture of products, comfortable buildings, etc.) which consume enormous amounts of energy. In addition, population and economic growth aggravates the situation, imposing additional pressure on the energy chain.

Human beings are responsible for the environmental crisis, so it is essential to examine the reasons why more and better services are constantly demanded, why the superfluous becomes convenient, the convenient becomes necessary and the necessary becomes essential [10]. An initial examination of this side of the energy chain raises the following questions:

- What drives the growth of final services?
- What activity indicators could explain the evolution of services?
- Which magnitudes should be measured to construct sound activity indicators?
- Can or should energy policy set thresholds for final services?

In particular, buildings are a consuming sector where energy services can be easily identified and where energy demand is largely dependent on human needs and behaviour. Citizens want spacious, hygienic, comfortable, well-equipped and illuminated buildings, but to what extent is this demand sustainable? How much floor space does a person need? What temperature range and what levels of ventilation are needed to ensure thermal comfort and indoor air quality? How much volume do we need to preserve our food? In summary, what activities and services drive the demand of energy in buildings?

Thus, the so-called *services-side transition* is concerned with behavioural and lifestyle changes to reduce the demand for more and better energy services. Its ultimate goal should be energy *sufficiency* (also called conservation), the reduction of energy consumption due to the decrease in the quantity or quality of the service provided [11].

Demand side focus

The demand side of the energy chain consumes energy products to provide energy services. This process is normally carried out in two steps. First, conversion devices (also referred to as energy using products) transform the final energy into useful energy (mainly thermal or mechanical). Secondly, in passive systems the useful energy is degraded to provide the final services.

Consequently, demand-side energy savings can be achieved by improving efficiency of conversion devices by lowering *Final Energy Factor* ($FEF = E_F / E_U$), but also by improving passive systems to provide the same service with less energy use. Taking heating systems as an example, it is not sufficient to use a heat pump instead of a boiler for its higher efficiency, but buildings envelopes should be designed to ensure thermal comfort with less useful energy demand.

In summary, *demand-side transition* should aim at increasing the efficiency of useful energy (improvement of *passive systems*) and of final energy (improvement of *active systems*). Focusing on the building sector, the following research questions arise:

- What passive systems are present in buildings?
- How and where can useful energy be accounted for?
- Should useful energy demand of passive systems be limited?
- What measures should be taken to reduce *FEF*?

Supply side focus

The energy sector transforms natural resources into energy products. Lately, the reduction in the use of non-marketed biomass, the increase of electrification and the development of renewable sources have substantially modified the efficiency of energy production and its inverse, the *Primary Energy Factor* ($PEF = E_P / E_F$).

On the one hand, electrification implies a reduction in primary efficiency (increase in *PEF*), compared to the direct use of fossil fuels without transformation. On the other, the development of non-combustible renewables reduces emissions and raises efficiency, if the direct equivalent approach ($PEF = 1$) is assumed in primary energy accounting of hydro, wind and solar PV [12].

Consequently, *supply-side transition* is now subject to the pressure imposed by development and decarbonisation (from fossil fuels to biofuels and from black to green electricity). It is essential to analyse the impact that fuel mix and transformation types have on the efficiency of the energy system, to assess supply-side contributions to the improvement of overall efficiency and the reduction of carbon intensity ($f = F / E_P$). Key research questions for the supply side are the following:

- How and at what pace should the fuel mix evolve to reduce emissions?
- Is defossilization compatible with economic growth in non-developed nations?
- Should nuclear energy and natural gas be used as "bridge fuels" for energy transition?
- How do changes in supply side impact on energy efficiency and carbon intensity?
- Which indicators are required for cross-country comparisons of supply-side transition?

1.2. Research topics: Gaps and objectives

The research topics of this thesis are set out below, based on the framework outlined in the previous section. For each topic, the gaps to be filled and the research goals are highlighted. Scope and limitations for each topic are also noted.

First, the impact of energy use on CO_2 emissions is analysed. This global approach aims to quantify the driving forces that make emissions change by the definition of an *Emissions Indicators Pyramid*. Secondly, the focus moves to the supply side to analyse the effect of the energy sector on the overall efficiency. This research topic aims to assess the impact of structural effects, mainly transformation type and fuel mix, on the *energy sector efficiency*. Finally, on the base of the energy chain, *final services in buildings* are examined to define and quantify main activity and efficiency drivers of consumption changes in this sector.

1.2.1. Drivers of energy-related emissions

Since energy-related CO_2 emissions are the most important source of the anthropogenic global warming [13], the first research topic aims to analyse the driving forces of consumption and emissions to provide effective means for its mitigation. To this end, the global energy chain can be condensed into two major blocks: supply and demand side (Fig. 2). Moreover, human activity is usually quantified in a first proxy by the Gross Domestic Product (G) that comprises demographic (P) and wealth (g) effects ($G = P \cdot g$).

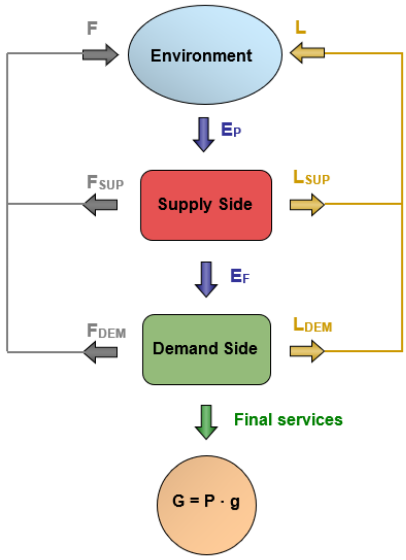

Fig. 2: Condensed version of the global energy chain. L_{SUP} and F_{SUP} are the energy losses and the emissions of the supply side and L_{DEM} and F_{DEM} are the energy losses and the emissions of the demand side, respectively.

The separate effects of supply and demand sides on the overall efficiency can be assessed by the decomposition of the energy intensity (e):

$$e = \frac{E_P}{G} = \frac{E_P}{E_F} \cdot \frac{E_F}{G} = PEF \cdot e_F \qquad \text{(Eq. 1)}$$

where PEF (Primary Energy Factor) is the inverse of the efficiency in the energy sector, supply side, and e_F (final energy intensity) is the inverse of the efficiency in in the end-use technologies, demand side.

Similarly, to separate emissive and non-emissive fuels, the carbon intensity (f) can be decomposed as:

$$f = \frac{F}{E_P} = \frac{E_{P,fos}}{E_F} \cdot \frac{F}{E_{P,fos}} = s_{fos} \cdot f_{fos} \qquad \text{(Eq. 2)}$$

where $E_{P,fos}$ is the primary energy supply of fossil fuels, s_{fos} is the fossil share in primary energy and f_{fos} is their carbon intensity.

This way, an extended version of the Kaya Identity for emissions evaluation is proposed:

$$F = P \cdot g \cdot PEF \cdot e_F \cdot s_{fos} \cdot f_{fos} \qquad \text{(Eq. 3)}$$

The novelty and interest of this decomposition lies in its adequacy to separate both the effects of production and consumption efficiencies, as well as the impact of defossilization[1] and fossil fuel carbon intensity.

This approach led to the revision of the Kaya Identity framework for classifying indicators and decomposition studies in the literature. In absence of methodological consensus on emissions analyses, a pyramid approach is proposed to set a hierarchy of indicators, which could serve as a guide for analysis standardisation and comparison. The application of the proposed *emissions indicators pyramid* to developed (OECD) and developing (non-OECD) regions is the first research goal of this dissertation since it should help to examine regional transitions for a sustainable future and their policy implications.

[1] Note that s_{fos} drops explain shifts towards non-emissive fuels and renewable penetration, once the nuclear share is discounted.

1.2.2. Energy efficiency drivers of the energy sector

The results of the first research topic led to the conclusion that, unfortunately, emissions peak has not been already reached, despite significant improvement of final energy intensity. However, efficiency in the energy sector is decreasing in developing nations due to higher electrification levels and lower use of direct energy forms, while being roughly constant in the OECD region despite decarbonization policies and renewables promotion. Thus, the focus is moved to the supply side to explain changes in *PEF* due to transformation and fuel types and assess to what extent efficiency in the production of energy could be improved. To this aim, the supply side of the energy chain is expanded to show the different paths from primary to final energy (Fig. 3).

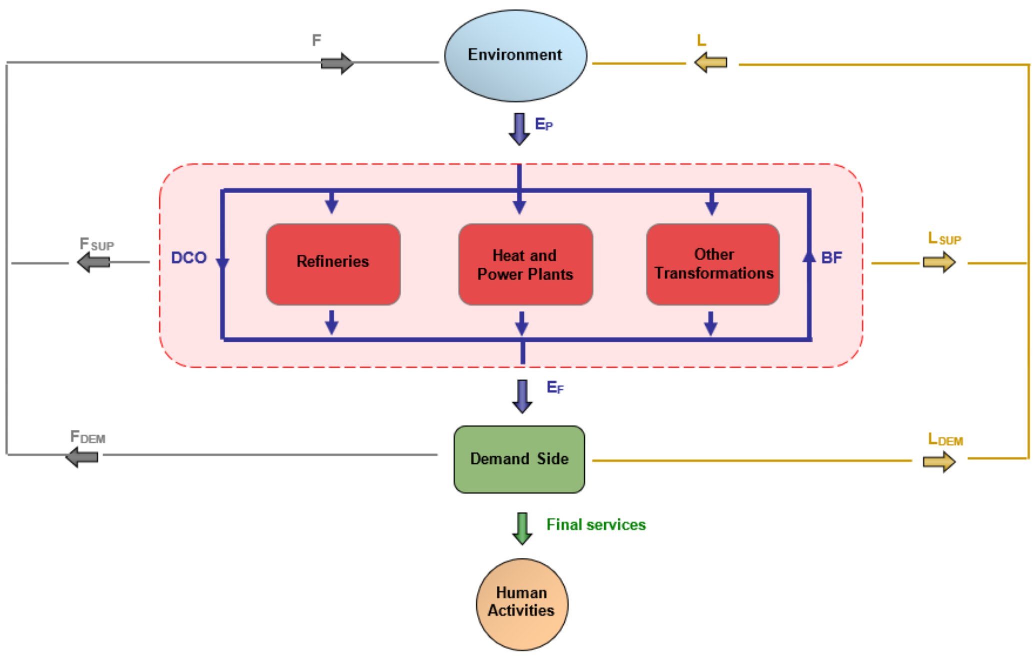

Fig. 3: Supply-side extension for the global energy chain.

