# Chapter 9: Buildings

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# Executive summary

In 2018, buildings accounted for more than one-third of global $CO_2$ emissions (when direct, indirect and embodied emissions from buildings are considered) and about one third of global energy and electricity demand out of which 60% was due to residential buildings (*robust evidence, high agreement*). Compared to 2010, $CO_2$ emissions from buildings experienced an increase of 10% driven mainly by the construction of new buildings in the developing world. Africa is the region with the highest increase of $CO_2$ emissions in both residential and non-residential buildings (*robust evidence, high agreement*).

The building sector is one of the end-use sectors with a high mitigation potential (*robust evidence, high agreement*). Beyond efficiency measures, sufficiency measures are now also being considered to reduce buildings' emissions. Moreover, buildings have an active role in the energy system, with users becoming now prosumers (*robust evidence, high agreement*).

Furthermore, sufficiency measures may deliver energy savings even before they are implemented through efficiency and behaviour as sufficiency avoids energy demand without costs. As an action, energy sufficiency aims at reducing the input of technically supplied energy towards sustainable levels, with a qualitative or quantitative change in the service or utility from energy. Sufficiency therefore is a concept that should be integrated during the whole lifetime of a building already from the initial planning even before the consideration of efficiency, behavioural, or renewable energy measures. This would lead to consideration of parameters such as space, design, size and construction type, equipment, and their use. Given the lower limit of energy sufficiency and the fact that many people around the world still lack appropriate access to energy services, energy sufficiency is not only about demand reduction but also about matters of distribution and equity. The aim is to ensure well-being and Decent Living Standard (DLS).

Energy in building is influenced by the type and composition of the building. In this case identification of building type is required to understand its heterogeneity. Residential buildings constitute a large proportion of all the buildings and deliver on well-being for all therefore effective implementation of climate change mitigation measures in residential buildings is of paramount as they also deliver on other SDGs such as ending poverty, health, sustainable cities.

Buildings have evolved from local vernacular architecture to modern smart buildings. The evolution has a significant impact on energy consumption of buildings and its associated greenhouse gases emissions. In a generic point of view, building services include shelter, nutrition, sanitation, thermal comfort, communications, and illumination. These services are delivered through building management systems, energy generation; distribution and supply; heating, ventilation, air conditioning (HVAC); escalators and lifts; facade engineering; fire safety; detection and protection; ICT networks; lighting; lighting protection; refrigeration; plug loads; security and alarm systems; and water, water heating, drainage and plumbing. Technological advancements have been used to improve the efficiency of the services. Integration of the system with the renewable energy systems, wireless communication systems, and building management systems; the use of ice refrigeration, solar photovoltaic power, thermal energy storage technologies in the air conditioning process; and use of solar thermoelectric cooling technologies in refrigeration are some of the such advancements.

Despite the UN Sustainable Energy For All (SE4All) objectives and the SDG targets, the global use of traditional biomass increased by 3% over the period 2010-2018. The highest increase was observed in Africa and Latin America and Caribbean countries. The rest of the developing world experienced a decrease in the use of traditional biomass (*robust evidence, high agreement*).

Electrification of thermal energy services such as heating and hot water, increased cooling demand and increased energy demand driven by the high penetration of digital technologies are among the emerging trends in energy demand in almost all regions (*robust evidence, high agreement*). Over the period 2010-2018, lighting is the only energy service which has experienced a decrease in its energy demand almost everywhere. The only two exceptions are Africa and Eastern Asia where lighting energy demand increased as a result of the increased access to electricity which took place without necessarily taking advantage of the technological breakthrough of LED technologies (*high evidence, medium agreement*).

Energy in building is influenced with the type and composition of the building. In this case identification of building type is required to understand its heterogeneity. Residential buildings constitute a large proportion of all the buildings therefore climate change mitigation for residential building sector is of paramount.

For decarbonization, actions are needed in sufficiency, efficiency and RES, while a life cycle perspective is considered (*robust evidence, high agreement*). Sufficiency measures aim to reduce the need for technically supplied energy towards sustainable levels through qualitative or quantitative changes in the demand for services, for instance the consideration of parameters such as space, design and construction, equipment, and uses. Sufficiency measures should be integrated during the whole lifetime of a building and before the consideration of efficiency, behavioural, or renewable energy measures. Given the lower limit of energy sufficiency and the fact that many people around the world still lack appropriate access to energy services, energy sufficiency is not only about demand reduction but also about matters of distribution and equity.

Technological mitigation options and strategies are extensive, but their contribution to climate change is not always quantified (*high evidence, low agreement*). Technological advancements have been used to improve the efficiency of the services. Integration of the system with the renewable energy systems, wireless communication systems, and building management systems; the use of ice refrigeration, solar photovoltaic power, thermal energy storage technologies in the air conditioning process; and use of solar thermoelectric cooling technologies in refrigeration are some of the such advancements. Technological options include passive options to improve the building envelope (windows, walls and roofs mainly, after good building shape and orientation) and active technologies that can be implemented in the building envelope or in the energy systems. These technologies can change the building to become a small power plant, producing energy. Digitalisation (smart buildings, smart meters and smart appliances) are key to decrease emissions in buildings (*low evidence, high agreement*).

Non-technological and behavioural mitigation actions in buildings are among the sufficiency measures which have a great effect in energy use and GHG emissions, are also required to increase the uptake of technical mitigation measures, and to guarantee demand-supply flexibility. Households with current adequate service levels are willing to change, but additional infrastructural and policy support is needed to implement the major lifestyle changes required to significantly reduce GHG emissions from buildings (*robust evidence, high agreement*). Broadly speaking, non-technological measures include "curtailment" behaviours, which are everyday practices such as turning off unnecessary lights, "efficiency" behaviours, which are one-time decisions to implement a low carbon solution upfront such as insulating the building envelope or buying super-efficient appliances, and "acceptance" behaviours which are social, institutional and organisational barriers or enablers, at different levels, of the technical mitigation measures. Even in a context of a low carbon energy system, behavioural issues are key guarantee of demand-supply flexibility in terms of tolerance to increased automation and varying service levels. Income, climate, energy price and size are key determinants of buildings energy consumption. Motivations are triggered by contextual needs, such as after moving in, driven by conform or urgent replacements of dysfunctional elements, or social and environmental values and aspirations. Maintaining the heritage and aesthetic value of the property, may as well hinder the installation of additional insulation if no technical solutions are easily available. The decisions show high positive correlation to governmental support, and peer information. Local professionals and practitioners can to date both encourage and discourage the installation of additional insulation, according to their knowledge and training.

Existing technologies and practices allow transforming the building sector by 2050 in a way that it will emit very low GHG emissions in developed countries and relatively low GHGs emissions in developing countries. Literature models the emission reduction potential up to 90% of emissions as compared to 1990 in Europe and North America (*robust evidence, high agreement*), up to 70% as compared to baseline emissions in Asia (*robust evidence, high agreement*), up to 45% as compared to baseline emissions in Africa (*low evidence, medium agreement*), and up to 25% as compared to baseline emissions in South America (*low evidence, low agreement*). Additional potential could be delivered by the reduction of embodied emissions in buildings (*low evidence, high agreement*).

Low-energy and low-carbon buildings are possible today in every climate and every location worldwide (*high evidence, medium agreement*). Materials, components, systems and technologies are available but stricter implementation of policies and building technical capacity are needed to change current construction practices. However, to achieve carbon neutrality, the optimal trade-offs between energy and carbon emissions depend on the share of renewable energy that supplies the buildings (*medium evidence, high agreement*). Moreover, buildings have an active role in the energy system, with users becoming now prosumers (*robust evidence, high agreement*).

The realisation of this mitigation potential requires an acceleration of building retrofit rates in developed countries (*robust evidence, high agreement*) and an immediate introduction of very ambitious building and equipment standards in developing countries to avoid the lock-in effect due to high construction rates (*robust evidence, high agreement*).

The estimates of the potential and its associated costs should be treated with caution because they rely on the number of assumptions and uncertainties such as stock turnover, technological limitations, urbanization rates, investment costs, baseline emissions, discount rates and others (*robust evidence, high agreement*). The actual investment costs are likely to be higher than the models predict (*medium evidence, medium agreement*).

Climate factors are highly determinant of energy demand, and climate variability and extreme events will increase energy consumption and adaptation measures will be needed (*high evidence, high agreement*). Most of the literature focuses on the impacts of climate change on heating and cooling needs in buildings. The associated impacts on energy consumption are expected to be higher in hot summer and warm winter climates, where cooling needs are more relevant (*medium evidence, medium agreement*). This will induce shifts to electrical demand and affect energy consumption, increasing emissions when electricity generation is fossil-based. Although heating demand in cold climate regions can be expected to decrease with climate change and, to a certain extent, outweigh the increase in cooling demand, the effects on total primary energy requirements are uncertain (*low evidence, high agreement*). Other climate change impacts on buildings, that largely vary per world region, include risk of indoor overheating, reduced efficiency of onsite energy production and impacts to building structures, construction and building material properties and associated health impacts.

Adaptation interacts with mitigation since measures to cope with climate change impacts can increase energy consumption, which may lead to higher GHG emissions (*high evidence, medium agreement*). Nevertheless, conflicts between climate change adaptation and mitigation in buildings can be reduced by adopting efficiency, sufficiency and building envelope measures (*low evidence, high agreement*). Thus, strong energy efficiency measures need to be adopted and climate change should be considered in the design of new buildings in a way that they can operate in both current and future climates to avoid higher adaptation costs of retrofitting existing building stock.

Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential for achieving the United Nations Sustainable Development Goals (*high evidence, high* *agreement*). Specifically, the multiple co-benefits of mitigation actions go far beyond the goal of climate action (SDG13) and contribute to further activating fifteen other SDGs. The promotion of improved cook-stoves and electrification in developing countries as well as energy efficiency interventions in buildings that live energy-poor households in both developed and developing economies bring significant health gains through improved indoor air quality and thermal comfort as well as reduced financial stresses (*medium evidence, high agreement*). Furthermore, these actions improve social wellbeing, primarily in developing countries by enabling people to read, socialize, and be more productive, as well as children to attend school, but also in developed economies by providing more private and comfortable spaces for various activities in home, and helping residents to avoid social isolation, improve social cohesion, etc. (*medium evidence, high agreement*). Last, energy efficiency measures in buildings result in significant macro- and micro-economic effects, such as increased productivity of labour, increased rent and sale prices of energy efficient buildings, creation of new jobs and economic development, improvements in aspects of energy security, etc. (*medium evidence, high agreement*). Particularly in developing countries if the mitigation measures are carried out by locals, the impact on economy, employment and social wellbeing will be substantial (*limited evidence, medium agreement*).

In order to decarbonize the global building stock a number of new and innovative policies and financial mechanisms have to be adopted, in addition more traditional policies (*robust evidence, high agreement*). Building codes have proven to be effective in increasing the efficiency of buildings and have been adopted by many countries (*robust evidence, high agreement*). The next generation of building codes in many jurisdictions at national or local level mandate all new buildings to be net zero energy, this could be replicated in different regions. The most advanced announced building code sets requirements to make buildings positive energy and carbon neutral over the lifecycle of the building. There is no single policy, but the need to organize the policies in packages with different types of instruments (*robust evidence, high agreement*).

Due to population growth and increasing standards of living the demand for building space is increasing (*robust evidence, high agreement*). This will call on new policies for changing end-user behaviour and lifestyles, and limit personal carbon emissions linked to buildings services, through price signals, information, allowances and some mandatory policies, if needed (*robust evidence, high agreement*). Attention must be paid to distributional effects, energy poverty, justice and equity (*robust evidence, high agreement*).

At the same time polices shall also address to embedded carbon in new building construction, in particular the demand for cement, steel and other building materials. Policies based on Life cycle Assessment (LCA) and circular economy can foster a transition to sustainable building materials (*robust evidence, high agreement*). Financing mechanisms are essential for the transformation of the building sector to address the high upfront investments costs for renovation of existing buildings and the installation of on-site renewable energies (*robust evidence, high agreement*).

## 9.1 Introduction

In 2018, global buildings $CO_2$ emissions (when direct, indirect and embodied emissions are considered) accounted for 32.2%[1] of global $CO_2$ emissions (International Energy Agency 2019a). In terms of final energy demand, buildings accounted for 29% of the global energy demand and 29.3% of the global electricity demand (International Energy Agency 2019a). This is a 10% increase compared to 2010. Importantly, the highest increase in buildings emissions and energy demand have taken place in the developing world as a result of the improved of Standard of Living for millions of people and this increase is expected to continue in the coming years with the implementation of SDGs and the increased well-being for all.

Therefore, emissions reduction and mitigation measures in the building sector received more and more attention in recent years. This is supported by the growing scientific evidence about the identified mitigation potential in the building sector. In fact, among all end-use sectors, the building sector plays a central role in the low carbon transition in the long run (IPCC, 2018; IEA, 2019b).

This chapter aims at updating the knowledge on the building sector since the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Ürge-Vorsatz et al. 2014) from a mitigation perspective. Changes since AR5 are reviewed, including: the latest development of building service and components (Section 9.2), new building related GHG emission trends (Section 9.3), latest technological (Section 9.4) and non-technological (Section 9.5) options to mitigate building GHG emission, global and regional cost analysis (Section 9.6), links to adaptation (Section 9.7) and sustainable development (Section 9.8), and sectoral barriers and policies (Section 9.9).

Buildings are very heterogeneous in many different aspects, from their components (envelope, structure, etc.) to their services (shelter, heating, etc.) to their types (residential and non-residential, sometimes also called commercial). The heterogeneity is also reflected in size, value-added, function, and climate. This heterogeneity is described in detail in Section 9.2.

It should be highlighted that the buildings chapter in AR6 has set its limits to individual buildings and cluster of buildings, keeping the difference with the urban system (Chapter 8).

Compared to AR5, this assessment introduces four novelties (i) the scope of $CO_2$ emissions has been extended from direct and indirect emissions considered in AR5 to embodied emissions, (ii) beyond efficiency measures to mitigate GHG emissions in the built environment, the contribution of sufficiency measures to climate mitigation are also considered, (iii) compared to SR1.5, the link to sustainable development, well-being and Decent Living Standard (DLS) for all has been further developed and strengthened, and finally (iv) the active role of buildings in the energy system by making passive consumers prosumers is also assessed.

The novelties introduced in this assessment reflect the growing literature on each of them and the inclusion of each concept in recent and/or announced policy changes as described briefly in the following sections:

1. The scope of emissions in the building sector. Three scopes have been considered in this assessment:
    a. Direct emissions: Building sector GHG emissions refer to emissions within the buildings, which includes direct energy related emissions ($CO_2$, $NH_4$, and $N_2O$) within buildings and F-Gases emissions related to aerosols, fire extinguishers, soundproof

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[1] Based on preliminary data provided by the IEA for the purpose of this report. Final figures will be provided for the SOD. Embodied emissions considered in these estimates are those related to cement and steel only.

windows, and HVAC equipment. $CO_2$ emissions are by far the dominant greenhouse gas from direct emissions.

b. Indirect emissions: The second category of emissions allocated to buildings are the indirect ones which result from power generation used to produce electricity for building as well as heat production. The indirect emissions represent the largest share of overall building emissions.

c. Embodied emissions: The third category of emissions from buildings refers to the emission from the building life cycle assessment (LCA) perspective. This means GHG emission is not only related to the day-to-day operation of the building, but also building related up-stream and down-stream value chain, such as GHG emissions from the building materials production, building construction, and building demolition and recycle of the waste building material, should be considered.

Including embodied emissions in this assessment reflects the growing literature (Röck et al. 2020; Cang et al. 2020) on this third category of emissions and their role in mitigation pathways. It also reflects on the announced changes in building policies. According to (Schwarz et al. 2019), the announced French 2020 building code for new buildings includes requirements to reduce emissions for the three scopes described above. Furthermore, after more than forty years of naming building codes thermal regulation, the 2020 French building code for new buildings will be named Environmental building code to ensure new buildings will contribute to the recently adopted French carbon neutrality target for 2050.

2. Going beyond efficiency and including sufficiency measures in mitigation pathways and policies

Sufficiency is not a new concept. It was introduced in early nineties by (Sachs, 1993). Sufficiency goes beyond the dominant framing of energy demand under efficiency and behaviour (Jensen et al. 2016). While efficiency measures address the improvement of energy intensity, sufficiency measures address the energy services which deliver well-being (Kalt et al. 2019). Sufficiency tackles the drivers of energy demand and aims at avoiding them. This is in line with the first pillar of the AVOID (sufficiency), IMPROVE (efficiency) and SHIFT (to renewables) framework developed in Chapter 5 and corresponds to the emphasis on improving wellbeing with service provisioning systems that are low in energy input, as explained in Chapter 5.2, and as quantitatively explored in Chapter 5.3. Furthermore, while efficiency addresses only the energy consumption dimension and the behaviour approach puts the responsibility on individuals, sufficiency addresses the resource nexus which links energy to land-use, food and minerals and calls for changes in the organisation of societies and their economies. The sufficiency scope goes far beyond the technological improvements of the efficiency scope and the use of each appliance separately. Sufficiency considers human needs and well-being in the broader context of planetary boundaries (Heindl and Kanschik 2016a). Moreover, (Lorek and Spangenberg 2019) argue that combining sufficiency with efficiency allows addressing the rebound effect.

Therefore, when evaluating climate change mitigation measures in buildings one of the first considerations to be taken into account is the differences and the complementarities between sufficiency and efficiency measures (International Energy Agency 2013; Cabeza and Chàfer 2020). Sufficiency includes those measures that do not require energy to be implemented (i.e. bioclimatic design, natural ventilation, land-use optimisation, and some behavioural changes such as wearing warm clothes when it is cold instead of increasing indoor temperature (see section 9.5)). Moreover, sufficiency measures contribute to deliver energy savings if they are implemented before efficiency ones as sufficiency avoids the demand for energy without compromising on the well-being of the occupants. On the other hand, efficiency delivers the required energy services with a minimum of energy and preferably from renewable energy sources to ensure buildings are decarbonised. The combination of sufficiency, efficiency and renewable is followed throughout this chapter.

There is not yet an agreed international definition of sufficiency. However, sufficiency is framed around three pillars in the literature including infrastructure which drives the demand for energy services, social organisation which influences behaviour and resource efficiency which links energy to other resources such as land, water, food and minerals (Saheb & al, 2020).

A review of the sufficiency measures in residential sub-sector by Šćepanović et al. (2017) highlights the importance of contexts to realise their mitigation potential. This review discusses the first two pillars of sufficiency and suggests considering (i) the physical (environmental) context and (ii) the socio-economic context when assessing sufficiency measures and their mitigation potential. Environmental context includes building factors such building type (single-family home) multi-family apartment), climate, urban/rural, automation of buildings and its impact on behaviour change while socio-economic context includes factors such as household size, co-housing, co-working space, ownership of appliances and equipment which usually relates to shared economy. The former was identified by (IEA, 2013) as one of the sufficiency pillars which leads to reduce the demand for heating and cooling without compromising on the well-being of the occupants. It links the building sector to land-use and urban policies while the socio-economic context links buildings to the broader organisation of the society.

The third pillar of sufficiency relates to resource efficiency which is addressed today by the circular economy. In fact, there is growing literature on a circular economy approach to the built environment. Circular economy aims at avoiding the construction of unnecessary buildings. It is also about extending the lifetime of buildings and their components, and reusing/recycling them after their lifetime. Key concepts of the circular economy approach that have been applied to the buildings sector include cradle-to-cradle (Wilts 2016; Bjørn and Strandesen 2011), zero waste (Ghisellini et al. 2016; Wilts 2016; Lehmann 2011), blue economy (Wilts, 2016), and eco-efficiency (Ghisellini et al. 2016).

3. Linking climate mitigation to SDGs and well-being for all.

Providing Decent Living Standards (DLS) for all is one the ultimate objectives of SDGs. Literature suggests that mitigation measures in the built environment go beyond meeting SDG 7 on affordable and clean energy and SDG 13 on climate action and contribute indirectly to meeting other SDGs. (Roy et al. 2018) shows that climate mitigation actions in the built environment contribute to achieving 16 out of the 17 SDGs. In fact, decarbonisation of the built environment contribute to reducing health care expenditures and thus poverty (SDG1), achieving good health and well-being (SDG3), improving quality of education (SDG4) and enhancing gender equality (SDG5) (McCollum et al. 2018; Maidment et al. 2014; Berrueta et al. 2017). Other scholars argue that improvements in social wellbeing associated with mitigation actions in the built environment such as improved access to energy sources, energy poverty alleviation, increased thermal comfort etc., contribute to achieving 11 SDGs, including good health and well-being (SDG3), quality of education (SDG4), affordable and clean energy (SDG7), sustainable cities and communities (SDG11), and peace, justice and strong institutions (SDG16) (Saheb et al. 2018a) (Berrueta et al. 2017; Liddell and Guiney 2015; Cameron et al. 2016; Ürge-Vorsatz et al. 2016; McCollum et al. 2018) (see section 9.8).

4. Integrating buildings in the energy systems

   Buildings are contributing to the great challenge of the energy sector where consumers take an active participation, becoming prosumers (users who consume and produce energy) (Sánchez Ramos et al. 2019; Miller and Senadeera 2017). This aspect will be discussed in Section 9.5. Moreover, the prosumer concept is very much related to the fact that buildings are changing their role in the energy system and in cities, by becoming power plants (Ürge-Vorsatz et al. 2020). Decarbonisation of buildings includes a broad perspective addressed in the chapter, from using materials with less embodied carbon to the on-site production of low-carbon electricity, always starting by avoiding the demand for energy and lower energy consumption through the implementation of sufficiency measures followed by efficiency ones.

The four novelties introduced in this assessment link the building sector to other sectors and call for more sectoral coupling when designing mitigation solutions as shown in Figure 9.1. GHG emissions of the building sector are related to all other chapters in this report. The guidelines and methodologies used in Chapters 1, 2, 3, 4 and 5 are adopted in this chapter. Detailed analysis in building GHG emissions are discussed based on the general analysis of Chapters 2, 3 and 4, drivers of energy demand are discussed in Chapter 2. Tight linkages between this chapter and other sectoral Chapters, which are Chapters 6, 7, 8,10 and 11 are assessed as shown in Figure 9.2. Furthermore, Chapter 9 provides a sound basis for the cross-sectoral prospection (Chapter 12), policies (Chapter 13), international cooperation (Chapter 14), investment and finance (Chapter 15), innovation (Chapter 16), and sustainable development (Chapter 17).

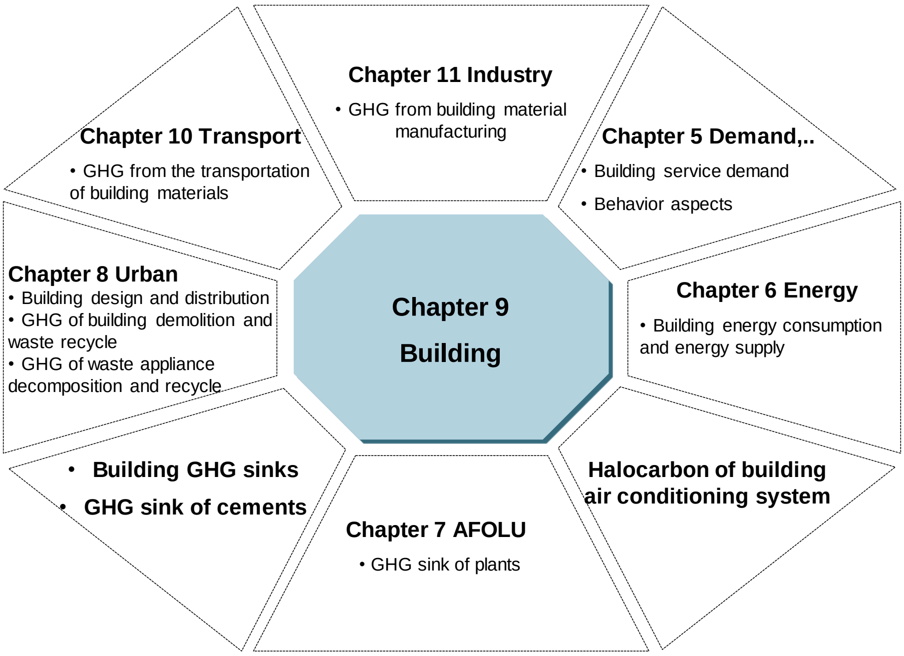


**Figure 9.1 The connection between Chapter 9 with other chapters**

Bibliometric overview of the literature related to buildings: a literature map was carried out, to enable a robust and transparent assessment of the role of buildings in climate change mitigation (Cabeza et al. 2020b). The studied period was mainly from 2013 to 2019 and the literature search was carried out both in the Web of Science and in Scopus. The search included all the sections of this chapter and a long exclusion list was developed. The links between the topics with more papers can be found in Figure 9.2. The figure shows three clear clusters, one related to climate change and more non-technological, sociotechnical and institutional topics (e.g. climate change, opportunity, government, practice), one related to the building itself (e.g. structure, concrete, mechanism), and one related to energy efficiency and heating and cooling in buildings (e.g. energy savings, temperature, ventilation).

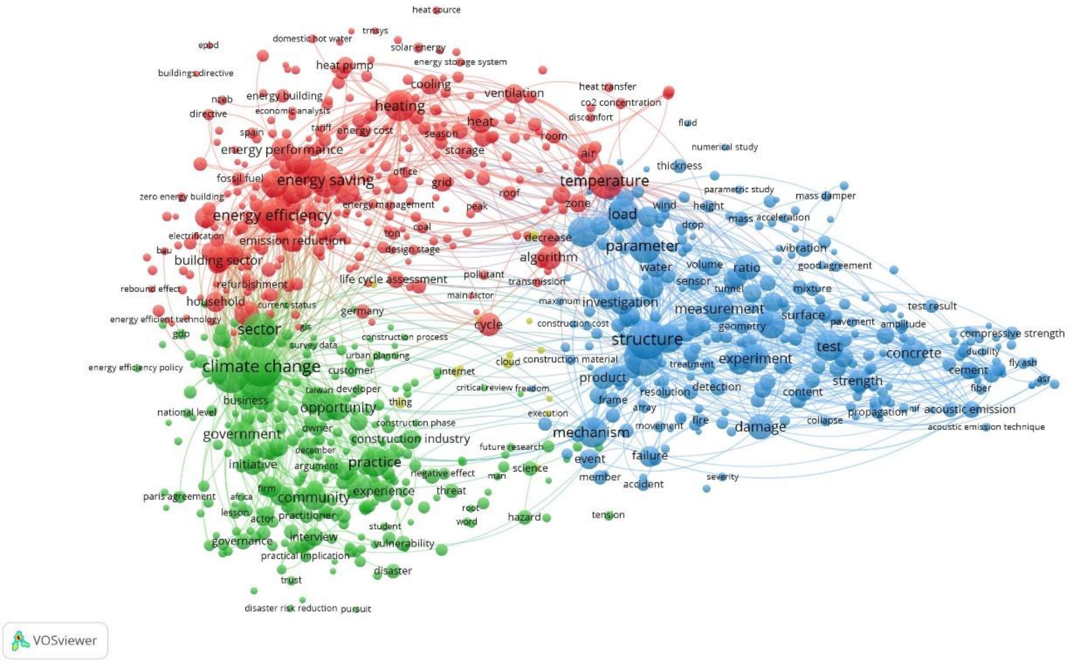


**Figure 9.2 Literature map of the chapter Buildings (Cabeza et al. 2020b)**

## 9.2 Services and components

This section mainly details the boundaries of the building sector rather than evaluate mitigation potentials that are done in following sections.

### 9.2.1 Building types

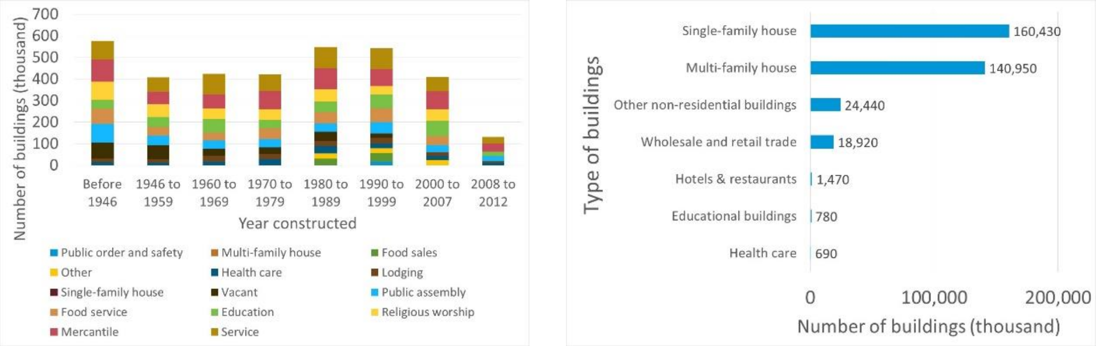
Building types and their composition affect the energy consumption for building operation as well as the GHG emissions (Hachem-Vermette and Singh 2019). They also influence the energy cost in the influence of ventilation (MacNaughton et al. 2015) therefore, an identification of building type is required to understand the heterogeneity of this sector. Buildings are classified as residential and non-residential buildings. Residential buildings can be classified as slums, single-family house and multi-family house or apartment/flats building. Single-family house can be divided between single-family detached (including cottages, house barns, etc.) and single-family attached (or terrace house, small multi-family, etc.). Non-residential buildings have a much broader use, and the different types are shown in Table 9.1.

**Table 9.1 Types of non-residential buildings**

| Type of building | Specific | Use |
|---|---|---|
| Cultural | Theatres and performance | Theatre |
| | | Cinema |
| | | Arts centre |
| | | Auditorium |
| | | Amphitheatre |
| | | Concert / opera House |
| | Museums & Exhibit | Museum |
| | | Gallery |
| | | Pavilion |
| | | Exhibition centre |
| | Library | -- |
| | Cultural centre | -- |
| Educational | Kindergarten | -- |
| | Higher education | University/College |
| | | Institute |
| | Middle education | Elementary and middle school |
| | | High school |
| | Research Centre | -- |
| | Laboratory | -- |
| | Other facilities | Dorms |
| | | Students hall |
| Sports | Recreation & Training | Gymnasium |
| | | Fitness club |
| | | Sports field |
| | Stadiums | -- |
| Healthcare | Health | Hospital |
| | | Day care |
| | | Dental clinic |
| | | Rehabilitation centre |
| | | Asylum |
| | | Retirement |
| | | Clinic |
| | Wellbeing | Spa |
| | | Term |
| | | Sauna |

| | | |
|---|---|---|
| | | Bath house |
| | Veterinary | Veterinary clinic |
| | | Animal shelter |
| Hospitality | Casino | -- |
| | Hotel | -- |
| | Lodging | Hostel |
| | | Motel |
| | | Cabins & lodges |
| | Nightlife | Pub |
| | | Night club |
| | | Dance club |
| | Restaurants & Bars | -- |
| Commercial & Offices | Institutional buildings | -- |
| | Market | -- |
| | Office Building | -- |
| | Retail | -- |
| | Shopping Centres | -- |
| Public | Security | Fire station |
| | | Police station |
| | | Emergency services facilities |
| | Military | -- |
| | Government | Embassy |
| | | City hall |
| | | Ministry building |
| | | Municipal building |
| | | Other public administrations buildings |
| Religious | Worship | Church |
| | | Cathedral |
| | | Monastery |
| | | Temple |
| | | Chapel room |
| | | Mosque |
| | | Synagogue |
| | Burial | Cemetery |
| | | Crematorium |
| | | Memorial centre |
| Industrial | Factory | -- |
| | Energy plant | -- |
| | Warehouse | -- |
| | Data-centre | -- |
| | Transportation | Airport |
| | | Train station |
| | | Bus station |
| | | Port |
| | | Metro station |
| | Agricultural | Abattoir/slaughterhouse |
| | | Farmhouse |
| | | Barn/stable |
| | | Greenhouse |

Data of building stock is available for USA (Administration 2020a,b) and EU-28 (Union 2020) (Figure 9.3). The number of buildings constructed every decade in the USA varies between 400,000 and 550,000. In Europe, about 90% of buildings are residential; between those around 55% are single-family houses and 45% are multi-family houses. About 40% of non-residential buildings are wholesale and retail trade buildings.



(a) (b)

**Figure 9.3 Trends in buildings stock. (a) USA** (Administration 2020b,a)**, (b) EU-28** (Union 2020)

### 9.2.2 Building components

An understanding of the methods for assembling various materials, elements, and components is necessary during both the design and the construction phase of a building. A building can be broadly divided into parts: the substructure which is the underlying structure forming the foundation of a building, and the superstructure, which is the vertical extension of a building above the foundation.

There is no global classification for the building components. For that reason, Table 9.2 and Figure 9.4 try to summarise the building components found in literature (Asbjørn 2009; Ching 2014; Mañá Reixach 2000). Moreover, buildings have evolved from the use of vernacular architecture, manly characterised by the use of local materials and knowledge, to a more modern architecture, which includes smart buildings and new technologies. Vernacular architecture it is still the prominent one in developing countries. This evolution of buildings is shown in Figure 9.5.

**Table 9.2 Building components**

| | | |
|---|---|---|
| Substructure | Foundation | Footing |
| | | Basement |
| | | Plinth |
| Superstructure | Primary | Walls - heavyweight walls |
| | | Columns |
| | | Floors - ceilings |
| | | Roofs |
| | | Sills and lintels |
| | | Stairs |
| | Supplementary components | lightweight walls |
| | | Curtain walls |
| | Completion components | Doors |
| | | Windows |
| | Finishing work | Plastering and painting |
| | Building services | Plumbing |
| | | Electrical |
| | | Water supply |
| | | Sewerage |
| | | Equipment |
| | | Furniture |
| | | Etc. |

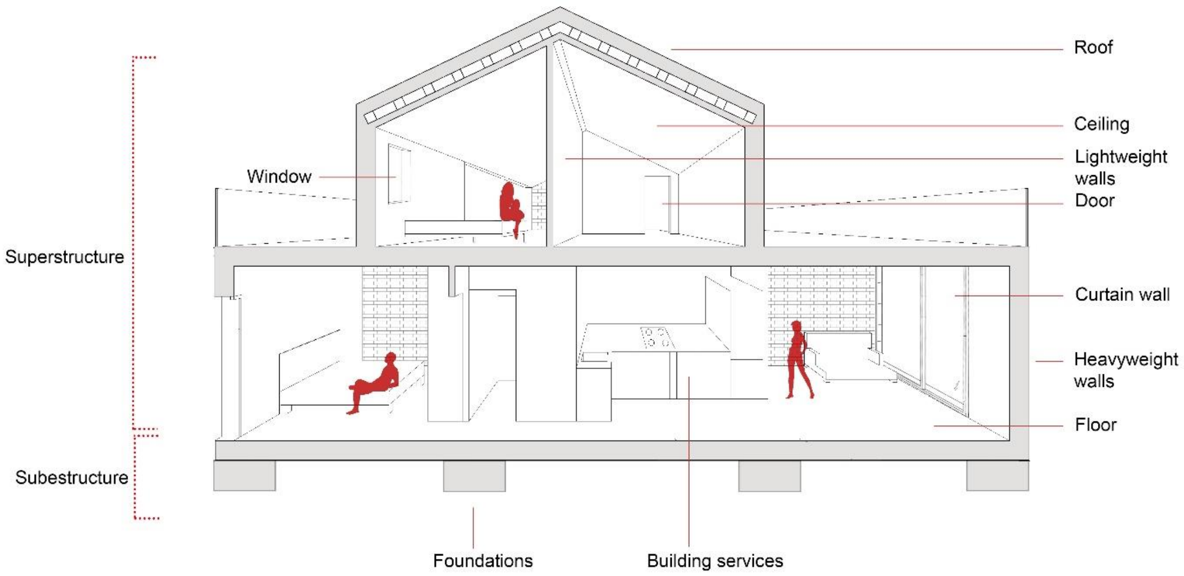


Figure 9.4 The main building components

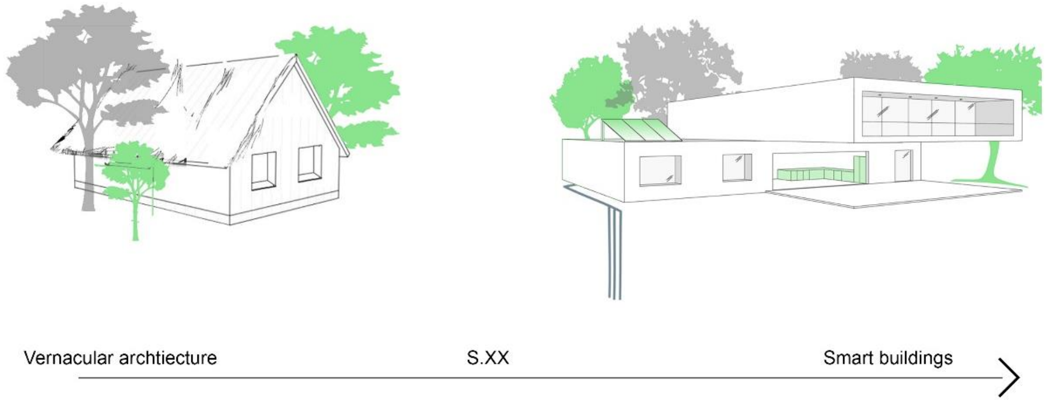


Figure 9.5 Evolution of the building construction

### 9.2.3 Building services

Building services make buildings more comfortable, functional, efficient, and safe. In a generic point of view, building services include shelter, nutrition, sanitation, thermal comfort, entertainment and communications, and illumination. These services are delivered through building management systems, energy generation; distribution and supply; heating, ventilation, air conditioning (HVAC); escalators and lifts; facade engineering; fire safety; detection and protection; ICT networks; lighting; lighting protection; refrigeration; security and alarm systems; and water, water heating, drainage and plumbing. (Illankoon and Lu 2019) already stated that building services are indispensable for low-energy buildings and that in practice are today considered independently while if considered holistically the result would be much greater.

Figure 9.6 shows schematically the means used to deliver on building energy services available in today buildings.