Losses on the supply side (L_{SUP}) are mainly due to extraction and treatment of natural resources, transformation losses in conversion plants, distribution losses and energy sector own use, that is energy products that are consumed for energy generation. Direct Carry Over (DCO) refers to those products that suffer no conversion (natural gas, biomass, etc.) and Backward Flow (BF) indicates final products that go upstream to be used as other transformation inputs.

However, energy sector structure is not only shaped by transformation types but also by the fuel mix, that is strongly dependent on fuel availability and prices, economic and technological development, geopolitical conflicts and the access to renewable sources. Consequently, the analysis of the efficiency of the energy sector is a complex problem that involves both transformation and fuel types.

The review of the literature on energy efficiency analysis has revealed the lack of a methodology to disentangle structural changes on the supply side. The impact on *PEF* of converted or directly used energy commodities is commonly disguised, and so are the effects of different transformation types and energy sources. Additionally, there is no exhaustive comparative analysis of changes in efficiency for the main consuming nations.

Thus, the analysis of energy efficiency drivers for the energy sector is the second research goal for this thesis. A progressive extension of the emissions pyramid is proposed by decomposing energy intensity to explain structural effects as energy transformation and fuel types. This topic could also contribute to better understanding of supply side transition and their policy implications. Additionally, a cross-country comparison on energy efficiency drivers for the most consuming and emitting nations in the world could also provide relevant insights of their energy systems.

1.2.3. Activity drivers of energy use in buildings

The demand-side structure (Fig. 4) is mainly shaped by the consuming sectors: industry, transport, buildings and others, which clusters minor activities such as agriculture, forestry and fishing. Despite energy use in every sector is increasing globally, buildings are the most consuming, currently accounting 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 energy efficiency improvement and on-site renewable generation [14].

In recent decades, energy regulation on this field has been tightened by setting efficiency requirements on conversion devices within buildings and by limiting the energy demand of building envelopes, the passive systems that provide the comfort service. In some developed nations, buildings are even required to have nearly-zero energy consumption through the integration of on-site renewables, mainly solar thermal and photovoltaics [15].

Many countries have implemented buildings energy certification programmes to improve efficiency, minimise consumption and inform occupants about their energy use [16]. Today, most of the conversion devices in buildings are subject to product policies such as minimum energy performance requirements or energy labelling schemes, at least in developed nations [17]. However, efforts to improve the efficiency of this sector seem insufficient, as its energy consumption has grown globally at an average rate of 1.2 %/yr over the last 20 years [18].

A growing population with higher incomes demands more and better services in buildings. Increasing affluence allows for higher comfort and equipment levels and more living and leisure space. In addition, changes in lifestyles increase the amount of time spent inside buildings for work, education, business, health and leisure activities. Therefore, it seems clear that researchers and policy makers must pay additional attention to the services side to combine efficiency in consuming energy with sufficiency in their demand.

Human activity in buildings and its corresponding energy use can only be analysed and monitored if reliable information is collected, not only in terms of energy data, but also in terms of stock description (floor area, building type, number of buildings, occupation and equipment level, etc.). In the last decade, many international and national organisations have made efforts for activity data collection, but this new valuable information has not been sufficiently analysed in the literature and there are still remarkable limitations.

Consequently, as a third research topic, final services in buildings are examined to explain main activity and efficiency drivers of consumption changes, to reveal data collection requirements to enable proper monitoring of the services side transition in buildings. A third pyramid approach is proposed to progressively decompose energy use in buildings and explain the impact of those activity drivers for which information is available. A detailed discussion of results is provided for China, the European Union (EU) and the United States (US), which account for about half of the global buildings' consumption.

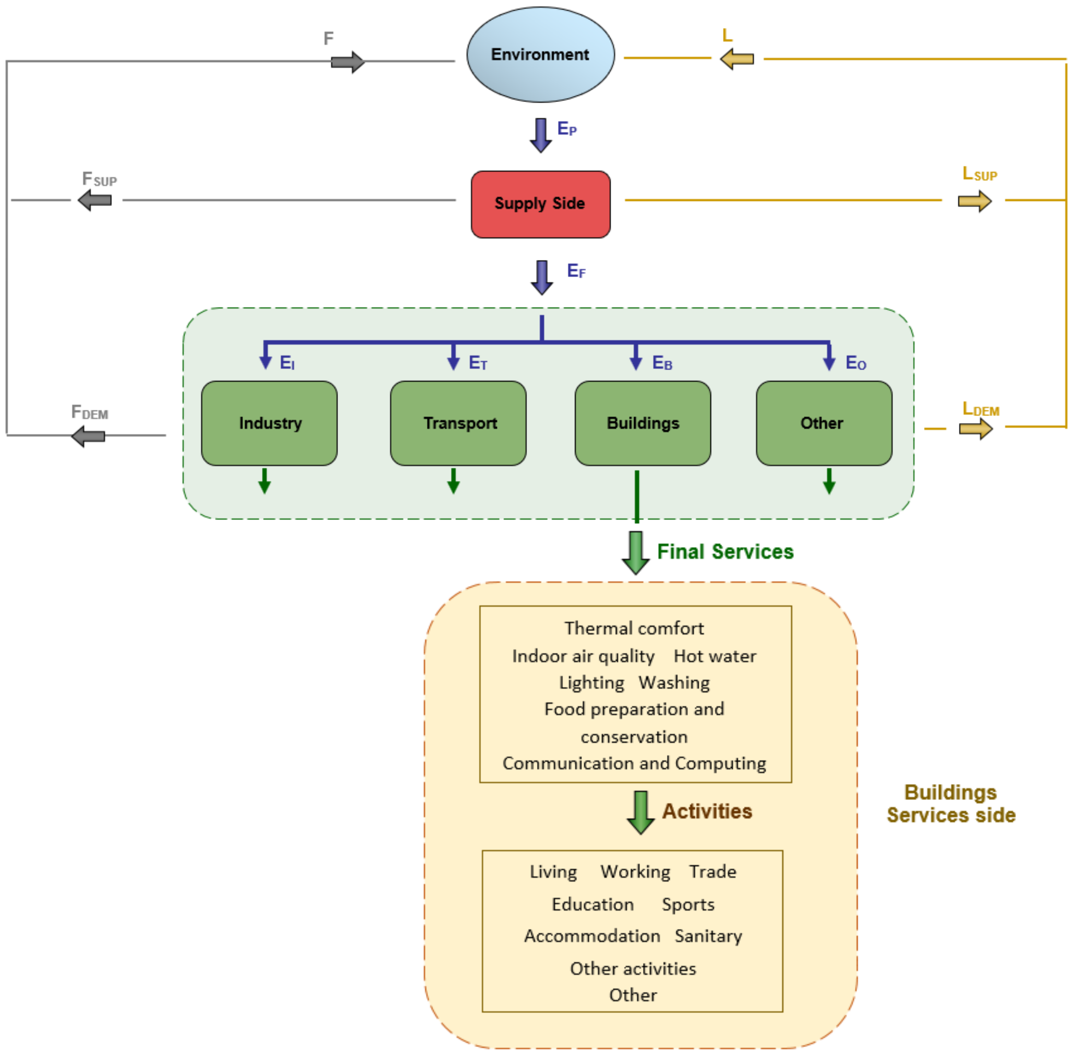

Fig. 4: Services-side extension for the buildings sector. E_I, E_T, E_B and E_O are the final energy consumption in industry, transport, buildings and others, respectively.

1.3. Contents

The contents of this document are in line with the stated objectives. Section 2 summarises the main contributions, results and discussion of the research papers comprising this thesis by compendium of publications.

First, section 2.1 addresses the drivers of the energy-related CO_2 emissions from the broader perspective of the global energy chain. An *emissions indicators pyramid* is proposed to set a hierarchy of indicators and the approach is applied to developed (OECD) and developing (non-OECD) countries to understand regional transitions for a sustainable future and their policy implications.

In chapter 2.2, the focus is placed on the supply side of the energy system to explain changes in its efficiency. A second pyramid is presented as an extension of the emissions pyramid to progressively decompose energy intensity to explain structural effects of transformation processes and fuel types. Its application to most consuming nations provides a cross-country comparison on energy efficiency drivers, as well as relevant insights of their energy systems that could contribute to better understanding of supply side transition.

Chapter 2.3 focuses on the demand side and final energy services. Particularly, on the buildings sector for being the most consuming, currently accounting for a third of global consumption and a quarter of CO_2 emissions. Thus, a third pyramid is proposed to examine their energy use, explain main activity and efficiency drivers of consumption changes and reveal data collection requirements to enable proper monitoring. A detailed discussion of results is provided for China, the EU and the US, which account for about half of the global buildings' consumption.

Finally, main conclusions of research topics are summarized in section 3, as well as future developments along the research line.

In addition, the scientific papers composing this thesis by compendium of publications are included in the Annexes. The publication in Annex A corresponds to the first research topic, which addresses the global approach to the drivers of energy-related emissions; Annex B contains the research paper on the impact of the supply side on energy efficiency (topic II); and Annex C groups the publications related to the buildings sector (topic III).

2. MAIN RESULTS AND DISCUSSION

This chapter devotes a section to each of the research topics outlined in the introduction. For each section, the main contributions are highlighted, the methodological approach is presented and the main results are discussed. For more details, see the corresponding articles in Annex B.

2.1. Global focus – Drivers of energy-related emissions

2.1.1. Introduction

Measures to mitigate climate change will not be effective without gaining deep insights into emissions changes [4,5]. In this respect, in 1990, as an application of the previous IPAT equation [19], the Kaya Identity (KI) [20] identified four underlying factors for CO_2 emissions (F): population (P), wealth (g), energy intensity (e) and carbon intensity (f):

$$F = P \cdot \frac{G}{P} \cdot \frac{E}{G} \cdot \frac{F}{E} = P \cdot g \cdot e \cdot f \quad \text{(Eq. 4)}$$

where G is Gross Domestic Product (GDP) and E is energy consumption.

In the Kaya Identity, population and wealth are activity drivers which aim to measure the demand of energy services. Energy intensity indicates efficiency, so it addresses the impact of technology in the global energy chain and could counteract increments in activity by reducing the energy needed to provide the unit of service. Finally, carbon intensity sets a relation between emissions and energy to assess the effect of energy sources. Thus, the reduction of any of these indicators could curb emissions growth.

The Kaya Identity has become a standard in the research field. Nevertheless, the disaggregation of the CO_2 emissions into drivers is not unique, as the factors in the KI may be also decomposed or combined to define additional indicators. The decomposition of the factors would provide further insights by exploring aspects which are hidden in the original identity. However, the disaggregation is not always possible or convenient due to the data unavailability and their harder collection requirements. In contrast, simplified versions of the KI combine factors to allow for a basic assessment of the emissions drivers, to outline the global context or to highlight some effects. The choices of the aggregation level and of the indicators to analyse depend on the purpose of the study.

2.1.2. Contributions to the state-of-the-art

The literature review of the studies that apply the KI, either in its original, simplified or extended form, has revealed that the lack of a standard nomenclature and a vague definition of indicators leads to confusion and inconsistency. Moreover, despite many researchers have disaggregated the indicators of the KI to analyse further aspects, the effects of the different sides of the energy system (supply and demand) have not been isolated, although they require separate treatment for the definition of sound specific policies. As for their application, detailed decomposition analyses have been only found at national level, so global and regional trends are still to be broken down.

Consequently, this chapter aims to present a methodology to define and quantify the emissions drivers that comprehensively explain how the energy system impacts on the environment. Its main contributions to the state-of-the-art are:

- The proposal of a pyramid approach that sets a hierarchy of emissions drivers, allowing conclusions to be drawn in a stepwise manner, rather than focusing on a single decomposition.
- The novel extension of the KI to deeply analyse efficiency and carbon drivers, separating the impacts of the supply – demand sides and of the fossil – green energy sources.
- The illustration of the methodology on global figures and on the developed (OECD) and developing (non-OECD) regions, due to the lack of detailed decompositions in the literature targeting this geographical coverage.
- The application of the methodology to past (1990-2019) and future (2019-2040) trends, to explain the reasons for emissions changes and identify the future actions targeting each of the drivers.
- The comparison between the stated policies scenario from the International Energy Agency [21] and the IPCC mitigation pathways [22,23] in terms of the proposed indicators, to demonstrate their interest in unravelling policies implications and shedding light on future actions towards sustainability.

2.1.3. Methodology

This section is embargoed so as not to conflict with the terms and conditions of access of the scientific article in which its content has been published [24].

The publication can be accessed by following the link:
https://www.sciencedirect.com/science/article/abs/pii/S0959652621025427.

2.1.4. Main results and discussion

This section is embargoed so as not to conflict with the terms and conditions of access of the scientific article in which its content has been published [24].

The publication can be accessed by following the link:
https://www.sciencedirect.com/science/article/abs/pii/S0959652621025427.

2.1.5. Scientific publications for the dissemination of the results

The results and discussion summarised in this chapter are published as a research paper whose characteristics and metrics are gathered in Table 1.

Table 1: Publications related to the research topic I.

Research paper	
Title	Revisiting Kaya Identity to define an Emissions Indicators Pyramid
Authors	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre
DOI	https://doi.org/10.1016/j.jclepro.2021.128328
Journal	Journal of Cleaner Production
Reference	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, Revisiting Kaya Identity to define an Emissions Indicators Pyramid, J. Clean. Prod. 317 (2021) 128328.
Metrics	
Indexing database	Web of Science/Journal Citation Reports
Journal Impact Factor	11.072
Year	2021
Category	ENVIRONMENTAL SCIENCES
Rank	24/279
Quartile	1
Citations	7 (Google scholar) / 4 (Scopus / Web of Science)

2.2. Supply side focus – Efficiency drivers of energy production

2.2.1. Introduction

Within the drivers introduced and analysed in the previous chapter, the energy intensity is of special interest, since it has been the main mitigating factor for past CO_2 emissions. Energy efficiency measures have been proved as feasible and effective worldwide, so they should remain as a keystone in the definition of future pathways to sustainable development. However, the energy intensity is subject to underlying structural effects that may be further decomposed.

A simplified scheme of the energy system (Fig. 5) shows the main energy flows and processes between energy resources and final services and allows its split in demand and supply sides. On the left side, the *energy sector* or *supply side*, involves the extraction of primary resources (Primary Energy, E_P) to be transformed into energy products, either through conversion plants or directly carried over (DCO), and subsequently distributed to final users (Final Energy, E_F). Within the supply side, energy can be lost as it is own used by the energy sector (OU) for heating, pumping, traction and other purposes, or degraded in conversion plants and distribution lines as transformation (L_{CP}) and distribution losses (L_D), respectively. On the right, the *demand side* concerns the consumption of final energy in the consuming sectors through end-use technologies where it is degraded for the provision of final services. Thus, the energy intensity clusters the performances of supply and demand sides of the energy system.

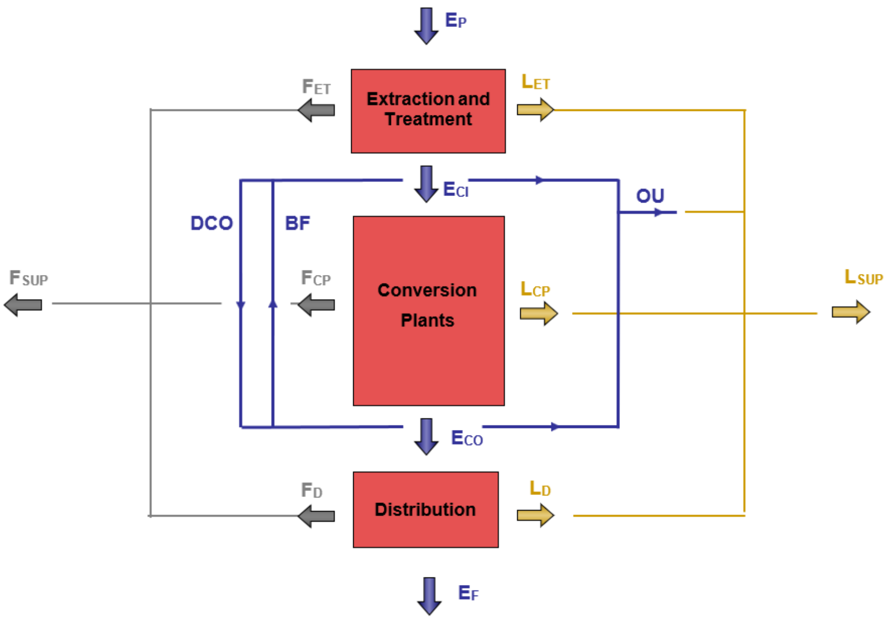

Fig. 5: Simplified scheme of the energy sector.

As studied before, the energy intensity can be decomposed to separately analyse the performances of the demand and supply sides of the energy system, by the introduction of two additional efficiency indicators: final energy intensity ($e_F = E_F/G$) and Primary Energy Factor ($PEF = E_P/E_F$), respectively.

$$e = e_F \cdot PEF \qquad \text{(Eq. 5)}$$

The efficiency of the supply and demand sides are both aggregated variables, meaning that they can be expressed as the sum of sub-categories. In addition to technology improvements, structural shifts among sub-categories contribute to changes in the energy efficiency and should be analysed as additional driving forces. The supply side structure is shaped by the transformation processes and fuel types. In this chapter, both structures are analysed to fill the gaps in the literature and to propose answers to the subsequent research questions.

2.2.2. Contributions to the state-of-the-art

Despite efficiency has been disaggregated into drivers in the literature to different extents, there is not any comprehensive description of the energy system and its hierarchical decomposition. The efficiency of supply side of the energy system (*PEF*) has hardly been analysed. The impact on the efficiency of converted or directly carried over energy commodities is disguised, and so are the effects of different transformations and fuel types. Additionally, there is no exhaustive comparative analysis of the changes in the efficiency of the main consuming nations.