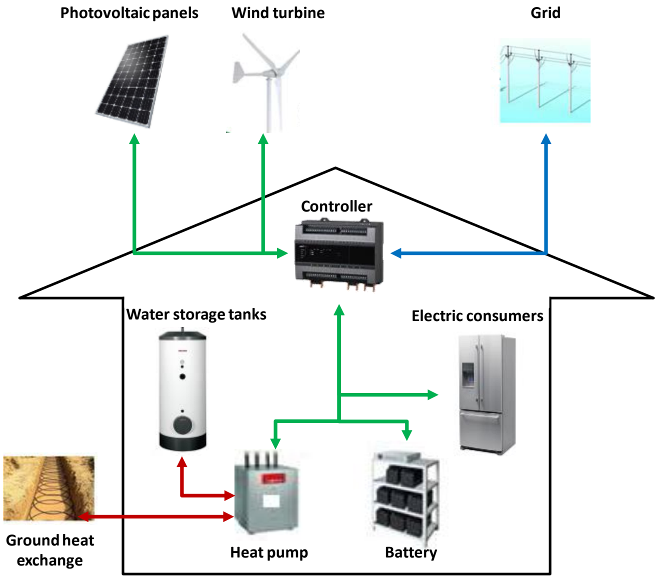


**Figure 9.6 Schematic diagram of building energy services** (Shcheklein et al. 2017)

A building management system is a system of devices configured to control, monitor, and manage equipment in or around a building or building area and is meant to optimize building operations and reduce cost (Kelsey Carle Schuster, Youngchoon Park 2019). Recent developments include the integration of the system with the renewable energy systems (Arnone et al. 2016); most improved and effective user interface (Rabe et al., 2018); integrated with wireless communication (Chavan et al. 2018).

Natural ventilation offsets energy consumption in buildings (Azmi et al. 2017; Taleb 2015). Building designs have to consider provision of adequate ventilation. Enhanced ventilation has higher benefits to the public health than the economic costs involved (MacNaughton et al. 2015).

The use of air conditioning systems in buildings will increase with the experienced rise in temperature (Davis and Gertler 2015; De Falco et al. 2016) (see Section 9.7). This can ultimately lead to high energy consumption rates. Therefore, adoption of energy efficient air conditioning is pertinent to balance the provision of comfortable indoor conditions and energy consumption. Some of the new developments that have been done include ice refrigeration (Xu et al. 2017), the use of solar photovoltaic power in the air conditioning process (Davis and Gertler 2015) and use of common thermal storage technologies (De Falco et al. 2016) all of which are geared towards minimizing energy consumption and greenhouse gas emissions.

On the refrigeration systems, the recent developments include the use of solar thermoelectric cooling technologies as an energy efficient measure (Liu et al. 2015); use of nanoparticles for energy saving (Azmi et al. 2017) to mention some.

Lambertz et al. 2019 (Lambertz et al. 2019) stated that when evaluating the environmental impact of buildings, building services are only considered in a very simplified way; this document considers building energy services and sanitary. The literature relating building services and climate change (Vérez and Cabeza 2020) shows that literature on building services considers elevators, lighting and light sources, ventilation related to computer simulation, energy efficiency related to office buildings, human aspects related to economics, and intelligent buildings related to architecture; finally, climate change impacts are related to thermal comfort. Building services consider climate change aspects only when considering building energy services and lighting, but others are not included in those studies. Recently, the importance of embodied energy is highlighted (Parkin et al. 2019).

## 9.3 New developments in emission trends and drivers

### 9.3.1 Past emissions trends

### *9.3.1.1 Global emissions trends*

Total $CO_2$ emissions in the building sector reached 11.81 Gt in 2018 out of which 56% were indirect[2] emissions resulting from the use of carbonised electricity and heat, followed by 26% of direct emissions and 18% of emissions resulting from the use of cement and steel[2] for the construction and/or refurbishment of buildings (Figure 9.7).

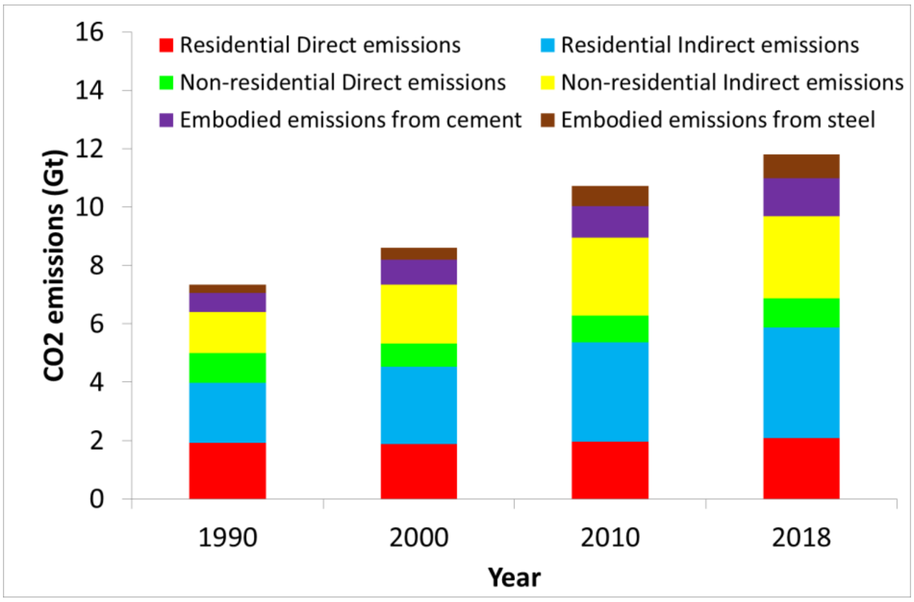


**Figure 9.7 Trends in global direct, indirect and embodied $CO_2$ emissions in the building sector**
(International Energy Agency 2019b)

Over the period 2010-2018, global $CO_2$ emissions in the building sector experienced an increase of 10% while the shares of $CO_2$ emissions per sub-sectors remained stable with the residential sub-sector representing 60% of total $CO_2$ emissions of the global building stock. Over the same period, indirect $CO_2$ emissions increased by 11% in residential buildings and 6% in non-residential ones while direct emissions increased by 7% in the former and 8% in the latter.

Direct emissions from $CH_4$ and $N_2O$ were, in 2018, negligible compared to direct $CO_2$ emissions with 0.01Gt of $CH_4$ emissions and 0.0001 Gt of $N_2O$ emissions. The following section will therefore focus on $CO_2$ emissions only.

### *9.3.1.2 Regional $CO_2$ emissions trends*

The building stock in the developed world experienced a decrease of its direct and indirect emissions except in North America where an increase of a 3% was observed in residential buildings and almost no changes were experienced in direct emissions in non-residential buildings in this region over the period 2010-2018. The highest decrease of direct emissions was observed in residential buildings in Europe with 19% decrease, followed by non-residential in Europe with 10% decrease while in developed Asia-Pacific the decrease of direct emissions was at 3% in residential buildings and 3.6% in non-residential ones (Table 9.3).

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[2] Preliminary figures based on IEA data provided for indication only. Final figures will be provided in the SOD.

Regarding indirect emissions, North America and Europe have both experienced a decrease of their emissions. The highest decrease was observed in North America as a result of a shift from coal to gas in power generation, followed by Europe as a result of the increased penetration of renewables in power generation under the implementation of the 2020 renewable energy target (see Section 9.9 on policies). Developed Asia-Pacific countries experienced an increase of 4% of non-residential buildings indirect emissions due to the use of coal in power generation. When it comes to embodied emissions, based on the preliminary data available, Asia-Pacific is the only developed region which has experienced a decrease of its emissions from both steel and cement while Europe and North America have both experienced an increase of their emissions.

The building stock in the developing world experienced an increase of its direct, indirect and embodied emissions driven by the increase access to energy (see Section 9.8 on SDGs) and the economic growth in many of the developing and emerging countries. The only decrease in emissions observed was in the non-residential Eurasian building stock which might be due to the slow economic activity in the major countries in the region. The highest increase in direct emissions was observed in Africa in both residential, 44%, and non-residential, 52%, buildings while the highest increase in indirect emissions was observed in Eastern-Asia, with 62% in residential buildings and 66% in non-residential ones, followed by the region of South and South Asia and developing Pacific, with 53% in residential buildings and 43% in non-residential ones, driven by the use of coal for power generation in both regions (Table 9.3). When it comes to embodied emissions in steel and cement, the highest increase was observed in the region of South and South-East Asia and developing Pacific, with 67% increase from the use of cement and 54% increase from the use of steel.

**Table 9.3 Trends in regional direct, indirect and embodied $CO_2$ emissions in the building sector over the period 2010-2018** (International Energy Agency 2019c)

| Region | Direct | | Indirect | | Embodied[3] | |
|---|---|---|---|---|---|---|
| | Residential | Non-residential | Residential | Non-residential | Cement | Steel |
| North America | +3% | -0.4% | -23% | -19% | +8% | +2% |
| Europe | -19% | -10% | -20% | -18% | +6% | +8% |
| Asia-Pacific Developed | -3% | -3.6% | -4.2% | +4% | -10% | -12% |
| Latin America and Caribbean | +8.6% | +8.2% | +19.4% | +19.5% | +1% | Not available |
| Africa | +44% | +52% | +25% | +21% | +29% | +15% |
| Middle East | +4.4% | Not available | +28% | +33% | +26% | +12% |
| Eurasia | +44% | -13% | -14% | -9% | +30% | +42% |
| Eastern Asia | +25% | +17.5% | +62% | +66% | +7% | +13% |
| South and South-East Asia and developing Pacific | +20% | +18% | +53% | +43% | +67% | +54% |

Regional aggregation is based on IEA 2019 World Energy Outlook aggregation which differs from the IPCC AR6 regional aggregation for Europe (IEA aggregation includes Israel, Belarus, Moldova and Macedonia).

### 9.3.1.3 *Emissions from Halocarbons*

According to Hu and Cabeza, 2020, building sector halocarbon emission exceeded those of industry production process and became in 2017 the dominant source of HFCs emission. There are five regions which are the main building HFCs emitters. The United States and the EU are the historical high

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[3] Preliminary figures based on IEA data provided for indication only. Final ones will be provided in the SOD.

emitters of halocarbons while China emerged, recently, as the third emitter of Halocarbons followed by Japan and Russia. Assessment of Halocarbons emissions from these five countries/regions reveals that around 60% of the HFCs emissions are related to the building sector. Furthermore, global estimates show that building HFCs account for 8% total building sector GHG emission, which is equivalent to cooling related $CO_2$ emission in 2017 (Hu and Cabeza 2020).

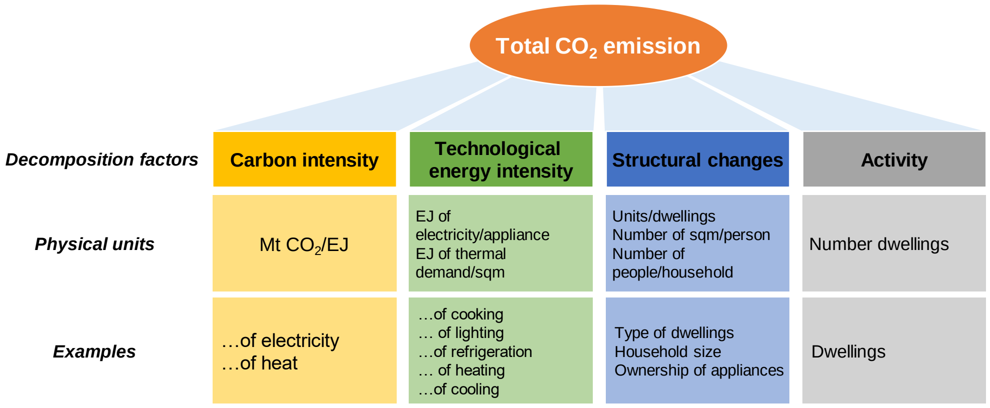
#### *9.3.1.4 Drivers of $CO_2$ emissions*

In this assessment, the review focuses on the main decomposition logic described in Chapter 2, adopted for the building sector by considering four identities (Figure 9.8) including:

1. The carbon intensity identity which is calculated separately for electricity and for heat in $MtCO_2/EJ$
2. The technological energy intensity identity which is calculated separately for each energy service (i.e. lighting, refrigeration, heating, cooling)
3. The structural identity which considers trends in dwellings occupancy (number of square meters per person), household size (number of persons per dwellings) and ownership of appliances and equipment (number of appliances per dwellings).
4. The activity which considers trends in the number of dwellings for residential buildings. In the case of non-residential buildings, the activity is estimated by considering the value added for each building type (i.e. office buildings, warehouse). However, due to the lack of data on the activity per building type, the decomposition analysis is not considered for non-residential buildings.

Total $CO_2$ emissions are decomposed as follows:

$$CO_2 emissions = Carbon\ intensity \cdot Technological\ energy\ intensity \cdot Structural\ intensity \cdot Activity$$



| Decomposition factors | Carbon intensity | Technological energy intensity | Structural changes | Activity |
|---|---|---|---|---|
| Physical units | Mt $CO_2$/EJ | EJ of electricity/appliance<br>EJ of thermal demand/sqm | Units/dwellings<br>Number of sqm/person<br>Number of people/household | Number dwellings |
| Examples | …of electricity<br>…of heat | …of cooking<br>… of lighting<br>…of refrigeration<br>… of heating<br>…of cooling | Type of dwellings<br>Household size<br>Ownership of appliances | Dwellings |

**Figure 9.8 Decomposition logic of $CO_2$ emissions in the residential sub-sector**

[Place holder, decomposition analysis of the drivers will be included in SOD]

### 9.3.2 Past energy demand trends

#### *9.3.2.1 Global trends in energy demand*

Over the period 2010-2018, global energy demand of buildings increased by 10% (Figure 9.9). The highest increase was observed in non-residential buildings, with a 13% increase against 8% in residential energy demand. In the former, the energy demand increase was driven by Eastern Asia with a 55% increase, followed by Africa with 43% and the region of South and South-East Asia and developing Pacific which has experienced an increase of 34%. Energy demand of non-residential buildings in North America experienced the lowest increase with 4% more total energy demand while Europe and the developed Asia and Pacific have experienced a decrease of the non-residential energy demand of 3% and 1% respectively.

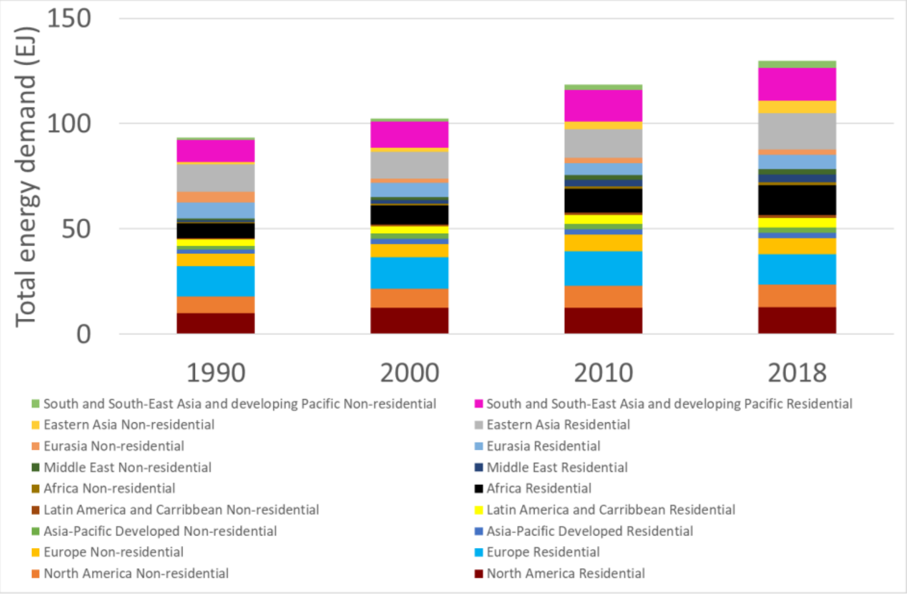


**Figure 9.9 Total energy demand per sub-sector and region** (International Energy Agency 2019c)

Similarly, residential energy demand experienced an increase in all regions except Europe and the developed Asia and Pacific where residential energy demand decreased by 11% and 5% respectively. Although, the residential floor area increased by 11% in the former and 7% in the later. The highest increase of residential energy demand was observed in Eastern Asia, with a 26% increase followed by Africa which has experienced an increase of 26%. Middle East and Eurasia have both experienced an increase of 15% in their residential energy demand over the same period while North America experienced a slight increase of 1% of its residential energy demand despite the increase of residential floor area by 11%.

The negative correlation between the residential energy demand and the residential floor area observed in Europe, the developed Asia and Pacific region and North America could be explained by the implementation of building energy codes in these regions for more than 40 years in almost all the countries (see Section 9.9) in these regions and the high penetration of efficient technologies (see Section 9.4) as a result of efficiency standards (see Section 9.9). Similarly, the positive correlation between residential energy demand and residential floor area could be explained by the lack of policies targeting the reduction of energy demand of the building stock in most of the countries in these regions (see Section 9.9) as well as the low penetration of highly efficient technologies (see Section 9.4).

### *9.3.2.2 Use of biomass*

Biomass can be used for cooking, heating but also for the construction of buildings. The use of biomass in the form of wood as a construction material in buildings contributes to greenhouse gas emissions abatement by storing carbon and displacing high carbon materials such as cement, brick and steel (Committee on Climate Change, 2018). This would contribute to reducing embodied emissions of the built environment. Furthermore, clean biomass is used in developed countries for generating heat and power for buildings (Ortwein 2016)(Ericsson and Werner, 2016) which contributes to reducing the indirect emissions of buildings. However, the use of clean biomass in modern heating remains low (International Energy Agency 2019d) despite its mitigation potential. Clean biomass could also be used for cooking and for heating using modern appliances such as pellet-fed central heating boilers.

On the other hand, traditional biomass is still an important source of energy in the developing world. The global use of traditional biomass decreased by only 3% over the period 2010-2018 despite the international effort under SDGs (see Section 9.8) to reduce the harmful impact of the use of traditional biomass. In fact, the use of traditional biomass is associated with public health risks such as premature deaths related to inhaling fumes from cooking (International Energy Agency 2019d). Dixon et al. (2015) argues for improved cooking stoves and the use of charcoal with high efficiency to limit the health risks of the use of biomass.

The highest decrease in the use of traditional biomass was observed in Eastern Asia, with a 41% decrease, followed by Middle East with 10% decrease and the region of the South and South-East Asia and developing Pacific with a decrease of 8%. Africa experienced the highest increase in the use of traditional biomass, with a 20% increase, over the period 2010-2018, followed by Latin America and Caribbean countries which have experienced an increase of 3% in the use of traditional biomass. Traditional biomass is also still in use in some of the developed countries for district heating such as in Turkey where more than 14 % of the energy production is derived from traditional biomass (Toklu 2017); Greece where traditional biomass is mentioned as one of the potential source for energy production (Michopoulos et al. 2014); and Portugal where traditional biomass is considered as one of the potential energy sources (Ferreira et al. 2017).

#### 9.3.2.3 Emerging trends in residential energy demand

Over the period 2010-2018, three trends have emerged in residential energy demand. These new trends include the changes in electricity demand due to the electrification of thermal energy services, the increased global cooling demand and the increased energy demand due to the use of digital technologies as described below.

*Changes in electricity demand*

Over the period 2010-2018, global electricity demand increased by 25% (Figure 9.10) driven by the increased access to electricity in deprived regions as a result of the implementation of SDG 7 (See Section 9.8). The highest increase of electricity demand was observed in Eastern Asia with 97% increase, followed by a 64% increase in the region of South and South-East Asia and developing Pacific and a 37% increase in Africa. Europe and the developed region of Asia Pacific have both experienced a decrease in their electricity energy demand of 5% and 7% respectively while North America experienced a slight increase of 1%. This reflects the policies implemented in these regions (see Section 9.9) which have led to a high penetration in these regions of efficient technologies (see Section 9.4).

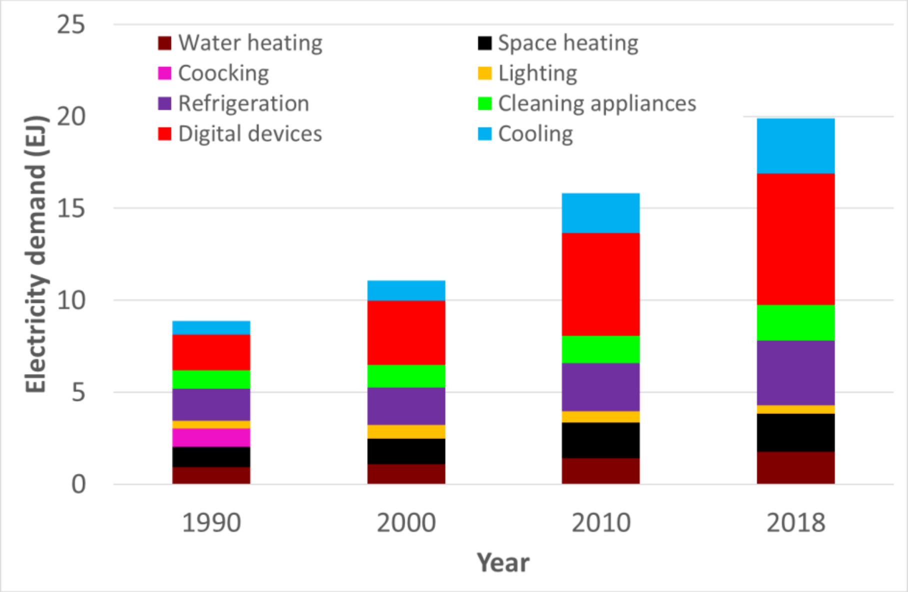


**Figure 9.10 Trends in global electricity demand per energy services** (International Energy Agency 2019c)

An important emerging trend in electricity demand is the use of electricity for thermal energy services such as cooking, hot water and space heating. Over the period 2010-2018, global electricity demand for cooking increased by almost 36% driven by electricity demand in Eastern Asia where it has more than doubled, followed by Eurasia which has experienced an increase of 40%. Electricity demand for cooking has almost stagnated in North America while it increased by 4.5% in the developed region of Asia and Pacific.

Hot water is the second energy service experiencing a global increase in electricity demand. Over the period 2010-2018, electricity demand for hot water increased by 24% driven by the increase of hot water electricity demand in Eastern Asia where it has more than doubled and in the region of South and South-East Asia and developing Pacific where hot water electricity demand has almost doubled. Africa, Middle East and Eurasia experienced an increase of more than 30% in electricity demand for hot water while North America and Europe have experienced an increase of more than 5% each. The developed region of Asia Pacific is the only region which has experienced a decrease of 10% in its electricity demand for hot water.

Regarding electricity demand for space heating, the global increase experienced over the period 2010-2018 was at 7% which makes it the lowest increase of electricity demand per energy service. The highest increase was observed in the region of South and South-East Asia and developing Pacific where electricity demand for space heating has more than doubled, followed by Eastern Asia where an increase of 79% was observed. Europe experienced the highest decrease of electricity demand for space heating, with a 26% decrease over the same period.

Electricity demand for cleaning appliances has also experienced, an increase in all regions except North America which has experienced a decrease of 3%. The highest increase was observed in Eastern Asia, with 81% increase, while the lowest increase was experienced in Europe with 8.4% increase over the period 2010-2018.

Global electricity demand for lighting is the only one which has experienced a decrease over the period 2010-2018. The observed global decrease of 24% in lighting demand was driven by a decrease of electricity demand for lighting in all regions except Eastern Asia and Africa which have experienced an increase of 14% and 8.8% respectively. This increase could be explained by the increased access to electricity in the developing world as a result of the implementation of SDG 7 (see Section 9.8). The highest decrease in electricity demand for lighting was observed in the developed region of Asia Pacific, with a 46% decrease, while the lowest decrease was observed in Middle East with a 2% decrease over the same period.

*Cooling energy demand*

Over the period 2010-2018, global cooling demand increased by 40% in the residential sub-sector (Figure 9.11). The highest increase was observed in Eastern Asia where cooling demand has more than doubled, followed by the region of South and South-East Asia and developing Pacific, with an increase of 98%, and Africa, with an increase of 96% of cooling demand, over the same period. Eurasia and the developed region of Asia-Pacific are the only two regions which have experienced a decrease in their cooling demand, with 17% and 10% decrease respectively. Europe, Latin America and Caribbean countries as well as Middle East have also experienced an increase of their cooling demand of 24%, 53%, 44% respectively.

The increased cooling demand can be partly explained by the increased ownership of room air-conditioners per dwellings in all regions to address global warming. The highest increase, 32%, in ownership of room air-conditioners was observed in the region of South and South-East Asia and developing Pacific while Europe, Latin America and Caribbean countries, Eastern Asia and Africa experienced an increase of 21% in households' ownership of room air-conditioners. The lowest increases in room air-conditioners ownership were observed in the Middle East and North America with 1% and 8% each as these two markets are almost saturated.

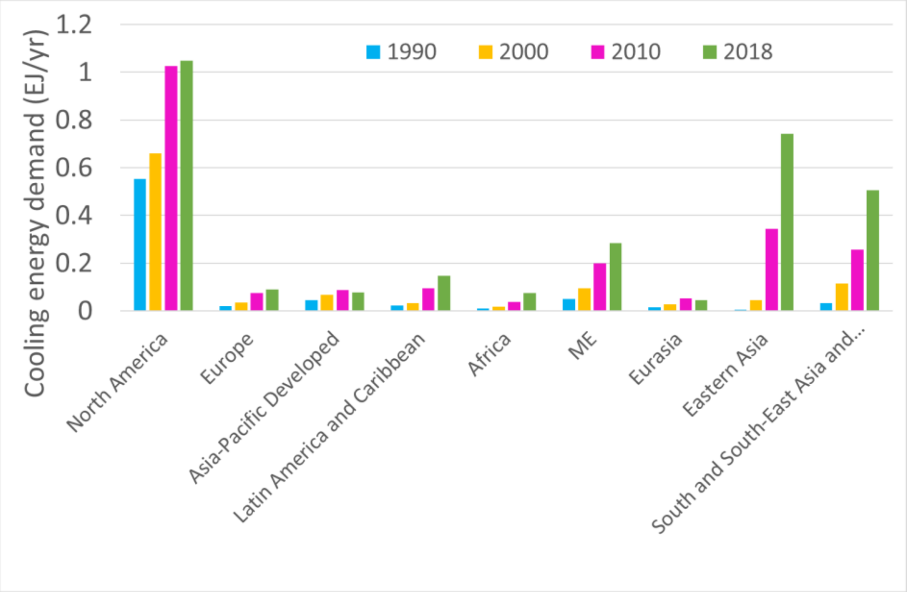


**Figure 9.11 Trends in cooling energy demand in residential sub-sector per region** (International Energy Agency 2019c)

*Energy demand of digital appliances*

Another important trend in residential energy demand is the increased demand driven by the penetration of digital appliances. Global energy demand from digital appliances reached 7.14 EJ in 2018, this is 27% increase compared to 2010 (Figure 9.12). Over the period 2010-2018, the highest increase was observed in Eastern Asia where energy demand of digital appliances has more than doubled, followed by Eurasia and the region of South and South-East Asia and developing Pacific with 84% and 52% increase respectively. Energy demand of digital appliances experienced an increase of 42% in Africa and less than 10% in Europe and North America. The only region which has experienced a decrease in the energy demand of digital appliances is the developed Asia-Pacific. This might be due to the efficiency level of the digital appliances used in this region (see Section 9.4).

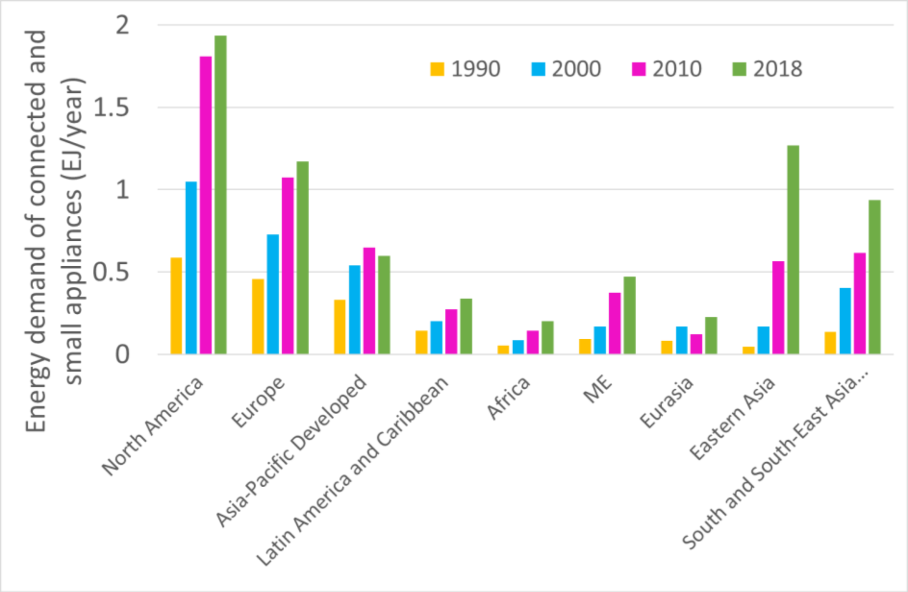


**Figure 9.12 Trends in energy demand of digital appliances per region** (International Energy Agency 2019c)

The increase of energy demand from digital appliances does not necessarily follow the increase in ownership of such products. While Eastern Asia experienced the highest increase in energy demand of digital appliances, the increase of ownership in this region was only at 16%. This suggests that the use of digital appliances (see Section 9.5) is an important driver in the increase of energy demand of digital appliances. The highest increase in ownership of digital appliances was observed in the region of South and South-East Asia and developing Pacific, with a 33% increase, followed by Eurasia with an increase of 27%. The lowest increase in ownership of digital appliances was observed in the developed region of Asia and Pacific and North America, with 3% and 8% increase respectively, which shows that these two markets are close to saturation of digital technologies.

### 9.3.3 [Place holder: Future emissions and energy demand scenarios]

This section will include illustrative pathways to make the global building stock carbon neutral and will be based on the analysis of the scenarios submitted to IIASA database.

## 9.4 Mitigation technological options and strategies towards zero carbon buildings

Literature in this topic is extensive, but unfortunately most studies and reviews do not relate themselves to climate change mitigation, therefore there is a clear gap in reporting the mitigation potential of the different technologies (Cabeza et al. 2019). It should be highlighted that when assessing the literature, it is clear that a lot of new research is focussed in the improvement of control systems, including the use of artificial intelligence or Internet of Things (IoT).

This section is organised as follow. First, the key points from AR5 and special reports are summarized, following with a summary of the technological developments since AR5, specially focussing in residential buildings.

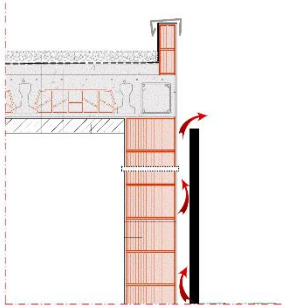
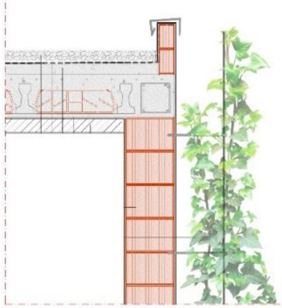
### 9.4.1 Key points from AR5 and special reports

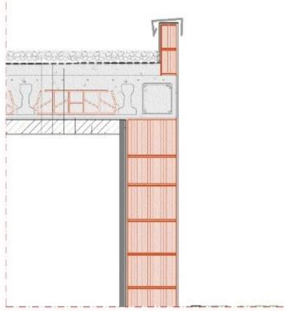
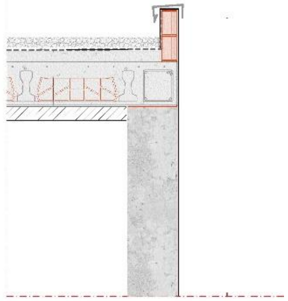
AR5 Chapter 9 on Buildings (Ürge-Vorsatz et al. 2014) presents mitigation technology options and practices to achieve large reductions in building energy use as well as a synthesis of documented examples of large reductions in energy use achieved in real, new, and retrofitted buildings in a variety of different climates and of costs at building level. A key point highlighted is the fact that the conventional process of designing and constructing a buildings and its systems is largely linear, losing opportunities for the optimization of whole buildings. Several technologies are listed as being able to achieve significant performance improvements and cost potentials (daylighting and electric lighting, household appliances, insulation materials, heat pumps, indirect evaporative cooling, advances in digital building automation and control systems, and smart meters and grids to implement renewable electricity sources).

### 9.4.2 Technological developments since AR5 and emerging solutions

There are many technologies that can reduce energy use in buildings (Finnegan et al. 2018), and those have been extensively investigated. Other technologies that can contribute in achieving carbon zero buildings are less present in the literature. Common technologies available to achieve zero energy buildings were summarized in Cabeza and Chàfer (Cabeza and Chàfer 2020) and are presented in Table 9.4 to Table 9.8.

**Table 9.4. Advantages and disadvantages of different passive wall strategies. Adapted from (Cabeza and Chàfer 2020)**

| | Typology – technology | Advantages | Disadvantages | Energy savings | |
|---|---|---|---|---|---|
| | | | | Value [%] | Conditions/comments |
|  | Trombe wall | - Capability to be integrated with new technologies such as PV systems.<br>- Reduction of building's energy consumption, and decrease of moisture and humidity of interior spaces in humid regions.<br>- The indoor temperatures are more stable than in most other passive systems. Prevention of excessive sunshine penetration into the inhabited space.<br>- Installation is relatively inexpensive, where construction would normally be masonry, or for retrofitting existing buildings with uninsulated massive exterior walls.<br>- The time delay between absorption of the solar energy, and delivery of the thermal energy to the living space can be used for night-time heating.<br>- Trombe wall not only provides thermal comfort in the spaces connected to itself, but also contributes to the enhanced thermal comfort condition of adjacent spaces | - In regions with mild winters and hot summers, over heating problems may outweigh the winter benefits.<br>- In a climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink.<br>- Trombe walls have low thermal resistance causing to transfer the heat flux from the inside to the outside of a building during the night or prolonged cloudy periods.<br>- The amount of gained heat is unpredictable due to changes occur in solar intensity.<br>- Trombe walls are aesthetically appealing | 20% (Bojić et al. 2014) | Annual heating – Mediterranean climate<br>--<br>Simulation |
| | | | | 18.2% and 42.2% (Bevilacqua et al. 2019) | Heating cold climate and cooling cold climate<br>--<br>Simulation |
|  | Vertical Greenery Systems (Green walls / Green facades) | - Enhancing building aesthetics.<br>- Improving the acoustic properties.<br>- Reduction of heat gains and losses.<br>- Ability to be integrated with existing buildings. | - Providing a living environment for mosquitoes, moths, etc.<br>- Requiring significant, and consistent maintenance measures.<br>- Water drainage can be involved in complexities, and difficulties. | 58.9 % Green wall<br>33.8 % Green facade (Coma et al. 2017) | Cooling season warm climate<br>--<br>Experimental study |
| | | | | 37.7% and 50% (Djedjig et al. 2015) | Hot climate<br>--<br>Cold climate<br>--<br>Cooling Savings<br>--<br>Simulation |

| | | | | | |
|---|---|---|---|---|---|
| | | | | 12% (Chen et al. 2013) | Cooling savings<br>--<br>Tropical climate<br>--<br>experimental |
| | | | | 20.5 %<br>(Haggag et al. 2014) | Cooling savings<br>--<br>Hot climate<br>--<br>Experimental |
|  | PCM Wall systems | - Availability at different temperatures<br>- High volumetric energy storage | - Low thermal conductivity<br>- Flammability<br>- Low thermal and chemical stability | 19 – 26%<br>(Khoshbakht et al. 2016) | Heating savings<br>--<br>Mediterranean climate<br>--<br>Experimental |
| | | | | 0 up to 29%<br>(Saffari et al. 2017) | Heating savings in different climates<br>--<br>Simulation |
| | | | | 9.28%<br>(Seong and Lim 2013) | Annual cooling savings<br>--<br>Temperate climate<br>--<br>Simulation |
|  | AAC Walls (Autoclaved aerated concrete) | - High volumetric energy storage | - Production cost per unit is higher than other ordinary concretes<br>- It is not as strong as conventional concrete<br>- The process of autoclaving concrete requires significant energy consumption | --- | --- |

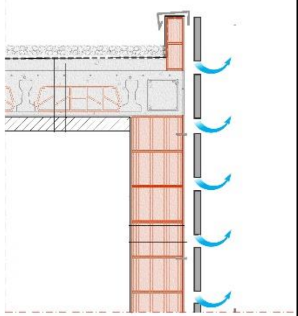
| | | | | | |
|---|---|---|---|---|---|
|  | Double Skin Walls | - Provision of sufficient visual connection with the surroundings<br>- Facilitation of entering a large amount of daylight without glare<br>- Offering attractive aesthetic values<br>- Promotion of natural ventilation and thermal comfort without any electricity demand<br>- Acoustic insulation | - Higher cost for designing, construction, and maintenance compared to traditional single facades<br>- Increase weight of building structure<br>- Risk of overheating during sunny days<br>- Additional maintenance and operational costs<br>- Increased airflow velocity inside the cavity<br>- Potential issues associated to fire propagation | 33%<br>28%<br>(Pomponi et al. 2016) | Heating savings<br>Cooling<br>--<br>Average of reviews |
| | | | | 9%<br>8%<br>(Andjelković et al. 2016) | Heating<br>Cooling<br>--<br>Moderate climate<br>--<br>Simulation |
| | | | | 51 %<br>16%<br>(Khoshbakht et al. 2016) | Annual savings of Temperate and subtropical climate<br>--<br>Simulation |

**Table 9.5. Advantages and disadvantages of different passive roof strategies. Adapted from (Cabeza and Chàfer 2020)**

| | Typology – technology | Advantages | Disadvantages | Energy savings | |
|---|---|---|---|---|---|
| | | | | Value [%] | Conditions/comments |
| | Cool Roofs | - Reduction of the solar heat gain in the building increasing the solar reflectance of the roof surface<br>- improvement of indoor and outdoor thermal conditions in summer and the decrease of the building energy demand | - May also cause significant heating penalties during cold seasons<br>- Not appropriate in cold climates | 0.3 – 27 %<br>(Rosado and Levinson 2019) | Cooling season<br>--<br>Warm climate<br>--<br>Simulation |

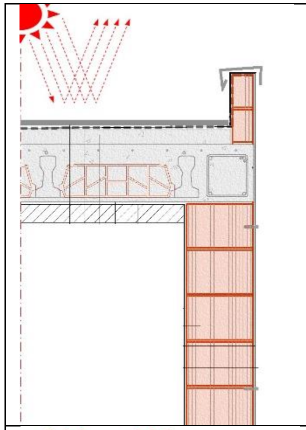
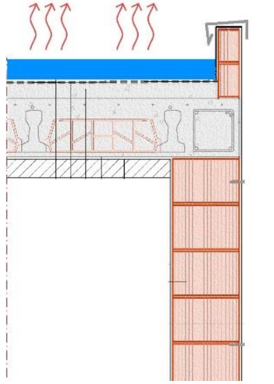
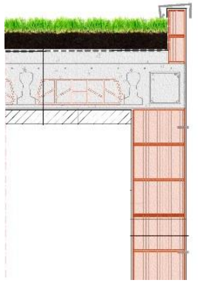
| | | | | | |
|---|---|---|---|---|---|
|  | | | | 17 – 25% (Costanzo et al. 2016) | Cooling season<br>--<br>Mediterranean climate<br>--<br>Simulation |
|  | Roof ponds | - Processes indirect evaporative cooing and/or radiant cooling are combined to provide passive cooling<br>- They can also be used for passive heating in winter<br>- Knowledge available on design and operation of the systems<br>- Useful in arid and temperate climates; can be used in humid climates<br>- Performance is not affected by building orientation<br>- They do not increase indoor humidity | - Increase weight of building<br>- Only to be used in flat roofs<br>- Affection of accessibility of roof for other uses<br>- Potential leakage and contamination of water<br>- Only useful for one- or two-story buildings | 30% (Spanaki et al. 2014) | Annual savings<br>--<br>Mediterranean climate<br>--<br>Simulation |
|  | Green roofs | - Enhancing building aesthetics.<br>- Improving the acoustic properties.<br>- Reduction of heat gains and losses.<br>- Ability to be integrated with existing buildings.<br>- Reducing greenhouse gas emissions, air pollution and urban heat island effects in highly populated areas | - Increase weight of building<br>- Maintenance | 16, 7% (Coma et al. 2016) | Cooling season<br>--<br>Mediterranean climate<br>--<br>experimental |
| | | | | 15,2% (Yang et al. 2015) | Cooling season<br>--<br>Sub-tropical climate<br>--<br>Experimental |

**Table 9.6. Advantages and disadvantages of different active technologies. Adapted from (Cabeza and Chàfer 2020)**

| Typology – technology | Advantages | Disadvantages | Energy savings | |
|---|---|---|---|---|
| | | | Value [%] | Conditions/comments |
| Thermally activated building systems<br>(TABS) | - Reduce energy and cost operation | - TABS with high thermal mass, as hollow core slabs or active concrete core, have significant slow response time.<br>- The performance evaluations of real building systems using active slabs for ventilation are still rough limited | - 17- 24% (Prívara et al. 2011) | - Ceiling radiant heating panels<br>- Monitoring |
| | | | - 15% (Sourbron et al. 2013) | - Ceiling radiant heating panels<br>- Simulation |
| Heat Pumps | - | - | - | - |
| Evaporative condensers | - Used in hot climates to enhance the heat rejection process by using the cooling effect of evaporation | - Frost formation is the most detrimental and significant problem that happens on the finned-tube evaporator in air conditioning and refrigerating systems | 15-58% (Harby et al. 2016) | - Hot dry climate |
| Smart ventilation | - Reduces energy consumption and costs<br>- Improve internal air quality | - Sometimes energy overconsumption appear | Up to 60% (Liu et al. 2019) | -- |
| Heat recovery system | - No cross contamination depending of the type of heat recovery system<br>- High efficiency | - Difficult to integrate depending of the type of heat recovery system<br>- Cost depending of the type of heat recovery system | -- | -- |

**Table 9.7. Advantages and disadvantages of different cooling strategies. Adapted from (Cabeza and Chàfer 2020)**

| Typology – technology | Advantages | Disadvantages | Energy savings | |
|---|---|---|---|---|
| | | | Value [%] | Conditions |
| Direct evaporative cooling | - Reduction of pollution emissions<br>- Life cycle cost effectiveness<br>- Reduction of peak demand<br>- Cheap | - Not good when ambient humidity >40% | | |

| | | | | |
|---|---|---|---|---|
| Indirect evaporative cooling | - Higher air quality than direct evaporative cooling<br>- More efficient than vapour compression systems | - Installation and operation more complex than direct evaporative systems | | |
| Evaporative-cooled air conditioning | - Less energy consumption during peak demand<br>- Lower electricity cost | - Energy savings potential limited to high ambient temperatures<br>- Higher water use cost | | |
| Liquid pressure amplification | - Significant energy savings | - Energy savings potential limited to low ambient temperatures<br>- More expensive than conventional vapour compression systems | | |
| Thermal energy storage | - Significant reduction of electricity costs<br>- Required smaller ducts | - COP lower than conventional vapour compression systems<br>- Expensive both in capital and operation costs | | |
| Heat recovery | - High energy efficiency in temperate climates | - Larger than conventional air-handling units<br>- Expensive both in capital and operation costs | | |
| Ground-coupled | - Less noise and GHG emissions than conventional vapour compression systems | - Requirements of earth surface<br>- Very high upfront costs<br>- Expensive both in capital and operation costs | | |
| Chilled-ceiling | - Less refrigeration use due to use of cooled water instead of chilled water | - Unable to moderate indoor humidity<br>- Risk of condensation at cold surface | | |
| Desiccant cooling | - Humidity control is improved when coupled with conventional systems | - Corrosive materials<br>- Large response time<br>- Crystallization of materials maybe a problem<br>- Expensive both in capital and operation costs | | |
| Ejector cooling | - More simple installation, maintenance and construction than conventional compression systems | - Need of a heat source >80ºC<br>- Lower COP than conventional compression systems | | |
| Variable refrigerant flow | - Efficient in part load conditions | - Requirement of extra control systems<br>- Cannot provide full control of humidity | | |

**Table 9.8. Advantages and disadvantages of different energy sources of heating in buildings. Adapted from (Cabeza and Chàfer 2020)**

| Typology – technology | Advantages | Disadvantages | Energy savings | |
|---|---|---|---|---|
| | | | Value [%] | Conditions/comments |
| Geothermal energy or ground source heat pumps | - Abundant and clean<br>- Provides year around low cost heating and cooling using district energy technology<br>- Not affected by climate | - Expensive start-up and maintenance due to corrosion<br>- Risk of toxic emissions<br>- Subsidence, landscape change, and polluting waterways<br>- Long construction time<br>- Hard to assess resource<br>- High cost | -- | -- |
| Solar energy | - Abundant supply<br>- Less environmental damage compared to other renewable options<br>- Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers<br>- Medium – high cost depending of the system used | - Storage and backup issues<br>- Not constant supply | 22 % (Irshad et al. 2019) | PV integrated with the TE |
| | | | 12 – 25 % (Luo et al. 2017) | Double skin façade using photovoltaic blinds (PV-DSF)<br>--<br>Changsha, Hunanprovince, China<br>--<br>Summer conditions |
| Biomass energy | - Abundant with a wide variety of feedstock and conversion technologies<br>- Indigenous fuel production and conversion technology in developing countries<br>- Low cost | - May release GHGs during biofuel production<br>- Landscape change and deterioration of soil productivity | -- | -- |

### 9.4.3 Appliances and lighting

Electrical appliances have a significant contribution to a household electricity consumption (Pothitou et al. 2017). According to the International Energy Agency (International Energy Agency 2019a), appliances (referred to those available not related to heating, ventilation and air conditioning/cooling) are responsible for around 17% of final electricity use in buildings. Table 9.9 shows the final energy used variation of appliances and the contribution of each one of the different drivers (activity, structure, and efficiency) in the period 2000-2017. It is clear traditional appliances (refrigerator, freezer, television, etc.) have a very low impact in the total energy intensity growth, which is due to the new appliances, also called plug loads. On the other hand, energy efficiency will have its maximum energy efficiency increase in the traditional appliances.

**Table 9.9. Energy intensity improvements in appliances in the period 2000-2007** (International Energy Agency 2019a)

| **Appliance type** | **Total (EJ)** | **Drivers** | | |
|---|---|---|---|---|
| | | **Activity (EJ)** | **Structure (EJ)** | **Efficiency (EJ)** |
| *Appliances* | *+4.6* | *+3.5* | *+1.6* | *-0.5* |
| Refrigerator | +0.2 | +0.7 | +0.1 | -0.6 |
| Freezer | 0.0 | +0.1 | 0.0 | -0.1 |
| Dishwasher | +0.1 | +0.1 | 0.0 | 0.0 |
| Washing machine | +0.1 | +0.2 | 0.0 | -0.1 |
| Clothes dryer | +0.1 | 0.1 | 0.0 | -0.1 |
| Television | -0.4 | +0.6 | +0.4 | -1.4 |
| Plug loads | +3.6 | +1.7 | +2.1 | 0.0 |

Ownership of appliances, the use of appliances, and the power demand of the appliances are key contributors (Jones et al. 2015). The drivers in energy use of appliances are the appliance type (e.g. refrigerators), number of households, number of appliances per household, and energy used by each appliance (Cabeza et al. 2014). At the same time, household energy-related behaviours are also a driver of energy use of appliances (Khosla et al. 2019). Trends show that appliances account for an increasing amount of building energy consumption. Appliances consume electricity and not fuels (fossil or renewable), with a relatively high carbon footprint. Rapid increase in appliance ownership (Cabeza et al. 2018b) can affect the electricity grid. Moreover, energy intensity improvement in appliances such as refrigerators, washing machines, TVs, and computers has counteracted the substantial increasing in ownership and use since the year 2000 (International Energy Agency 2019a).But appliances also are a significant opportunity for energy efficiency improvement. Research on energy efficiency for different appliances worldwide and showed that this research started in different time frames in different countries (Figure 9.13) (Cabeza and Vérez 2020). This figure presents the number of occurrences of a term (the name of a studied appliance) appearing per year and per country, according to the references obtained from a Scopus search. The figure shows that most research carried out was after 2010. And again, this figure shows that research is mostly carried out for refrigerators and for brown appliances such as smart phones. An interesting point highlighted before is the relation between water consumption and appliances energy efficiency. Moreover, the research carried out worldwide is not only devoted to technological aspects, but also to behavioural aspects and quality of service (this last one related to digital television or smart phones).

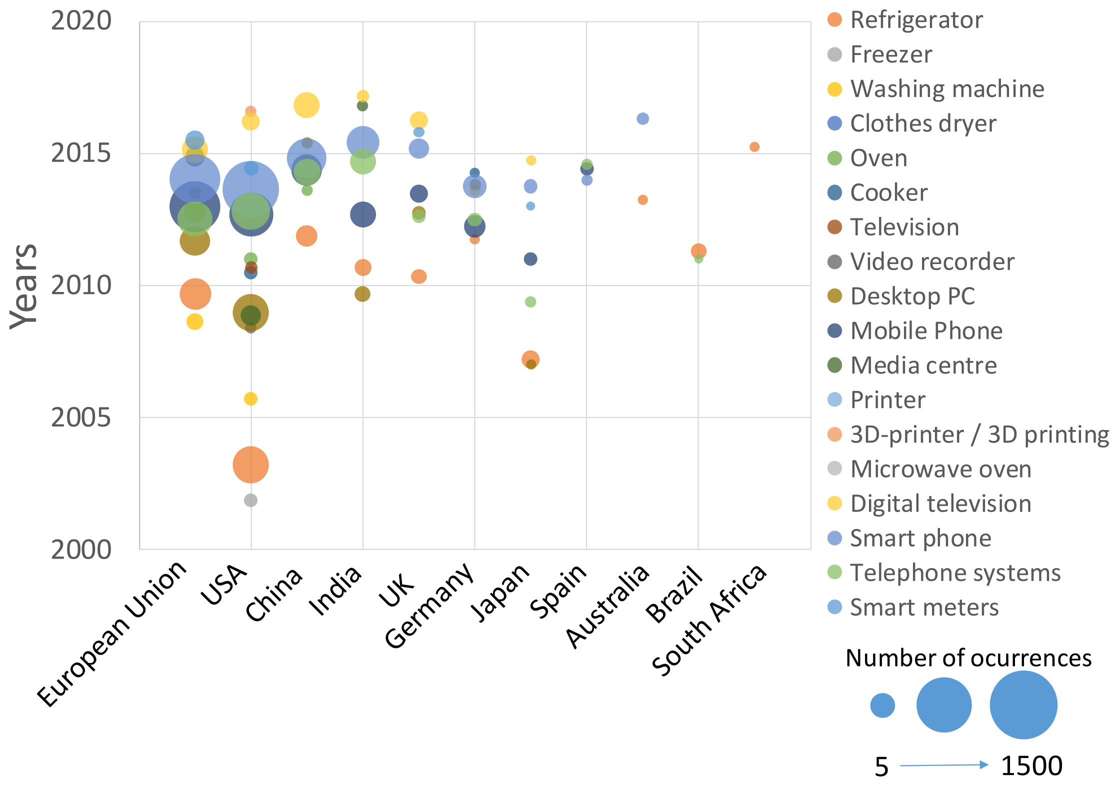


**Figure 9.13. Energy efficiency in appliances research. Year and number of occurrences of different appliances in each studied country/territory**

When analysing when research started in a country, it is interesting to see that in most cases, the research started after the policies were implemented or labelling standards were developed. IEA TCP 4E (IEA-4E 2014) shows that the first labels for refrigerated appliances in USA appeared in 1993 while in EU in 1999, and Australia in 2000, being those the first countries to implement them. Accordingly, the USA and the EU are the countries/territories with earlier research on the topic. Similarly, Japan started research on refrigerators in 2007 and implemented the label already in 2004, in a time frame shorter than the above cited countries. Research around policies is linked to cost analysis and climate change aspects.

Lighting energy accounts for around 19% of the global electricity consumption (Attia et al. 2017; Enongene et al. 2017; Baloch et al. 2018). Many studies have reported the correlation between the decrease of energy consumption and the improvement of the energy efficiency of lighting appliances (Table 9.10, Figure 9.14). Today, the new standards recommend the phase out of incandescent light bulbs and their substitution by more efficient technologies such as compact fluorescent lighting (CFL) and light-emitting diodes (LEDs). Due to the complexity of these systems, simulation tools are used for the design and study of such systems, which can be summarized in Baloch et al. 2018 (Baloch et al. 2018).

Single-phase induction motors are extensively used in residential appliances and other building low-power applications. Conventional motors work with fixed speed regime directly fed from the grid, giving unsatisfactory performance (low efficiency, poor power factor, and poor torque pulsation). Variable speed control techniques improve the performance of such motors (Jannati et al. 2017).

**Table 9.10. Types of domestic lighting devices and their characteristics (Adapted from** (Attia et al. 2017)**)**

| Type of lighting device | Code in plan | Lumens per watt [lm/W] | Colour temperature [K] | Life span [h] | Energy use [W] |
|---|---|---|---|---|---|
| Incandescent | InC | 13.9 | 2700 | 1000 | 60 |
| Candle incandescent | CnL | 14.0 | 2700 | 1000 | 25 |
| Halogen | Hal | 20.0 | 3000 | 5000 | 60 |
| Fluorescent TL 8 | FluT8 | 80.0 | 3000-6500 | 20000 | 30-40 |
| Compact fluorescent | CfL | 66.0 | 2700-6500 | 10000 | 20 |
| LED GLS | LeD | 100.0 | 2700-5000 | 45000 | 10 |
| LED spotlight | LeD Pin | 83.8 | 2700-6500 | 45000 | 8 |
| Fluorescent T5 | FluT5 | 81.8 | 2700-6500 | 50000 | 22 |
| LED DT8 | LeDT8 | 111.0 | 2700-6500 | 50000 | 15 |

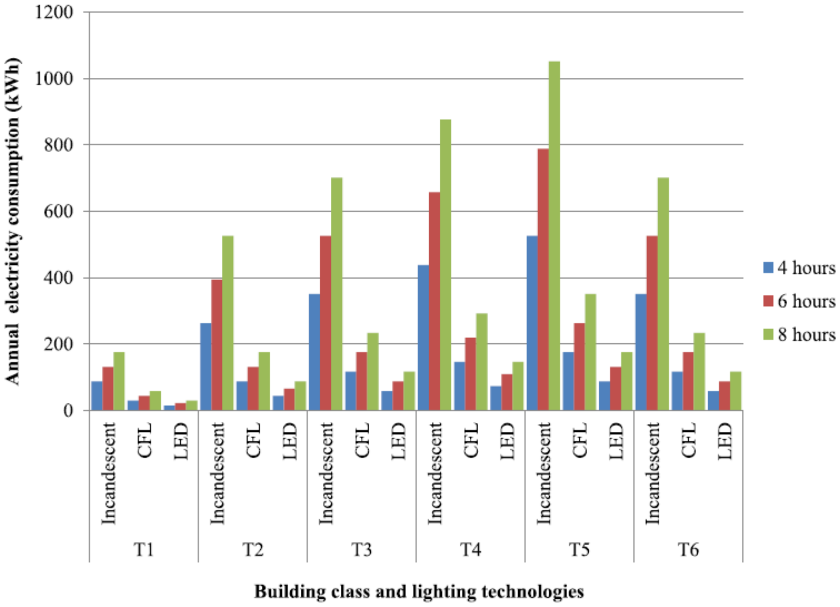


**Figure 9.14. Energy consumption of different lighting devices depending on lighting hours** (Enongene et al. 2017)

## 9.4.4 Digitalization in buildings (IoT and smart buildings)

Energy-related ICT can affect household electricity use directly via home-automation systems that optimize energy use and through behavioural change (Bastida et al. 2019). This last one will be assessed in Section 9.5 with the first one is shortly summarised here.

### *9.4.4.1 Smart buildings*

Smart buildings were first developed as the efficient use of energy and the optimization of the ventilation technology connected with new ways of constructing buildings (low-energy and passive houses, respectively). Today the term *smart building* is also linked with the networking of home automation systems, home appliances, and communications and entertainment electronics, also called *internet of things*, IoT (Shah et al. 2019). As stated by (Schieweck et al. 2018), living in a smart building often also means a drastic change of some living habits of the building occupants.

#### *9.4.4.2 Smart meters*

But smart buildings also mean using advanced metering infrastructure (AMI) that enables measuring electricity demand at high resolution (from seconds to hours) and allows communication between appliances, households, and utilities (Yildiz et al. 2017). The most used AMIs are smart meters, which are having a high penetration in buildings and at a very high rate. Smart meters are devices capable of exchanging information about consumers energy use between those consumers and energy producers or providers (Hmielowski et al. 2019). Literature raised benefits and trade-offs on the use of smart meters. Benefits include help to companies to effectively manage electrical grids, greater energy efficiency, reduced $CO_2$ footprint, market participation, more effective energy services, reduce of costs for consumers, and increase in market flexibility. Trade-offs include concerns about the increase exposure to radiation, about the potential increase of electricity prices by companies during peak use times, threats to public privacy because this technology collects data in real time, and data security issues.

#### *9.4.4.3 Smart appliances*

Within the control strategies to improve energy efficiency in appliances, energy monitoring for energy management has been extensively researched. Abubakar et al. 2017 (Abubakar et al. 2017) present a review on those methods. The paper distinguishes between intrusive load monitoring (ILM), with distributed sensing, and non-intrusive load monitoring (NILM), based on a single point sensing. A comparison of the communication methods used for load monitoring in appliances is presented in Table 9.11. Another classification of monitoring techniques in buildings is presented by Hong et al. 2015 (Hong et al. 2015), which distinguished between macroscopic monitoring (using GIS and/or LIDAR) and microscopic monitoring (to monitor factors such as thermal transmittance and heat transfer coefficient, sensible heat release, thermal bridges, and air temperature).

**Table 9.11. Comparison of wireless communication methods in appliances** (Abubakar et al. 2017)

| Communication method | Data rate | Range | Operating frequency | Power consumption |
|---|---|---|---|---|
| Zigbee | 20, 40 & 50 kbit/s | 10-100 m | 900-928 MHz | Very low |
| WIFI | 54 Mbit/s | 50-100 m | 2, 4 & 5 GHz | High |
| Bluetooth | 1 Mbit/s | 10 m | 2.4 GHz | High |
| IR wireless | 20-140 kbit/s | <10 m (line of sight) | 300 GHz to 430 THz | Low |
| | 115 kbit/s | | | |
| | 4 & 16 Mbit/s | | | |

### 9.4.5 Embodied energy and embodied carbon in building materials

The decrease in energy demand in buildings is highlighting the importance of embodied energy and embodied carbon in building materials (Ürge-Vorsatz et al. 2020). Buildings are recognised as built following five building frames: concrete, wood, masonry, steel, and composite frames (International Energy Agency 2019e); but other building frames should be considered to include worldwide building construction practice, such as rammed earth and bamboo (Cabeza et al. 2020a).

The most prominent materials used following this frames classifications are the following. Concrete, a man-made material, is the most widely used building material. Wood has been used for many centuries for the construction of buildings and other structures in the built environment; and it remains as an important construction material today. Steel is the strongest building material; it is mainly used in industrial facilities and in buildings with big glass envelopes. Masonry is a heterogeneous material using bricks, blocks, and others, including the traditional stone. Composite structures are those involving multiple dissimilar materials. Bamboo is a traditional building material throughout the world tropical and sub-tropical regions. Rammed earth can be considered to be included in masonry construction, but it is a structure very much used in developing countries that is finding new interest in developed ones (Cabeza et al. 2020a).

The literature evaluating the embodied energy in building materials is extensive, but that considering embodied carbon is much more scarce (Cabeza et al. 2020a). Recently this evaluation is done using the methodology life cycle assessment (LCA), but since the boundaries used in those studies are different, varying for example, in the consideration of cradle to grave, cradle to gate, or cradle to cradle, the comparison is very difficult (Moncaster et al. 2019). As example, bamboo was used in a residential building in traditional Chinese construction in a cradle to grave LCA, accounting 2.58 MJ/kg as total embodied energy and 0.13 kg $CO_2$/kg as total embodied carbon (Yu et al. 2011). Rammed earth was used in a residential building in a cradle to grave LCA, accounting 5.96 MJ/kg as total embodied energy and 2.85 kg $CO_2$/kg as total embodied carbon; while if rammed earth is used in compressed earth blocks in the same study, the values are 3.94 MJ/kg as total embodied energy and 1.66 kg $CO_2$/kg as total embodied carbon (Fernandes et al. 2019). Masonry is mainly accounted using a cradle to gate LCA, giving values around 3 MJ/kg as total embodied energy and 0.22 kg $CO_2$/kg as total embodied carbon. Concrete is found in many more studies with different boundaries in the LCA, finding values between 0.75 and 3.50 MJ/kg as total embodied energy and between 0.11 and 0.31 kg $CO_2$/kg as total embodied carbon(Hammond and Jones 2011). Wood literature is noted to be ambiguous in most part of literature, depending on the database and established system boundaries considered for the LCA study. In addition, the type of wood and the origin of it can change the final embodied energy. For instance, an “air dried sawn hardwood“ has an embodied energy of 0.50 MJ/kg, while a “medium density fibreboard (MDF)” has 11.30 MJ/kg (Lawson 1996).

### 9.4.6 Reduction of emissions due to the change in construction methods (from traditional on-site construction to industrialization of walls to 3D printing of walls)

Traditional construction produces high amount of waste materials that are disregarded afterwards, but industrialized production of walls although reducing the amount of waste production is recognized to being more expensive if the amount of pieces is not high enough, since the moulds needed are relatively expensive; moreover, the production of those moulds/scaffolds presents high GHG emissions (Shakor et al. 2019). But industrialized construction has other advantages such as better fabrication, precise production of elements, and prints of any geometries.

3D printing, also known as rapid prototyping or as additive manufacturing, can revolutionise the building industry. Advantages of 3D printing is a simpler construction from CAD data, a huge reduction of total costs, better quality control, and the possibility of producing high-performance components (such as beams and columns) in controlled environments. Some drawbacks are the low stiffness and strength of the printed building materials, and the limited printing size.

### 9.4.7 Exemplary buildings – case studies

#### *9.4.7.1 Low- and net-zero energy buildings*

Nearly zero energy (NZE) buildings or low-energy buildings are possible in all world relevant climate zones (Ürge-Vorsatz et al. 2020) (Figure 9.15). Moreover, they are possible both for new and retrofitted buildings. Different envelope design and technologies are needed, depending on the climate and the building shape and orientation. For example, using the Passive House standard an annual heating and cooling energy demand decrease between 75% and 95% compared to conventional values can be achieved. Table 9.12 lists several exemplary low- and NZE buildings with some of their feature.

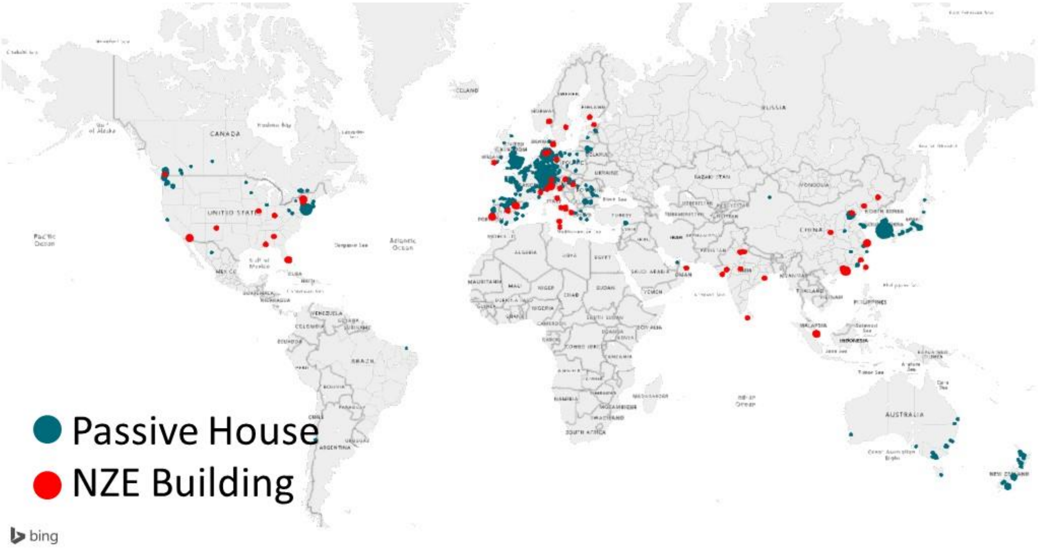


**Figure 9.15. Regional distribution of documented low-energy buildings(Ürge-Vorsatz et al. 2020)**

**Table 9.12. Selected exemplary low- and net-zero- energy buildings worldwide (Adapted from (Ürge-Vorsatz et al. 2020))**

| Building name and organization | Location | Building type | Energy efficiency and renewable energy features | Energy performance |
|---|---|---|---|---|
| SDB-10 at the software development company, Infosys | India | Software development block | • Hydronic cooling and a district cooling system with a chilled beam installation<br>• Energy-efficient air conditioning and leveraged load diversity across categorized spaces: comfort air conditioning (workstations, rooms), critical load conditioning (server, hub, UPS, battery rooms), ventilated areas (restrooms, electrical, transformer rooms), and pressurized areas (staircases, lift wells, lobbies)<br>• BMS to control and monitor the HVAC system, reduced face velocity across DOAS filters, and coils that allow for low pressure drop | EPI of 74 mWh/m$^2$, with an HVAC peak load of 5.2 W/m$^2$ for a total office area of 47,340 m$^2$ and total conditioned area of 29,115 m$^2$ |
| Y.S. Sun Green Building by an electronics manufacturing company Delta Electronics Inc., | Taiwan | University research green building | • Low cost and high efficiency are achieved via passive designs, such as large roofs and protruded eaves which are typical shading designs in hot-humid climates and could block around 68% of incoming solar radiation annually<br>• Porous and wind-channelling designs, such as multiple balconies, windowsills, railings, corridors, and make use of stack effect natural ventilation to remove warm indoor air;<br>• Passive cooling techniques that help reduce the annual air-conditioning load by 30% | EUI of the whole building is 29.53 kWh/m$^2$ (82% more energy-saving compared to the similar type of buildings) |
| BCA Academy Building | Singapore | Academy Building | • Passive design features such a green roof, green walls, daylighting, and stack effect ventilation<br>• Active designs such as energy-efficient lighting, air-conditioning systems, building management system with sensors and solar panels<br>• Well-insulated, thermal bridge free building envelope | First net zero energy retrofitted building in Southeast Asia |
| Energy-Plus Primary School | Germany | School | • Highly insulated passive house standard | Off grid building with an EPI of 23 kWh/m2/yr |

| | | | | |
|---|---|---|---|---|
| | | | • Hybrid (combination of natural and controlled ventilation) ventilation for thermal comfort, air quality, user acceptance and energy efficiency<br>• Integrated photovoltaic plant and wood pellet driven combined heat and power generation<br>• Classrooms are oriented to the south to enable efficient solar shading, natural lighting and passive solar heating<br>• New and innovative building components including different types of innovative glazing, electro chromic glazing, LED lights, filters and control for the ventilation system | |
| NREL Research Support Facility | USA | Office and Research Facility | • The design maximizes passive architectural strategies such as building orientation, north and south glazing, daylighting which penetrates deep into the building, natural ventilation, and a structure which stores thermal energy<br>• Radiant heating and cooling with radiant piping through all floors, using water as the cooling and heating medium in the majority of workspaces instead of forced air<br>• Underfloor ventilation with demand-controlled dedicated outside air system (DOAS)<br>• Roof-mounted photovoltaic system and adjacent parking structures covered with PV panels | EPI of 110 kWh/$m_2$/yr with a project area of 222,000 $ft^2$ with the goal the largest commercial net-zero energy building in the country |

#### 9.4.7.2 Data-centres

Data-centres are dedicated buildings or part of buildings for accommodating large amount IT equipment such as servers, data storage and communication devices, and network devices, which are always stacked onto rows of computer racks and cabinets to minimize the required ground space. Data-centres are responsible for about 2% of global electricity consumption (Avgerinou et al. 2017) The enormous energy demand arises from the highly packaging IT equipment, which is up to 100 times higher than a standard office accommodation (Chu and Wang 2019). To fulfil the cooling demand of a typical data-centre, normally a chilled water system and an airflow loop. In a typical data centre the cooling energy is as large as the IT energy. Some energy efficient cooling technologies have been adopted, such as free-cooling, liquid cooling, low-grade waste heat recovery, absorption cooling, etc. In addition, the heat recovery can provide useful heat for industrial and building applications.

#### 9.4.7.3 Warehouses

Warehouses are major contributors to the rise of greenhouse gas emissions in supply chains (Bartolini et al. 2019). The expanding e-commerce sector and the growing demand for mass customization have even led to an increasing need for warehouse space and buildings, particularly for serving the uninterrupted customer demand in the business-to-consumer market. Warehousing activities contribute roughly 11% of the total GHG emissions generated by the logistics sector across the world. Following this global trend, an increasing attention to green and sustainable warehousing processes has led to many new research results regarding management concepts, technologies and equipment to reduce warehouses carbon footprint, i.e. the total emissions of GHG in carbon equivalents directly caused by warehouses activities.

#### 9.4.7.4 Historical and heritage buildings

Historical buildings, defined as those built before 1945, are usually low-performance buildings by definition and represent almost 30–40% of the whole building stock in European countries (Cabeza et al. 2018a). Historical buildings often contribute to townscape character, they create the urban spaces that are enjoyed by residents and attract tourist visitors. They may be protected by law from alteration not only limited to their visual appearance preservation, but also concerning materials and construction techniques to be integrated into original architectures. On the other hand, a heritage building is a historical building which, for their immense value, is subject to legal preservation. The integration of renewable energy systems in such buildings is more challenging than in other buildings. The review carried out by (Cabeza et al. 2018a) different case studies are presented and discussed, where heat pumps, solar energy and geothermal energy systems are integrated in such buildings, after energy efficiency is considered.

## 9.5 Mitigation non-technological options and strategies

The literature on non-technological mitigation measures in the building sector covers all behavioural components of buildings energy demand and associated climate impact. Broadly speaking, non-technological measures include "curtailment" behaviours, which are everyday practices such as turning off unnecessary lights, "efficiency" behaviours, which are one-time decisions to adopt low carbon solutions such as installing solar panels, and "acceptance" behaviours which are social, institutional and organisational issues seen as either barriers or enablers, at different levels, of the technical mitigation measures. Although selected examples of these behavioural issues for buildings are included in other Chapters that cover non-technological mitigation measures more generally, this section provides an exhaustive overview and categorization of knowledge on non-technological mitigation options from the building sector.

The section is set out to first understand non-technological drivers of buildings energy demand and emissions (Section 9.5.2); then to list non-technological actions for carbon neutrality in the building sector (Section 9.5.3) categorized as (i) passive building management and operation, (ii) flexible comfort and energy demand, (iii) circular and shared economy, and (iv) organizational, institutional and social acceptance; finally to understand how to get these actions implemented/adopted (Section 9.5.4). The latter is a necessary starting point in the design of policies that will trigger such motivations. These policy interventions are however addressed in Section 9.9 together with additional economical, entrepreneurial, organizational, and law/legislation issues.

### 9.5.1 Key points from AR5

In AR5, behavioural and lifestyle impacts for buildings were covered only in Chapter 9, 9.3.10. Factors of 3 to 10 differences were found worldwide in non-residential and residential energy use for buildings with same function, occupancy and comfort levels. Traditional control strategies for both lighting, cloth drying and ventilation were found to majorly contribute to lower energy use, but also were found being progressively replaced by fully controlled indoor climates through mechanical systems that result in increased energy demand. Alternative mid-way solutions successfully combining manual and automated control were found to be emerging. Flexibility in both requirements for thermal comfort – such as higher indoor temperatures in summer than in winter – and social norms – such as relaxed business dress codes – were found to lead to substantial energy savings.

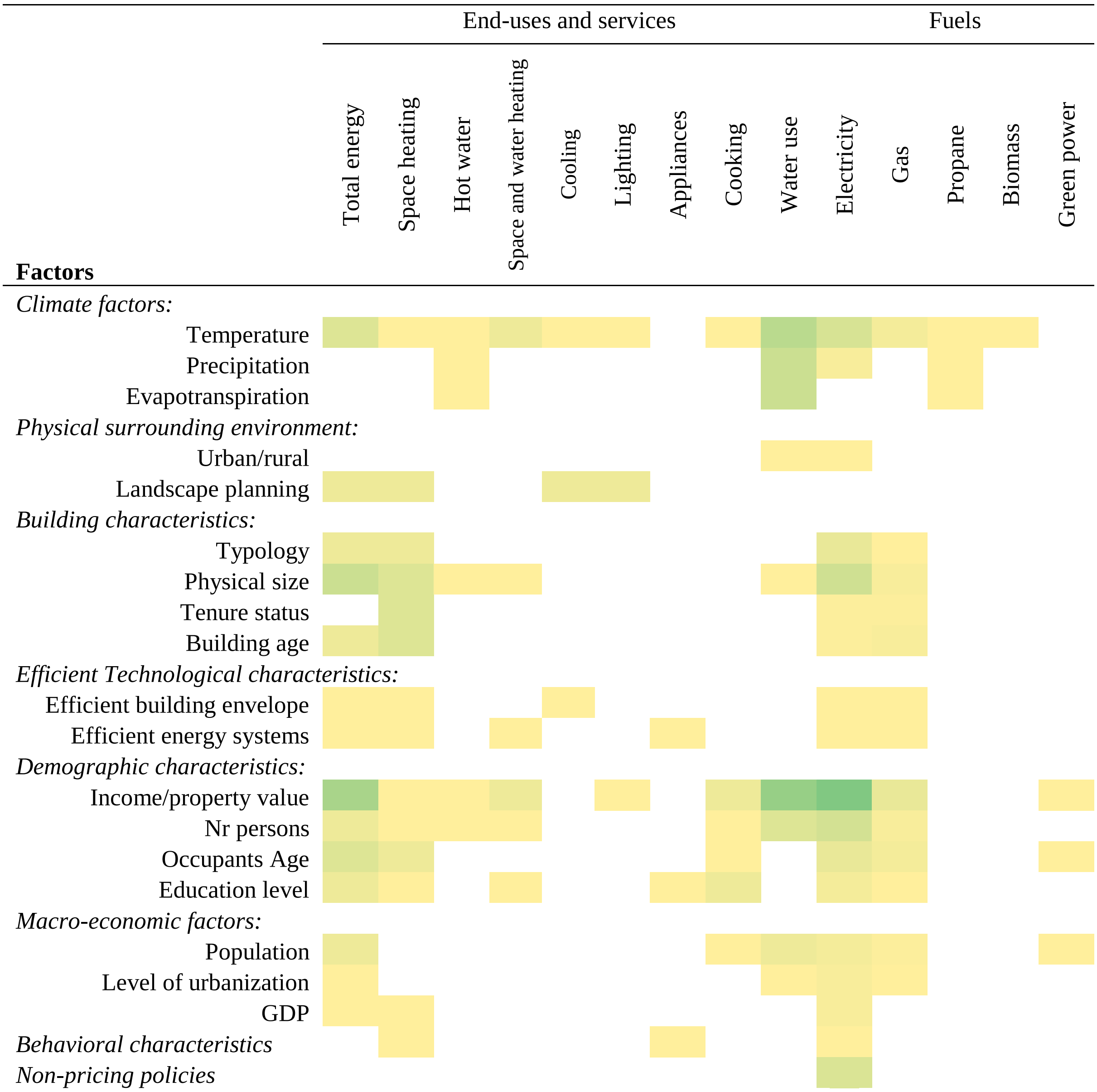
Quantitative modelling of the impact of future lifestyle change on energy demand was found to show that, in developed countries where energy service levels are already high, lifestyle change can produce substantial energy use reductions of at least 20 % in the short term and 50% in the long therm. Similar absolute reductions are not possible in developing countries where energy services demands need to grow to satisfy development needs. However, the rate of growth can be reduced by lower consumption lifestyles.

### 9.5.2 Non-technical determinants of energy demand and carbon emissions

Many studies have analysed what factors determine carbon emissions or energy demand, the focus on the first being scarce. Energy demand is studied in terms of service/end use, fuel or energy expenditure. Developed Countries are in focus two thirds of the literature. Of the remaining, a half focus on Asia and Developing Pacific, followed by equal aims on Latin America and Caribbean, as well as Africa and Middle East, with Eastern Europa and West-Central Asia barely investigated. An interest on electricity use dominates in all regions.