Consequently, the contributions of this chapter to the state-of-the-art are:

- The proposal of a novel methodological framework based on an energy intensity pyramid for its decomposition in structural and efficiency indicators.
- The focus on the supply side of the energy system, to progressively decompose the Primary Energy Factor by transformation and fuel type.
- The application of the methodology to the six most consuming [25] and emitting [26] nations in the world (US, EU, China, India, Japan and Russia), to provide relevant insights of their energy systems for the adjustment of national energy policies through the discussion of past

trends and changes in intensity drivers.

Despite its interest, the methodology cannot be applied to future trends, as the data requirements for its assessment are too demanding and not available.

2.2.3. Methodology

This section is embargoed so as not to conflict with the terms and conditions of access of the scientific article in which its content has been published [27].

The publication can be accessed by following the link:
https://www.sciencedirect.com/science/article/abs/pii/S0306261921002105.

2.2.4. Main results and discussion

This section is embargoed so as not to conflict with the terms and conditions of access of the scientific article in which its content has been published [27].

The publication can be accessed by following the link:
https://www.sciencedirect.com/science/article/abs/pii/S0306261921002105.

2.2.5. Scientific publications for the dissemination of the results

The results and discussion summarised in this chapter are published as a research paper whose characteristics and metrics are gathered in Table 2.

Table 2: Publications related to the research topic II.

Research paper	
Title	A cross-country review on energy efficiency drivers
Authors	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre
DOI	https://doi.org/10.1016/j.apenergy.2021.116681
Journal	Applied Energy
Reference	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, A cross-country review on energy efficiency drivers, Appl. Energy. 289 (2021) 116681.
Metrics	
Indexing database	Web of Science/Journal Citation Reports
Journal Impact Factor	11.446
Year	2021
Category	CHEMICAL ENGINEERING
Rank	9/142
Quartile	1
Citations	6 (Google scholar / Scopus / Web of Science)

2.3. Final services focus – Activity drivers of energy use in buildings

2.3.1. Introduction

On the demand side of the energy system, the energy consumption is shaped by the weights of the consuming sectors, namely industry, transport, buildings (both residential and tertiary) and others (covering minor activities such as agriculture, forestry and fishing).

Globally, consumption in every sector increased over the period 2000 – 2019 (Fig. 6), while their shares in final consumption remained slightly constant [18]. Buildings were the most consuming sector, followed by industry and transport, and increased by 1.2%/yr since 2000. 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 [28].

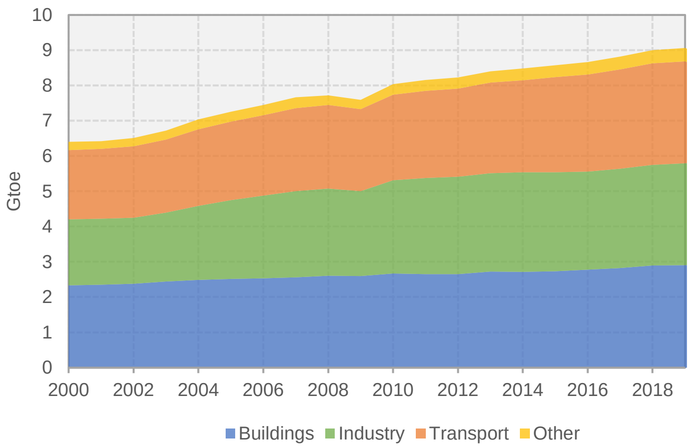

Fig. 6: Final global energy consumption by sector. Based on IEA data [18,29,30].

Final energy can be allocated to the various consuming sectors, where it is converted into useful energy through conversion devices (also known as energy-using products). Then, useful energy is degraded to provide final services within passive systems. However, for each sector, the products that use energy, the services to be provided and the magnitudes that drive the demand for these services differ significantly. Thus, decompositions must analyse the consuming sectors independently and their corresponding final services before constructing a broad approach for the demand side. In this section, the focus is set on the buildings sector for a deep analysis of activity and efficiency drivers.

2.3.2. Contributions to the state-of-the-art

In 2019, buildings were responsible for about a third of global energy consumption and a quarter of CO_2 emissions [31]. They even represented 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 [18]). 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 [14]. However, the development, evaluation and monitoring of these policies could only succeed if comprehensive, homogeneous and consistent information on energy and activity in buildings is available [32]. Unfortunately, gathering this information among the existing sources is a major challenge, resulting in few studies about this sector compared to industry and transport.

The lack of analysis for the buildings sector leads to the following research questions:

- Which activity indicators drive buildings energy consumption?
- Which are the appropriate indicators for the definition of the energy efficiency of buildings?
- How can buildings energy consumption be decomposed?
- Are the necessary data for the analysis of building energy use available?

Consequently, this chapter aims to develop a methodology that answers the research questions above and contributes to filling the research gap related to the buildings sector.

2.3.3. Methodology

This section is embargoed in order to ensure confidentiality, as its content may be subject to publication.

2.3.4. Main results and discussion

This section is embargoed in order to ensure confidentiality, as its content may be subject to publication.

2.3.5. Scientific publications for the dissemination of the results

Part of the results and discussion summarised in this chapter are published in two research papers whose characteristics and metrics are gathered in Table 3.

Table 3: Publications related to the research topic III.

Research paper I	
Title	A review on buildings energy information: Trends, end-uses, fuels and drivers
Authors	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan
DOI	https://doi.org/10.1016/j.egyr.2021.11.280
Journal	Energy Reports
Reference	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on buildings energy information: Trends, end-uses, fuels and drivers, Energy Reports. 8 (2022) 626–637.
Metrics	
Indexing database	Web of Science/Journal Citation Reports
Journal Impact Factor	4.937
Year	2022
Category	ENERGY & FUELS
Rank	58/119
Quartile	2
Citations	47 (Google scholar) / 37 (Scopus) / 30 (Web of Science)
Research paper II	
Title	Activity and efficiency trends for the residential sector across countries
Authors	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, P. Bertoldi
DOI	https://doi.org/10.1016/j.enbuild.2022.112428

Journal	Energy and Buildings
Reference	M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, B. Paolo, Activity and efficiency trends for the residential sector across countries, Energy Build. 273 (2022) 112428.
Metrics	
Indexing database	Web of Science/Journal Citation Reports
Journal Impact Factor	7.201
Year	2022
Category	CIVIL ENGINEERING
Rank	8/138
Quartile	1
Citations	1 (Google scholar / Scopus / Web of Science)

3. CONCLUSIONS

The impact of energy use on the planet due to its related CO_2 emissions continues to grow, despite the adoption of efficiency and decarbonisation policies and the widespread environmental awareness. Climate change mitigation will only succeed if the driving forces of consumption and emissions are deeply analysed, and effective means are provided to reverse their trends.

In this context, the global energy chain needs to be described in a comprehensive manner to examine every link in the chain. For its analysis, this thesis proposes three pyramid approaches that establish a hierarchy of indicators to break down the energy system at different levels and allow conclusions to be drawn in a stepwise manner.

In a first pyramid, the whole energy system is examined based on the Kaya Identity, quantifying the effects of activity, efficiency and carbon drivers on CO_2 emissions trends. At its lowest level, a novel decomposition is defined to analyse the impacts of the supply and demand sides, and of emitting and non-emitting energy sources, in addition to the socioeconomic drivers (population and wealth). The energy intensity is split into supply-side and demand-side efficiencies, and carbon intensity is broken down into the fossil share and the fossil carbon intensity.

The approach allows for the identification of the reasons for past emissions changes, future actions towards sustainability and policy implications. An encouraging change has begun, as the developed region (OECD) has been able to decouple activity and emissions growths since 2007. However, recent efforts upon efficiency and decarbonisation in the developing region (non-OECD) remain insufficient to offset their economic and demographic growths. Regarding efficiency drivers, the improvement in final energy intensity (efficiency of the demand side) allows reducing the gap between regions, thanks to the spread of enhanced end-use technology. On the supply side, the available technologies have made electrification compatible with efficiency gains in the energy sector only in the OECD (reduction of the Primary Energy Factor, *PEF*). As for carbon drivers, the increasing gas share in developed countries has induced a decrease in fossil carbon intensity, while the promotion of renewables has pushed down the fossil share. In contrast, carbon indicators in the non-OECD have only improved since 2013, as their economic boom mainly relied on coal. Thus, it seems that the developing region follows the favourable performance of the developed nations but delayed by its later economic development. Current political intentions will only allow for emissions stabilisation as decreases in developed nations counteract increases in emerging countries.

However, keeping temperature rise below 1.5ºC requires a 70% drop in global emissions by 2040 in comparison with 2019 figures. More stringent policies must be urgently adopted to narrow the gap between stated policies and sustainable pathways. Carbon drivers should be especially addressed as they deviate significantly from their sustainable targets. In the short term, policies should encompass fossil share reductions and gas surge, while research and investment make the transition to full defossilisation feasible. In addition, globalisation should be seen as an opportunity to reduce regional inequality, as it enables the diffusion of advanced technology, knowledge and expertise. Developed nations must intensify efforts to accelerate their emissions drop and to support the reversal of emerging nations trends to succeed in climate change mitigation.

Despite energy policies rely on carbon intensity as the main mitigating factor for climate change, historical trends have clearly placed energy efficiency as the unique driver curbing emissions growth. During the last decades, energy efficiency measures have been proved as feasible and effective worldwide, so they should remain as a keystone in the definition of future pathways to sustainable development.