Factors studied include household and building characteristics, climate, physical surrounding environment, as well as technological, behavioural and macroeconomic factors. Additional key determinants are the efficiency of technological systems, which is addressed in Section 9.4, and existing pricing and non-pricing policies, which are addressed in Section 9.8. Worldwide, income, energy price and outdoor temperature are unequivocal drivers of buildings energy demand and carbon emissions, followed by other indicators of size such as population or heated floor area. More detailed observations are presented in the subsections below.

**Table 9.13 Key determinants of buildings energy demand for end uses, services and fuels. Shades of colour indicate the amount of evidence (white, none; green, much).**



| | End-uses and services | | | | | | | | | Fuels | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Factors** | Total energy | Space heating | Hot water | Space and water heating | Cooling | Lighting | Appliances | Cooking | Water use | Electricity | Gas | Propane | Biomass | Green power |
| *Climate factors:* | | | | | | | | | | | | | | |
| Temperature | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | 🟨 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | |
| Precipitation | | | 🟨 | | | | | | 🟩 | 🟨 | | 🟨 | | |
| Evapotranspiration | | | 🟨 | | | | | | 🟩 | | | 🟨 | | |
| *Physical surrounding environment:* | | | | | | | | | | | | | | |
| Urban/rural | | | | | | | | | 🟨 | 🟨 | | | | |
| Landscape planning | 🟨 | 🟨 | | | 🟨 | 🟨 | | | | | | | | |
| *Building characteristics:* | | | | | | | | | | | | | | |
| Typology | 🟨 | 🟨 | | | | | | | | 🟨 | 🟨 | | | |
| Physical size | 🟩 | 🟩 | 🟨 | 🟨 | | | | | 🟨 | 🟩 | 🟨 | | | |
| Tenure status | | 🟩 | | | | | | | | 🟨 | 🟨 | | | |
| Building age | 🟨 | 🟩 | | | | | | | | 🟨 | 🟨 | | | |
| *Efficient Technological characteristics:* | | | | | | | | | | | | | | |
| Efficient building envelope | 🟨 | 🟨 | | | 🟨 | | | | | 🟨 | 🟨 | | | |
| Efficient energy systems | 🟨 | 🟨 | | 🟨 | | | 🟨 | | | 🟨 | 🟨 | | | |
| *Demographic characteristics:* | | | | | | | | | | | | | | |
| Income/property value | 🟩 | 🟨 | 🟨 | 🟨 | | 🟨 | | 🟨 | 🟩 | 🟩 | 🟨 | | | 🟨 |
| Nr persons | 🟨 | 🟨 | 🟨 | 🟨 | | | | 🟨 | 🟩 | 🟩 | 🟨 | | | |
| Occupants Age | 🟩 | 🟨 | | | | | | 🟨 | | 🟨 | 🟨 | | | 🟨 |
| Education level | 🟨 | 🟨 | | 🟨 | | | 🟨 | 🟨 | | 🟨 | 🟨 | | | |
| *Macro-economic factors:* | | | | | | | | | | | | | | |
| Population | 🟨 | | | | | | | 🟨 | 🟨 | 🟨 | 🟨 | | | 🟨 |
| Level of urbanization | 🟨 | | | | | | | | 🟨 | 🟨 | 🟨 | | | |
| GDP | 🟨 | 🟨 | | | | | | | | 🟨 | | | | |
| *Behavioral characteristics* | | 🟨 | | | | | 🟨 | | | 🟨 | | | | |
| *Non-pricing policies* | | | | | | | | | | 🟩 | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Energy prices* | 🟩 | 🟩 | 🟨 | 🟨 | | 🟨 | | 🟩 | 🟩 | 🟩 | 🟨 | | 🟨 | 🟨 |

__Sources__: **Total energy use:** (Ahmed, 2013) (Chen and Pitt 2017)) (Filippini and Hunt 2012)) (Molinos-Senante et al. 2016))(Otsuka, 2018) (Sreekanth et al. 2011)) (Summerfield et al. 2015) (Tilov et al. 2019)) (Xing et al. 2015)) (Zhang and Lahr 2018)); **Space heating**: Bernstein & Madlener 2011; Asche et al. 2012; Brounen et al. 2012, (Harold et al. 2015), (Aghdaei et al. 2017))(Couture, 2012(Couture et al. 2012) (Engvall et al. 2014)) (Fazeli et al. 2016)) (Lasshof and Stoy 2016); (Lindberg et al. 2019))(Oh, 2019); (Rafiee et al. 2019)); (Surmann and Hirsch 2016)); (Weber and Gill 2016)); **Hot water:** (Singh et al. 2017); **Space and water heating**: (Bissiri et al. 2019)) (Hansen 2016))(Ó Broin, 2015)(Fann, 2016); **Cooling:** Ali, 2011(Ayoub 2019)) Oh, 2019)(Aghdaei, 2017 (Aghdaei et al. 2017); **Lighting:** (Arthur, 2012)( (Rosenberg 2014)) (Ayoub 2019))(Oh, 2019)**; Appliances:** (Kavousian et al. 2015a)**; Cooking:** (Arthur, 2012) (Arawomo 2019)) (Makki et al. 2013a)) (Ajayi 2018))**; Water usage:** (Asci et al. 2017)) (Ashoori et al. 2016))(Chang, 2017)(Chang, 2019)(Clarke, 2017)(Dharmaratna, 2012)(Dhungel, 2014; Dhungel, 2014)(Ghavidelfar, 2017)Ghavidelfar, 2017)(Griffioen, 2014); **Electricity:** Motlagh, 2017; Yao, 2014; Sakah, 2019; Romero-Jordan, 2016; Romero-Jordan, 2014; Rhodes, 2014; Ye, 2018; Karuppusamy, 2014; Silva, 2017; Cetinkaya, 2015; Cuddington, 2015; Arisoy, 2014; Gautam, 2018; Okajima, 2013; Labandeira, 2012; Zhou, 2013; Shen, 2017; (Cialani, 2018), (Villareal, 2016), (Yin, 2016), (Dubovik, 2017), (Dilaver, 2011), (Chindarkar, 2019), (Campbell, 2018), (Casarin, 2011), (Carter, 2012), (Gomez, 2013), (Tian, 2016), (Wiesmann, 2011), (Blazquez, 2013), (Dicembrino, 2013), (Huang, 2015), (Hidalgo, 2018), (Saunoris, 2013), (Fullerton, 2015); **Gas:** Altinay, 2016, Burke, 2016, Chalal, 2017, Harold, 2015, Kontokosta, 2017, Li, 2018, Lim, 2019, Majcen, 2013, Malzi, 2019, Oliver, 2016; Payne, 2011; Steadman, 2014; Tian, 2015; Tian, 2016; Yu, 2014; Propane: Shenoy, 2011; **Biomass:** Kristofel, 2016; **Green Power:** Gillingham, 2019.

#### *9.5.2.1 Climate and physical environment*

Climate factors are highly determinant of energy demand. Outdoor temperature, sunshine hours and rainfall are highly positively significant (Tol et al. 2012; )(Harold et al. 2015)). Indoor and outdoor water use exhibits seasonal change and is significantly influenced by temperature, and precipitation and evapotranspiration have a direct effect on outdoor water use such as irrigation (Ouyang et al. 2014). Also, heating load tends to have a consistent nature, whereas cooling load are of a more intermittent nature.

The physical environment is studied in terms of density, capacity, and spatial effects. It is implicit in the building and urban typologies (Section 9.1.2.2), with single family houses and rural areas generally being less compact, and apartment buildings and urban areas. Urban households consume more electricity than rural households (Huang 2015)(Miah et al, 2011; Feng et al 2011; Zhao et al. ,2012; Huang, 2015), as urban residents usually have a relatively affluent lifestyle (Niu et al, 2012). Other aspects of urbanization as well as 2D and 3D typologies have been discussed in Chapter 8. The presence of garden has a positive impact on water demand, and imitation and neighbouring/special effects are observed (Ramachandran and Johnston, 2011; Janmaat 2013; de Maria André and Carvalho, 2014).

Climate variability and extreme events may drastically increase energy consumption (Mashhoodi et al. 2019). For climate change effects on future energy demand, see Section 9.8.

#### *9.5.2.2 Characteristics of the building and its technological systems*

Building typology, construction year and dwellings' floor area (or other variables that measure physical size, e.g. number of bedrooms, or lot size) are positively correlated to energy demand. Residential consumption increases with the amount of occupant but shows economies of scale in that the consumption per capita diminishes proportionally to the number of occupants (Ouyang et al., 2014 ; de Maria André and Carvalho, 2014). Multifamily apartments have the lowest daily maximum electricity consumption in the winter, followed by town houses and finally, detached (free-standing) houses (Kavousian et al, 2013). For all typologies and end-uses, vintage has a negative correlation as recently built buildings must comply with increasingly strict standards (Harold et al. 2015) (Brounen et al. 2012; (Harold et al. 2015)Kavousian et al, 2014). Only for electricity consumption no significant correlation is observed to building age (Kavousian et al. 2013). As buildings are being renovated, the renovation year is instead a key indicator sometimes included in the property register (Mangold et al, 2016; Österbring et al, 2018).

Heating expenditure tends to be higher for home owners than for renters (Meier & Rehdanz 2010, Harold et al, 2015) (Harold et al. 2015). Owner-occupied households tend to have more efficient electrical appliances but also consume more electricity than renter-occupied households (Kavousian et al. 2015b; Huang 2015).

#### 9.5.2.3 *Demographic and macroeconomic factors*

Income has generally a positive correlation to energy demand (Kavousian et al. 2015b). For residential water demand, the elasticity is found to be low (Ouyang et al. 2014; Andr and Carvalho 2014). Affluence is deeply embedded in these variables as higher-income households have larger homes and lots. On average across all the OECD countries, the long run elasticities regarding price and income are found to be−0.51 and 0.94 respectively, with Ireland being the most elastic (MacNaughton et al. 2018)(Bernstein and Madlener, 2012).

[Placeholder – table of price/income elasticities per world region]

Single-parent and elderly households consume more and the gender of the chief economic supporter has no significant effect (Harold et al. 2015)(Brounen et al., 2012; Harold et al 2015). Retired occupants and females consume water than those with a 'working' occupational status and males (Makki et al, 2013; de Maria André and Carvalho, 2014; Kavousian et al, 2015). Similarly, larger families are found to use less electricity and enjoy economies of scale (Bedir et al, 2013; Kavousian et al, 2013; 2015; Huang, 2015). Families in a later stage of the family life cycle have higher electricity demand than do younger families suggesting that the development of an aged society may increase electricity consumption (Huang 2015). Households with higher educational levels are consuming more electricity and gas (Hidalgo et al, 2018; Harold et al., 2015). Although high-income households tend to use more efficient water-using appliances and are likely to be more educated and therefore more environmentally sensitive, their higher living standards require more water (Makki et al. 2013b).

#### 9.5.2.4 *Behaviour and policies*

Occupant behaviour plays an extensive role in household energy consumption. Households consume more at the weekends and on public holidays, and self-employed occupants consume significantly more than households with employed occupants, probably because many of these jobs are in-house (Harold et al. 2015; Hidalgo et al. 2018). Behavioural components such as the frequency of use of the heating system and chosen temperature settings correlate with energy consumption (Li et al. 2019). Lifestyle related behaviours such as sharing heating and cooling appliances, using non-electricity using mechanisms to achieve thermal comfort, and cultural practices also have significant impact on total energy use (Khosla et al. 2019). Households with tendency to make major lifestyle changes to save energy are indeed more efficient on average (Kavousian et al. 2015b). Finally, some studies have demonstrated that efficient behaviour leads to more efficient behaviour. E.g. the installation of PV leads to higher awareness of their PV systems as well as increased communication about environmental behaviour in the family, affect people's concern and norms, and tend to increase environmental behaviour (Hondo and Baba, 2010).

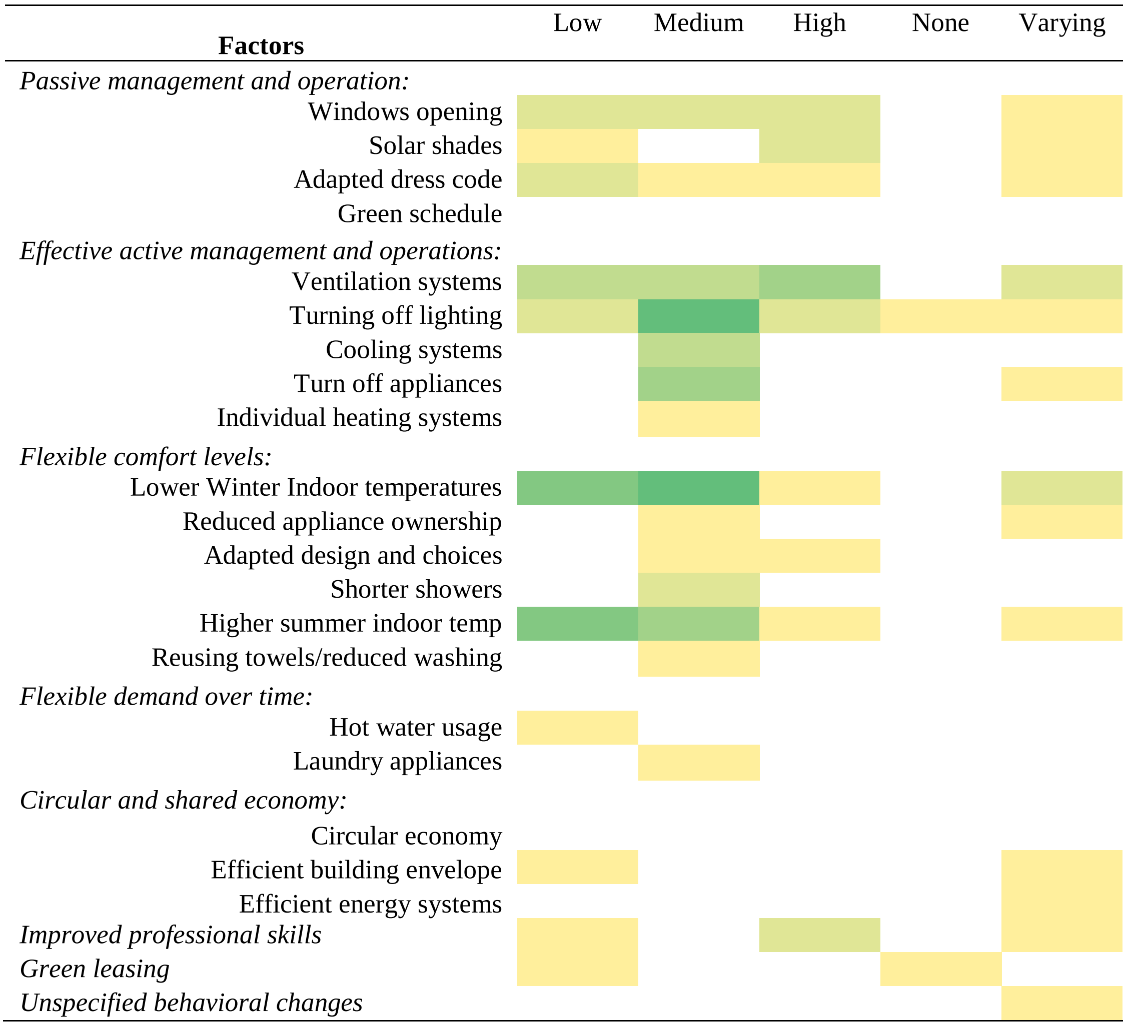
In most energy modelling tools, however, human-building interactions (i.e. occupant behaviour) are rarely simulated, and are usually represented solely through occupancy schedules that assume average behaviour for all of the building occupants. These behavioural patterns are based on surveys that in many cases have not been updated for decades and have questionable relevance today (Shipworth, 2013; Gaetani et al. 2016;). Quantifying the influence of design-driven consumption and behaviour-driven consumption is therefore critical.

### 9.5.3 Defining behavioural interventions

Whereas the literature agrees on that non-technological measures are key for a low-carbon building sector, (van Sluisveld et al., 2016) Creutzig et al, 2018; Mundaca et al, 2019) they have attracted less attention than technological measures (Ruparathna et al. 2016; Vence and Pereira 2019; Vérez and Cabeza 2020). For instance, lifestyle changes lead to a 15% reduction of $CO_2$ emissions in the residential sector worldwide compared to baseline emissions, and to lower reductions in mitigation scenarios as the effectiveness in the end-use sectors overlaps with more technology-oriented measures, with lifestyle changes in the housing domain modelled as reduced demand for space and water heating, capped household dimensions, reduced rates of appliances ownership and phase out of tumble dryers, and use the best available technology energy consumption for technology functions as a proxy for all sorts of more efficient use of appliances (van Sluisveld et al. 2016b). In other integrated modelling assessments that present specific results for the buildings sector non-technological measures are covered by exogenously assuming various levels of demand for the different scenarios modelled (Eom et al. 2012; Chaturvedi et al. 2014; Zhou et al. 2014; Wang et al. 2018; Gambhir et al. 2019).

There is no clear taxonomy nor definitions for occupancy behaviour or behavioural change, so the classification proposed in this section takes the departure on the analysis of literature, combines and actualizes existing frameworks, and exhaustively populates the resulting taxonomy with all the measures found in the recent literature.

**Table 9.14 Estimated climate mitigation potential for categories of non-technological interventions. Shades of colour indicate the amount of evidence (white, none; green, much).**



| Factors | Low | Medium | High | None | Varying |
|---|---|---|---|---|---|
| *Passive management and operation:* | | | | | |
| Windows opening | 🟩 | 🟩 | 🟩 | | 🟨 |
| Solar shades | 🟨 | | 🟩 | | 🟨 |
| Adapted dress code | 🟩 | 🟨 | 🟨 | | 🟨 |
| Green schedule | | | | | |
| *Effective active management and operations:* | | | | | |
| Ventilation systems | 🟩 | 🟩 | 🟩 | | 🟩 |
| Turning off lighting | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 |
| Cooling systems | | 🟩 | | | |
| Turn off appliances | | 🟩 | | | 🟨 |
| Individual heating systems | | 🟨 | | | |
| *Flexible comfort levels:* | | | | | |
| Lower Winter Indoor temperatures | 🟩 | 🟩 | 🟨 | | 🟩 |
| Reduced appliance ownership | | 🟨 | | | 🟨 |
| Adapted design and choices | | 🟨 | 🟨 | | |
| Shorter showers | | 🟩 | | | |
| Higher summer indoor temp | 🟩 | 🟩 | 🟨 | | 🟨 |
| Reusing towels/reduced washing | | 🟨 | | | |
| *Flexible demand over time:* | | | | | |
| Hot water usage | 🟨 | | | | |
| Laundry appliances | | 🟨 | | | |
| *Circular and shared economy:* | | | | | |
| Circular economy | | | | | |
| Efficient building envelope | 🟨 | | | | 🟨 |
| Efficient energy systems | | | | | 🟨 |
| *Improved professional skills* | 🟨 | | 🟩 | | 🟨 |
| *Green leasing* | 🟨 | | | 🟨 | |
| *Unspecified behavioral changes* | | | | | 🟨 |

**<u>Sources</u>**: **Passive management**: (Van Den Wymelenberg 2012; Markandya et al. 2015; Ruparathna et al. 2016; Singh 2016; Alders 2017; Sun and Hong 2017; Talele et al. 2018; Galassi and Madlener 2018); **Active management:** (Darby et al. 2016; Volochovic et al. 2012; Tokuda et al. 2013; Ayoub et al. 2014; Rafsanjani et al. 2015; Peng et al. 2015; Dong et al. 2015; Ruparathna et al. 2016; Singh 2016; Taniguchi et al. 2016; Alders 2017; Hansen and Hauge 2017; Sanguinetti et al. 2017; Sun and Hong 2017; Kusumadewi and Limmeechokchai 2017; Sköld et al. 2018; Rakha et al. 2018; Valencia et al. 2018; Ahl et al. 2019; Sánchez-García et al. 2019; van der Grijp et al. 2019; Talele et al. 2018); **Flexible comfort levels**: (Volochovic et al. 2012; Brown et al. 2013; Ayoub et al. 2014; Cao et al. 2014;

Dong et al. 2015; Singh 2016; Andersen et al. 2016; Taniguchi et al. 2016; Sanguinetti et al. 2017; Sun and Hong 2017; Chang et al. 2017; Sköld et al. 2018; Galassi and Madlener 2018; Ahl et al. 2019; van der Grijp et al. 2019; Talele et al. 2018); **Flexible demand over time:** ; **Circular and shared economy:** (Hasegawa 2016; Ala-Mantila et al. 2017; Hansen and Hauge 2017; Fell et al. 2014)**; Improved professional skills:** (Ruparathna et al. 2016; D'Oca et al. 2014; Salo et al. 2016; Dixon et al. 2015)**; Green leasing:** (Roussac and Bright 2012; Purohit and Höglund-Isaksson 2017) Hewitt 2018, Isaksson et al 2019**; Unspecified behavioural changes**: (Day and O'Brien 2017).

#### *9.5.3.1 Active and passive management and operation*

Passive management refers to the manual operation of the building envelope, the activities in the rooms of the building, and to adapted human clothing. Management of the building envelope includes: appropriate window opening for cooling during warm periods; closing solar shades and curtains to reduce solar gains during warm periods and minimize losses during cold nights; optimize natural lighting by opening blinds and curtains during the day (Christidou et al. 2014; Volochovic et al. 2012). Quantitative modelling of such measures is included in building performance simulations most common for non-residential buildings, for instance as probability for a window being open in relation to indoor globe temperature for several values of constraint on opening (Rijal et al. 2012). The allocation of the different activities of the building to maximize the energy efficiency of the building is called green schedule and has so far attracted more attentions in commercial and educational buildings (Rafsanjani et al. 2015; Klein et al. 2012). Additional small savings are available through professional design, such as placing refrigerator away from the oven, the radiators or the windows, but leave little room for changes by the occupants once they are in place (Christidou et al. 2014). Residents are little inclined to using an extra pullover when feeling cold (van der Grijp et al. 2019), but further studies are needed to evaluated clothing adjustment studies and air-conditioning operation (Parag and Sovacool 2016).

Active management refers to the efficient human control of building technical systems under the simple rule of only using something when needed. Efficient lighting practices include using small lighting support for focused tasks and turning off unnecessary lights, the latter being is a very effective measure to reduce summer peak demand (Dixon et al. 2015; Taniguchi et al. 2016). Environmental and physical factors as well as incentives and policies affect occupants lighting demand in institutional buildings (Salem and Elwakil 2017). The application of the Daylight-Saving Time in the US has been demonstrated to increase up to 7% lighting consumption (Rakha et al. 2018), so its validity may be considered. Efficient cooking practices include: fit size of cooking pan to the heating plate; use pressure cooker and, for small quantities, microwaves oven; turn off electric stove minutes before finishing cooking; cover pots while cooking. Efficient use of appliances includes to unplug the mobile charger when the phone is charged, avoid stand-by regime in TV and computer (Dixon et al. 2015), select eco-mode in dish and cloth washing appliances, and limit the temperatures of the fridge and freezer. Energy saving practices for hot water include shifts to shorter showers and turning off taps while washing and shaving (Christidou et al. 2014). A summary of the current adoption rates of these practices are shown in Table 9.16 and Figure 9.18. Such energy saving practices can save up to 25% (Teng et al. 2012; Berezan et al. 2013; Hsiao et al. 2014; Abrahamse and Steg 2013; Peschiera and Taylor 2012; Volochovic et al. 2012) and should be facilitated whenever possible. High behavioural control is so far proven difficult to achieve (Ayoub et al. 2014; Sköld et al. 2018).

Technical measures to that could trigger passive management (e.g. feedback) and automated management solutions (e.g. sensors that emulate occupant behaviour) are addressed in Section 9.4.

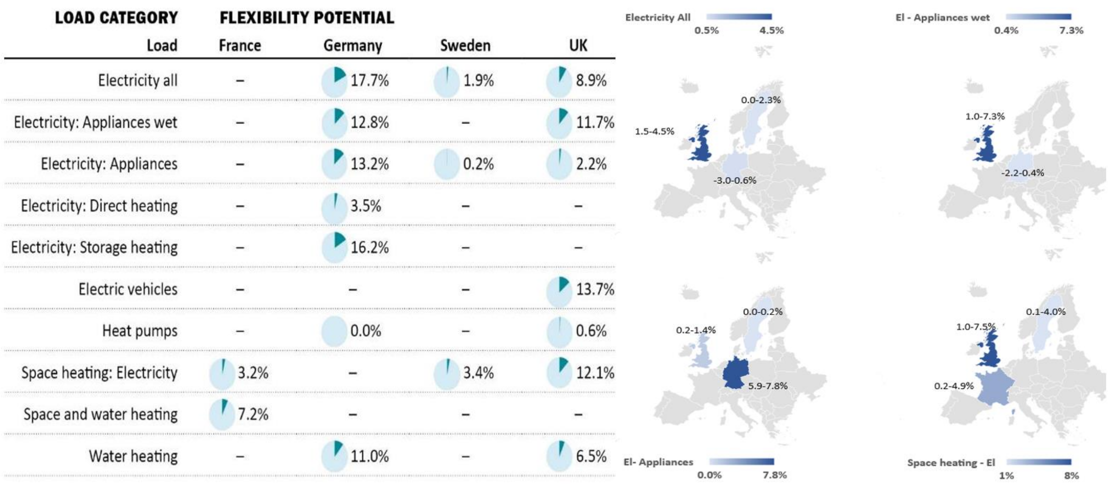
#### *9.5.3.2 Flexible comfort requirements*

The concept of "flexible" behaviour refers to preferences and requirements, which can be adjusted in terms of levels of stringency and timeframe. In the later, the desired level of service is the same, but it can be shifted over time.

Adjustment in the temperature of the heating in winter and the cooling in summer results in savings of of 5% -15%, and up to 25% is possible if the set point temperature is increased by 3◦C or thermostats are adjusted to occupant presence (Ayoub et al. 2014; Christidou et al. 2014; Sun and Hong 2017; Taniguchi et al. 2016)(Da and Hong, 2013). In office buildings, each a 1 °C decrease in the default set-point temperature cause reductions in the chosen settings by 0.38 °C, with the users being more favourable to smaller changes of 1°C than to 2°C (Brown et al. 2013). Energy savings for zonal control refrigeration can vary up to 20% due to occupant behaviour (Sun and Hong 2017). Adaptive behaviours are affected by the distribution of the office space and interior design, amount of occupants, visual comfort and outdoor view, ease to use control mechanisms (Talele et al. 2018)(Ó Brien and Gunay 2014). In households, concentrating occupancy in the room with AC has been proven to reduce energy demand (Taniguchi et al. 2016).

Households are willing to adopt measures that do not greatly affect their way of life (e.g. use fewer devices and maintain them better, upgrade home appliances to A+++, Lower in-house temperature by 1C, install hourly thermostats, switch electricity provider, etc.) to reduce their emissions by 30% voluntarily, but only if forced would incorporate additional measures to achieve a 50% reduction (e.g. move to a low energy house or smaller apartment, insulate your envelope, adjust indoor temperature by 3C, install renewable energy or replace heating systems) (Sköld et al. 2018). Users of NZEBs are less willing to take on behavioural measures (e.g. turning off lamps, taking shorter showers) than to implement efficiency measures (appliances showed) or take part in energy savings informal training (comparing energy use and exchanging best practices with neighbours) (van der Grijp et al. 2019).

With demand side measures, such as shifting demand a few hours, peak net demand can be reduced up to 10-20% (Zimmermann 2009; Gils 2014, Stötzer et al., 2015), a similar potential is available for short-term load shifting during evening hours (Aryandoust & Lilliestam, 2017). Human factors play an important role in DSM. Although different household types show different consumption patterns and thus an individual availability of DSM capacity during the day (Fischer et al., 2017), there is limited (Shivakumar et al., 2018) or inexistent (Nilsson et al., 2017; Drysdale et al., 2015) information of consumers response to ToU pricing, specifically among those living in apartments (Bartusch & Alvehag, 2014). Consumers are shown to lack acceptance towards comfort changes (noise, overnight heating) and increased automation (Sweetnam et al., 2019; Bradley et al., 2016, Drysdale et al., 2015). Behavioral benefits are identified in terms of increased level of energy awareness of the users (Rehm et al., 2018), measured deliberate attempts of the consumers to reduce and/or shift their electricity usage (Bradley et al., 2016). Households that changed their times-of-use did so primarily to try and use their PV electricity in the home. Environmental motivations were also important for some participants in their shifting (Bradley et al., 2016).



| LOAD CATEGORY | FLEXIBILITY POTENTIAL | | | |
|---|---|---|---|---|
| Load | France | Germany | Sweden | UK |
| Electricity all | – | 17.7% | 1.9% | 8.9% |
| Electricity: Appliances wet | – | 12.8% | – | 11.7% |
| Electricity: Appliances | – | 13.2% | 0.2% | 2.2% |
| Electricity: Direct heating | – | 3.5% | – | – |
| Electricity: Storage heating | – | 16.2% | – | – |
| Electric vehicles | – | – | – | 13.7% |
| Heat pumps | – | 0.0% | – | 0.6% |
| Space heating: Electricity | 3.2% | – | 3.4% | 12.1% |
| Space and water heating | 7.2% | – | – | – |
| Water heating | – | 11.0% | – | 6.5% |

**Figure 9.16 Summary of flexibility potentials (share of the load that can be shifted) by type of load, up-scaled at the country level. Maximum carbon emission reductions (share of total emissions of electricity in the residential sector that could be avoided). Source: Mata et al, 2019**

## 9.5.4 Defining a low carbon economy

### *9.5.4.1 Sufficiency*

Faced with population growth, rising incomes and preferences for more goods and services, emission reduction gains are unable to offset emission growth around the world (Harris et al. 2008). Addressing this challenge requires a new approach that goes beyond the technological improvements and even behavioural changes and considers human needs and well-being in the broader context of planetary boundaries (Heindl and Kanschik 2016). The sufficiency concept was introduced in early nineties by Sachs (1993). It has been increasingly researched with more than a hundred publications by today (Toulouse et al. 2019). Most of this research takes place in Europe, especially within Germany, France and Switzerland (ibid.).

A universal definition of energy sufficiency has not yet been introduced. One important distinction regards the state of energy sufficiency and the necessary actions to get there. As a state, energy sufficiency describes a situation in which people's energy needs are met adequately and equitably while ecological limits are respected (Darby and Fawcett 2018). Energy sufficiency, then, both has an upper and a lower bound, occupying the space between energy overconsumption and energy poverty (Fawcett and Darby 2019). This concept has its roots in the ideas of Raworth (2012), who invented the concept of the 'sufficiency donut' to describe a "safe and just space for humanity" that lies between a social foundation that satisfies basic human needs and an environmental ceiling. With respect to the minimum requirements at the lower bound, an energy sufficiency state demands that energy services satisfy the needs for health, shelter, work, communication and mobility (Fawcett and Darby 2019). With respect to the absolute limits at the upper bound, such a state requires that all relevant ecological parameters that are implicated with energy service provision are considered. These include multiple dimensions from atmospheric carbon, air pollution and biodiversity levels to land use (e.g. due to biomass plantations), water availability (e.g. due to hydropower plants) and resources needed for energy services infrastructure (e.g. due to mines, pipes, power plants) (Darby and Fawcett 2018). As an action, energy sufficiency aims to reduce the input of technically supplied energy towards sustainable levels, with a qualitative or quantitative change in the service or utility from energy (Thomas et al. (2017). This can be understood in contrast to energy efficiency actions, which aim to reduce the input of energy while holding the service or utility from energy constant. To achieve these reductions in supplied energy, energy sufficiency actions seek to change daily routines, practices and infrastructure so that human needs and desires can be adequately met by less energy-demanding services (Bierwirth and Thomas

2019). Given the lower limit of energy sufficiency and the fact that many people around the world still lack appropriate access to energy services, energy sufficiency is not only about demand reduction but also about matters of distribution and equity (Darby and Fawcett 2018).

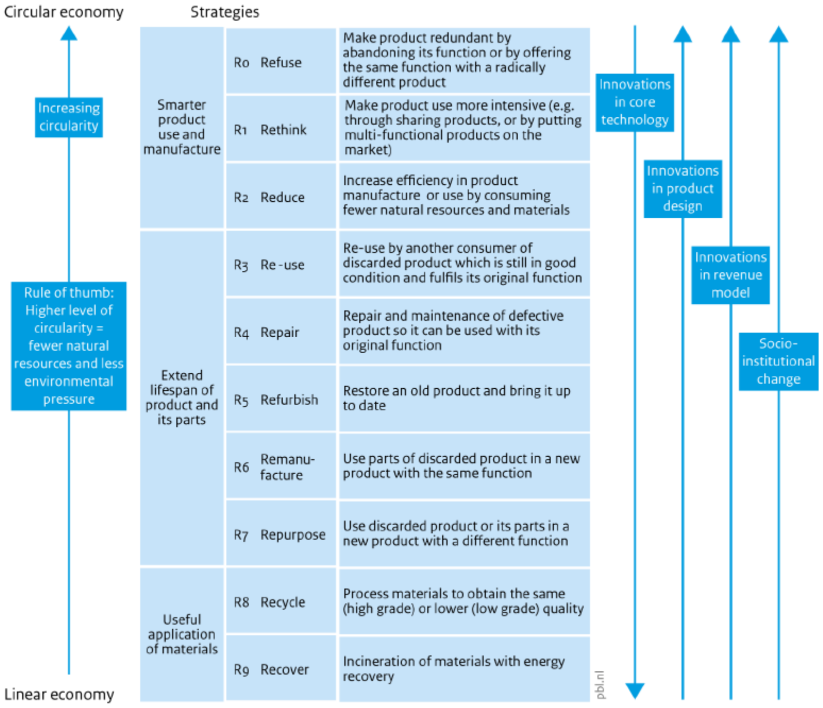
Energy sufficiency in a building was put forward by Bierwirth and Thomas (2019) as an adequate space thoughtfully designed and constructed and sufficiently equipped for reasonable use. This would lead to consideration of such parameters as space, design and construction, equipment, and use. Sufficiency therefore is a concept that should be integrated during the whole lifetime of a building already from the initial planning even before the consideration of efficiency, behavioural, or renewable energy measures. Doing so, sufficiency measures may deliver energy savings even before they are implemented through efficiency and behaviour as sufficiency avoids energy demand without costs and without compromising on the well-being of the occupants. Furthermore, it may deliver the required energy services with a minimum of energy from renewable energy sources thus saving materials and other resources for the production and use of renewable energy installations.

There are several foci of the sufficiency definition: emission sufficiency, energy demand sufficiency and energy service sufficiency (Brischke et al. 2015). These translate to such metrics as $CO_2$ emissions/person $yr^{-1}$, electricity consumption/person/annum, or a measure of living area per person ($m^2$/person) (Bierwirth and Thomas 2019). There is a conceptual challenge of defining the lower and upper bounds of these indicators. Bierwirth and Thomas (2019) suggested that minimum standards set by social courts and agencies could point the lower bounds. As for the upper bounds, scientific estimates on environmental ceilings could serve as a guide.

At national level, there have been several studies that have determined sufficiency savings potential for particular sectors and contexts. They usually calculate the amount of energy that could potentially be saved through energy sufficiency adjustments in a given year, when compared to the trend of energy demand in a business as usual scenario (in kWh $yr^{-1}$ or in %) (Brischke et al. 2015). Econcept (2013) found that 15% of final energy consumption could be saved by reducing the living area by a third and 10-18% could be saved by switching to sufficient equipment and usage of this (e.g. sufficient use of hot water or information technology). In France, the négaWatt scenario project modelled that by implementing energy sufficiency policies, a decrease in final energy demand of the residential building sector of 21% is possible until 2050 when compared to a business-as-usual scenario (Toulouse et al. 2017). Another study compared different energy sufficiency pathways – from moderate to radical – in the Nord-Pas-de-Calais region in France and found a sufficiency savings potential ranging between 13% and 30% for the residential and tertiary building sector (Virage-Energie 2016). Finally, a German study found a large sufficiency potential for individual households – half of a household's final energy consumption and twice as much as the energy efficiency savings potential (Brischke et al. 2015).

#### *9.5.4.2 Circular economy*

The built environment has become the world largest consumer of raw materials (WEF 2016). The traditional economy model is based on a linear principle of extract, produce, consume and dispose with little consideration of ecological and social impacts (Sauvé et al. 2016). EPA (2009) calculated that in the US only 20-30% of construction and demolition waste are recycles or reused, while the discarded waste contains lumber, asphalt, soil, concrete, and gypsum that could find further potential applications. In contrast, the circular economy model, which was introduced in the 1960s (Kirchherr et al. 2017), aims to preserve natural capital, optimize renewable energy resources, prevent waste and design out negative externalities (ARUP 2016). It relies on a principle of reduce, reuse and recycle (Preston 2012; Ghisellini 2016; Fischer and Pascucci 2017). The European Waste Framework Directive (2008) added the 'recover' stage to the circular economy cycle. Furthermore, Potting and others (2017) identified a list of 'R-strategies' as presented in Figure 9.17, that have been developed to achieve less resource and material consumption in product chains and could make economy more circular.



| Strategies | | | |
|---|---|---|---|
| Smarter product use and manufacture | R0 | Refuse | Make product redundant by abandoning its function or by offering the same function with a radically different product |
| | R1 | Rethink | Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market) |
| | R2 | Reduce | Increase efficiency in product manufacture or use by consuming fewer natural resources and materials |
| Extend lifespan of product and its parts | R3 | Re-use | Re-use by another consumer of discarded product which is still in good condition and fulfils its original function |
| | R4 | Repair | Repair and maintenance of defective product so it can be used with its original function |
| | R5 | Refurbish | Restore an old product and bring it up to date |
| | R6 | Remanufacture | Use parts of discarded product in a new product with the same function |
| | R7 | Repurpose | Use discarded product or its parts in a new product with a different function |
| Useful application of materials | R8 | Recycle | Process materials to obtain the same (high grade) or lower (low grade) quality |
| | R9 | Recover | Incineration of materials with energy recovery |

**Figure 9.17 Circularity strategies within the production chain. Source: Potting et al. (2017)**

Stahel (2013, 2014 in Ghisellini 2016) argued that the recycling principle, may be the least sustainable solution compared to the other principles of the circular economy (namely, reduction and reuse) in terms of resource efficiency and profitability. Furthermore, it cannot last forever because in some cases, recycling is limited by nature (entropy law), material complexity, and abuse (Stahel 2013 in Ghisellini 2016). While the foregoing also applies to the reuse principle, both principles share the general objective of waste reduction.