To assess the impact of environmental policies on the efficiency of the energy system, a second pyramid is proposed to decompose energy intensity into its underlying factors. The focus is set on the supply side, to progressively decompose the Primary Energy Factor into structural and efficiency indicators by transformation and fuel type. The application of the methodology to the six most consuming and emitting nations in the world (US, EU, China, India, Japan and Russia) provides relevant insights to better understand their supply side transition and policy implications.

The national decompositions into demand and supply efficiencies confirm the results of the regional analysis performed in the previous pyramid. The final energy intensity has been the main responsible for the efficiency improvement in every country, while *PEF* has only contributed to reducing the energy intensity in developed nations, raising concerns about the difficulties of an economy to thrive without worsening the efficiency of its energy sector.

Developing countries structures by transformation types are dominated by directly carried over energy forms, unlike those in developed nations dominated by refineries. Structural changes have worsened energy intensity in every country due to shifts from highly efficient transformations such as Direct Carry Over (China and India), refineries (US, EU and Japan) and heat plants (Russia), with an average *PEF* about 1.1, towards electrification, with an average *PEF* about 2.5. The improvement of transformation efficiency in developed countries has been high enough to cancel unfavourable structural changes, leading to slight but commendable gains in the efficiency of the energy sector. On the contrary, for developing nations, lower transformation efficiencies and more adverse structural changes were responsible for significant losses in their energy sector efficiency.

Over other transformations, the effects of fuel shifts in electricity and heat plants are highlighted. A hopeful structural change is found in the EU, as electricity generation moves from coal and nuclear to efficient combined cycle gas plants and renewables, which are favoured by the 100% conversion efficiency assumption for non-thermal sources within the direct equivalent approach. Thus, the promotion of renewable electrification is twice convenient: it uses a non-emissive fuel to reduce carbon intensity and induces gains in energy sector efficiency to reduce energy intensity. Additionally, the improvement of power plants efficiencies for almost every fuel has caused non-negligible efficiency gains in every country but Russia. In summary, the acceleration of renewable electrification, efficient power plants and coal phase out are the basis for the supply-side energy transition to a sustainable future.

Finally, the demand side of the energy system is further analysed. The energy demand is shaped by the weights of the consuming sectors, namely industry, transport, buildings and others, which must be independently analysed due to the heterogeneity of their final services, conversion devices and activity drivers. Among the consuming sectors, the focus is set on buildings, due to their significant impact (a third of global energy consumption and a quarter of CO_2 emissions in 2019) and the lack of studies compared to industry and transport due to data limitations.

A third pyramid is then proposed to decompose buildings energy consumption in the activity, efficiency and structure indicators that drive their demand for final services and consumption. As for activity drivers, the effects of population, floor area, urbanisation (area per capita), occupation (number of buildings per capita), buildings size (area per building) and climate (degree-days) are examined. The buildings efficiency is defined by the energy use intensity (koe/m^2) since floor area is assumed to be the main activity indicator. The structural effect of the stock changes among buildings subsectors (tertiary and residential) is also assessed.

Despite their interest, these decomposition analyses are only applied to the US, the EU and China due to the lack of data for other nations or regions. The main limitations concern information on the buildings stock, such as number of buildings, floor area, occupancy and level of equipment. The case of tertiary buildings is particularly critical, due to the difficulties in collecting data, as they are often multi-tenant and share different activities.

Buildings energy consumption has risen because of the increase in the floor space, almost compensated by the efficiency gains that limited its growth to some 0.2%/yr in the US and the EU. However, the impressive expansion of the Chinese area owing to faster economic growth, continued shift from rural to urban areas and reduced inequity in terms of area per capita (half the European and a quarter the American in 2000), has risen consumption by 2.4%/yr despite its improved energy intensity.

The reason for the area growths was mainly the increasing urbanisation in China and the EU, coupled with the upward effect of the rising population. In contrast, urbanisation decreased in the US, due to the reduction of the buildings sizes, and slightly offset the effect of the significant population growth.

Energy use intensity decreased in every country under study. In the US and the EU, wealth enabled the spread of efficient equipment and buildings designs, while in China, the economic growth did not immediately translate into a higher demand for energy services and resulted in a faster growth in area than in consumption. Consequently, energy intensity in developed countries (around 16 koe/m^2) is still twice that in China (7 koe/m^2), due to energy conservation habits rather than to higher efficiency levels.

Changes in energy use intensity can be further decomposed to reveal the effect of climate and structural changes among buildings subsectors. In the US, the decrease in energy use intensity was a result of the warmer weather and the improvement of the normalised intensity, slightly counteracted by the shift towards tertiary buildings, twice more intensive than residential ones. In the EU, the colder weather contributed to rise consumption, despite this effect was successfully compensated by the significant drop in its corrected intensity and the structural change of reduced tertiary shares.

In China, as in other developing countries, consumption cannot be corrected assuming a linear regression with heating degree-days, since the response to weather variations does not necessarily result in an increase in energy use, but in a decrease in thermal comfort, as low income levels restrict energy expenditure. Thus, the energy use intensity is only decomposed to assess the structural effect of the significant growth of the tertiary buildings share, which resulted in a small reduction in consumption, due to poorly equipped tertiary buildings with energy use intensities surprisingly below those of residential ones.

In the future, data collection needs to be improved to allow for the evaluation of the gap between stated policies and mitigation pathways in the buildings sector. The development, implementation and monitoring of energy policies can only succeed if they are based on relevant disaggregated and reliable information.

In summary, this thesis confirms the interest of the research line: Global Energy analysis and diagnosis. In particular, three research topics have been examined through different pyramid approaches and their corresponding decomposition analysis: drivers of energy-related CO_2 emissions in developed and developing regions, efficiency drivers of energy production in the six most emitting nations and, activity and efficiency drivers of energy use in buildings for the three most consuming countries.

The main advantages of the novel methodology should be noted. Firstly, it provides a comprehensive description of the overall energy chain and the links where actions can be taken to reduce the environmental impact. Secondly, it could provide guidance for future analyses and for the standardisation of procedures. Thirdly, it could help energy statisticians in their analysis and reporting duties. Fourthly, it disaggregates activity, efficiency and carbon indicators that are crucial for explaining trends in emissions and consumption and, ultimately, the results of its application provide meaningful insights for energy and climate policy target setting.

However, some research topics in this line require further investigation. Future scenarios will need to develop detailed supply-side data to enable their evaluation and to determine the pace at which the fuel mix should evolve to reduce emissions without detriment to efficiency. Moreover, changes in the supply should be analysed to assess not only their effect on efficiency, but also on other mitigation indicators such as carbon intensity. On the demand side, the consuming sectors that had been left out of the scope of this thesis (mainly industry and transport) should be examined and the structural effect of changes among all of them assessed. Furthermore, additional efforts are required for useful energy accounting, to assess and improve the efficiency of end-use technologies (*Final Energy Factor*), and to minimise the energy input to passive systems for the provision of final services.

Energy transitions on both the supply and demand side are mandatory to keep emissions at safe levels and curb climate change. However, they must be accompanied by sufficiency and conservation policies targeting human and economic activity to bring the demand for final services within reasonable and responsible limits. In addition, other aspects of our environmental footprint must be carefully addressed, to move not only towards decarbonisation, but also towards resource efficiency and circular economy.

To sum up, technological advances must be coupled with a greater global awareness of energy as a scarce and polluting commodity that leads to the adoption of true conservation habits. Governments must move from words to deeds to drive the transformation of the entire energy system, with the necessary participation of the big tech companies. However, citizens must assume their responsibility for energy demand and take action to address its consequences for the future of the planet.

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[32] González-Torres M, Pérez-Lombard L, Coronel JF, Maestre IR, Paolo B. Activity and efficiency trends for the residential sector across countries. Energy Build 2022;273:112428. https://doi.org/10.1016/j.enbuild.2022.112428.

ANNEX A:
PUBLICATION RESEARCH TOPIC I

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ANNEX B:
PUBLICATION RESEARCH TOPIC II

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ANNEX C:
PUBLICATIONS RESEARCH TOPIC III

Energy Reports 8 (2022) 626–637

Contents lists available at ScienceDirect

Energy Reports

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

Review article

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

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Buildings energy information

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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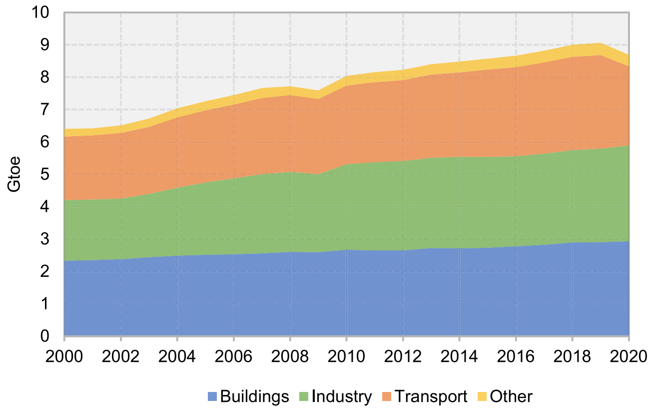

Fig. 1. Final global energy consumption by sector.
Source: Based on IEA data (IEA, 2021e,d,b)

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

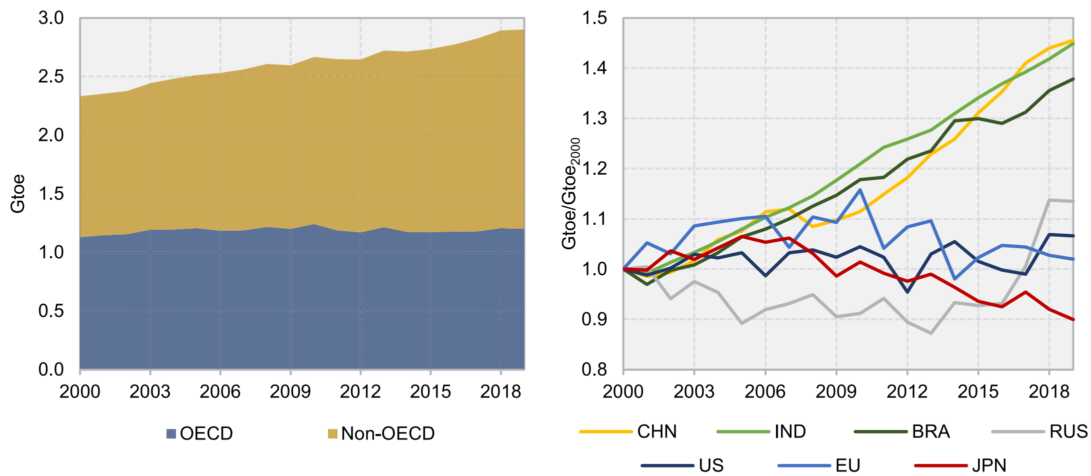

Fig. 2. Final energy consumption in buildings: OECD and the non-OECD (left), China, India, Brazil, Russia, US, EU, Japan (right). *Source:* Based on IEA (2021e) and Odyssee (2021) data.