Finally, the work of Kirchherr et al. (2017)(Kirchherr et al. 2017) outlined the systems perspective as a core principle of the circular economy. From their point of view, the system perspective may have replaced the R-framework based on the frequency analysis of circular economy definitions in peer reviewed publications.

Pomponi and Moncaster (2017), Mercado (2019) and ARUP (2018) (Pomponi and Moncaster 2017; Mercado 2018; ARUP 2018)reviewed a range of opportunities in the built environment that could be offered by the circular economy approach. These include 3D-printing, reuse of structural steel, and recyclable insulation with recycled content, which apply the concept.

When implementing circular economy principles and practices in companies and firms within the private sector, the transition goes beyond just changing existing ecosystems, it involves also considering new forms of internal collaboration within the organizations, which calls for internal adaptation to new interdependencies and complexities (Grandori & Soda 1995, Grandori 1997 in Fischer 2017 and in Mercado 2019). Thus, the transition process towards circularity could enable interesting conditions for: 1) organizational innovation; 2) collaboration and trade; and 3) rethinking the way in which regulations, laws, and property rights operate, which may finally allow the identification of sustainable solutions. Fischer and Pascucci (2017)(Fischer and Pascucci 2017) argued the main challenges are to understand: 1) how to facilitate such transition when it is constrained by an institutional system that is aligned with the status quo of a linear economy; and 2) the role of inter-firm collaborations in this process.

#### *9.5.4.3 Shared economy*

The other new economy approach is shared economy. This approach aims to generate an increased utilization rate of products or systems by enabling or offering shared use, access or ownership. At the same time, it enhances off-site design and the use of collaborative production facilities. The sharing platform model is centred on the sharing of products and assets that have a low ownership or use rate. Companies that leverage this model can maximize the use of the products they sell, enhance productivity and value creation. The examples are peer to peer accommodation (Airbnb), and neighbours helping neighbours (TaskRabbit, NeighborGoods). Peer to peer accommodation (Rademaekers et al. 2017; Ludmann 2019) and reuse of buildings (Hertwich et al. 2020), are also discussed in Chapter 5 (Section 5.3.4.2).

### 9.5.5 Adoption of climate mitigation solutions for existing and new buildings – reasons and willingness

This section aims to map reasons for adoption of climate mitigation solutions for existing and new buildings, per type of solution, decision maker, and region; in order to highlight the relevance of stakeholders' perspectives for policy design. Corresponding policy implications are however presented in Section 9.9.

**Table 9.15 Reasons for adoption of climate mitigation solutions, for renovation of existing buildings and new buildings. The sign represents if the effect is positive (+) or negative (-), and the number of signs represents confidence level (++, many references; +, few references).**

| | **Climate mitigation solutions buildings** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Sufficiency** | **Efficient technical systems** | **On-site renewable energy** | **Performance standards** | **Low-carbon materials** | **Smart home and digitalization** | **Demand-supply flexibility** |
| ***Economic:*** | | | | | | | |
| Subsidies/microloans | + | + | ++ | + | | + | + |
| Low/high investment costs | | +/- | ++/-- | +/-- | + | - | |
| Short payback period | + | | + | + | + | + | + |
| High potential savings | ++ | + | ++ | + | | + | + |
| Market driven demand | | | | + | | | |
| Higher resale value | | | | + | | + | |
| Split incentives | - | | | - | | | - |
| Constrained budgets and profits | + | + | + | + | | | + |
| ***Information and support:*** | | | | | | | |
| Interactive feedback | | | | | | + | |
| Governmental support and capacity/lack of | ++ | +/- | ++/- | +/- | + | + | +/- |
| Information and labelling/lack of | +/- | ++/- | ++/- | +/- | | +/- | +/- |
| Smart metering | | | + | | | + | |
| Participative ownership | | | + | | + | | |
| Peer effects | + | + | ++ | | | + | |
| Professional advice/lack of | +/- | +/- | +/- | +/- | | | |
| Social norm | | | + | | | | |
| ***Technical:*** | | | | | | | |
| Condition of existing elements | + | + | | + | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Efficient back-up systems | | + | | | | + | |
| Natural resource availability | | | + | | | | |
| Performance and maintenance concerns | - | - | - | -- | - | - | |
| Limited alternatives available | | | - | - | - | | |
| ***Attitudes and values:*** | | | | | | | |
| After moving in | + | | | | | | |
| Appealing novel technology | + | + | + | | | + | + |
| Social and egalitarian world views | + | | + | | | + | |
| Willingness to pay | | + | ++ | + | | + | |
| Heritage or aesthetic values | - | - | - | - | | - | |
| Environmental values | + | + | + | + | + | + | |
| Heritage and aesthetic values | | | | | | | |
| Status and comfort/lack of | + | + | + | +/- | | +/- | |
| Lack of control, privacy and security | | | - | - | | -- | |

**Sources**: **Sufficiency:** (Miezis et al. 2016; Ozarisoy and Altan 2017; Curtis et al. 2017; Zuhaib et al. 2017; Kim et al. 2019; Howarth and Roberts 2018; Tsoka et al. 2018; Hernandez-Roman et al. 2017; Friege 2016; Lilley et al. 2017; Ketchman et al. 2018; Gährs et al. 2015); **Efficient technical systems:** (Mortensen et al. 2016; Qiu et al. 2014; Heiskanen and Matschoss 2017; Zografakis et al. 2012; Clancy et al. 2017; Bright et al. 2019; Tumbaz and Moğulkoç 2018; Trencher and van der Heijden 2019; Wittchen et al. 2017; Christidou et al. 2014; Hernandez-Roman et al. 2017; Chun and Jiang 2013; Hong et al. 2016; Chu and Wang 2019; Ketchman et al. 2018; Curtis et al. 2018) ; **On-site RES:** R(Roth et al. 2018; Radmehr et al. 2014; Overholm 2015; Lay et al. 2013; Qureshi et al. 2017; Heiskanen and Matschoss 2017; Shukla et al. 2017; Vimpari and Junnila 2019; Kosorić et al. 2019; Jung et al. 2016; Stauch and Vuichard 2019; Jimenez et al. 2016; Hai et al. 2017; Abreu et al. 2019; Sagebiel and Rommel 2014; De Groote and Verboven 2019; Frey and Mojtahedi 2018; Wolske et al. 2018; Dong and Sigrin 2019; Torani et al. 2016); **Performance standards**: Lien 2019 (Societies and Simulation 2015; Olsthoorn et al. 2019; Taleb and Pitts 2009; Balta-Ozkan et al. 2013; Herrera-Avellanosa et al. 2019; Jain et al. 2017; Bright et al. 2019; Kamari et al. 2017; Halila et al. 2017; Collins and Curtis 2018; Hwang et al. 2017; Balta-Ozkan et al. 2015; Kieft et al. 2017; Haines and Mitchell 2014; Ketchman et al. 2018); **Low-carbon materials**: Lien 2019, Tozer 2019, Thomas 2014, (Tozer 2019; Steinhardt and Manley 2016); **Smart home and digitalization:** Wong 2016,, Kendel 2015(Poortinga et al. 2012; Moser 2017; Pal et al. 2019; Nikou 2019; Tan et al. 2017; Vimpari and Junnila 2019; Safdar et al. 2019; Shih 2013; Hwang et al. 2017; Balta-Ozkan et al. 2015; Zhuang and Wu 2019; Vassileva and Campillo 2016; Chen and Sintov 2016); **Demand-supply flexibility:** (Liang et al. 2017; Soland et al. 2018; Lee and Tanverakul 2015; Seidl et al. 2019).

#### *9.5.5.1 Sufficiency measures to avoid energy demand*

Sufficiency measures to avoid energy demand (Section 9.4.3) and behavioural changes (Section 9.5.3). Consumers are positive to energy saving practices in different degrees, as summarized in Table 9.16.

**Table 9.16 Adoption levels of different behavioural energy saving practices, by sector and region.**

| **Adoption levels** | **Behavioural energy saving practice** | **Geographical specificities** | **Sectorial specificities** |
|---|---|---|---|
| 100-75% | Limit window opening if heating/cooling system is on | | |
| | Switch off unnecessary lights | | |
| | Repair leaking taps | | |
| | Adapted dress code | | |
| 50-75% | Eco-mode in dish and cloth washing appliances | | |
| | Shift to short shower | | |
| | Manage curtains and blinds to limit heating and cooling demand | | |
| | Fit size of cooking pan and the heating plate | | |
| | Turn off tap while washing and shaving | | |
| 25-50% | Use pressure cooker | | |
| | Use small support lighting for focused tasks | | |
| | Turn off electric stove minutes before finishing cooking | | |

| | | | |
|---|---|---|---|
| | Microwave warming of small food quantities | | |
| 0-25% | Limit temperatures of fridge and freezer | | |

Sources: Cited in the text of Section 9.5.3 and this Section 9.5.4.

In North America and Europe (Northern, Western, Southern and Eastern), personal attitudes and values, and existing information and support are the most and equally important reasons for improving the thermal performance of the building envelope. Consumers have some economic concerns and little technical concerns, the later related to the performance and maintenance of the installed solutions (Friege 2016; Tsoka et al. 2018). In other world regions the literature is limited.

Motivations are triggered by contextual needs, such as after moving in, driven by conform or urgent replacements of dysfunctional elements, or social and environmental values (Friege et al 2016, Friege 2016, Mortensen et al 2016, Liley at al 2017; Howarth and Roberts 2018, Kim et al 2019). Maintaining the heritage and aesthetic value of the property(Haines and Mitchell 2014), may as well hinder the installation of additional insulation if no technical solutions are easily available (Bright et al. 2019). The decisions show high positive correlation to governmental support (Tam et al. 2016; Ozarisoy and Altan 2017; Gährs et al. 2015; Miezis et al. 2016), and peer information (Friege 2016; Friege et al. 2016). Local professionals and practitioners can to date both encourage (Ozarisoy and Altan 2017; Friege 2016) and discourage the installation of additional insulation, according to their knowledge and training (Curtis et al. 2017; Zuhaib et al. 2017; Tsoka et al. 2018). For instance, if energy renovations of the buildings' envelope are not normative, cooperative ownership may be a barrier in apartment buildings, in which all the owners must agree to insulate the roof (Miezis et al. 2016). Similarly, product information and labelling may be helpful or overwhelming (Miezis et al. 2016; Ozarisoy and Altan 2017; Curtis et al. 2017; Lilley et al. 2017; Bright et al. 2019) . Consumers without education and training are more likely to reject migration technologies (Hernandez-Roman et al. 2017; Ketchman et al. 2018).

The intervention is required to be cost efficient, although value could be placed in the amount of energy saved (Mortensen et al. 2016; Lilley et al. 2017; Howarth and Roberts 2018; Kim et al. 2019) or the short payback period (Miezis et al. 2016). Subsidies have a positive effect (Swan et al, 2017). Non-private interventions are hindered by constraints in budgets and profits, as well as institutional barriers and complexities (Miezis et al. 2016; Zuhaib et al. 2017; Curtis et al. 2017; Tsoka et al. 2018; Kim et al. 2019).

#### *9.5.5.2 Installation of renewable energy sources (RES)*

Although consumers are willing to install distributed RES worldwide, and information has successfully supported their cost-efficient roll out, some economic and governmental support is still necessary for their full deployment. Little technical issues remain that hinder the adoption of distributed RES. [Placeholder – paragraph on regional specificities]

Investments in residential PV are realized by comparatively rich homeowners who expect reasonable high and secure return on investments (Hampton and Eckermann 2013; Schaffer and Brun 2015). Homeowners and environmentally concerned are more likely to prefer demand charges when compared to renters (Liang et al. 2017). In contrast, the investors' ecological attitude seems to play a minor role than individual attitudes towards solar PV and social normative concerns (Abreu et al. 2019) for the adoption of small-scale installations. Regional neighbourhood effects are observed that point at the importance of specified craft skills and/or intermediary agents (Schaffer and Brun 2015).

When purchasing a new heating system, comfort, economic and ecological aspects, as well as information play a role (Decker and Menrad 2015; Claudy et al. 2011) Being environmentally aware seems to reduce a consumer's probability of investing in new heating equipment but does seem to increase the probability of purchasing biofuel-based heating equipment (Lillemo et al. 2013). Living in a cold climate significantly increases the probability of investing in a pellet stove (Sopha et al.,2010).

### *9.5.5.3 Smart building, digitalization and demand-supply flexibility*

Demand-supply flexibility measures (shift to distributed power and energy storage (Section 9.4.7) and digitalization [Section 9.4.4]) are being adopted mostly in North America, Europe and Asia-Pacific Developed regions. New players in the DSM market are emerging changing customer utility relationships, as the grid is challenged with intermittent loads and integration needs for ICTs, interfering with consumers' requirements of autonomy and privacy (Wolsink 2012; Parag and Sovacool 2016). Although most private PV owners, of this small minority of consumers, would make their storage system available as balancing load for the grid operator, the acquisition of new batteries but a vast majority of consumers requires incentives (Gährs et al. 2015). For distributed energy hubs, social acceptance depends on the amount of local benefits, whether in economic, environmental, or social terms (Kalkbrenner and Roosen 2015), and increases around demonstration projects (von Wirth et al. 2018). However, governments and energy utilities are assumed by consumers as responsible drivers of the energy transitions (Seidi et al (2019).

In all, the needs of consumer groups are diverse, and no model of utility/customer interaction is found preferable (Soland et al. 2018). The successful implementation of demand-supply flexibility needs novel models of interaction, based on trust and transparent communication (Wolsink 2012; Nyborg and Røpke 2013; Soland et al. 2018). Further research is needed to identify acceptance of new agents and (prosumer) roles on the energy market, as well as on the influence of different narrative framings (global, national, regional and local) on acceptance (Seidi et al (2019).

### *9.5.5.4 Willingness to adopt*

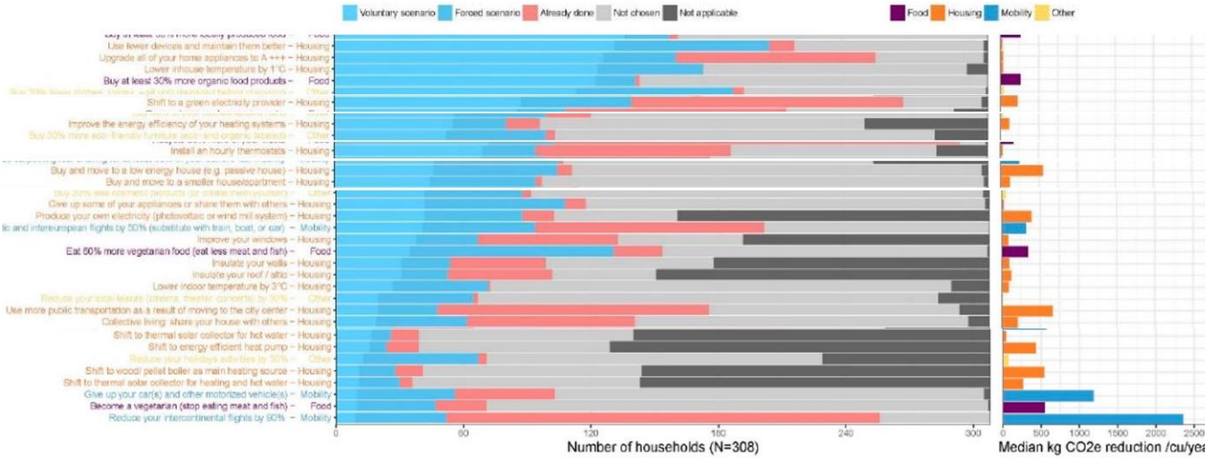


**Figure 9.18 Willingness to adopt different low-carbon measures for buildings. Source: Sköld et al 2018.**

### *9.5.5.5 Translating motivations into market segmentations for targeted policies*

Consumer´s attitudes and behavioural factors are important for policy design (Liang et al. 2017). Motivations translated into taxonomies of consumers can be used for targeted policy making (Zhang et al. 2012; Marshall et al. 2015; Haines and Mitchell 2014; Gram-Hanssen 2014; Friege et al. 2016; Hache et al. 2017; Ketchman et al. 2018). Policy reviews for specific market segments (Marzano et al. 2018) and empirical studies investigating energy relevant investment decisions need to be taken further through a multidisciplinary approach to energy consumption patterns and accordingly tailored policies (Boyd 2016)( Kastner and Bobeth, 2018).

In addition, the markets exhibit different stages of maturity e.g. capacity in the building trade to carry out efficiency focused retrofits (Heiskanen and Matschoss 2017; Baumhof et al. 2018; Wilson et al. 2018). Only a fraction of these listed studies investigates societal transformation processes using decision factors from the Diffusion of Innovation theory (DOI, Rogers, 2010), such as demographic/housing characteristics/location of residence, decision-maker dispositions, beliefs about consequences for and beyond the household, social influences and policy measures(Kastner and Stern 2015). These factors play varying roles at different stages of the innovation/technology diffusion process (e.g. section of S-Shaped diffusion curve), so that educated, pioneering people with less concern for costs or concrete benefits are vital at the early stage, whereas the mainstream market (often middle-aged, middle-income people) make adoption decisions based on costs and benefits (Heiskanen and Matschoss 2017). For example, experienced consumers or planning to invest could be the first target group of new energy pricing, these consumers are more likely to accept it (Liang et al. 2017). Quantitative market segmentation data could inform policy penetration, and facilitate the development of business models and early stage technologies, ensuring that the right target user is approached (Haines and Mitchell 2014).

## 9.6 Global and regional costs and potentials

Previous sections illustrate that existing individual technologies and practices allow constructing and retrofitting of individual buildings, which emit very low GHGs during building operation. During the last decade, we have observed a growing number of such buildings in all parts of the world. Since AR5 there has been a growing amount of literature, which calculates emission reduction potential at national level for different countries worldwide, if these will penetrate at scale. The analysis of these figures shall be cautious, because they rely on the number of assumptions containing uncertainties. As discussed in the previous sections, the reduction of embodied emissions represents the next opportunity and a new trend in literature is appearing to analyse this potential at national level.

### 9.6.1 Review of literature calculating potentials and costs for different world countries

Table 9.17 presents the review of literature published since AR5, which quantifies the potential for GHG mitigation in the buildings sector and associated costs for different countries worldwide. The review is structured by region. Most studies rely on a technology-reach, bottom-up approach. The studies tend to use one or several mitigation strategies from the following: reduction of energy demand; improvement of energy efficiency of thermal envelopes, building systems, equipment, and appliances; and fuel switch to low carbon energy carriers including buildings-integrated renewables. To some extent, these strategies can replace each other; therefore, the conclusion on the ranking of measures, which may bring the highest potential is not always straightforward. Furthermore, most studies which were prepared for the countries in cold climates consider measures as a package due their technological complementarity, and therefore ranking of individual measures was not possible.

Europe and North America have the richest amount of literature among all continents, which amount has grown since AR5 and AR4, though it was also available that time. In line with their GHG emission reduction commitments and due to their declining reference scenario emissions, emission reductions in some European countries are often provided versus a base year. Overall, the literature attests that by 2050, the countries on these continents may reduce up to 90% of their emissions as compared to 1990.

The amount of literature on potentials in Asia has increased since AR5 and AR4. Many studies from this continent estimate the GHG emission reduction potential of up to 70% and even more than 90% as compared to their baseline emissions in 2050, even though the baseline emissions grow sharp.

African and South American countries have very limited amount of literature estimating the potentials. The only recent report available for South Africa illustrated the potential to reduce emissions up to 45% versus the business-as-usual baseline in 2050. The Argentinean and Brazil studies report the potential in the order of magnitude 10-25% versus baseline final energy consumption and/or emissions in 2050. Similar to Asia, these potentials are estimated versus growing baselines.

With the declining amount of energy and emissions during the building operation stage, the importance of embodied emissions in buildings grows. This is reflected in the emerging literature, which assesses lifecycle emissions embodied in buildings at national level. (Peñaloza et al. 2018) calculated that in Sweden, 25% of $CO_2$ emissions embodied into building materials could be avoided over 2017-2117.

The studies presented in Table 9.17 rely on different analytical approaches to analyse the costs associated with the realisation of potentials. Some calculate total either/or incremental investment cost; some conduct a cash-flow analysis; and some calculate annualized incremental costs. For a few comparable European studies, which conduct an assessment of the sector transformation aiming at emission reduction by 80-90% in 2050 as compared to 1990, the annual incremental costs are between 1% and 3.5% of GDP (Kjell Bettgenhäuser and Andoni Hidalgo 2013; Markewitz et al.)( Novikova et al. 2016a, b).

**Table 9.17 Review of literature quantifying potentials for GHG mitigation in buildings using a bottom-up approach**

| A | B | C | D | E | F | G | H | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|
| **Region and country** | **End-uses** | **Sector** | **Technological options considered** | **Policies considered** | **Type** | **Base/end years** | **% change to baseline or base year** | **Indicators considered for cost calculation** | **Measures with the highest potential** | **Reference** |
| **<u>1. Europe</u>** | | | | | | | | | | |
| EU 27 | SH,<br>SC,<br>WH,<br>RE | R | Three tracks separated after speed and depth of renovation. Focus on HVAC, building envelope and RE | | Techno-economic | 2012 - 2050 | CO2/final energy:<br>Track 1: - 34% / -32%<br>Track 2: - 86% / -52%<br>Track 3: -88% / -80% | Total costs [billion USD]<br>Track1: 9.3*;<br>Track2: 10.0*;<br>Track3: 9.7* | | Bettgenhäuser and Hidalgo 2013 |
| Albania | SH,<br>SC,<br>WH | R | Roofs, basement, walls, windows; HVAC and hot water. | Building codes, Public subsidies: grants and low-interest loans | Techno-economic | 2015 - 2030 | CO2/final energy:<br>Moderate: -73%/-27%<br>Ambitious: -73%/-35% | Moderate / ambitious scenarios: Investment cost: USD 174* / 205* million per yr. | Roofs, basement, walls | Novikova et al. 2016b |
| Cyprus | SH,<br>SC,<br>WH,<br>L | R, NR, P | Demolition, new construction, retrofits (envelope, systems and RES) | Building code, grants, concessional loans, certificates, information campaigns | Techno-economic | 2013 - 2050 | Final energy:<br>Moderate: - 7%<br>Ambitious: -17% | | Energy efficiency packages | Economidou et al. 2018 |
| Denmark | SH,<br>WH | R | Retrofits | Renovation strategy and building regulation requirements for existing buildings | Techno-economic | 2011-2050 | 29,2-41,1 % energy saving compared to 2011 level<br>-0,5-36,9 % savings in 2050 compared to BAU scenario | Net costs: USD -242* million to USD 19436* million spend on renovation from 2011 to 2050 | Retrofit packages | Wittchen KB & Kragh J |
| Denmark | SH,<br>WH | R, NR, P | Retrofits | Renovation strategy and building regulation requirements for existing buildings | Techno-economic | 2013-2050 | 8.8-17.7 % energy savings in 2050 | Net costs: USD 0-11548 million* spend from 2013-2050 | Retrofit packages for existing buildings | Wittchen KB, Kragh J & Aggerholm S. |
| Germany | SH,<br>SC,<br>WH,<br>RE | R | Three scenarios separated in speed and depth of renovation. Focus in HVAC systems and building envelope and RES use | | Techno-economic | 2012 - 2050 | CO2/final energy compared to base year:<br>Reference: -55% / -43%<br>Fast renovation: -76% / -70%<br>Deep renovation: -86% / -80% | | | Bettgenhäuser and Hidalgo 2013 |
| Germany | SH | R, NR, P | Demolition, new construction, retrofits (envelope, systems and RES) | Demand reduction, energy efficiency standards | Techno-economic | 1990 - 2050 | CO2 compared to base year<br>- 71% (BAU scenario);<br>- 91% (MAX - Maximum reduction scenario) | Net Costs: USD 1415* billion (BAU) vs USD 1500* billion (MAX) | Comprehensive retrofit packages | Markewitz et al. 2015 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| France | SH | R | new construction, renovation of existing buildings | Carbon tax, tax credits, zero-interest loans, reduced VAT, white certificates, building codes | Techno-economic | 2013-2050 | Final energy: -21% or -48% compared to base year | | | Giraudet et al., 2018 |
| Montenegro | SH, SC, WH | R | Roofs, basement, walls, windows; HVAC and hot water. | Building codes, Public subsidies: grants and low-interest loans | Techno-economic | 2015 - 2030 | CO2/final energy:<br>Moderate improvement: -19%/-13%<br>Ambitious improvement: - 46%/-23% | Moderate / ambitious scenario: Investment cost: USD 52* / 91* million per yr.<br>or: 2.2* / 6.1* USD/m2 | Roofs, basement, walls | Novikova et al. 2016a |
| Serbia | SH, SC, WH | R | Roofs, basement, walls, windows; HVAC and hot water. | Building codes, Public subsidies: grants and low-interest loans | Techno-economic | 2015 - 2030 | CO2/Final energy:<br>Moderate improvement: - 27%/-17%<br>Ambitious improvement: - 16%/-27% | Moderate / ambitious scenarios: Total investment cost: USD 934* / 1223* million per yr.<br>Or: 3.3* / 4.8* USD/m2 | Roofs, basement, walls | Novikova et al. 2016b |
| Spain | SH, SC | R | Roofs, walls, floor | Building code | Techno-economic | 2013 - 2063 | Final energy:<br>-40% | Energy price + material insulation | Mineral and glass wool with ad hoc insulation thickness | Braulio-Gonzalo and Bovea, 2017 |
| Sweden** | SH, SC | R | Building systems in timber, concrete, steel and low-carbon concrete for multi-family and single-family dwellings | | Technical | 2017-2117 | CO2:<br>-25% | | 1. Low-impact concrete and timber buildings in substitution of conventional concrete.<br>2. RE in material manufacturing | Peñaloza et al. 2018 |
| Swiss | SH, SC, WH | R, NR, P | Roofs, basement, walls, HVAC, hot water systems: RES, heat pumps | CO2-tax, high energy prices, subsidy programme, building codes, ban of fossil heating system | Techno-economic | 1990 - 2050 | CO2 compared to base year -80% to -90% | - Investment and life cycle costs per m2 and cumulative for 3 periods<br>- Economic impact | Heat pumps (highest contribution), biogas (replaces natural gas), district heating, wood, solar thermal. Insulation of buildings | Iten et al. 2017 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Greece | SH, SC, WH, A | R, NR, P | New construction and retrofits, bulbs, appliances, solar thermal systems, boiler replacement | Retrofit incentives; Energy efficiency standards | Technical | 2005-2050 | CO2 compared to BAU<br>Residential: Moderate -9%, Ambitious -27%;<br>Non-residential: Moderate -13%, Ambitious -13% | | Residential: retrofits; Non-residential: appliances, heat pumps | Mirasgedis et al. 2017 |
| UK | SH | R, NR, P | Wall insulation, Loft insulation, Double glazing, Draught proofing | existing policies are assumed to continue to 2030 and beyond | Techno-economic | 1990 - 2050 | -35% (technical options) to -38% (policy extension) | Annualised cost (USD billion/year):<br>Baseline: 48.2*<br>Policy extension: 51.9*<br>Technical options: 71.4* | | Dolman et al. 2012 |
| UK | SH, WH, A | R, NR | Combined heat and power unit, hot water tanks for heat storage, district heating network | | Techno-economic | 2016 - 2040 | CO2 compared to base year: -70% (-86% - including thermal storage) | Total annualised costs: (a)including thermal storage: USD 5.7 mil* (b) excluding thermal storage: USD 5.9 mil* | CHP unit based DH network with thermal storage. | Oluleye et al., 2016 |
| UK | SH, WH | R | Air source heat pumps with thermal storage (i.e. electric heat storage) | | Techno-economic | 2016 - 2030 | Final energy compared to base year: peak electricity demand reduction: 78.2%, total electricity demand reduction: 8.4% | Annual Cost (USD/year): 2.767* (system lifetime is 15 years) | (1) Air source heat pump with electric heat storage<br>(2) Air source heat pump without electric heat storage | Oluleye et al., 2018 |
| **2. North America** | | | | | | | | | | |
| Alberta, Canada | SH, SC, WH, A, L | R | Lights, appliances, air/ground heat pumps, thermostats, heat recovery, boilers, shower heads, waste heating, ceiling, doors, walls, windows, furnaces. | | Techno-economic | 2013-2050 | CO2 / Energy use:<br>-16% / -11%<br>CO2 compared to base year:<br>+67% change from 2013 to 2050 | Marginal cost from -991* to 261* USD/tonne CO2 eq.<br>Marginal net present value from -2.8* to 0.9* billion USD | (1) lighting<br>(2) furnace<br>(3) wall insulation<br>(4) appliances | Subramanyam et al. 2017 |
| Alberta, Canada | SH, SC, WH, A, L | NR, P | Lights, appliances, air/ground heat pumps, thermostats, heat recovery, boilers, shower heads, waste heating, ceiling, doors, walls, windows, furnaces, auxiliary | | Techno-economic | 2013-2050 | CO2. / Energy use:<br>-21% / -13%<br>CO2 compared to base year:<br>+87% change from 2013 to 2050 | Marginal cost from -762* to 3.8* USD/tonne CO2 eq.<br>Marginal net present value from -2.7* to 0.08* billion USD | (1) heat pumps (ground)<br>(2) wall insulation<br>(3) condensing boiler<br>(4) lighting | Subramanyam et al. 2017 |
| Alberta, Canada | A | R | Energy star appliance adoption for refrigerators, dishwashers, freezers, clothes washers/dryers, ranges | $300 incentive for energy star appliances | Economic | 2012-2050 | Energy consumption compared to base year:<br>All appliances: -21% | | (1) Dishwashers, (2) Clothes washers, (3) Ranges, (4) Clothes dryers, (5) Refrigerators, (6)Freezers | Saeidreza et al. 2017 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Canada | SH, SC, A, L | R | Conservation: 1) air sealing, 2) roof insulation, 3 ) wall insulation, 4 ) thermostats 5) appliances, 6) lighting, 7) water heating, 8) space cooling and 9) space heating; 10) fuel switching, 11) RE. | Electricity export, nuclear phase-out, fuel switch | Techno-economic | 1990-2050 | CO2: Residential: -91%; Non-residential: -86-89%<br>Compared to base year: Residential 43 MT, Non-residential 26 MT | | Conservation | Trottier Energy Futures Project 2016, elements also published in Vaillancourt, Bahn, Frenette, Sigvaldason 2017 |
| United States | SH, SC, WH, A, L | R, NR | Heating, cooling, ventilation, water heating, lighting, refrigeration, clothes washing/drying, building envelope | 20% capital cost credit for fuel switch | Techno-economic | 2005-2050 | CO2:<br>Residential (New): -4.4% to -4.9%<br>/ (Existing): -7.7% to -8.7%<br>Non-residential (New): -1.6% to -2.2%<br>/ (Existing): -1.1% to -1.2% | all three of the examined technology performance tiers achieve between 71-82% of CO2 emissions reductions cost-effectively by 2050. | (1) Heat pump water heaters<br>(2) Cold-climate heat pumps<br>(3) High efficiency building envelopes<br>(4) Occupant-centric controls | Langevin, J., Harris, C.B., and Reyna, J. (2019). Assessing the potential to reduce U.S. building $CO_2$ emissions 80% by 2050. *Joule*, |
| USA - California | SH, SC, WH, A, L | R, NR | Three models: S1, S2, S3:<br>S1: heat pump HVAC & water heating, commercial LED lighting, more efficient equipment & appliances<br>S2: Energy efficiency improvements by factor 1.8<br>S3: Energy reduction by 90% in new buildings and 50% retrofits | S1 and S2: service demand reduction | Techno-economic | 1990-2030 | S1: -19% relative to ref scenario<br>S2: -31% relative to ref scenario<br>S3: -31% relative to S1 | S1: Levelized costs (2015-2030): $15.6 per hh per yr.<br>S2: Levelized costs (2010-2030): $1.5 per hh per yr.<br>Number of households: 11,502,870 | | Sonia Yeh et al. 2016 |
| **4. Africa** | | | | | | | | | | |
| South Africa | SH, SC, WH, A, L | R | Residential: 1. Appliances, 2. Geyser blankets, 3. Insulation (new buildings), 4. Insulation (retrofit), 5. Lights, 6. SWHS, 7. LPG stove, 8. Passive building | - | Techno-economic | (1) 2010 - 2030<br>(2) 2010 - 2050 | (1) CO2: - 29%<br>(2) CO2: - 46% | Marginal abatement cost in 2030: all negative besides 7. and 4. | Constructing passive buildings with improved thermal design | Department of Environmental Affairs, 2014 |
| South Africa | SH, SC, WH, A, L | NR, P | 1. Lights, 2. Heat pumps (retrofit), 3. Heat pumps (new buildings) 4. HVAC (heat recover- new buildings, variable speed drives (retrofit/new) AC-new buildings), 5. appliances, 6. Passive building | - | Techno-economic | (1) 2010 - 2030<br>(2) 2010 - 2050 | (1) CO2 - 22%<br>(2) CO2 - 45% | Marginal abatement in 2030: all negative. | Installation of HVAC with heat recovery in new buildings | Department of Environmental Affairs, 2014 |
| **5. Asia** | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Armenia | SH, SC, A, L | R, NR, P | Residential: 1. Lights, 2. Refrigerators, 3. AC, 4. TV, 5. insulation,<br>Non-residential and public: 1. AC, 2. Public lights | - | Techno-economic | 2015 - 2035 | CO2:<br>Residential: - 40,5%<br>Non-residential and public: - 37,9% | Marginal abatement cost (USD/tCO2).<br>Residential:<br>1, 2, 3, 5: negative<br>4: > 50<br>Non-residential and public:<br>1: negative<br>2: >25, but <50 | Top 3 residential: 1, 5, 2<br>Non-residential in descending order: 2, 1 | Timilsina et al. 2016 |
| China | SH, SC, A, L | R, NR | HVAC, Lightning, Appliances, Retrofit, Fuel switch, Renewables. (Strategies focusing on rural areas) | standards and codes, performance testing, smart metering, training programmes, guide books, licensing | Technical | 2010 - 2050 | Co2 (difference to BAU)<br>Technical potential: - 71%<br>Political potential: - 41% | None. | | |
| China | SH, SC, WH, A, L | R, NR | heat metering, waste heat recovery, heat pumps, PV, washing machines, AC. refrigerators, TV. (Focus on hotels and restaurants) | standards and codes, performance testing, smart metering, pricing reform, development, training, licensing | Technical | 2016-2050 | CO2:<br>Synergistic emission reduction scenario: - 58.1%<br>Policy scenario: - 27.9% | None. | (1) Renewable energy application<br>(2) green building standard<br>(3) saving heat and more efficient home appliances | Tan et al. 2018 |
| India | SH, SC | R, NR | Air conditioning (1. small, 2. medium (only in residential), 3. large), refrigerators (4. small, 5. large) | - | Techno-economic | 2010 - 2050 | CO2: >99% / Final energy: 1.6 - 6% | Marginal abatement cost (USD/tCO2eq):<br>1. 2. 3.: Negative in residential sector. | Air conditioning (1. small, 2. medium (only in residential), 3. large) | Purohit et al. 2016; Sharma et al. 2017 |
| India | SH, SC | R (new buildings) | 1. Walls material (various types), 2. Roof/flooring material (various types), 3. Wall insulation, 4. Roof insulation, 5. Glazing type. | - | Techno-economic | - | CO2 / Primary Energy (Life-cycle LC)<br>-31%/-28% (minimum LC energy)<br>-17%/-17% (minimum LC costs) | Life cycle (LC) costs*<br>-3% (minimum LC energy)<br>-18% (minimum LC costs) | (1) Wall material: stabilized earth blocks<br>(2) Roof/flooring material: filler slabs<br>(3) roof insulation | Mastrucci & Rao, 2019 |
| Georgia | SH, SC, A, L | R, NR, P | Residential: 1. Lights, 2. Refrigerators, 3. Washing, 4. TV, 5. Windows, 6. Roof insulation, 7. Wall insulation<br>Non-residential and Public: 1. Indoor Lights, 2. Street Lights, 3. Windows, 4. Roof insulation, 5. Wall insulation | - | Techno-economic | 2015 - 2035 | CO2:<br>Residential: - 14,6%<br>Non-residential and public: - 43,3% | Marginal abatement cost (USD/tCO2).<br>Residential:<br>1, 2, 3, 5, 6, 7: negative<br>4: > 50<br>Non-residential and public:<br>all: negative | Top 3 residential: 5, 1, 7<br>Top 3 non-residential: 1, 5, 4 | Timilsina et al. 2016 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Russia | SH, SC, A, L | R, P | Space conditioning, Thermal integrity, Lightning, Appliances, Renewables | standards and codes, training programmes, economic incentives, pilot projects | Technical | 2010 - 2050 | CO2: 62%<br>reduction 50% compared to 2013 levels | Total cost to achieve 62% reduction: USD 913 billion. Increment 8% (retrofit) 7% (new construction) (from 2014 to 2050). USD 25.4 billion per year | | |
| **6. South America** | | | | | | | | | | |
| Brazil | SH, SC, WH, A, L | R | 1. NG stoves, 2. NG water heater, 3. LPG stoves, 4. Shower, 5. Solar PV (Northeast region), 6. SWHS, 7. Solar PV (Southeast region), 8. Lighting, 9. Solar PV (South region), 10. Freezer, 11. Refrigerator, 12. AC, 13. Solar PV (North region), 14. Solar PV (Midwest region) | | Techno-economic | 2010 - 2050 | Final energy: - 25%<br>Compared to base year:<br>+ 20% (with all measures)<br>+ 50% (BAU) | Marginal abatement cost (USD/tCO2 ).<br>1-3: negative<br>4-14: >200 | Top 3:<br>3, 7, 11 | González-Mahecha et al. 2019 |
| Argentina | SH, SC, WH, A, L | R, P | 1. Lighting, 2. Refrigerator, 3. Water heaters (sanitary water) 4. Solar water heater (sanitary water), 5. Public lighting, 6. Heat pumps, 7. Hot water saving, 8. Thermal envelope | Energy Efficiency law | Techno-economic | 2017 - 2030 | CO2: -8.1%<br>by option: 1. -3.4%, 2. -2%, 3. -0.4%, 4. -0.17%, 5. -0.78%, 6. -0.54%, 7. -0.5%, 8. -0.2% | - | Top 3:<br>1, 2, 5 | a) Gabinete Nacional de Cambio Climático, 2017<br>b) Inventario de Gases de Efecto Invernadero de la República Argentina, 2012 |
| **7. Global** | | | | | | | | | | |
| World | SH, SC, WH, A, L | R, NR, P | Rapid energy efficiency deployment, RE, integrated energy systems | mandatory performance targets, economic incentives, fuel switch | Techno-economic | 2014 - 2060 | Final energy:<br>- 30% (in scenario with peak of energy demand in 2020)<br>- 18% (with energy demand peak in 2045) | | Wall insulations and efficient heating / cooling systems | IEA 2017: Energy Technology Perspectives 2017 |
| World | SC, A | R, NR | Air conditioning (1. small, 2. medium (only in residential), 3. large), refrigerators (4. small, 5. large) | Energy efficiency standards | Techno-economic | 2005-2100 | CO2: >99%<br>Final energy: Technical (-60 to -72.7%) | Marginal abatement cost (Euro/tCO2eq):<br>1. 2. 3. : Negative in residential sector and 4 in non-residential | Top 3: Air conditioning (1. small, 2. medium (only in residential), 3. large) | Purohit and and Höglund-Isaksson (2017); Höglund-Isaksson et al. (2017); UNEP (2019) - forthcoming |

**Notes**

Column B: SH-space heating, SC – space cooling, WH – water heating, A – appliances, L – lighting; Column D: Acronyms - NG - natural gas, LPG - liquified, PV - photovoltaics, SWHS - solar water heating systems, AC - air conditioners; Column C: R-residential, NR-non-residential, P – public; Column F: Techno-economic potential is an estimate of GHG mitigation compared with a baseline or reference case that can be achieved by a mitigation option with a given cost (per tonne) of carbon avoided over a given period. Technical potential here is a potential without cost consideration.; Column H and I: The potential in this column presents the potential of GHG emission reduction (if another is not specified in Notes, for example - final energy savings) compared to the baseline and/or base year for the end-uses given in column B and for the sectors indicated in column C; Column J: Qualitative estimate(s) of costs associated with the realization of the potential indicated in column H and I for instance CO2 marginal abatement cost, cost of energy conserved, total investment need, annualized investment cost, and/or others

* Numbers indicated with (*) are using the following exchange rates: 1 GBP = 1,26912 USD, 1 EUR = 1,13657 USD, 1 CAD = 0,761932 USD, source: https://www.xe.com/de/currencyconverter/

* Lifecycle assessment studies

### 9.6.2 Potentials and costs at global level

This section will provide an estimate of the potential for $CO_2$ emission reduction and associated costs at regional and global level in 2050. The estimate will be provided as an interval (from xx $tCO_2$ to xx$tCO_2$) using the template of Table 9.18. The methodology to prepare these estimates is described in Box below.