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

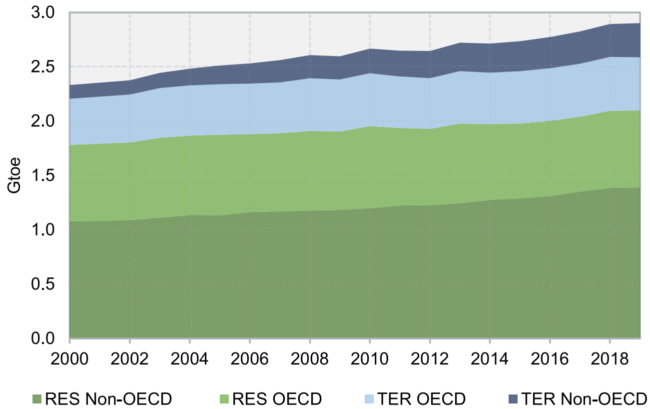

Fig. 3. Residential (RES) and tertiary (TER) energy consumption for the OECD and the non-OECD.
Source: Based on IEA data (IEA, 2021e).

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%*)

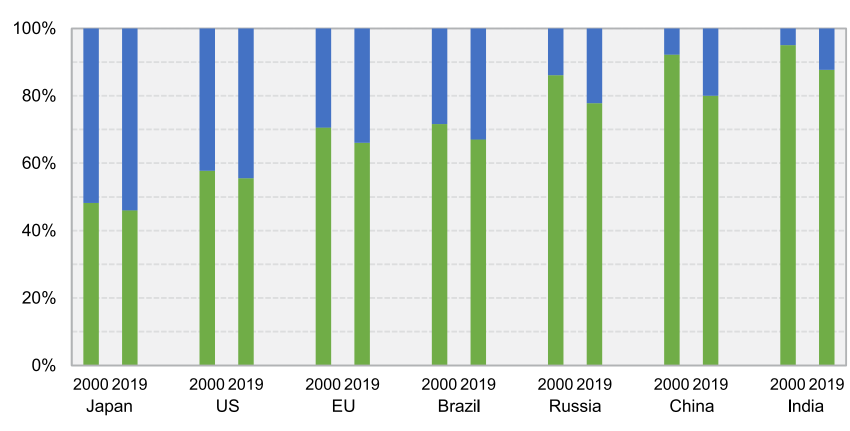

Fig. 4. Residential and tertiary shares for Japan, US, EU, Brazil, Russia, China and India.
Source: Based on IEA (2021e) and Odyssee (2021) data.

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 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

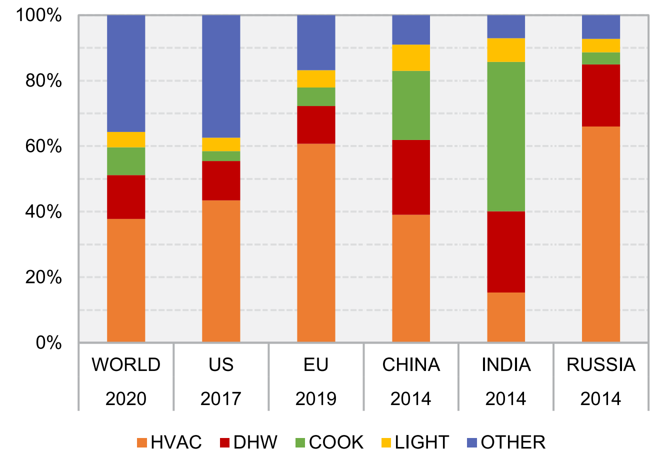

Fig. 5. Buildings consumption by end-uses for the world, US, EU, China, India and Russia.
Source: Based on IEA (2021d, 2017), U.S. Energy Information Administration (EIA) (2019) *and* Odyssee (2021) *data.*

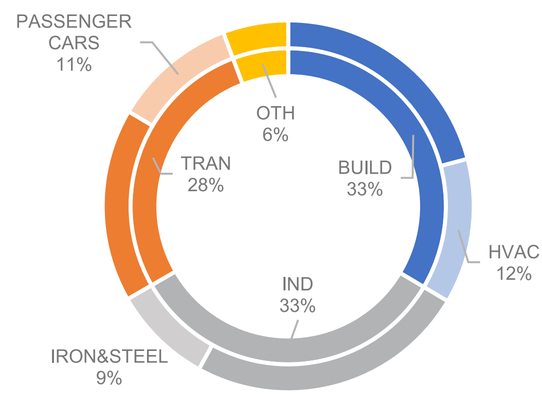

Fig. 6. Main end-uses by consuming sector. World, 2020.
Source: Based on IEA data (IEA, 2021d).

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

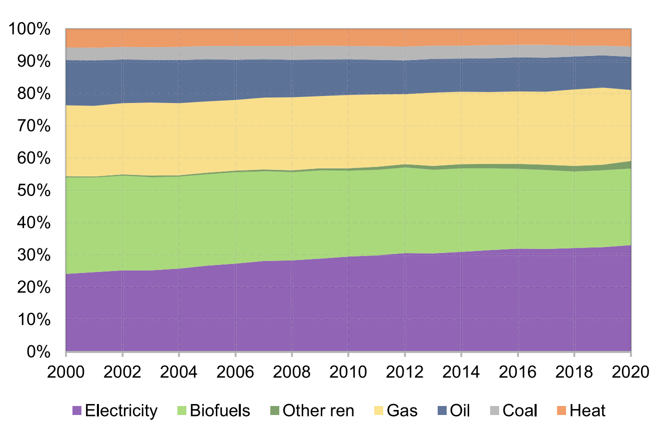

Fig. 7. Buildings fuel mix evolution for the world.
Source: Based on IEA data (IEA, 2021e,d).

(*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).

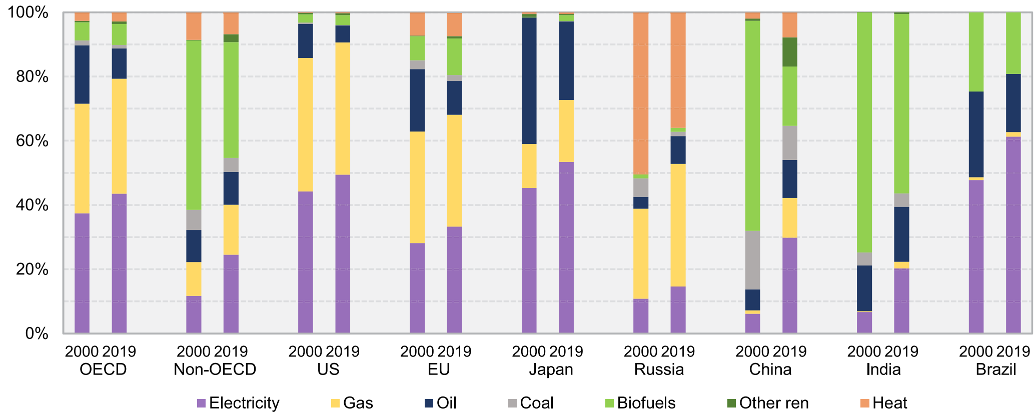

Fig. 8. Changes of buildings fuel mix (2000–2019) for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil.
Source: Based on IEA (2021e) and Odyssee (2021) data.

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.

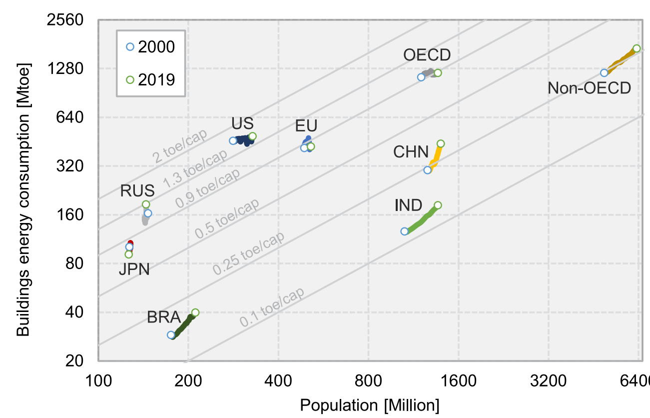

Fig. 9. Buildings consumption vs. population for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil.
Source: Based on IEA (2021e), Odyssee (2021) and World Bank (2021) data.

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

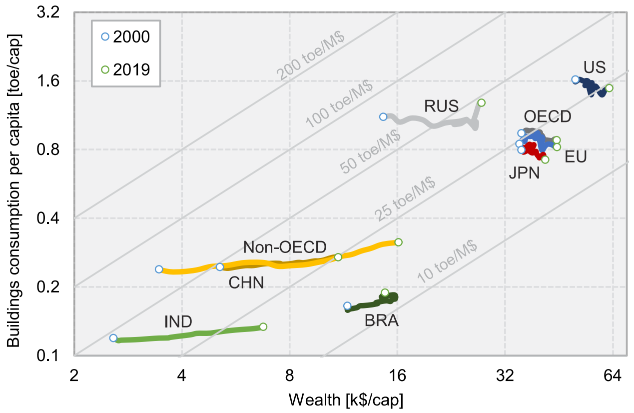

Fig. 10. Buildings consumption per capita vs. wealth for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil.
Source: Based on IEA (2021e), Odyssee (2021) and World Bank (2021) data.

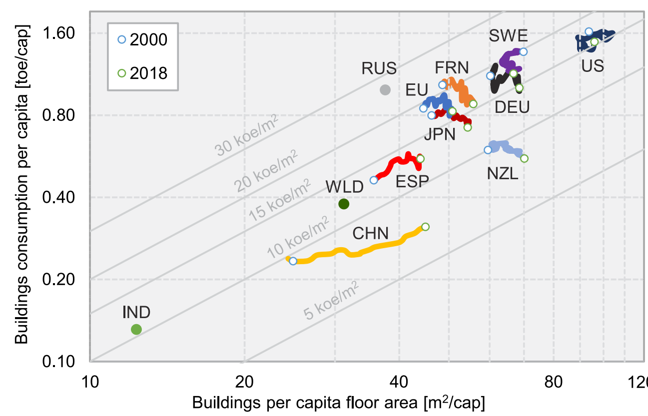

Fig. 11. Buildings per capita energy consumption vs. per capita floor area selected countries: World, US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Indian and Russian values are only available for 2017 and 2013, respectively. World figures correspond to 2019.
Source: 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.

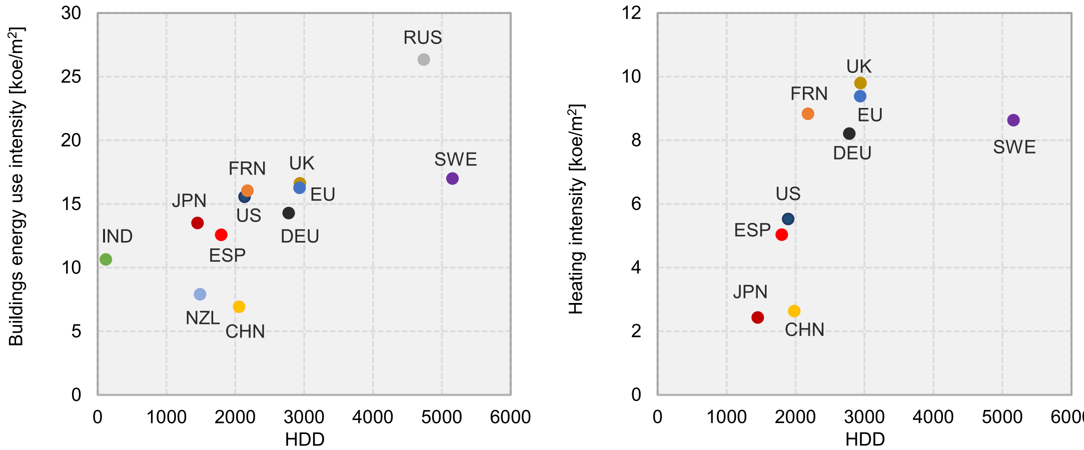

Fig. 12. Buildings energy use intensity (left) and heating energy intensity (right) vs. Heating Degree Days for selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Figures correspond to 2018, except for India (2017) and Russia (2013) (left) and US (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).

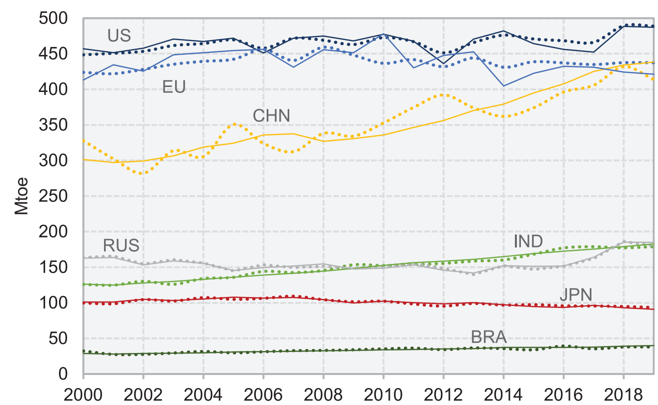

Fig. 13. Weather-adjusted (dashed lines) and real (solid lines) buildings energy use in US, EU, China, India, Japan and Russia.

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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Activity and efficiency trends for the residential sector across countries

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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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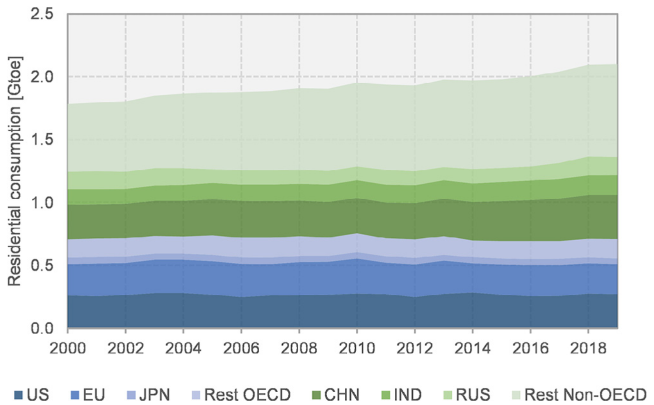

Fig. 1. Residential energy consumption [Gtoe] in the period 2000–2019. Based on IEA data [4].

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

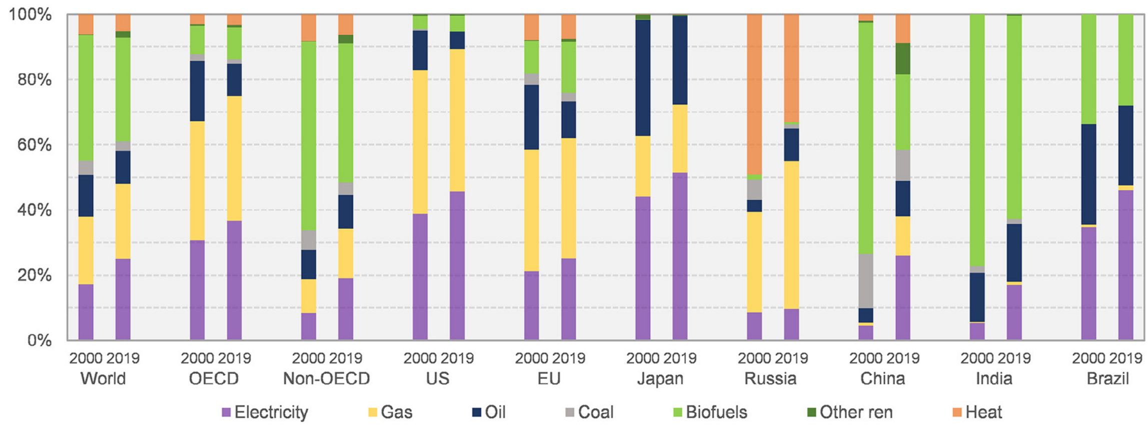

Fig. 2. Changes in residential fuel mix (2000–2019) for the world, the OECD and the non-OECD regions and US, EU, Japan, Russia, China, India and Brazil. Data based on IEA [4] and Odyssee [24] data.

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

[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.

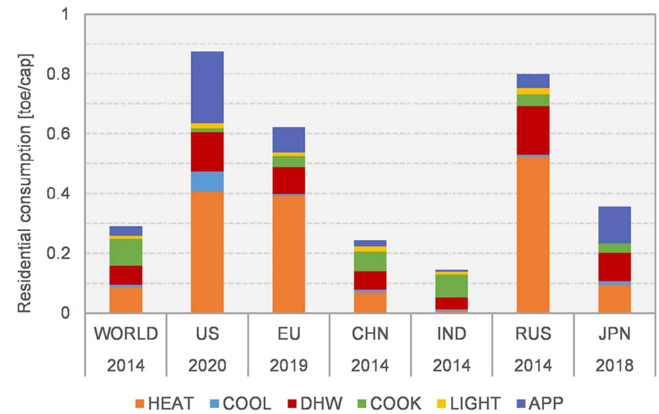

Fig. 3. Residential per capita consumption by end-uses for the world, US, EU, China, India, Russia and Japan. Based on IEA [25,26], EIA [27], Odyssee [24], World Bank [28] data.

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.