**Table 9.18 Potential and costs for $CO_2$ mitigation in buildings at regional and global level, 2050**

| | Baseline, WEO 2019 Current Policy Scenario | Potential in cost categories (USD/tCO2eq) | | | | |
|---|---|---|---|---|---|---|
| | million tCO2 | <0 | 0-20 | 20-50 | 50-100 | >100-200 |
| Developed countries | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |
| Eastern Europe and West-Central Asia | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |
| Latin America and Caribbean | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |
| Africa and Middle East | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |
| Asia and developing Pacific | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |
| GLOBAL TOTAL | | xx-xx | xx-xx | xx-xx | xx-xx | xx-xx |

Box 9.1 STARTS HERE

**Box 9.1: Methodology to estimate the global potentials and costs of $CO_2$ mitigation in buildings**

The box describes the methodology, which will be used to estimate the global potential for $CO_2$ emission mitigation in the buildings sector and associated costs. The estimate will be provided as an interval, in total amount as well as in cost categories for the year 2050. The potential will be interpolated to 2030 using a linear method. The intervals will be prepared as a summary of estimates, which rely on both bottom-up and top-down/AIM studies. Only studies covering a comprehensive range of measures and/or their packages are being covered. They include a comprehensive improvement of thermal envelopes of existing buildings and construction of new advanced buildings including HVAC and controls; equipment and appliances including cooking; and lighting. The intervals will consist of:

- The estimates based on top-down global studies: the key top-down/AIM studies providing global estimates with a breakdown by region and cost category are being reviewed. The estimates of the potential are being entered using the template below. The entries are potential as % of baseline emissions.
- The estimates based on bottom-up global studies: the key bottom-up studies providing global estimates with a breakdown by region and cost category are being reviewed. The estimates of the potential are being entered using the template below. The entries are potential as % of baseline emissions.
- The estimates based on bottom-up national studies: the potential per region is being estimated as an aggregation of estimates provided by national studies. It is further being broken down into cost categories based on studies, providing such detail in regions. The estimates of the potential are being entered using the template below. The entries are potential as % of baseline emissions.

The estimates as % of baselines emissions will be multiplied with baseline emissions to report the absolute amounts of the potential. These baseline emissions refer to the current policy scenario of World Energy Outlook (International Energy Agency 2019c).

| | Bottom-up studies | | Top-down/AIM studies | Intervals of potential estimates as provided by BU and TD studies |
|---|---|---|---|---|
| | Estimates based on national studies | Estimates of key global studies | Estimates of key global studies | Estimates of global studies |

| | Total | <0 | 0-20 | 20-50 | 50-100 | >100 | Total | <0 | 0-20 | 20-50 | 50-100 | >100 | Total | <0 | 0-20 | 20-50 | 50-100 | >100 | Total | <0 | 0-20 | 20-50 | 50-100 | >100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Developed countries | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |
| Eastern Europe and West-Central Asia | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |
| Latin America and Caribbean | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |
| Africa and Middle East | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |
| Asia and developing Pacific | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |
| GLOBAL TOTAL | | | | | | | | | | | | | | | | | | | x-x | x-x | x-x | x-x | x-x | x-x |

Box 9.1 ENDS HERE

### 9.6.3 Determinants of the potentials and costs

The estimates of the potential and its associated costs should be treated with caution because they rely on the number of assumptions containing uncertainties. These include stock turnover, technological limitations e.g. in urban areas, investment costs, baseline emissions, discount rates and others, including governance and institutional capacities.

#### *9.6.3.1 Stock turnover*

Buildings have a long lifetime and the feasibility of transforming the buildings stock towards low carbon depends on construction, demolition, and retrofit rates. As Figure 9.19 illustrates, high construction rates and high building replacement rates in developing countries offer an opportunity to realize a large amount of the potential in new buildings, introducing ambitious building codes(UNEP and IEA 2017). We observe however a significant lock-in effect associated with the long lifetime of buildings and infrastructure in developed countries and numerous barriers to building retrofits as discussed in Section 9.9, in particular in urban areas, making retrofit rates assumed in many decarbonisation scenarios questionable (Seto et al. 2016; Ürge-Vorsatz et al. 2018; Khosla and Janda 2019). (Sandberg et al. 2016) simulated retrofit rates in eleven European countries and concluded that only minor future increases in the renovation rates of 0.6–1.6%, are expected. These rates are significantly lower than 2.0–3.0% assumed in the studies reviewed in Table 9.17 to decarbonize the buildings stock by 2050.

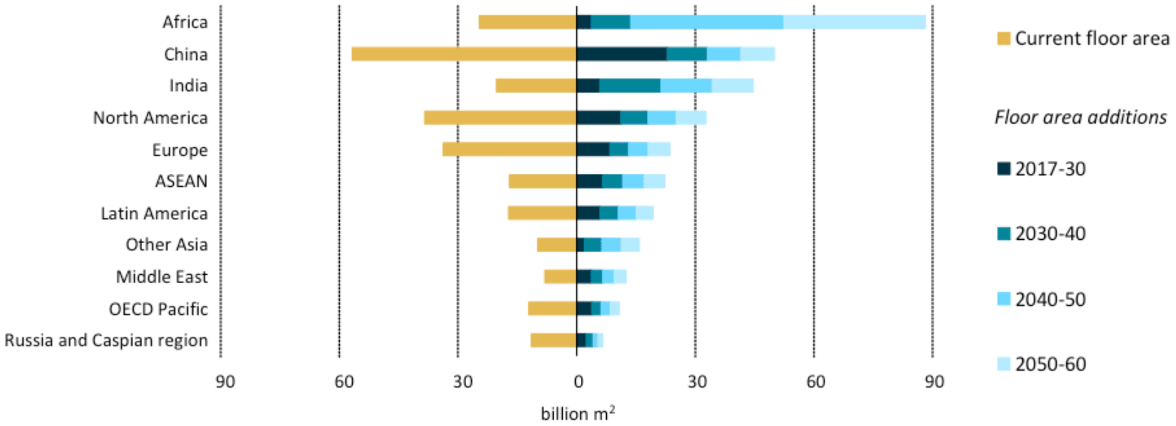


**Figure 9.19 Global floor area additions by 2016 by key regions** (UNEP and IEA 2017)

**Notes**: OECD Pacific includes Australia, New Zealand, japan and Korea; ASEAN is an Association of Southeast Asian Nations.

### *9.6.3.2 Investment costs*

**Similar, literature provides examples of many advanced new buildings in all parts of the world, which achieve very low GHG emissions at low incremental costs as compared to standard practice.**

**Figure 9.20 Cost and funding of solar energy installations over time (May et al. 2018)**

Table 9.19 provides such examples for the US and China. Based on the review of 79 case studies, Erhor-Kluttig et al. (2017) concluded on the average incremental costs of nearly zero energy buildings at 2.3%, 13.9%, 5.4%, and 10.0% versus those of buildings constructed according to minimum energy performance requirement in Germany, Italy, Denmark, and Slovenia. The investment cost to achieve such high performance has declined in Europe during the last ten years, among other factors due to a learning curve of renewable installations (Figure 9.20), which were possible to integrate in buildings, especially in non-urban areas.

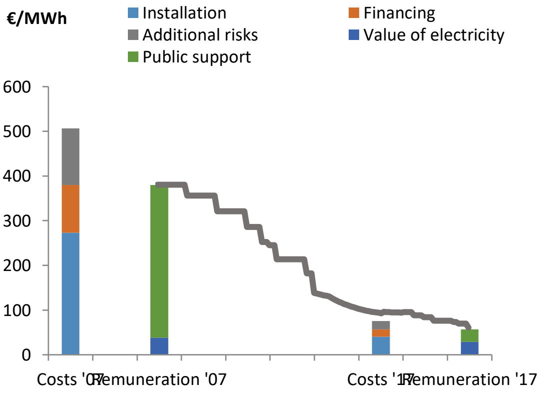


**Figure 9.20 Cost and funding of solar energy installations over time (May et al. 2018)**

**Table 9.19 Incremental costs of green-certified buildings** (Zhang et al. 2017)

| Reference | Country | Building type | Certification | Certification level | Incremental cost |
|---|---|---|---|---|---|
| Kats (2003) | US | Office building, school | LEED | Platinum | 6.5% |
| | | | | Gold | 1.8% |
| | | | | Silver | 2.1% |
| | | | | Certified | 0.7% |
| U.S. General Services Administration (2004) | US | Courthouse | LEED | Gold | 1.4-8.1% |
| | | | | Silver | -0.03%-4.4% |
| | | | | Certified | -0.4%-1.0% |
| Kats (2006) | US | Office building | LEED | Gold | 7.8%-8.2% |
| | | | | Silver | 3.1%-4.2% |

| | | | | | |
|---|---|---|---|---|---|
| | | | | Certified | 1.4%-2.1% |
| Kats (2006) | US | School | LEED | Gold | 0.0%-6.3% |
| | | | | Silver | 0.0%-3.0% |
| | | | | Certified | 0.0%-3.6% |
| Langdon (2004), Langdon (2007a) | US | Academic, Laboratory and Library buildings, Community center, Ambulatory care facility | LEED | Average | Not significant |
| Langdon (2007b) | Australia | Office building | Green Star | 6 star | 9.0%-11.0% |
| | | | | 5 star | 3.0%-5.0% |
| Construction Industry Institute (2008) | HKSAR, China | Office building | Green Star | Platinum | 3.2% |
| | | | | Gold | 1.3% |
| | | | | Silver | 0.8% |
| | | Residential building | HK-BEAM | Platinum | 3.4% |
| | | | | Gold | 1.7% |
| | | | | Silver | 0.8% |
| Target Zero (2012) | UK | Office building | HK-BEAM | Outstanding | 9.8% |
| | | | | Excellent | 0.8% |
| | | | | Very good | 0.2% |
| Yip et al. (2013)[a] | China | Public building | CGBL[b] | 3-star | 0.1%-6.9% |
| | | | | 2-star | 1.0%-7.9% |
| | | | | 1-star | 0.1%-1.5% |
| | | Residential building | CGBL | 3-star | 0.5%-7.0% |
| | | | | 2-star | 0.09%-2.6% |
| | | | | 1-star | 0.0%-7.5% |
| MOHURD of China (2015)[a] | China | Public building | CGBL | 3-star | 4.2% |
| | | | | 2-star | 2.6% |
| | | | | 1-star | 0.5% |
| | | Residential building | CGBL | 3-star | 5.4% |
| | | | | 2-star | 2.9% |
| | | | | 1-star | 1.0% |

**Note:** [a] The incremental costs reported in RMB/m2 are converted to percentages using the construction costs of ordinary office buildings (3850 RMB/m2) and ordinary residential buildings (2250 RMB/m2) reported by Rider Levett Bucknall (2017). [b] CGBL indicates “Chinese Green Building Label”.

While there is no such evidence of new advanced buildings, the investment costs into the acceleration are likely to be higher than it is assumed by the models. Models typically assume an incremental share of investment costs which relates to better technologies, assuming these improvements occur at the moment of business-as-usual improvement of buildings. The acceleration of retrofit rates will require investing into incremental and business-as-usual costs for a large share of the stock, which is not expected to be renovated in the business-as-usual case. This could be a significant amount of investment because business-usual costs could be higher than incremental costs as illustrated in Figure 9.21. Furthermore, numerous barriers discussed in Section 9.9 constrain access to information and choice of technologies thus often resulting in higher investment costs than they could be in the perfect situation assumed by the models.

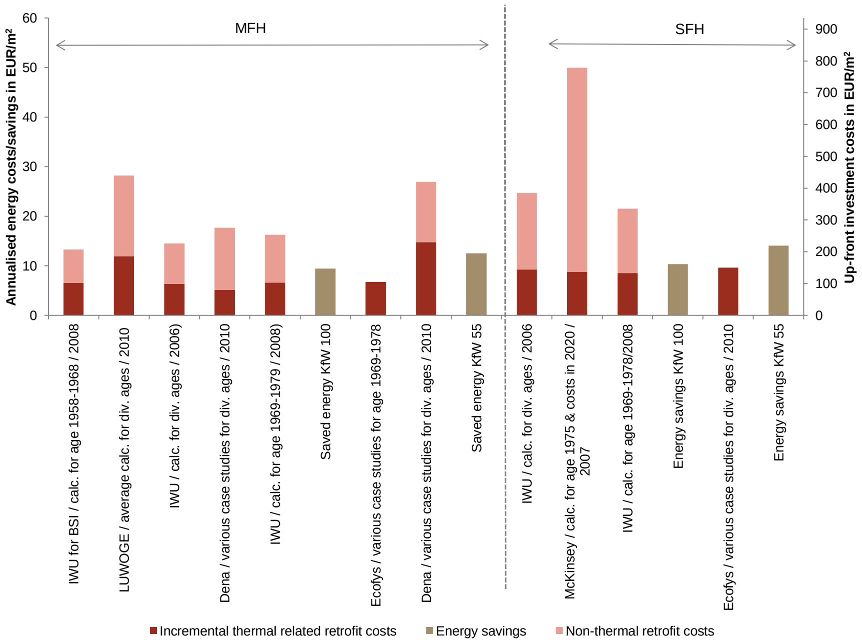


**Figure 9.21 Summary of several retrofit cost studies. The figure depicts thermal incremental and other (non-thermal) retrofit costs. The left axis of the graph shows the annualized costs and savings, while the right axis of the graph shows costs as up-front investments** (Neuhoff, Karsten; Amecke, Hermann; Novikova, Aleksandra; Stelmakh 2011)(Neuhoff, Karsten; Amecke, Hermann; Novikova, Aleksandra; Stelmakh 2011)

### *9.6.3.3 Baseline emissions*

The potential in the studies reviewed is often provided as a share of baseline emissions or energy consumption calculated in these studies. There are the number of uncertainties how baseline emissions will develop (Econometrics and Garden 2015) and the choice of the baseline impacts significantly the amount of the potential. Some of the European studies presented in Table 9.17 assumed a baseline with declining emissions. For instance, the reference $CO_2$ emissions and final energy consumption for Germany in 2050 were estimated by Bettgenhäuser and Hidalgo (Kjell Bettgenhäuser and Andoni Hidalgo 2013) at the level of -55% and – 43% as compared to 2012. Having such an ambitious baseline leads to a conservative estimate of the potential as compared to less ambitious baselines.

## 9.7 Links to adaptation

Buildings are capital-intensive and long lasting assets designed to perform under a large range of climate conditions for decades into the future (Hallegatte, 2009; Pyke et al., 2012). The long life span of buildings means that the building stock will be exposed to future changes in climate (Wan et al. 2012a; Hallegatte 2009; de Wilde and Coley 2012) and, as such, adaptation measures will be necessary.

Buildings are the interface between indoor and outdoor environments, therefore, changes in the later induced by climate change will have consequences on the former (de Wilde and Coley 2012). The impacts of climate change on buildings can affect building structures, building construction, building material properties, indoor climate and building energy use (Andrić et al. 2019). Many of those impacts interact with mitigation strategies for the buildings sector in different ways.

### 9.7.1 Climate change impacts and adaptation in buildings

The majority of the literature on climate impacts on buildings focuses on the impacts of climate change on heating and cooling needs (de Wilde and Coley 2012; Wan et al. 2012b; Andrić et al. 2019). The associated impacts on energy consumption are expected to be higher in hot summer and warm winter climates, where cooling needs are more relevant (Wan et al. 2012a; Li et al. 2012; Andrić et al. 2019) . It can be expected that higher cooling and lower heating needs may induce shifts to electrical demand (Wan et al. 2012a; Li et al. 2012), which could lead to higher emissions when electricity generation is fuelled by fossil-fuels (Li et al. 2012).

Increasing temperatures can lead to higher cooling needs and, therefore, energy consumption (Schaeffer et al. 2012; Li et al. 2012; Wan et al. 2012a; International Energy Agency 2018; Andrić et al. 2019; Clarke et al. 2018). The impacts of increased energy demand for cooling can have systemic repercussions, which in turn can affect the provision of building services. For instance, higher loads may lead to grid failure and supply interruptions (Andrić et al. 2019). There are three effects in place. Firstly, higher temperatures increase the number of days/hours in which cooling is required. Secondly, as outdoor temperatures increase, the cooling load will be higher to maintain the same indoor temperature (Andrić et al. 2019). These first two effects are usually measured by cooling degree-days[4] (CDD) and there is a vast literature on studies at the global (Clarke et al. 2018) and regional level (Andrić et al. 2019). Other studies use statistical econometric analyses to capture the empirical relationship between climate variables and energy consumption (Auffhammer and Mansur 2014; van Ruijven et al. 2019).

The third effect is that higher summer temperatures can provide incentives for purchasing space cooling equipment (Auffhammer 2014; Davis and Gertler 2015; De Cian et al. 2019). Space cooling energy needs have grown faster than any other end use in buildings in the last thirty years, mostly driven by population and economic growth in warm regions (International Energy Agency 2018). Warmer climates can induce a higher ownership of cooling equipment, especially in developing countries.

Although heating demand in cold climate regions can be expected to decrease with climate change and, to a certain extent, outweigh the increase in cooling demand, the effects on total primary energy requirements are uncertain (Li et al. 2012; Wan et al. 2012a). Also, studies have found that increases in buildings energy expenditures for cooling more than compensate the savings from lower heating demands in most regions (Clarke et al. 2018). Nevertheless, negative impacts are identified in the literature when it comes to heating in buildings. Climate change may affect the economic feasibility of district heating systems, for which demand density is a key parameter, and continuous starts and stops of can affect the operation of central heating systems (Andrić et al. 2019).

Studies raise the concern that energy efficiency measures aimed at building envelope, such as insulation improvements, may exacerbate overheating in a warmer climate (Dodoo and Gustavsson 2016; Fosas et al. 2018). If this is the case, there may be a conflict between mitigation through energy efficiency building regulations that promote insulation and climate change adaptation (Fosas et al. 2018).

On site energy production in buildings can also be affected by climate change. Changes in cloud formation can affect global solar irradiation and, therefore, the output of solar photovoltaic panels (Burnett et al. 2014). Also, the efficiency of solar photovoltaic panels decrease with higher temperatures (Simioni and Schaeffer 2019), which may impact their economic feasibility and power generation potential.

[Placeholder – paragraph on impacts on building structure (e.g. extreme climate events)]

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[4] CDD can be generally defined as the sum of the difference between an indoor set point temperature and outdoor air temperature whenever it is hotter outside.

### 9.7.2 Links between mitigation and adaptation

Adaptation interacts with mitigation because measures to cope with climate change impacts can increase energy consumption, which may lead to higher GHG emissions (de Wilde and Coley 2012; Li et al. 2012; Kalvelage et al. 2014; Clarke et al. 2018). To avoid higher emissions and additional stress on power systems, strong energy efficiency measures need to be adopted (Davide et al. 2019). Repairing damage to building infrastructure caused by climate change may cause emissions in the construction and building materials sectors.

Mitigation alternatives through passive approaches may increase resilience to climate change impacts on thermal comfort. Passive energy saving measures could reduce the cooling needs associated with higher temperatures (Wan et al. 2012b; Andrić et al. 2019). However, climate change may reduce their effectiveness (Ürge-Vorsatz et al. 2014) and, thus, their mitigation potential.

In cold climates, high energy performance buildings (e.g. ZEB, Passive House, etc.) use increased insulation and airtightness to reduce heat losses, which can potentially increase the risk of overheating (Gupta and Gregg 2012). However, (Fosas et al. 2018) argue that, while overheating may occur as a result of poor insulation design, better insulation may actually reduce overheating, when properly projected. This means that the apparent trade-off between mitigation through building insulation can be overcome by clever designs.

While adaptation on the existing building stock may be more expensive and require building retrofit, climate change must be considered in the design of new buildings, so that they can operate in both current and future climates, which has implications for construction costs (Hallegatte 2009; de Wilde and Coley 2012; Pyke et al. 2012b). Building codes and regulations are usually based on historical climate data, which can lead to poor design of thermal comfort in future climate (Hallegatte 2009; de Wilde and Coley 2012; Pyke et al. 2012b) and non-efficient active adaptive measures based on mechanical air conditioning (De Cian et al. 2019). However, adaptation measures incur in costs today, while their future benefits, although existing, are uncertain (Dittrich et al. 2016). The uncertainty about future climate change may create difficulties for projecting parameters for the design of new buildings (Hallegatte 2009; de Wilde and Coley 2012). This can be especially relevant for social housing programs (Triana et al. 2018) and in developing countries.

## 9.8 Links to sustainable development

### 9.8.1 Overview of contribution of mitigation options to sustainable development

A growing body of research acknowledges that mitigation actions in buildings may have substantial social and economic value beyond their direct impact of reducing energy consumption and/or GHG emissions (Ürge-Vorsatz et al. 2016; Deng et al. 2017; Reuter et al. 1891; IEA 2014; US EPA 2018; Kamal et al. 2019). In other words, the implementation of energy efficiency improvements in the residential and non-residential sector holds numerous multiple impacts (co-benefits, adverse side-effects, trade-offs, risks, etc.) for the economy, society and end-users (Ürge-Vorsatz et al. 2016; Bleyl et al. 2019) in both developed and developing economies, which can be categorized into the following types (Reuter et al. 1891; Ürge-Vorsatz et al. 2016): (i) health impacts due to changing indoor and outdoor conditions; (ii) environmental effects; (iii) resource efficiency impacts; (iv) impact on social wellbeing (e.g., improved access to energy sources, energy poverty alleviation, improved thermal comfort); (v) microeconomic effects (e.g., productivity gains in non-residential buildings); (vi) macroeconomic effects (e.g., creation of new jobs, long-term reductions in energy prices); and (vii) energy security implications.

Table 9.20 provides an overview of the co-benefits and risks associated with the implementation of mitigation actions in buildings.

From the above, it is obvious that well-designed and effectively implemented mitigation actions in the sector of buildings have significant potential for achieving the United Nations (UN) Sustainable Development Goals (SDGs). Specifically, the multiple impacts of energy efficiency policies and measures go far beyond the goal of climate action (SDG13) and contribute to further activating a great variety of other SDGs. The first part of Table 9.2 summarizes the analysis carried out in the context of the Special Report on Global Warming of 1.5°C (Roy et al. 2018) demonstrating that the main categories of GHG emission reduction interventions in buildings, namely the implementation of energy efficiency improvements, improved access and fuel switch to modern low carbon energy, and behavioural changes, contribute to achieving 16 out of a total of 17 SDGs. Following the seven-point scale proposed by Nilsson et al. (Nilsson et al. 2016), the interactions between mitigation options and the SDGs have been evaluated and presented also in Table 9.2, highlighting that mitigation actions in buildings interacts positively with 16 SDGs (with a score of greater than +1 for 14 SDGs), while some rather minor negative interactions (score -1) were identified with 5 SDGs.

The second part of Table 9.21 presents a more detailed analysis on how the various dimensions of GHG emission reduction actions on buildings (i.e., the basic types of multiple impacts defined previously) generate benefits across multiple SDG targets. For example, health benefits associated with mitigation actions in buildings contribute in reducing health care expenditures and thus poverty (SDG1), achieving good health and well-being (SDG3), improving quality of education (SDG4) and enhancing gender equality (SDG5) (McCollum et al. 2018; Maidment et al. 2014; Berrueta et al. 2017). Similarly, improvements in social wellbeing associated with mitigation actions such as improved access to energy sources, energy poverty alleviation, increased thermal comfort etc., seem to contribute in achieving 11 SDGs, among of which good health and well-being (SDG3), quality of education (SDG4), affordable and clean energy (SDG7), sustainable cities and communities (SDG11), and peace, justice and strong institutions (SDG16) (Saheb et al. 2018a)(Berrueta et al. 2017; Liddell and Guiney 2015; Cameron et al. 2016; Ürge-Vorsatz et al. 2016; McCollum et al. 2018).

Despite wider recognition of the multiple benefits of investing in energy efficiency and low carbon technologies, their assessment is usually based only on energy savings and costs (Ürge-Vorsatz et al. 2016). A review of a relatively limited number of studies made by Vorsatz et al. (2016) (Ürge-Vorsatz et al. 2016) and Payne et al. (2015) (Payne et al. 2015)showed that the size of multiple benefits of energy efficiency programs in the sector of buildings may range from 22% up to 7,400% of the corresponding energy cost savings. In 7 out of 11 case studies reviewed, the value of the multiple impacts of energy efficiency were equal or greater than the value of energy savings. Even in these studies several effects have not been measured and consequently the size of co-benefits of energy efficiency may be even higher. Quantifying and if possible, monetizing, these wider impacts of climate action would facilitate their inclusion in cost-benefits analysis, strengthen the adoption of ambitious emissions reduction targets, and improve coordination across policy areas reducing costs (Oluleye and Smith 2016; Thema et al. 2017).

Here, a review of recent advances focuses on selected co-benefits / risks of mitigation actions in the buildings sector, with a view to providing methods, quantitative estimates (in physical or monetary terms) that can be utilized in the decision-making process, and information on their contribution to relevant SDGs.

## 9.8.2 The nexus of climate mitigation actions in buildings and health impacts

### *9.8.2.1 Lack of access to clean energy*

Over 3 billion people worldwide, most of whom live in Asia, Africa, and the Americas, still use polluting fuels, such as fuelwood, charcoal, dried crops, cow dung, and kerosene in low-efficiency stoves for cooking and heating as well as kerosene for lighting, generating household air pollution (HAP), which adversely affects the health of the occupants of the dwellings, especially children and women (WHO 2016; IEA,IRENA,UNSD,World Bank 2018; Quinn et al. 2018; Rahut et al. 2017; Mehetre et al. 2017; Rosenthal et al. 2018; Das et al. 2018; Xin et al. 2018; Liu et al. 2018). Exposure to HAP from burning these fuels is estimated to have caused 3.8 million deaths from heart diseases, stokes, cancers, acute lower respiratory injections in 2016 (IEA,IRENA,UNSD,World Bank 2018) .

It is acknowledged that integrated policies are needed to address simultaneously universal energy access, limiting climate change and reducing air pollution (WHO 2016; Rafaj et al. 2018) showed that a scenario achieving these sustainable development goals in 2030 will imply in 2040 2 million fewer premature deaths from HAP compared to current levels, and 1.5 million fewer premature deaths in relation to a reference scenario, which assumes the continuation of existing and planned policies. The level of incremental investment needed in developing countries to achieve universal access to modern energy was estimated at around $0.8 trillion cumulatively to 2040 in the scenarios examined (Rafaj et al. 2018).

At the core of these policies is the promotion of improved cook-stoves and the use of cleaner fuels by poor households in developing countries. Most studies agree that the use of cleaner energy options such as LPG, ethanol, biogas, and electricity are more effective in reducing the health impacts of HAP compared to improved biomass stoves (see for example (Rosenthal et al. 2018; Steenland et al. 2018; Goldemberg et al. 2018; Larsen 2016). On the other hand, climate change mitigation policies may increase the costs of clean fuels (e.g., LPG, electricity), slowing down their penetration in the poor segment of the population and restricting the associated health benefits (Cameron et al. 2016). In this case appropriate access policies should be designed to efficiently shield poor households from the burden of carbon taxation (Cameron et al. 2016). Most studies agree that the health benefits associated with improved cook-stoves and cleaner cooking are high and improve substantially the benefit-cost ratio of such a transition (e.g., (García-Frapolli et al. 2010; Aunan et al. 2013), with only a few claiming that these health benefits represent a relatively small amount of the total cost and benefit associated with the installation of improved cook-stoves (e.g., (Jeuland et al. 2018; Malla et al. 2011).

1 **Table 9.20 Overview of potential co-benefits and risks associated with mitigation actions in buildings**

| Category of Impact | Co-benefits / Risks |
|---|---|
| Health impact | Health benefits due to:<br>• Better indoor air quality.<br>• Energy poverty alleviation (lower winter excess mortality and morbidity, improved mental health attributed to reduced stress associated with bill payments, etc.).<br>• More natural lighting indoors.<br>• Better ambient air quality.<br>• Elimination of the heat island effect. |
| Environmental impact | • Reduced local air pollution and the associated impact on ecosystems (acidification, eutrophication, etc.).<br>• Reduced corrosion of infrastructures.<br>• Reduced sewage production. |
| Resource efficiency impact | Improved resource management including water and energy. |
| Impact on social wellbeing | • Increased disposable income from decreased energy expenditures.<br>• Reduced disposable income from distributional costs of new policies.<br>• Energy poverty alleviation.<br>• Improved access to energy sources.<br>• Reduced energy access (in cases of increases in the cost of energy, high investment costs needed, etc.)<br>• Increased thermal comfort.<br>• More lighting indoors.<br>• Reduced noise impact.<br>• Rebound effects.<br>• Increased productive time for women and children (replacing traditional cook-stoves) |
| Microeconomic effects | • Productivity gains in non-residential buildings.<br>• Enhanced asset values through improvements in buildings and capitalization of energy savings.<br>• Fostering innovation. |
| Macroeconomic impacts | • Impact on GDP growth due to energy savings.<br>• Impact on GDP growth due to energy availability and increased productive time for women.<br>• Positive employment effects (positive direct impact of energy efficiency and RES investments, positive indirect impact associated with energy savings).<br>• Decreased employment in the fossil energy sector.<br>• Decline of energy prices due to reduced energy demand.<br>• Positive impact on public budgets from energy cost savings, reduced need for energy and unemployment subsidies, reduced health care costs, additional income tax, etc. |
| Energy security | • Access to modern energy resources.<br>• Reduced import dependency.<br>• Increase of supplier diversity.<br>• Smaller reserve requirements.<br>• Increased sovereignty and resilience. |

2

**Table 9.21 Aspects of mitigation actions in buildings and their contributions to the 2030 Sustainable Development Goals**

| **Dimensions of climate change mitigation in buildings** | **SDG1: No Poverty** | **SDG2: Zero Hunger** | **SDG3: Good Health & Wellbeing** | **SDG4: Quality Education** | **SDG5: Gender Equality** | **SDG6: Clean Water & Sanitation** | **SDG7: Affordable & Clean Energy** | **SDG8: Decent Work & Economic Growth** | **SDG9: Industry, Innovation & Infrastructure** | **SDG10: Reduced Inequalities** | **SDG11: Sustainable Cities & Communities** | **SDG12: Responsible Consumption & Production** | **SDG13: Climate Action** | **SDG14: Life Below Water** | **SDG15: Life on Land** | **SDG16: Peace, Justice & Strong Institutions** | **SDG17: Partnerships for the Goals** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Type of interventions* | | | | | | | | | | | | | | | | | |
| Accelerating energy sufficiency and energy efficiency improvements | +2/-1 | +2 | +2 | +2 | +1 | +2 | +2 | +2/-1 | +2 | +1/-1 | +2 | +1 | | | +2 | +2 | +2 |
| Improved access and fuel switch to modern low carbon energy | +2 | 0/-1 | +2 | +1 | +1 | +2/-1 | +2 | +2 | +2 | | +3 | +2/-1 | | | +2 | +2 | +2 |
| Behavioral changes | +2 | | +2 | | | +2 | +2 | +2 | +2 | | +2 | +2 | | | | +2 | |
| *Dimensions of mitigation actions* | | | | | | | | | | | | | | | | | |
| Health impact | X | | X | X | X | | | | | | | | | | | | |
| Environmental impact | | X | | | | X | | X | | | X | | | | X | | |
| Resource efficiency | X | X | | | | X | X | | X | | X | X | | | | | |
| Impact on social wellbeing | X | | X | X | X | X | X | X | | X | X | | | | X | X | |
| Microeconomic effects | | | | | X | | | X | X | | X | X | | | | | X |
| Macroeconomic impacts | | | | | | | | X | | X | X | | | | | | |
| Energy security | | | | | | | X | | X | | | | | | | | |

**Note**: The strength of interaction between mitigation actions and SDGs is described with a seven-point scale (Nilsson et al., 2016): (+3) indivisible (the action is inextricably linked to the achievement of a SDG) , (+2) reinforcing (the action aids the achievement of a SDG) , (+1) enabling (the action creates conditions that further a SDG), (0) consistent (no significant positive or negative interactions), (-1) constraining (the action limits options on a SDG), (-2) counteracting (the action clashes with a SDG), and (-3) cancelling (the action makes it impossible to reach a SDG). Also, the symbol X shows the interactions between co-benefits/risk associated with mitigation actions and the SDGs.

**Sources**: **SDG1**: (Grubler et al. 2018; Saheb et al. 2018a; Scott et al. 2014; Berrueta et al. 2017); **SDG2**: (Berrueta et al. 2017; Grubler et al. 2018); **SDG3**: (Saheb et al. 2018b; Grubler et al. 2018; Liddell and Guiney 2015; Willand et al. 2015; Burney et al. 2017; Saheb et al. 2018a; Rosenthal et al. 2018); **SDG4**: (Grubler et al. 2018; Maidment et al. 2014) Ortiz et al. 2017; **SDG5**: (Berrueta et al. 2017; Grubler et al. 2018; Burney et al. 2017; Saheb et al. 2018a; Rosenthal et al. 2018); **SDG6**: (Saheb et al. 2018a; Grubler et al. 2018; Holland et al. 2015; Fricko et al. 2016; Rao and Pachauri 2017); **SDG7**: (Saheb et al. 2018a; Berrueta et al. 2017; Liddell and Guiney 2015; Cameron et al. 2016; Ürge-Vorsatz et al. 2016; Thema et al. 2017; Mastrucci et al. 2019; Alawneh et al. 2019; Grubler et al. 2018; Rosenthal et al. 2018); **SDG8**: (Grubler et al. 2018; Saheb et al. 2018a; Ürge-Vorsatz et al. 2016; Thema et al. 2017; Mirasgedis et al. 2014; Alawneh et al. 2019); ; **SDG9**: (Saheb et al. 2018a; Thomas, S., L.–A. Brischke, J. Thema, L. Leuser 2018; Alawneh et al. 2019); **SDG10**: (Grubler et al. 2018; Cameron et al. 2016; Saheb et al. 2018a); **SDG11**: McCollum et al., 2018; Saheb et al., 2018; **SDG12**: Zhao et al 2017; McCollum et al., 2018; Saheb et al., 2018; Fricko et al. 2016; Rao and Pachauri, 2017; Alawneh et al. 2019; Grubler et al. 2018; **SDG15**: McCollum et al., 2018; Saheb et al., 2018; Bailis et al. 2015; Winter et al. 2015; Rosenthal et al. 2018; **SDG16**: Saheb et al., 2018; McCollum et al., 2018; Hult and Larson, 2016; **SDG17**: Kim and Sun, 2017; Saheb et al., 2018;

Electrification of households in rural or remote areas results also to significant health benefits. For example, in El Salvador, rural electrification of households leads to reduced overnight air pollutants concentration by 63% due to the substitution of kerosene as a lighting source, and 34-44% less acute respiratory infections among children under six (Torero 2016). In addition, the connection of the health centres to the grid leads to improvements in the quality of health care provided (Lenz et al. 2017).

#### *9.8.2.2 Energy poverty, indoor environmental quality and health*

Living in cold and damp housing is related to excess winter mortality and increased morbidity rates due to respiratory and cardiovascular diseases, arthritic and rheumatic illnesses, asthma, etc. (Thema et al. 2017; Payne et al. 2015; Camprubí et al. 2016; Wilson et al. 2016; Lacroix and Chaton 2015; Ormandy and Ezratty 2016; Mzavanadze 2018) found that in EU-28 the annual excess cold weather deaths during the period 1996-2014 accounted for around 323,000 cases, with approximately 22% of them attributable to indoor cold exposure; also, asthma diseases associated with indoor dampness amounted to over 71,000 Disability Adjusted Life-Years (DALYs) in 2015. In addition, lack of affordable warmth can generate stress related to chronic discomfort and high bills, fear of falling into debt, and a sense of lacking control, which are potential drivers of further negative mental health outcomes, such as depression (Payne et al. 2015; Liddell and Guiney 2015; Howden-Chapman et al. 2012; Wilson et al. 2016). Health risks from exposure to cold may be higher for low-income, energy-poor households, and in particular for those with elderly, young children, and members with existing respiratory illness (Payne et al. 2015; Poortinga et al. 2018; Thomson et al. 2017). High temperatures during summer can also be dangerous for people living in buildings with inadequate thermal insulation and inappropriate ventilation (Ormandy and Ezratty 2016)(Sanchez-Guevara et al. 2019; Thomson et al. 2019). In European Union, 19.2% of households reported being uncomfortably hot during summer in 2012, while this percentage reached 34% in Greece, 35% in Malta, 36% in Portugal and 50% in Bulgaria (Thomson et al. 2019). Summer energy poverty may increase significantly in the coming decades under a warming climate (for more information please see Section 9.7), with the poorest, who cannot afford installing air conditioning to keep them cool, to be the most vulnerable.