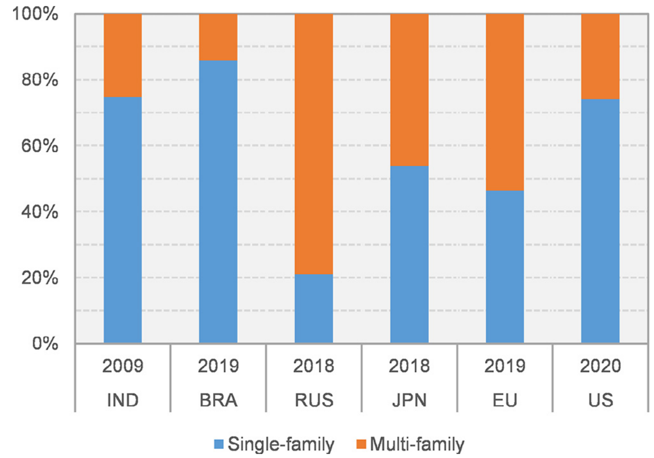

Fig. 4. Distribution of the dwelling stock by housing type (single-family and multi-family) based on the number of dwellings. Based on data from NSS [29], IBGE [30], ROSSTAT [31], SBJ [32], Odyssee [24], EIA [27]. Note that single-family in the US includes mobile homes.

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

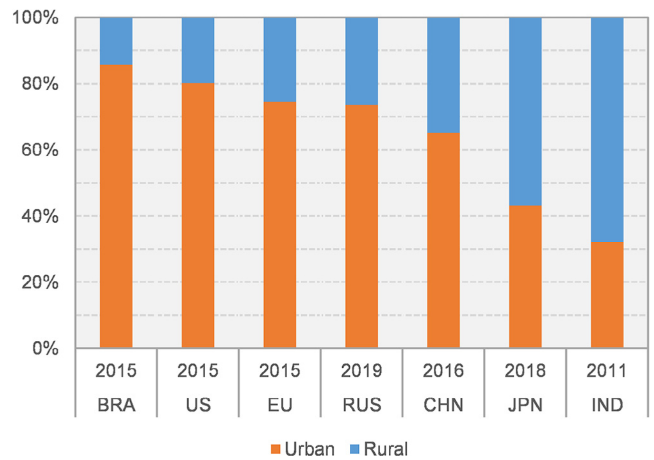

Fig. 5. Degree of urbanisation of the dwelling stock. Based on data from IBGE [33], EIA [27], Eurostat [34], ROSSTAT [31], Jiang et al. [35], SBJ [32] and NBO [36].

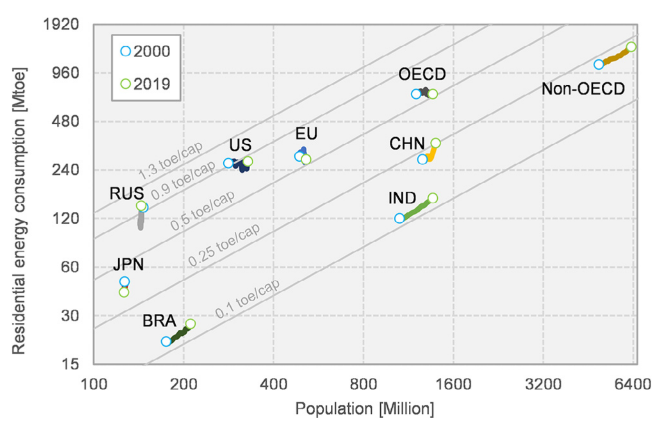

Fig. 6. Residential consumption vs population for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil. Based on IEA [4], Odyssee [24] and World Bank [28] data.

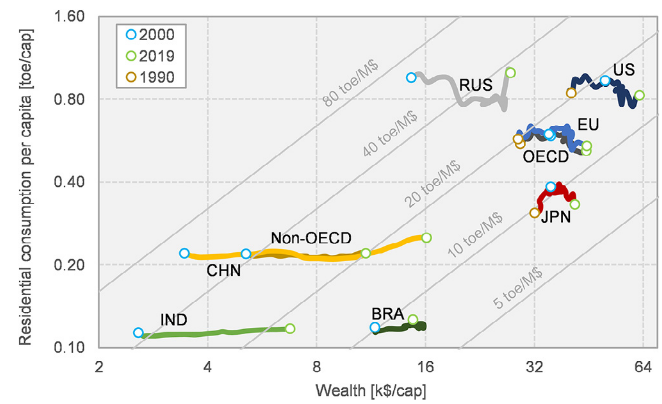

Fig. 7. Residential consumption per capita vs wealth (GDP per capita) for the OECD and the non-OECD regions and for US, EU, Japan, Russia, China, India and Brazil. Based on IEA [4], Odyssee [24] and World Bank [28] data.

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

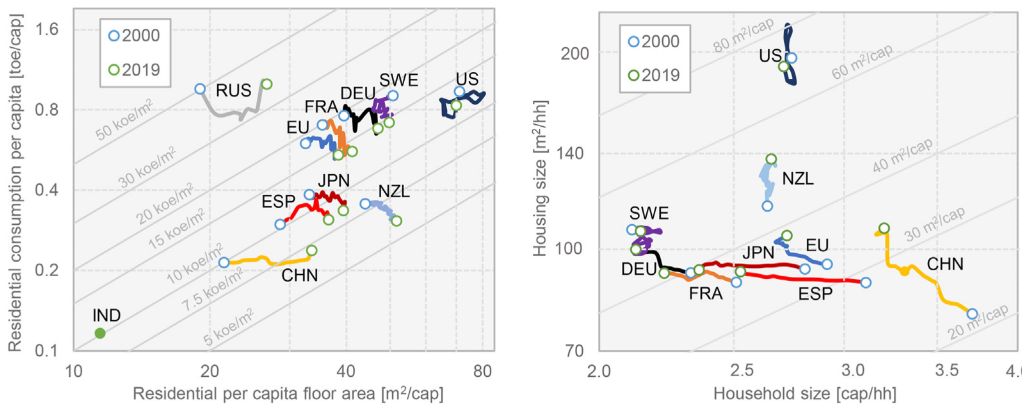

Fig. 8. Residential consumption per capita vs per capita floor area (left) and housing size vs household size (right) in selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24], Jiang et al. [35], AEEE [37], ROSSTAT [31] 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.

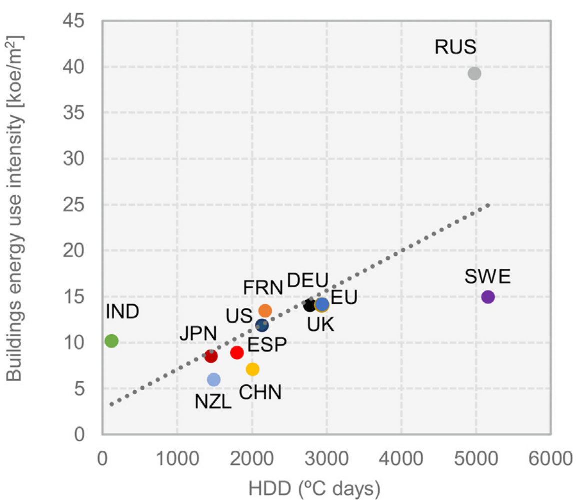

Fig. 9. Residential energy use intensity vs Heating Degree Days (HDD) in selected countries: US, EU, Japan, Russia, China, India, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26,38], Odyssee [24], Jiang et al. [35], AEEE [37], ROSSTAT [31] and World Bank [28]. Year 2018, except for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

result of sharing energy services and equipment (mainly HVAC) [79]. However, the results in Fig. 10 show poor or even inverse cor-

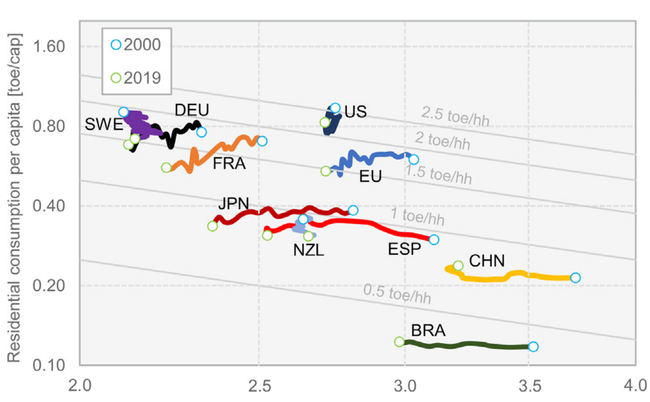

Fig. 10. Residential consumption per capita vs household size in selected countries: US, EU, Japan, China, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24], Jiang et al. [35] and World Bank [28]. Chinese data from 2001 to 2016, New Zealand and Japan only up to 2018.

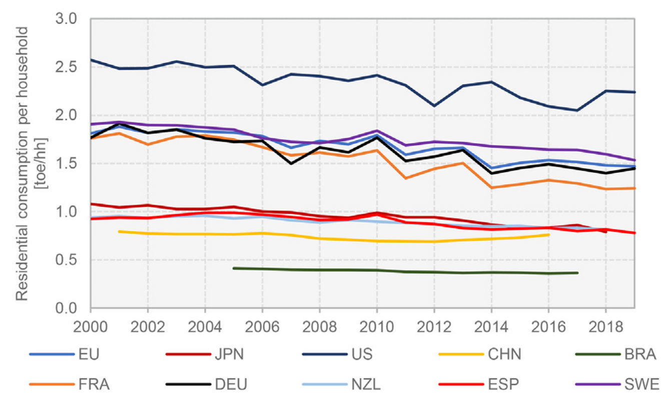

Fig. 11. Residential energy use per household in selected countries: US, EU, Japan, China, New Zealand, Spain, France, Germany and Sweden. Sources: IEA [4,26], Odyssee [24] and Jiang et al. [35].

relation 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.

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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