Improved energy efficiency in buildings (particularly to those that live energy-poor households) brings health gains through improved indoor temperatures and comfort as well as reduced fuel consumption and associated financial stress (Thomson and Thomas 2015; Poortinga et al. 2018; Curl et al. 2015; Lacroix and Chaton 2015; Liddell and Guiney 2015). On the other hand, households suffering most from energy poverty experience more barriers for undertaking building retrofits (Camprubí et al. 2016), moderating the potential health gains associated with implemented energy efficiency programs. This can be avoided if implemented policies to tackle energy poverty target the most socially vulnerable households (Lacroix and Chaton 2015; Camprubí et al. 2016), highlighting the importance of identifying energy-poor households. (Mzavanadze 2018) estimated that in EU-28 accelerated energy efficiency policies, reducing the energy demand in residential sector by 333 TWh in 2030 compared to a reference scenario, coupled with strong social policies targeting the most vulnerable households, could deliver additional co-benefits in the year of 2030 of around 24,500 avoided premature deaths due to indoor cold and around 22,300 DALYs of avoided asthma due to indoor dampness. The health benefits of these policies amount to €4.8 billion in 2030. The impacts on inhabitants in developing countries would be much greater than those in EU-28 owing to the much higher prevalence of impoverished household.

Apart from thermal comfort, the internal environment of buildings impacts public health through a variety of pathways including inadequate ventilation, poor indoor air quality, chemical contaminants from indoor or outdoor sources, traffic noise or poor lighting. Energy efficiency measures and particularly interventions aiming to improve thermal insulation of buildings may increase the risk of mould and moisture problems and reduce the air flow rates leading to indoor environments that are unhealthy, with the occupants suffering from the sick building syndrome symptoms (Wierzbicka et al. 2018; Cedeño-Laurent et al. 2018). On the other hand, if the implementation of energy efficiency interventions or the construction of green buildings is accompanied by adequate ventilation, the indoor environmental conditions are improved through less moisture, mold, pollutant concentrations, and allergens, which result in fewer asthma symptoms, respiratory risks, chronic obstructive pulmonary diseases, heart disease risks, headaches, cancer risks, etc. (Cowell 2016; Wilson et al. 2016; Thomson and Thomas 2015; Allen et al. 2015; Doll et al. 2016). Many studies have highlighted the crucial role of ventilation in creating healthy indoor environmental conditions, which result in health benefits (Hamilton et al. 2015; Militello-Hourigan and Miller 2018; Underhill et al. 2018; Cedeño-Laurent et al. 2018). As adequate ventilation imposes additional costs, the sick building syndrome symptoms are more likely to be seen in low income households (Shrubsole et al. 2016).

(Tonn et al. 2018) quantified a great variety of health-related benefits attributed to the two weatherization programs implemented in the US in 2008 and 2010, showing that their magnitude exceeds by a factor of 3 the corresponding energy cost savings yield (see Table 9.22).

#### *9.8.2.3 Outdoor air pollution*

According to WHO (IEA,IRENA,UNSD,World Bank 2018) around 4.2 million premature deaths worldwide (in both cities and rural areas) are attributed to outdoor air pollution. Only in China the premature mortalities attributed to $PM_{2.5}$ and $O_3$ emissions exceeded 1.1 million in 2010 (Gu et al. 2018). Mitigation actions in residential and non-residential sectors decrease the amount of fossil fuels burnt either directly in buildings (for heating, cooking, etc.) or indirectly for electricity generation and thereby reduce air pollution (e.g., PM, $O_3$, $SO_2$, $NO_x$), improve ambient air quality and generate significant health benefits through avoiding premature deaths, lung cancers, ischemic heart diseases, hospital admissions, asthma exacerbations, respiratory symptoms, etc. (MacNaughton et al. 2018)(Levy et al. 2016; Balaban and Puppim de Oliveira 2017). Several studies have monetized the health benefits attributed to reduced outdoor air pollution due to the implementation of energy efficiency measures in buildings, and their magnitude expressed as a ratio to the value of energy savings resulting from the implemented interventions in each case, are in the range of 0.08 in EU, 0.18 in Germany, 0.26-0.40 in US, 0.34 in Brazil, 0.47 in Mexico, 0.74 in Turkey, 8.28 in China and 11.67 in India (MacNaughton et al. 2018)(Levy et al. 2016; Diaz-Mendez et al. 2018)(Adrian Joyce, Sigurd Nass-Schmidt 2013). In developed economies the estimated co-benefits are relatively low due to the fact that the planned interventions influence a quite clean energy source mix (Tuomisto et al. 2015; MacNaughton et al. 2018). On the other hand, the health co-benefits in question are substantially higher in countries and regions with greater dependency on coal for electricity generation and higher baseline morbidity and mortality rates (MacNaughton et al. 2018; Kheirbek et al. 2014). It is noteworthy that the estimates presented above are influenced by the air pollutants included in analysis of the relevant studies, the dose-response function used for estimating the mortality and morbidity effects and the health impact values used.

### 9.8.3 Other environmental benefits of mitigation actions

Apart from the health benefits mentioned above, improved outdoor environmental conditions attributed to mitigation actions in the buildings sector are also associated with environmental benefits to ecosystems, by avoiding acidification and eutrophication, crops, biodiversity, building environment through reduced corrosion of materials, etc. (Thema et al. 2017; Mzavanadze 2018), while some negative effects cannot be excluded (e.g., (Dylewski and Adamczyk 2016)).

**Table 9.22 Present value of health-related benefits[1], energy cost savings and implementation costs per housing unit, resulted from the two weatherization programs implemented in 2008 and 2010 in the U.S. (in US $$_{2013}$)(Tonn et al. 2018)**

| | Total | Societal benefits | Direct financial benefits of households |
|---|---|---|---|
| *Heatlth-related benefits* | *14,148* | *12,332* | *1,816* |
| Asthma | 2,009 | 1,852 | 157 |
| Thermal stress-cold | 3,911 | 3,892 | 19 |
| Thermal stress-heat | 870 | 855 | 15 |
| Food assistance reduction | 832 | 832 | |
| Reduction in missed days at work | 201 | 40 | 161 |
| CO poisoning | 154 | 153 | 1 |
| Improvement in prescription adherence | 1,929 | 1,929 | |
| Reduction in use of short-term loans | 71 | | 71 |
| Home fires | 831 | 768 | 63 |
| Increased productivity at work due to improved sleep | 1,813 | 1,813 | |
| Increased productivity at home due to improved sleep | 1,329 | | 1,329 |
| Reduction in low-birth weight babies from heat-or-eat dilemma | 198 | 198 | |
| *Energy cost savings* | | | |
| Program Year 2008 | 4,890 | | |
| Program Year 2010 | 3,681 | | |
| *Total costs* | | | |
| Program Year 2008 | 4,695 | | |
| Program Year 2010 | 6,812 | | |

[1] The health-related benefits are further disaggregated to household benefits, which are limited to financial benefits accruable directly to the households, and societal benefits, which include the resulting decreases in expenses to public and private medical insurance plans, the value of lives saved, etc.

Also, very important are the effects of mitigation actions in buildings on the reduction of consumption of natural resources, namely fossil fuels, metal ores, minerals, etc. These comprise savings from the resulting reduced consumption of fuels, electricity and heat and the lifecycle-wide resource demand for their utilities, as well as potential net savings from the substitution of energy technologies used in buildings (production phase extraction) (Thema et al. 2017; EU 2016). (Teubler et al. 2020) found that the implementation of an energy efficiency scenario in European buildings will result in resource savings (considering only those associated with the generation of final energy products) of 406 kg per MWh lower final energy demand in the residential sector, while the corresponding figure for non-residential buildings was estimated at 706 kg per MWh of reduced energy demand. These savings could be monetized based on the additional investments required to provide them in the same quality and to prevent the associated damages to the environment. In addition, (Smith et al. 2016) claim that a switch to more efficient appliances could result in negative impacts from increased resource use, which can be mitigated by avoiding premature replacement and maximizing recycling of old appliances.

Furthermore, improved insulation and the installation of double- or triple-glazed windows result in reduced noise levels. (Smith et al. 2016) estimated that in the UK the annual noise benefits associated with energy renovations in residential buildings may reach £400 million in 2030 outweighing the benefits of reduced air pollution.

### 9.8.4 Social wellbeing

#### *9.8.4.1 Energy poverty alleviation*

(Bouzarovski and Petrova 2015) define energy poverty as “the inability to attain a socially and materially necessitated level of energy services”. For the poorest segment of the population in low- and middle-income developing countries it mainly concerns the lack of connection to electricity and the use of solid fuels and biomass for cooking (Pelz et al. 2018; Castaño-Rosa et al. 2019). For developed countries but also a part of the population in developing countries it is mainly related to unaffordable prices of fuel and energy services, which in combination with poor housing result to inadequate indoor conditions, such as low temperature and excess humidity in winter and high temperature in summer, poor indoor air quality, etc. (e.g., (Mzavanadze, Nora, Keleman, Agnes, Urge-Vorsatz 2015; Castaño-Rosa et al. 2019)).

In 2016 almost 1 billion people in developing countries didn’t have access to electricity, while approximately 3 billion people relied on polluting fuels and technologies for cooking (WHO 2016; IEA,IRENA,UNSD,World Bank 2018). Only in sub-Saharan Africa, nearly 600 million people (i.e., 70% of the population) live without electricity (Lee et al. 2017). (Thomson and Bouzarovski 2018) explored the problem of energy poverty in EU-28 through various indicators, estimating that 44.5 million people were unable to keep their homes warm in 2016, 41.5 million had arrears on their utility bills the same year, 16.3% of households faced disproportionately high energy expenditure in 2010, and 19.2% of households reported being uncomfortably hot during summer in 2012. (Okushima 2016) using the “expenditure approach” estimated that energy poverty rates in Japan reached 8.4% in 2013. (Mohr 2018) based on 2009 data estimated that about 56% of US households with incomes below 150% of the poverty line had fuel burdens above 10%.

The implementation of well-designed energy efficiency measures in buildings can reduce energy poverty and improve living conditions with significant benefits for health (already discussed in Section 9.8.2) and well-being (Smith et al. 2016; Payne et al. 2015; Tonn et al. 2018). The social implications of energy poverty alleviation for the people in low- and middle-income developing countries with no access to clean energy fuels are further discussed in Section 9.8.4.2. In other developing countries and in developed economies as well, the implementation of energy efficiency measures can improve the ability of households to affordably heat/cool a larger area of the home, thus increasing the space available to a family and providing more private and comfortable spaces for several activities like homework (Payne et al. 2015). By reducing energy expenditures and making energy bills more affordable for households, a “heat or eat” dilemma can be avoided resulting in better nutrition and reductions in the number of low birthweight babies (Payne et al. 2015; Tonn et al. 2018). Also, better indoor conditions, such as reduced exposure to cold, damp and mould in winter period and avoiding high temperatures in summer, can enable residents to avoid social isolation, improve social cohesion, lower crime, etc. (Payne et al. 2015).

(EU 2016) found that under an ambitious recast of Energy Performance Buildings Directive (EPBD), the number of households that may be lifted from energy poverty across the EU lies between 5.17 and 8.26 million. To capture these benefits, energy efficiency policies and particularly energy renovation programmes should target the most vulnerable among the energy-poor households, which very often are ignored by the policy makers. This is quite challenging, as there is no single and commonly accepted definition of energy poverty, while the application of different measurement methodologies often leads to divergent results (Deller 2018; Ntaintasis et al. 2019; Waddams Price et al. 2012). Also, several of these approaches do not account the depth of energy poverty and/or the frequency of feeling cold/warm, capturing the problem imperfectly. Several studies (e.g., (Herrero 2017; Deller 2018; Ntaintasis et al. 2019)) argue against single-indicator energy poverty metrics and advocate multiple-indicator approaches that explicitly acknowledge the shortcomings of each of the methods implemented. It is also worth mentioning that energy poverty measurement provides limited information for identifying energy-poor households (Deller 2018), which is a prerequisite for developing targeted policies to tackle the problem. Several recent studies recognize that energy poverty should be analyzed as a multidimensional social problem (Thomson et al. 2017; Mashhoodi et al. 2019).

Several recent studies recognize that energy poverty should be analysed as a multidimensional social problem (Thomson et al. 2017; Mashhoodi et al. 2019). In this context, energy poverty is related to energy efficiency, household composition, age and health status of its members, social conditions (single parent families, existence of unemployed and retired people, etc.), energy prices, etc. Also, some studies indicate that the geographical dimension can have a significant impact on the levels of energy poverty and should be taken into account when formulating response policies (e.g., (Mashhoodi et al. 2019; Besagni and Borgarello 2019)).

#### *9.8.4.2 Improved access to energy sources, gender equality and time savings*

In most low- and middle-income developing countries women and children (particularly girls) spend a significant amount of their time for gathering fuels for cooking and heating (WHO 2016; Rosenthal et al. 2018). Specifically, in Africa more than 70% of the children living in households that primarily cook with polluting fuels spend at least 15 hours and, in some countries, more than 30 hours per week in collecting wood or water, facing significant safety risks and constraints on their available time for education and rest(WHO 2016; Mehetre et al. 2017). Also, in several developing countries (e.g., in most African countries but also in rural areas in Latin America and elsewhere) women spend several hours to collect fuel wood and cook, thus limiting their potential for productive activities for income generation or rest (Galán-Marín et al. 2015; Mehetre et al. 2017; WHO 2016).

Expanding access to clean household energy for cooking, heating and lighting will largely help alleviate these burdens (Rosenthal et al. 2018; WHO 2016; Lewis et al. 2017). (Jeuland et al. 2018) found that the time savings associated with the adoption of cleaner and more fuel-efficient stoves by low-income households in developing countries are amount to 1.3-1.9 $/household-month, constituting the 23-43% of the total social benefits attributed to the promotion of clean stoves. Also, (Malla et al. 2011) analysed a number of energy-saving interventions in Nepal, Kenya and Sudan and found that apart from the case of Sudan, time savings constituted by far the most important benefit followed by fuel cost savings.

Electrification of remote rural areas and other regions that do not have access to electricity enables people living in poor developing countries to read, socialize, and be more productive during the evening, while it is also associated with greater school attendance by children (Douglas F.Barnes; Torero 2016; Rao et al. 2016). On the other hand, some studies clearly show that electricity consumption for connected households is extremely low, and there is low penetration of the electrical appliances that enable electricity-consuming activities (e.g., (Lee et al. 2017; Cameron et al. 2016). The implementation of appropriate policies to overcome bureaucratic red tape, low reliability, and credit constraints, is necessary for maximizing the social benefits of electrification.

### 9.8.5 Economic implications of mitigation actions

#### *9.8.5.1 Buildings-related labour productivity*

Improved energy efficiency in buildings, and particularly well-designed, operated, and maintained high-performance buildings with adequate ventilation, may result in productivity gains and improve the competitiveness of the economy through three different pathways (Bleyl et al. 2019; Thema et al. 2017; EU 2016; Niemelä et al. 2017; Mofidi and Akbari 2017; MacNaughton et al. 2015): (i) increasing the amount of active time available for productive work by reducing the absenteeism from work due to illness, the presenteeism (i.e., working with illness or working despite being ill), and the inability to work due to chronic diseases caused by the poor indoor environment; (ii) improving the indoor air quality and thermal comfort of non-residential buildings, which can result in better mental well-being of the employees and increased workforce performance; and (iii) reducing the school absenteeism due to better indoor environmental conditions, which may enhance the future earnings ability of the students and restrict the parents' absenteeism due to care-taking of sick children.

Productivity gains due to increased amount of active time for work is directly related to acute and chronic health benefits attributed to climate mitigation actions in buildings (see Section 9.8.2.2). Quantification and monetization of productivity gains due to reduced chronic mortality and morbidity is difficult as it usually overlaps with the wider health-related benefits associated with improved indoor and outdoor environment. The bulk of studies quantifying the impact of energy efficiency on productivity focus on acute health effects. Most of them highlight the importance of proper ventilation rate in buildings (MacNaughton et al. 2015)(Ben-David et al. 2017), which can reduce absenteeism due to sick days by 0.6–1.9 days per person per year (Thema et al. 2017; Ben-David et al. 2017). In a pan-European study, Chatterjee and Vorsatz (2018) showed that deep energy retrofits in residential buildings may increase the number of active days by 1.78-5.27 (with an average of 3.09) per year and person who has actually shifted to a deep retrofitted building. Similarly, the interventions in the tertiary buildings result in increased active days between 0.79 and 2.43 (with an average of 1.4) per year and person shifted to deeply retrofitted tertiary buildings.

As regards improvements in workforce performance due to improved indoor conditions (i.e., air quality, thermal comfort, etc.), (Kozusznik et al. 2019) conducted a systematic review on whether the implementation of energy efficient interventions in office buildings influence well-being and job performance of employees. Among the 34 studies included in this review, 31 found neutral to positive effects of green buildings on productivity and only 3 studies indicated detrimental outcomes for office occupants in terms of job performance. Particularly longitudinal studies, which observe and compare the office users' reactions over time in conventional and green buildings, show that green buildings have neutral to positive effects on occupants' well-being and work performance (Kozusznik et al. 2019; Thatcher and Milner 2016; Candido et al. 2019). (Bleyl et al. 2019) estimated that deep energy retrofits in office buildings in Belgium would generate a workforce performance increase of 10.4 to 20.8 €/m$^2$ renovated.

#### *9.8.5.2 Enhanced asset values of energy efficient buildings*

A significant number of studies confirm that homes with high energy efficiency and/or green features are sold at higher prices than conventional, low energy efficient houses. Table 9.23 summarizes the results of 15 studies from 12 different countries showing that energy efficient dwellings have a price premium ranging between 1.5% and 28%, with a median estimated at 7.8%, for the highest energy efficient category examined in each case study compared to reference houses with the same characteristics but lower energy efficiency. In a given real estate market, the higher the energy efficiency of dwellings compared to conventional housing, the higher their selling prices. However, a number of studies show that this premium is largely realized during resale transactions and is smaller or even negative in some cases immediately after the completion of the construction (Deng and Wu 2014; Yoshida and Sugiura 2015). A relatively lower number of studies (also included in Table 9.23) show that energy efficiency and green features have also a positive effect on rental prices of dwellings (Cajias et al. 2019; Hyland et al. 2013), but this is weaker compared to sales prices, and in a developing country even negative as green buildings, which incorporate new technologies such as central air conditioning, are associated with higher electricity consumption (Zheng et al. 2012). Increased sale and rental prices of energy-efficient homes give a measure of the investments that are cost-effective to be implemented by the landlords to upgrade the energy efficiency of their properties.

Regarding non-residential buildings, (EU 2016) reviewed a number of studies showing that buildings with high energy efficiency or certified with green certificates present higher sales prices by 5.2-35%, and higher rents by 2.5-11.8%. More recent studies in relation to those included in the review confirm these results (e.g., (Mangialardo et al. 2018; Ott and Hahn 2018)) or project even higher premiums (e.g., (Chegut et al. 2014)) found that green certification in the London office market results in a premium of 19.7% for rents).

**Table 9.23 Premium price for rent and sale in residential buildings with high energy performance and/or green features**

| Ref | Study | Country | From energy rating X to Y (Y/X) | Impact of energy performance | | Comments |
|---|---|---|---|---|---|---|
| | | | | *Sale* | *Rent* | |
| 1 | Tajani et al., 2018 | Italy (Bari) | A / [B,C,D,E,F] | 27.9% | | Evaluation based on energy performance certificates |
| | | | G / [B,C,D,E,F] | -26.4% | | |
| 2 | Ayala et al., 2016 | Spain | [A,B,C] / [D,E,F,G] | 9.8% | | Evaluation based on energy performance certificates |
| 3 | Marmolejo-Duarte and Chen, 2019 | Spain (Barcelona) | A / G | 7.8% | | Evaluation based on energy performance certificates |
| | | | D / G | 3.3% | | |
| 4 | Kahn and Kok, 2014 | US (California) | [Green label] / [non-labelled homes] | 5.0% | | Green labels considered comprise LEED, GreenPoint or Energy Star |
| 5 | Fuerst et al., 2015 | UK (England) | [A,B] / D | 5.0% | | Evaluation based on energy performance certificates |
| | | | C / D | 1.8% | | |
| | | | E / D | -0.7% | | |
| | | | F / D | -0.9% | | |
| 6 | Cajias et al., 2019 | Germany | A+ / D | | 0.9% | Evaluation based on energy performance certificates |
| | | | A / D | | 1.4% | |
| | | | B / D | | 0.1% | |
| | | | C / D | | 0.2% | |
| | | | F / D | | -0.1% | |
| | | | G / D | | -0.3% | |
| | | | H / D | | -0.5% | |
| 7 | Hyland et al., 2013 | Ireland | A / D | 9.3% | 1.8% | Evaluation based on energy performance certificates |
| | | | B / D | 5.2% | 3.9% | |
| | | | [F,G] / D | -10.6% | -3.2% | |
| 8 | Högberg, 2013 | Sweden | 10% improvement in energy performance | 4.0% | | |
| 9 | Davis et al., 2015 | UK (Belfast) | B / D | 28.0% | | Evaluation based on energy performance certificates |
| | | | C / D | 4.9% | | |
| | | | G / D | -2.0% | | |
| 10 | Jensen et al. 2016 | Denmark | [A,B] / D | 6.2% | | Evaluation based on energy performance certificates after the advertising requirement implemented by 1 July 2010 |
| | | | C / D | 5.1% | | |
| | | | E / D | -5.4% | | |
| | | | F / D | -12.9% | | |
| | | | G / D | -24.3% | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | Fuerst et al. 2016 | Finland (Helsinki) | [A,B,C] / D | 1.5-3.3% | | Evaluation based on energy performance certificates. The lower value in estimated when a set of detailed neighbourhood characteristics are included. Results of models 2 and 3 are presented here. |
| 12 | Cadena and Thomson, 2015 | US (Texas) | Green designation / No | 0.7% | | The models B, D, and F presented here incorporating as independent variable at least one green designation or green/energy efficient feature |
| | | | Green features / No | 1.7% | | |
| | | | Energy efficient features / No | 5.8% | | |
| 13 | Jayantha and Man, 2013 | Hong Kong | Green certification / No certification | 3.4-6.4% | | BEAM certification and GBC Award are used as the measurement of green residential buildings. |
| 14 | Brounen and Kok, 2011 | Netherlands | A / D | 10.2% | | Evaluation based on energy performance certificates |
| | | | B / D | 5.6% | | |
| | | | C / D | 2.2% | | |
| | | | F / D | -2.5% | | |
| | | | G / D | -5.1% | | |
| 15 | Deng et al., 2012 | Singapore | Platinum / No certification | 21.0% | | Evaluation of dwellings awarded with a Green Mark. |
| | | | [Gold plus, Gold] / No certification | 15.0% | | |
| | | | Green mark / No certification | 10.0% | | |
| 16 | Zheng et al., 2012 | China (Beijing) | Green features / No | 17.7% | -8.5% | Dwellings with green characteristics in relation to conventional ones. |
| 17 | Koirala et al. 2014 | US | Existence of energy efficiency building codes / No | | 23.3% | The existence of the codes IECC2003 through IECC2006 for American households is evaluated in this study |

#### 9.8.5.3 Macroeconomic effects

The implementation of mitigation actions in buildings is associated with macroeconomic implications such as changes in economic development measured through GDP and GVA, employment and available income, energy prices, public budgets, trade balance, etc. (IEA 2014; US EPA 2018; Thema et al. 2017; Hartwig and Kockat 2016; Yushchenko and Patel 2016).

Specifically, investments required for the implementation of mitigation actions, create, mainly in the short-run, increase in the economic output and employment in sectors delivering energy efficiency services and products, which are partially counterbalanced by less investments and lower production in other parts of the economy (Thema et al. 2017; EU 2016; US EPA 2018; Yushchenko and Patel 2016). The magnitude of these impacts depends on the structure of the economy, the extent to which energy saving technologies are produced domestically or imported from abroad, but also from the growth cycle of the economy with the benefits being maximized when the related investments are realized in periods of economic recession (Ürge-Vorsatz et al. 2014; Thema et al. 2017; Yushchenko and Patel 2016). Particularly in developing countries if the mitigation measures and other interventions to improve energy access are carried out by locals, the impact on economy, employment and social well-being will be substantial (Mills 2016; Lehr et al. 2016). As many of these programs are carried out with foreign assistance funds, it is essential that the funds be spend in-country to the full extent possible, while some portion of these funds would need to be devoted to institution building and especially training. (Mills 2016) estimated that a market transformation from inefficient and polluting fuel-based lighting to solar-LED systems to fully serve the 112 million households that currently lack electricity access will create directly 2 million new jobs in these developing countries, while the indirect effects could be even greater. (Anderson et al. 2014) based on a literature review, found that energy efficiency investments in residential and non-residential buildings in the US generate about 11 jobs per million dollars of investment (temporary employment occurring in years when these investments take place). In the EU, the implementation of various measures to promote energy efficiency in buildings can create 3.1-7.1 direct jobs per million euro of investment, with relevant indicators being estimated at 6.7 direct jobs per million euro for near zero energy buildings and 7.1 direct jobs per million euro for deep renovations (Econometrics and Garden 2015). Increases in product and employment attributed to energy efficiency investments also affect public budgets by increasing income and business taxation, reducing unemployment benefits, etc. (Thema et al. 2017), thus mitigating the impact on public deficit of subsidizing energy saving measures (Mikulić et al. 2016).

In addition, energy savings due to the implementation of mitigation actions will result, mainly in the long-run, in increased disposable income for households, which in turn may be spent to buy other goods and services, resulting in economic development, creation of new permanent employment and positive public budget implications (Thema et al. 2017; IEA 2014; US EPA 2018). According to Anderson et al. (2014), the production of these other goods and services is usually more labour-intensive compared to energy production, resulting in net employment benefits of about 8 jobs per million dollars of consumer bill savings in the US. These effects may again have a positive impact on public budgets. Furthermore, reduced energy consumption on a large scale is likely to have an impact on lower energy prices and hence on reducing the cost of production of various products, improving the productivity of the economy and enhancing security of energy supply (IEA 2014; Thema et al. 2017).

#### *9.8.5.4 Energy security*

GHG emission reduction actions in the sector of buildings affect energy systems by: (i) reducing the overall consumption of energy resources, especially fossil fuels; (ii) promoting the electrification of heat uses; and (iii) enhancing distributed generation through the incorporation of RES and other clean and smart technologies in buildings.

Specifically, increasing sufficiency and energy efficiency as well as behavioural changes of the occupants result in improving the primary energy intensity of the economy and reducing dependence on fossil fuels, which for many countries are imported energy resources (Thema et al. 2017; Boermans et al. 2015; Markovska et al. 2016).

Of particular interest is the impact of mitigation interventions in residential and non-residential buildings in the structure and reliability of the power sector. The electrification of final demand through the promotion of heat pumps for heating and cooling is expected to significantly increase the demand for electricity in buildings, which can be reversed by promoting nearly zero energy new buildings and a deep renovation of the existing building stock (Johan Couder 2017; Boermans et al. 2015). In addition, highly efficient buildings can keep the desired room temperature stable over a longer period and consequently they have the capability to shift heating and cooling operation in time (Boermans et al. 2015). These result in reduced peak demand, lower system losses and avoided generation and grid infrastructure investments. (Boermans et al. 2015) estimated that in the EU, a scenario promoting high efficiency buildings will save 165 TWh/y in relation to a low efficiency scenario with extensive use of heat pumps, while the resulting reduction in peak load and the associated increased flexibility of the power systems will lead to total CAPEX savings in 2050 of €89-153 billion and grid yearly operational savings of €1 billion.

Distributed generation and particularly the installation of RES technologies in buildings can also improve energy intensity and reduce fuel imports. On the other hand, the promotion of stochastic renewable energies changes the character of threats regarding energy security from political to technical (Andre 2018).

As a significant proportion of the global population, particularly in rural and remote locations, still lack access to modern energy sources, renewables can be used to power distributed generation or micro-grid systems that enable peer-to-peer energy exchange, constituting a crucial component to improve energy security for rural populations (Leibrand et al. 2019; Kirchhoff and Strunz 2019) . The technologies that could be used to this end, are primarily photovoltaics (Leibrand et al. 2019; Ahmad and Byrd 2013) as well as small wind turbines, small hydroelectric plants and biomass combustion devices (Geoff Stiles 2018), subject to the available potential in each region. For successful development of peer-to-peer micro-grids, financial incentives to asset owners are critical for ensuring their willingness to share their energy resources, while support measures should be adopted to ensure that also non-asset holders can contribute to investments in energy generation and storage equipment and have the ability to sell electricity to others (Kirchhoff and Strunz 2019).

## 9.9 Sectoral barriers and policies

### 9.9.1 Barriers, feasibility and acceptance

Understanding the reasons why some cost-effective investment in building energy efficiency and on-site generation are not taking place as expected by rational economic behavior is critical to design effective policies for decarbonize the building sector, as noted by (Cattaneo, 2019) (Cattano et al. 2013) "Consumer behaviour is complex and rarely consistent with the assumption of fully rational agents". Barriers to energy efficiency and on-site renewable technologies have been investigated and categorised by different scholars in different categories. Reddy (Reddy, 1991), Weber (Weber 1997), Sorrell (Sorrell et al., 2000), Reddy (Reddy, 2002), Sorrell (Sorrell e al., 2011). More recently Cagno (Cagno et al., 2012) classified barriers in a more granular manner according to the type of actors, their role in energy efficiency projects, and the economic structure, i.e.: (i) market; (ii) government/politics; (iii) technology/service suppliers; (iv) designers and manufacturers; (v) energy suppliers; (vi) capital suppliers; (vii) organisational; (viii) economic; (ix) behavioural; (x) competence; (xi) awareness. Vogel (Vogel et al., 2015) further extended the previous classifications by identifying 38 barriers to energy efficiency in building in Sweden, categorised into three analytical decision-levels: project level (lack of interest, information, etc.); sector level (barriers at the industrial level, e.g. resistance to change); and contextual level (institutional framework, regulations, policies, etc.). Zhang (Zhang and Wang, 2013) has identified major barriers to promoting energy efficiency in building on China. These are classified as: legal; administrative; financial; market; social. Khosla et al. 2017 and (Gupta et al. 2017) studied the building energy efficiency in a developing country, India, and (Gupta et al. 2017) classified barriers as: economic or financial barriers; governmental barriers; knowledge and learning barriers; market related barriers; organisational and social barriers; and technology barriers. (Masrom et al. 2017) identified the main barriers for energy efficiency in Malaysia. In almost all the classification schemes presented above the energy-end user behaviour is identified as a key barrier. Barriers are still present both in developed and developing countries notwithstanding a range of policies adopted in the last 30 years (Alam et al. 2019) to eliminate or reduce them and better understanding of barriers, in particular behavioural barriers is essential to design effective policies to decarbonise the building sector.

### 9.9.2 Rebound effects

The term “rebound effect” is commonly used to describe the lower than expected energy savings or the increase in energy services consumption that often follow the implementation of energy renovations or other energy efficiency interventions (Galvin 2015; Sorrell et al. 2018; Gillingham et al. 2016; Seebauer 2018; Ürge-Vorsatz et al. 2014). In the literature, this discrepancy between expected and realized energy savings is defined in various ways: usually as an elasticity, i.e., the proportionate change in energy services consumption that results from a marginal proportionate change in energy efficiency(Galvin and Sunikka-Blank 2017), but also as the percentage of the forecasted reduction in energy use that is lost due to consumer and market responses (Gillingham et al. 2016).

The rebound effects can be distinguished in four main components(Sorrell et al. 2018) (Sorrel et al. 2018; Athavale and Knaus, 2017; Lebot et al., 2004): (i) direct effects caused by the reduced cost of the energy service for which the energy efficiency has been improved, thus increasing its consumption; (ii) indirect effects caused by the re-spending of savings in the wider economy; (iii) secondary effects attributed to lower energy prices due to the large-scale implementation of energy efficiency measures as well as further adjustments in the demand and prices of other (non-energy) goods and services; and (iv) embodied effects, to the extent that the production of energy efficient technologies used is more energy intensive compared to baseline options. The total rebound effect is the net result of multiple mechanisms that in some cases reinforce and sometime offset one another.

This section mainly focuses on the direct and indirect rebound effects associated with the implementation of energy efficiency measures in buildings, which may affect significantly the effectiveness of the climate mitigation options implemented, as for example people may take the benefits of improved insulation in the form of warmer homes instead of reduced energy consumption (direct effect), or they spend the energy cost savings to buy other goods and services, which production requires additional quantities of energy and results in increased emissions (indirect effect).

The consideration of the rebound effects as a behavioural economic response of the consumers to cheaper energy services can only partially explain the gap between the expected and actual energy savings associated with the implementation of energy efficiency measures (Galvin and Sunikka-Blank 2017). A number of studies have shown that the prebound effect, a term used to describe the situation where there is a significant difference between expected and observed energy consumption of non-refurbished buildings, is implicated in high rebound effects upon retrofitting(Galvin and Sunikka-Blank 2017; Teli et al. 2016; Calì et al. 2016). This clearly implies that rebound effects are stronger in low-income households and those suffering from energy poverty (Teli et al., 2015; Berger and Holtl, 2019; Vilches et al. 2017; Poon, 2015; Seebauer, 2018; Sorrel et al. 2018). Audin et al. (2017) found that in the Netherlands the rebound effect for the lowest wealth quantile is double compared to the highest wealth quantile. On the other hand, in households whose members have a higher level of education and/or strong environmental values, the rebound is reduced (Seebauer, 2018).

Several studies examined in the context of this assessment showed that direct rebound effects for residential energy consumption, which includes heating, are significant and range between 5-51% in Europe (Galvin, 2015; Galvin and Sunika Blank, 2016; Teli et al. 2015; Cali et al. 2016; Copiello and Gabrielli, 2017; Aydin et al. 2017), 10-30% in the US (Thomas and Azevedo, 2013; Volland et al. 2016), and 82-159% in China (Lin and Liu, 2015). The direct rebound effects for energy services other than heating may be lower (Sorrell, 2018; Chen et al. 2018). The rebound effects may be reduced with the time as the occupants learn how to optimally use the systems installed in energy renovated buildings (Cali et al.2016) and seem to be lower in the case of major renovations leading to nZEB (Corrado et al., 2016). The combined direct and indirect or the indirect only rebound effects were found to range between -2 – 44% (Scheer et al. 2013; Cellura et al. 2013; Chitnis et al. 2013; Santos et al. 2018; Qiul et al. 2019; Thomas and Azevedo, 2013; Murray, 2013). It should be noted that there is great variation in estimates of the direct and indirect rebound effects, which stems from the end-uses included in the analysis, differences in definitions and methods used to estimate the rebound effects, the quality of the data utilized, the period of analysis and the geographical area in consideration (Gillingham et al., 2015; IRGC, 2013; Galvin, 2014). In tertiary buildings the rebound effects may be smaller, as the commercial sector is characterized by lower price elasticities of energy demand, while the comfort level in commercial buildings before renovation is likely to be better compared to residential buildings (Qiu, 2014).

Rebound effects in the sector of buildings could be considered as either a co-benefit since the mechanisms involved contribute to improved social wellbeing or a trade-off to the extent they reduce the expected energy savings, sometimes by a wide margin (Galvin and Sunikka-Blank, 2017; Sorrel et al., 2018). Considering rebound effects as a problem, appropriate policies could be implemented for their mitigation.

### 9.9.3 Policy instruments for energy efficient and low/zero carbon buildings

Several scholars have identified and assessed energy efficiency policies needed to address the "energy efficiency gap" (Hirst and Brown, 1990; Jaffe and Stavins, 1994) and eliminate, overcome, or reduce the above barriers. As in many other public policy sectors, and, in particular, in environmental policy, there is no single policy (or policy measure) able to overcome the barriers, but a range of polices are needed, often included in a policy package (Kern et al., 2017; Rosenow et al. 2017).

Based in the categorisation of environmental policies in three broad category by (Opshoor et al., 1994) and (Markandya et al., 2014) proposed to classify energy efficiency policies in three broad categories: the command and control (e.g. mandatory building codes; mandatory appliances standards, etc.); price instruments (e.g. taxes, subsides, tax deductions, credits, permits and tradable obligations, etc.); and information instruments (e.g. labels, energy audits, smart meters and feed-back, etc.). Shen (L. Shen et al., 2016) follows the three category classification in mandatory administration instruments, economic incentive instruments and voluntary scheme instruments and further subdivides these three categories in three further categories: law, regulation and code and standards; subsidies, tax and loan incentives; and R&D, certification and labels, government services.

The EU Energy Efficiency Directive in Article 7 (Rosenow et al., 2017; Bertoldi, 2020), introduces some policy instruments that EU Member States can adopt as alternative to Energy Efficiency Obligation schemes, which are: energy or $CO_2$ taxes; financing schemes and instruments or fiscal incentives; regulations or voluntary agreements; standards and norms for products, buildings and vehicles; energy labelling schemes; training and education. The MURE database proposes the following classification of policies for the household sector at a disaggregated level (Bertoldi and Mosconi, 2019). Seven broad classes are identified: two normative/regulatory classes, financial, fiscal and tariffs, information/education and training, voluntary type of measures, cross-cutting measures (e.g. energy or $CO_2$ taxation). The IEA Energy Efficiency Policies and Measures database propose the following policy types: behavioural measures; economic instruments; information and education; policy support; regulatory instruments; research, development and deployment (RD&D); and voluntary approaches (Bertoldi and Mosconi, 2019).

Many of the adopted policies aim at reducing energy consumption of new and existing buildings through technical measures such as insulation of the building shell and efficiency improvement of the building technical equipment providing the energy services (heating, cooling, lighting, etc.). Policies for low energy building have be adopted at national (national governments or EU) level (Enker and Morrison, 2017), at state or regional level (e.g. California) (Fournier et al., 2019), or at city level (e.g. New York) (Trencher and van der Heijden, 2019). Zhen (Zhen et al., 2019) find that national policies are instrumental in driving low carbon developments in cities, including buildings.

Several scholars highlighted the role of mandatory building energy codes, i.e. energy efficiency criteria included in the building codes, or specific regulation to set minimum energy performance requirements for new buildings (Enker and Morrison, 2017). Wang (Wang et al. 2019) finds that "Building energy efficiency standards (BEES) are one of the most effective policies to reduce building energy consumption, especially in the case of the rapid urbanization content in China". As compliance with building codes is carried out before the construction of the building when the building permits are issue, there is the need to strengthen the compliance checks with energy efficiency requirements. Evans (Evans et al, 2017) highlights the need for enforcement of building codes in order to achieve the estimate energy and carbon savings and she recommend some steps to improve enforcements, including institutional capacity and adequate resources (Evans et al., 2019). Yu (Yu et al., 2018; Yu et al, 2017) shows the role of building codes in reducing energy consumption of the building stock in India and the contribution to the India NDC. Aydin (Aydin and Brounen, 2019) carried out an ex-post policy evaluation showing that stringer buildings codes results in additional energy savings. Similar results are found by Scott (Scott et al., 2015) indicating that stringent building codes and equipment efficiency standards are cost-effective policies to reduce energy consumption in buildings and greenhouse gas emissions in US. In the 2010 the EU Energy Performance of Buildings directive (EPBD) has introduced the requirements for EU Member States to set the national energy requirement for buildings at the cost-optimal level (Zangheri et al., 2017, Corgnati et al, 2013).

In countries with a large existing building stock and low rate of new construction (e.g. the EU) it is important to consider mandatory building energy codes or regulation setting minimum energy performance requirements for existing buildings. In the EU this is mandated by the EPBD when buildings are retrofitted, however with some limitations (Bertoldi, 2018). While in countries with increasing building stock, in particular in developing countries, policies are more effective when targeting new buildings (Kamal et al., 2019; Liu et al., 2019).

A number of jurisdictions have adopted targets or code for nearly zero energy building (nZEBs) or net zero energy buildings (NZEBs). Definitions of NZEBs are presented and discussed among other in Marszal et al, 2011, D'Agostino and Mazzarella, 2019, Zhang et. al, 2015, Wells at al., 2018, Willians et al. 2016, Attia et al., 2017, Liu et al. 2019, covering different geographical areas, developing and developed countries, and both existing buildings and new buildings. In both nZEBs and NZEBs the residual energy consumption after the adoption of energy efficiency solutions and technologies must be met by on-site renewable generation, very often photovoltaic systems. The EU EPBD 2010 introduced the requirement for all new buildings to be nearly zero energy (nZEBs) by the end of 2020, however definitions of nZEB are left to EU Member States, which have different requirements for energy consumption limits and contribution of renewables (Bertoldi, 2018, Grove-Smith et al. 2018). California has also adopted a building code mandating for NZEBs for new residential buildings in 2020 and 2030 for commercial buildings (Feng et al., 2019). Several other jurisdictions have also adopted building codes, target or voluntary commitments (Feng et al., 2019). More recently a number of cities in particular in the US (e.g. New York, Washington DC, etc.) have adopted very stringent buildings codes.

Many barriers impede the energy refurbishment existing buildings (Palm and Reindl 2018; Bertoldi, 2020), from information gap to financing to split incentives. A potentially effective policy is mandating energy retrofits for low performances existing buildings, in particular when sold or rented (or conversely the impossibility to sell or rent a low performance building), possibly combined with information, technical assistance and financial incentives (Boza-Kiss and Bertoldi, 2018). As example since 2018 the UK does not allow by law the rental of low performance buildings/apartments, i.e. in the lowest two categories of the Energy Performance Certificates (EPC).

Li (Li et. al 2019) reviews the EU experience in the mandatory Energy Performance Certificates (EPC) for buildings adopted in the EU in the frame of the EPBD, the authors propose several measures to make the EPC more effective to drive the markets towards low consumption buildings. There is good evidence on the impact of EPC on property value and on the rental level. While Olaussen (Olaussen et al., 2017; Olaussen et al, 2019) and Hårsman (Hårsman  et al, 2016) showed that there is no impact,  a large number of authors (Chegut et al., 2016; Brounen and Kok, 2010; Kok and Jennen, 2011; Cajias and. Piazolo, 2013; Fuerst et al., 2015, Hyland et al., 2013; de Ayala et al. 2016; Cajias et al. 2019; Bisello et al., 2019; Chegut et al., 2019),  find a positive correlation between energy efficiency of the buildings as indicated in the EPC and the property value and/or rental price.

Mandatory energy performance disclosure of building energy consumption is a power policy instrument in particular for non-residential buildings (Hsu, 2014; Trencher et al., 2016) and could be more accurate than energy audits; Gabe (2016) show that mandatory disclosure is more effective than voluntary disclosure.

Current policies addressing split incentives in the building sector include regulatory measures (e.g. minimum standards for rented properties), information measures and labels, individual metering rules as well as financial models specifically designed to distribute costs and benefits to tenants and owners in a more transparent and fairer way. While it is clear that a one-size-fits-all solution cannot address all particularities across various segments of the building sector or national conditions, a number of common principles can be highlighted (Bird and Hernández 2012; Economidou and Bertoldi 2015; Castellazi et al. 2017). These include a more active engagement of building occupants in energy saving practices, the development of agreements benefitting all involved actors, acknowledgement of real energy consumption and establishment of cost recovery models attached to the property instead of the owner. It is also clear that more comprehensive policy packages are necessary to address misalignments between actors, which can successfully combine the provision of reliable information, delivery of right incentives and effective enforcement of regulations. For example, while revisions in tenant and condominium acts are necessary for reducing disincentives between landlord and tenant or between multiple owners, these acts alone cannot incentivise them to uptake an energy efficiency upgrade in a property (Economidou and Serrenho, 2019). Conversely, the implementation of innovative financing measures will not be successful if regulatory barriers are not adequately addressed.

Energy audits help to overcome the information barriers to energy efficiency investments, especially in small firm buildings (Kalantzis and Revoltella, 2019). In the EU energy audits are mandatory for large companies under the Energy Efficiency Directive (Nabitz and Hirzel, 2019), with some EU Member States having a long experience with energy audits, in particular Finland as part of the voluntary agreements with different industry and service sector branches (Cornelis 2019; Rezessy and Bertoldi 2011). Mandatory energy audits for buildings and building technical equipment are implemented in some large cities, with different frequency (Trencher et al., 2016). The State of New York has in place a subsidized energy audit for residential building since 2010 (Boucher et al. 2018).

Mandatory minimum efficiency standards or requirements for building technical equipment (e.g. HVAC, appliances, ICT, lighting, etc.) is a well-tested and successful instrument for improving energy efficiency in energy using products over the last 30 years (Wu et al., 2019; Scott et al., 2015, Sonnerschein et al 2019). Brucal and Roberts (2019) have shown that efficiency standards do reduce product price. McNeil et al. (2019) (McNeil et al. 2019) highlights how efficiency standards will help developing countries to reduce the power peak demand by a factor two, this reducing large investment costs in new generation, transmission and distribution networks. Minimum efficiency standards is a very common energy efficiency policy in most of the OECD countries, and other large economies, e.g. Russia, Brazil, India, South Africa, China, with an increase in the uptake also in developing countries, e.g. Ghana, Kenya, Tunisia, etc. In Japan there is a successful voluntary programme the Top Runner, with similar results of mandatory efficiency standards (Inoue and Matsumoto 2019).

Mandatory (and voluntary) energy labelling schemes for building technical equipment are very often implemented together with minimum efficiency standards, with the mandatory standard pushing the market towards higher efficiency and the label pulling the market (Bertoldi 2006). As for the minimum efficiency standards most the global largest economies and many developing countries have adopted it. Some labelling schemes are of a voluntary nature, e.g. the Energy Star programme in the US, which covers many different building equipment (e.g. appliances) and buildings.

Energy efficiency obligations (or energy efficiency resource standards or white certificates) have been introduced in some EU Member States, in several US States, Australia, South Kore and Brazil (Bertoldi et al., 2013; Lokey Aldrich and Koerner, 2018; Wirl, 2015; Choi et al., 2018; Palmer et al., 2013; Brennan and Palmer, 2013; Rosenow and Bayer, 2017; Fawcett et al, 2018; Rosenow et al., 2019). The EU Energy Efficiency Directive mandates EU Member States to implement energy efficiency obligations for energy companies or alternative policy measures delivering the same amount of energy savings (Rosenow and Bayer, 2017). In the EU currently there are 14 Member States using this policy instrument (Fawcett et al, 2018). This policy instrument helps in improving energy efficiency in buildings, but there is no evidence that it can foster deep renovations of existing buildings. Recently this policy instrument has been investigated is some non-OECD countries such as Turkey (Duzgun and Komurgoz, 2016) and UAE (Friedrich and Afshari, 2015). Another similar market based instrument is the energy saving auction mechanism implemented in some US States (Neme and Cowart, 2014), Switzerland (Radgen et al. 2016), in Germany (Langreder et al., 2019). Energy efficiency projects participate in auctions for energy savings based on the cost of the energy saved and receive a financial incentive, if successful.

Energy and/or carbon tax is a well-investigated climate and energy efficiency policy, which can help in reducing energy consumption (Sen and Vollebergh, 2018) and avoid the rebound effect (Bertoldi, 2020; Peng et al, 2019, Vivanco et al., 2016, Freire-González, 2020). The carbon tax has been adopted mainly in OECD countries and in particular in EU Member States (Hájek et al, 2019: Bertoldi, 2020; Sen and Vollebergh, 2018). Hájek (Hájek et al, 2019) concluded that the carbon tax is environmental effectives. There is high agreement that CO2 or energy taxis is an effective policy to reduce CO2 emissions, (Andersen, 2016; IPCC Special Report on 1.5 C, Chapter 4). It is hard to define the optimum level of taxation in order to achieve the desired level of consumption reduction or CO2 emission reduction (Metcalf and Weisbach, 2013). As for other energy efficiency policy distributional effect and equity considerations have to be carefully considered and mitigated (Borozan, 2019). High energy prices tend to reduce the energy consumption particularly in less affluent households, and thus attention is needed in order to avoid unintended effects such as energy poverty. The carbon tax revenues could be used for supporting investments in energy efficiency. Hence, the introduction of a carbon tax can be neutral or even positive to the economy, as investments in clean technologies generate additional revenues. In addition, in the long term, a carbon/energy tax could gradually replace the tax on labour reducing the labour cost (e.g. the example of the German Eco-tax), thus helping to create additional jobs in the economy. This is known in literature as double divided (Jaeger, 2013; Freire-González and Ho, 2019). Xiang (Xiang and Lawley, 2019) estimated the impact of the carbon tax in British Columbia substantially reduced residential natural gas consumption. Saelim (Saelim, 2019) investigate the short-run welfare effects associated with a simulated carbon tax on residential consumption in Thailand, showing that the carbon tax will have a low impact on welfare and it will be slightly progressive in Thailand. Lin and Li (Lin and Li, 2011) indicates that a carbon tax could reduce the energy consumption and boost the uptake of energy efficiency and renewable energies, while at the same time may impact social welfare and the competitiveness of industry. Solaymani (Solaymani, 2017) studied carbon and energy taxation in Malaysia, showing that a carbon tax result in higher emission reduction that an energy tax. Solaymani (Solaymani, 2017) shows that with tax revenue recycling the carbon tax increase in the welfare of rural and urban households. Van Heerden (Van Heerden et al. 2016) explored economic and environmental effects of the CO2 tax in South Africa. Van Heerden particular highlighted the negative impact on GDP. This negative impact of the carbon tax on GDP is, however, greatly reduced by the manner in which the tax revenue is recycled.

Taxes could also be used to penalise inefficient behaviour and favour the adoption of efficient behaviour and technologies. As example, taxes are already used in some jurisdictions to promote energy efficient appliances with lower VAT. Similarly, the annual building/property tax (and also the purchase tax) could be based on the $CO_2$ emissions of the buildings, rather than on the value of the building.

Provision of information (public campaigns, targeted technical information, etc.) is a common policy instrument to change energy end-user behaviour. The impact of information campaigns has been well analysed in (Diffney et al., 2013). Many authors agree that the effect of both targeted and general advertisement and campaigns have a short lifetime and the effects tend to decrease over time (Simcock, et al., 2014; Diffney et al., 2013, Reiss and White, 2008). The meta-analysis carried out by (Delmas et al., 2013) showed that energy audits and personal information were the most effective followed by providing individuals with comparisons with their peers' energy use. Delmas concluded that "non-monetary, information-based strategies can be effective at reducing overall energy use" (Delmas et al., 2013). The "social norms approach" integrates the social norms (referred to the perception of what is commonly done in a situation) as the basis for information and awareness measures on energy behaviour (Gifford, 2011; Schultz, 2007). Information is more successful when inspire and engage people: how people feel about a given situation often has a potent influence on their decisions (Slovic and Ellen Peters, 2006). The message needs to be carefully selected and kept as simple as possible focusing on the following: entertain, engage, embed and educate! (Owen and Dewick, 2015). Once the basic awareness is there, the second step would be to provide targeted information on potential energy efficiency, energy saving and sufficiency measures.

Energy consumption feedback with smart meters, smart billing and dedicated devices is another instrument recently exploited to reduce energy consumption (Zangheri et al, 2019; Buchanan et al., 2018) very often coupled with contest-based interventions or norm-based interventions (Bergquist et al., 2019). Hargreaves (Hargreaves, 2018) indicates that "the role for energy users in future energy transitions may be narrowed down to responding to the information they are given, by undertaking a relatively short list of actions designed to reduce their energy use". Hargreaves (Hargreaves, 2018) proposes five core types of action to reduce energy use: turn it off, use it less, use it more carefully, improve its performance, and replace it/use an alternative. According to Aydin (Aydin et al., 2018), technology alone will not be enough to achieve the desired energy savings due to the rebound effect. Considering energy end-users behaviour is important in policy design for the decarbonisation of the building sector, as end-users need to adopt efficient technologies and to adapt their behaviour to achieve energy savings (Zangheri et al, 2019). The lack of interest from household occupants, confusing feedback message and difficulty to relate it to practical intervention, overemphasis on financial savings and the risks of "fallback effects" where energy use returns to previous levels after a short time or rebound effects has been pointed out (Buchanan et al., 2015) as the main reasons for the failing of traditional feedback. Labanca (Labanca and Bertoldi, 2018) highlights the current limitations of policies for energy conservation and suggests complementary policy approach based on social practices theories.

From a policy perspective the decarbonisation of the building sector implies coupling technological change with the adoption of measures limiting energy consumption growth, i.e. policies and measure targeting energy conservation and sufficiency. To achieve this end, effective policies that trigger behaviour change related to energy conservation and energy sufficiency should be designed and adopted (IPCC, 2018). Technological options improving energy efficiency reduce energy input while keeping energy services constant, while energy conservation measures are reducing energy input by reducing energy services (e.g. lowering the thermostat setting in heating season and increasing it in cooling seasons). Neither efficiency nor conservation has a normative limit. Recently the concept of energy sufficiency as an alternative to energy efficiency and energy conservation has been introduced policy making. (Bertoldi, 2020). Thomas et al. (2019) define energy sufficiency as "a strategy aiming at limiting and reducing the input of technically supplied energy towards a sustainable level." In an energy sufficiency scenario, energy input is reduced while utility/technical service changes in quantity or quality, provided that energy services are still 'sufficient' for basic needs of the individual. The concept of energy sufficiency has been recently analysed by several scholars (Thomas et al., 2019: Brischke et al., 2015), in particular on ways to introduce sufficiency in policy making. Spangenberg (Spangenberg and Lorek, 2019) investigates the limitations and policy implications of the theory of planned behaviour and social practice theory and proposes an approach combining both theories resulting in an heuristic sufficiency policy tool. Sufficiency includes accepting lower level of comfort, when the comfort is created at the expenses of high energy consumption (e.g. over cooling a building in hot period) and reducing standards of living, by reducing indoor space or building size. Lorek (Lorek and Spangenberg, 2019) shows that increased living area per person counteracts efficiency gains in buildings. Lorek calls for policy instruments to include sufficiency in addition to efficiency by limiting building size. This could be achieved via mandatory and prescriptive measures, e.g. very progressive building codes (i.e. decreasing the energy per square meter for larger residential buildings), or financial penalties in the form of property taxation (e.g. non-linear and progressive taxation), or even more drastically with mandatory limits on building size per capita. Sufficiency touches upon individual liberties and social justice (Heindl and Kanschik, 2016), the authors suggest that policies promote more effectively voluntary sufficiency. In addition, they propose that sufficiency should be "integrated in a more comprehensive normative framework related to welfare and social justice". Thomas (Thomas et al., 2019) describes some of these policies with some based on the sharing economy principles, for examples co-sharing space, public authorities facilitating the exchange house between young and expanding families with elderly people, with reduce need for space.

A number of recent papers (Li et al, 2015; Li et al, 2018; Wadud et al., 2019; Fan et al., 2016; Fan et al., 2016; Raux et al., 2015; Marek et al., 2018, Fawcett and Parag, 2017) have further investigated the use of personal carbon allowances or of a person carbon trading proposed previously by several authors (Fleming, 1997; Ayres, 1997; Hillman, 1998; Bristow et al., 2010; Fawcett, 2010; Starkey, 2012; Raux and Marlot, 2005). Although there is not yet any practical implementation of this policy, which includes carbon emissions in the building sector as well as in the transport sector, it could offer an interesting alternative to carbon taxes, although there are several issues to be solved before it could be rolled out. Recently the city of Lahti in Finland has introduced a personal carbon allowance in the transport sector (Kuokkanen et al., 2020). Under this policy instrument the he national or local government sets the amount of emissions that a person can emit based on his/her energy consumption (house, transport fuel, air-travel, etc.). The scheme will allocate (free allocation, but some allowances could also be auctioned) to each person her/his carbon budget for the year. Trade of allowances between people can be organised. Personal carbon allowances will also foster renewable energies (energy consumption without carbon emissions) both in the grid and in buildings (e.g. solar thermal). In addition, the personal carbon allowances could make the carbon price more explicit to consumers, allowing them to know from the market value of each allowance (e.g. 1 kg of $CO_2$). Although in principle personal carbon allowances are very different from a carbon tax (setting of the quantity of emission reduction and leaving the price to the market vs. fixing the price and leaving the quantity to the market), if end-users are not be well informed and engaged, it could appear to them as a carbon tax on additional consumption. As already discussed, this policy instrument will shift the responsibility to the individual, with some categories having limited ability to change their carbon budget or to be engaged by this policy instruments. In addition, in common with many other environmental policies the distributional effects have to be assessed carefully as this policy instrument may favour well off people able to purchase additional carbon allowances or install technologies that reduce their carbon emissions (Wang et al., 2017, Burgess, 2016).

The concept of a "Personal Carbon Allowances" could also be applied to both residential and non-residential buildings, i.e. assigning a yearly amount of $CO_2$ emissions per building per year. This would be a less complex than personal allowances as buildings have metered or billed energy sources (e.g. gas, electricity, delivered heat, heating oil, etc.). The scheme could allocate the emission allowances to each individual building, and thus stimulate investments in energy efficiency and on-site renewable energies and energy savings resulting from behaviour actions (e.g. lowering thermostat temperature) by buildings occupant or landlords (the allowance could be split between landlord and tenant to take into account the split incentive barrier). For commercial buildings, some policies similar to this already exist, for example, the UK CRC Energy Efficiency *Scheme* or the Tokyo Metropolitan Carbon and Trade Scheme (Bertoldi et al., 2013).

Rather than trying to ‘discourage’ consumption (and inefficiency) with an additional energy tax and get through the complexities of trying to define an optimum level of taxation, public money can be used to reward and give incentives to energy saved, as a result of technology implementation, and/or as a result of energy conservation and sufficiency (Eyre, 2013; Bertoldi et al., 2013; Neme and Cowart, 2012; Prasanna et al, 2018). This can be seen as a core feature of a possible Energy Savings Feed-in Tariff (ES-FiT). The ES-FiT is a performance-based subsidy, whereby actions undertaken by end-users – both investments in energy efficiency technology and conservation and sufficiency measures – are awarded based on the real energy savings achieved. In terms of design, the ES FIT could be either based on the actual number of saved kWh of electricity or $m^3$ of gas (quantity-based ES-FiT, e.g. based on the actual quantity of savings) or based on a fixed threshold achieved (target-based ES-FiT). In the case of quantity-based FIT the subsidy is awarded based on saved amount of energy compared to a predefined and agreed energy consumption. In case of a target-based FIT, the FIT subsidy can be awarded contingent upon the reduction of the amount of consumed energy by a certain amount (target).

As highlighted in literature there is not a single energy efficiency policy able to decarbonise the building sector, due to the several barriers, and different type of buildings and the different socio economic and geographical locations on building, including development status, climate (cooling and/or heating), ownership structure, age, etc. Several studies have highlighted the role of effective policy packages for the de-carbonisation of the building sector, including mandatory targets, codes, the provision of information, financing and technical assistance for end-users (Table 9.24). In developed countries policy packages are investigated to increase the number of existing building refurbishment and the depth of the refurbishments. In addition, policy addressing life cycle analysis and reduction of embedded $CO_2$ emissions in building construction material are still to further investigated and developed. Building codes, building rating schemes and building level could be based on LCA emissions, rather than energy consumption in the use phase of the buildings. Embedded emissions have an increased importance in net zero energy buildings.

**Table 9.24. Categorisation of policy measures for energy efficiency in buildings (based on Bertoldi and Economidou, 2018)**

| Type of policy instrument | Example |
|---|---|
| Regulatory | Building codes; Minimum energy performance standards (MEPS) for new and existing buildings; Energy efficiency standards for appliances & equipment; building renovation obligations; Procurement regulations; Phase-out of inefficient equipment. Mandatory energy labelling. |
| Financial and fiscal | Grants/subsidies; Preferential loans; Tax incentives; Energy/Carbon taxation; Feed in Tariffs; Support for the producers of innovative technologies |
| Information and awareness | General Information; Information campaigns; Information Centres; Energy Audits; Energy labelling schemes; Governing by Example; |

| | |
|---|---|
| | Information exchange; Awareness campaigns; Demonstration programmes; Energy consumption feedback; Smart meters and smart billing. |
| Qualification, training and quality assurance | Professional training; Training courses; Vocational education, Quality standards. |
| Market-based | Incentives facilitating Third Party Financing / ESCOs; Energy Efficiency Obligation Schemes (EEOSs); White certificates; Technology deployment schemes. Personal Carbon Allowances/Personal Trading Schemes |
| Voluntary action | Voluntary certification and labelling programs; Voluntary and negotiated agreements (to reach emission reduction in a sector/company) |

### 9.9.4 Financing mechanisms and new business models for energy efficiency

A number of policy mechanisms above described provide non-repayable incentives for energy end-users in order to remove some of the barriers such as high upfront investments costs or long pay-back periods. Grants and subsidies, such as direct investment subsidies, are used by governments when optimal levels of investments cannot be fully supported by the market alone. They can partly help overcome the upfront cost barrier as they directly fill an immediate financial gap and thus enable a temporary shift in the market (Newell et al., 2019). These forms of support are usually part of policy mixes including further fiscal and financial instruments such as feed-in tariffs and tax breaks (Polzin et al., 2019). Other financial mechanisms included are described below.

Loans provide liquidity and direct access to capital, which can be more relevant for EE measures attached to high upfront costs, especially in deep renovation projects (Rosenow et al., 2014). To address some barriers (limitation of funding for energy renovation, high transition costs) international financing institutions and national governments provided subsidies in public-private partnerships so that financial institutions can offer customers loans with attractive terms (Olmos et al., 2012).

An energy efficient mortgage is a mortgage that credits a home's EE by offering preferential mortgage terms to extend existing mortgages to finance efficiency improvements. There are two types of energy mortgages: (1) the Energy Efficient Mortgages (EEMs), and (2) the Energy Improvement Mortgages (EIMs). EEMs and EIMs have a great potential for overcoming the main barriers to retrofit policies (Miu et al., 2018). The success depends on the improvement of the EE of a property with a positive impact on property value; and on the reduction of energy bills and the increase of the income in the

On-bill financing is a mechanism that reduces first-cost barriers by linking repayment of EE investments to the utility bill and thereby allowing customers to pay back part or all costs of EE investments over time (Brown, 2009). On-bill finance programmes can be categorised into: (1) on-bill loans (assignment of the obligation to the property) and (2) on-bill tariffs (payment off in case of ownership transfer) (Eadson et al., 2013).

Property Assessed Clean Energy (PACE) is a means of financing energy renovations and renewable energy improvements through the use of specific bonds offered by municipal governments to investors (Mills, 2016). The governments use the funds raised by these bonds to loan money towards energy renovations in residential or commercial buildings. The loans are repaid over the assigned long term (15-20 years) via an annual assessment on their property tax bill (Kirkpatrick & Bennear, 2014).

Loan guarantees are effective in reducing intervention borrowing costs (Soumaré & Lai, 2016). This scheme can facilitate the provision of affordable and sufficient financing for ESCOs (Bullier & Milin, 2013). The ESCO guarantees a certain level of energy savings and in this way shields the client from any performance risk. The loan goes on the client's balance sheet and the ESCO assumes full project performance risk (Deng et al., 2015).

Revolving funds is an innovative financing scheme that allows reducing investment requirements and enhancing EE investment impacts by recovering and reinvesting the savings generated qawan, 2014). Revolving fund could make retrofit cost-neutral in the long term and also could dramatically increase low carbon investment (Gouldson et al., 2015).

Carbon finance is an economic measure aimed at effectively solving the climate problem and it is an activity based on "carbon emission rights" and its derivatives (Liu et al., 2015). Carbon finance can promote low-cost emission reductions (Zhou & Li, 2019). Banks involved in carbon financing rely on CDMs as intermediaries in China, and focus on credit investment, financing, facing some risks (Zhang & Li, 2018). With the increasing popularity of Emission Trading Schemes, the auctioning carbon allowances creates a new revenue stream. Revenues from auctioning could be used to finance energy efficiency projects with grants or zero interest loans

Crowdfunding is a new and rapidly growing form of financial intermediation that channels funds from investors to borrowers (individuals or companies) or users of equity capital (companies) without involving traditional financial organizations such as banks (Miller & Carriveau, 2018). Typically, it involves internet-based platforms that link savers directly with borrowers (Oxera, 2015). It can play a significant role at the start of a renewable and sustainable energy project's life-cycle (Dilger et al., 2017).

The One Stop Shop (OSS) service providers for buildings energy renovations are organizations, consortia, projects, and even independent experts or advisors that usually cover the whole or large part of the customer chain from information, technical assistance, structuring and provision of financial support, to the monitoring of savings (Balson et al., 2016). OSSs are transparent and accessible advisory tools from the client perspective and new, innovative business models from the supplier perspective (Boza-Kiss & Bertoldi, 2018).

Energy Performance Contracting (EPC) is a tripartite agreement between representatives of the multi-apartment building, a house management company and Energy Services Company (ESCO) for EE improvements. The quality standards are a part of the EPC, because the contractor (ESCO) gives a guarantee regarding energy savings (Augustins et al., 2018) and an important role is played by the economic evaluation of the contract implementation (Tupikina et al., 2018).

### 9.9.5 Policies and Financing for on-site renewable energy generation

On site renewable energy generation is a key component for the decarbonisation of the building sector. As described in detail for the energy efficiency technologies on-site renewable technologies face barriers due to the high upfront investment costs, long pay-back period, unpredictable energy production, policy incertitude, architectural considerations, technical regulations for access to the grid, and future electricity costs (Mah et al., 2018; Agathokleous and Kalogirou, 2016).

Several policy instruments have been identified by scholars (Azhgaliyeva et al. 2018; Pitelis et al., 2020; Fouquet, 2013): direct investments, feed-in tariffs, grants and subsidies for investments, loans, taxes, (tradable) green certificates, information and education, strategic planning, codes and standards, building regulation (e.g. part of buildings codes), priority grid access, research, development and deployment and voluntary approaches.

Many authors indicate that most common implemented policy instruments are the feed-in tariffs (FiT) and the Renewable Portfolio Standards (Alizada, 2018; Zhuo et al, 2017). There is an on-going debate on the effectiveness of these two renewable energy policies. (Choi et al. 2018) analysed the economic efficiency of FIT and RPS in the South Korean, where first a FIT was implemented from 2002 to 2011 followed by an RPS since 2012 (Choi et al. 2018; Park and Kim, 2018).

A flat rate feed-in tariff (FiT) is a well-tested financial incentive adopted in many jurisdictions (e.g. Germany, France, Germany, Italy, Portugal, UK, Japan, Australia, several US states, Belgium, Japan, Brazil, China, South Korea, etc.) to encourage end-user to generate electricity from renewable sources such as rooftop photovoltaic systems and on-site PV systems (Pacudan, 2018). Both FITs and capital subsidies have been employed to promote the adoption of PV (Yamamoto, 2018). FiTs schemes pay a fix price established in advance for the electricity produced for a fixed period (Barbosa, et al., 2018). More recent there has been an increasing interest for dynamic FiTs taking into account electricity costs, hosting capacity, ambient temperature, and time of day. (Hayat et al., 2019). Since 2014, EU Member States have been obligated to move from FiT renewable subsidies to feed-in premiums (Hortay and Rozner, 2019), taking into account the electricity price. Lecuyer (Lecuyer, O., Quirion, 2019) argues under uncertainty over electricity prices and renewable production costs a flat feed-in tariff results in higher welfare than a feed-in premium. (Lecuyer, O., Quirion, 2019). One of the main concerns with FiT systems is the increasing cost of policies maintenance (Pereira da Silva et al., 2019; Zhang et. al, 2018; Roberts et al., 2019). In Germany, an earlier adopter of the FiT, the financial costs, passed on to consumers in the form a levy on the electricity price have increased substantially in recent years (Winter and Schlesewsky, 2019) resulting in opposition to the FiT in particular by non-solar customers. A particular set up of the FIT encourage self-consumption (Yamamoto, 2018) through net metering and net billing, which has a lower financial impact on electricity ratepayers compared with traditional FiTs (Pacudan, 2018; Roberts et al., 2019; Pereira da Silva et al., 2019).

In some countries, e.g. Australia (Zanderet al., 2019), South Korea (Choi et al., 2018), China (Yi et al., 2019), there is a transition from subsidies under the FiT to market-based mechanisms, such as RPSs and tendering. Compared with FIT, Renewable Portfolio Standards (RPS) or Obligations and the Tradable Renewable Energy Certificate (REC) have been adopted by governments in order to reduce the subsidy costs (Zhang et. al, 2018). RPS, REC trade and FIT subsidy should be implemented as complementary policies, not independent. (Zhang et. al, 2018).

Tenders are a fast spreading instrument to attract and procure new generation capacity from renewable energy sources (Bayer et al., 2018; Bento et al., 2019). In general, the assignment of remuneration payments is guarantee over long periods of time. A support scheme based on tenders allows a more precise steering of expansion and lower risk of excessive support that can be achieved (Klessmann et al., 2015). There is not yet the literature a quantitative assessment of its performance. Bento (Bento et al., 2019) indicated that tendering is more effective in promoting additional renewable capacity comparing to other mechanisms such as FiTs.

(García-Álvarez et al., 2018) carried out an empirical assessment of feed-in tariff and quota obligation policies for PV systems energy in EU over the period 2000–2014 concluding that that FiTs have a significant impact on installed photovoltaic capacity. Similar conclusions were reached by (Dijkgraaf et al., 2018) assessing 30 OECD member countries and concluding that there is a “positive effect of the presence of a FIT on the development of a country's added yearly capacity of PV”.

It is also important to take into account the rebound effect in energy consumption by on-site PV users, which might reduce up to one fifth of the carbon benefit of renewable energy (Deng and Newton, 2017).

In the new EU energy policy adopted in 2016, the end-user is at the centre as a key participant in the future electricity system (Zepter et al., 2019). Zepter indicates that “the current market designs and business models lack incentives and opportunities for electricity consumers to become prosumers and actively participate in the market by providing generation, storage, demand flexibility and other grid ancillary services". Services provides by prosumers include storage, energy productions, pier to pier trading, electric vehicle charging. Policy should allow for active participation of small prosumers (Zepter et al., 2019; Brown et al., 2019), local energy communities and new energy market actors such as aggregators (Iria and Soares, 2019; Brown et al., 2019). Aggregators are also important players for demand response (Zancanella et al, 2016). Klein et al (2019) explore the policy options for aligning prosumers with the electricity wholesale market, through price and scarcity signals.

## 9.9.6 Governance and Institutional Capacity

### *9.9.6.1 Governance*

Multilevel and polycentric governance is essential for implementing energy efficiency and renewable energies policies at different levels of government and decision making (international, national, regional/local).

International agreements (Kyoto, Montreal/Kigali, Paris, etc,) play a key role on stimulating countries to adopt policies and measures for energy efficiency and on-site generation (Bertoldi, 2018). International agreements and treaties can either set national targets for emission reductions, e.g. Kyoto protocol, and or ask nation states to set their own targets and climate energy plans, e.g. Paris Agreement (IPCC, 2018). Under the Paris Agreement National Determined Contributions (NDCs) present and describe the national policies and measures countries plan to implement in order to reduce GHG emissions and reach a self-determined target. Some NDCs contain emission reduction targets for subsectors, e.g. buildings and specific measures for subsectors. Some NDCs set energy efficiency and renewable targets (Bertoldi, 2018). In the EU since 2007 climate and energy policies are part of the same policy package. EU Member States have to produce energy efficiency plans every three years, which describes the energy efficiency policies in the different sectors, and since 2014 national building renovation plans, which contains a strategy for the long term renovation of the building stock. Similarly, national renewable plans are also submitted. Under the new Energy and Climate Governance EU Member States adopt and present by the end of 2020 integrated National Energy and Climate Plans.

Some policies are best implemented at international level. For example, efficiency requirements for traded goods and the associated test methods could be set at global level in order to enlarge the market, avoid technical barriers to trade and reduce the manufacturers design and compliance costs. This would also reduce the damping of inefficient equipment in countries with no or lower efficiency requirements. Also the policy development and implementation costs would be reduced as the technical analysis leading to the standard could be shared among governments. However, care has to be used in avoiding that local small manufacturing companies in particular in developing countries have the capacity to invest in updating production lines for meeting new stringent international efficiency requirements. An example of a possible global standard is the IEC energy efficiency classification for electric motors, allowing countries to set common standards (based on IEC classes) and common test methods. International markets can also be established for tradable certificates for energy savings and renewable in order to foster technology transfer and project implementation in developing countries.

As building energy consumption is dependent on local climate and building construction traditions regional and local government share an important role in promoting energy efficiency in buildings and local on-site renewable generation, through local building codes, which could be more challenging than national codes, constructions permits, urban planning [text to be expanded and several references to be added]. Example of new carbon neutral policies at city level includes New York, Washington DC, etc., with local policies to decarbonise the building sector by mandating all new buildings. Where it is impossible to retrofit towards net zero energy buildings, e.g. for historical buildings, cities may impose target at district level, where renewable generation sources could be share among buildings as well as having energy positive building compensating for energy consuming buildings. Local climate plans and local policies could also contribute to integrate the building sector with the local transport sector allowing new constructions in areas served by public transport or design new buildings ready for e-mobility

As energy efficiency, energy conservation, sufficiency, and on-site renewable measures will have a large impact on different stakeholders, citizens as building owner or building users, construction companies, equipment manufacturers, utilities, it has been highlighted in literature the importance of stakeholder consultation and active participation in policy making and policy implementation, including voluntary commitments and action. In particular, with the transformation of energy users in prosumers, their role and the role of buildings in energy markets will be transformed from passive role to an active role. The prosumers needs and voice should be included in policy negotiations among traditional business players, such as incumbent centralised power generation companies and utilities. Citizens and local communities may also establish local energy communities, providing local renewable energy production to serve the community and to export energy into the grid. Energy communities shall also be part of the policy development process and recognised for their role in fostering local business and increasing local welfare.

#### *9.9.6.2 Institutional capacity (to be developed further in SOD)*

Role of government, regulatory organisation, financial institutions, standardisation body, test laboratory in supporting the implementation of energy efficiency policies and on-site renewable generation.

Governments at all levels (from national to local) planning to introduce energy efficiency and on-site energy renewable generation policies needs technical capacity to design policies, carry our impact assessment and introduce effective and enforceable policies. When policies are discussed and possibly agreed with stakeholders, have a higher possibility of success.

In particular, the enforcement of policies needs attention. For policies on energy efficiency of products have to be randomly tested. For building code compliance there is the need to verify compliance after construction. Very often local authorities lack resources and technical capacity to carry out inspections to check code compliance. This issue is even more pressing in countries and cities with large informal settlements, where buildings are not respecting building codes for safety and other important issues.

Public authorities need for technical and economics competences (to understand complex technical issues and the knowledge gap in comparison to private sector experts), capacity and human and financial resources to design, implement, revise and evaluate policies and measures. The role of energy efficiency policy evaluation needs to be expanded, including the assessment of the rebound effect.

International support for institutional capacity (capacity buildings) for policy development, policy implementation and policy evaluation including the financial support and human resources for these tasks is of key importance in particular for developing countries, where technical skills may be lacking, such as testing laboratory, standards institute, enforcement and compliances technicians.

## 9.10 Conclusions and research gaps

### 9.10.1 Conclusions

With more than 30% of $CO_2$ emissions resulting from buildings energy demand, delivering on the Paris Agreement target and on SDGs are highly dependent on the effective implementation of mitigation solutions in the built environment. Literature and recent policy development argue for going beyond efficiency and for considering the combination of sufficiency, efficiency with the supply with renewable energy sources to ensure the global building stock will contribute its share to limiting global warming to well-below 2°C by the end of the century. Furthermore, the most advanced mitigation solutions identified consider the overall life-cycle of buildings and harvest the mitigation potential of the new trends such as digitalisation and the transformation of buildings into power plants.

The observed increase in emissions and energy demand in the built environment over the period 2010-2018 was driven mainly by the construction of new buildings in the developing world. This increase is expected to continue in the coming years driven by the legitimate aspiration for Decent Standard of Living (DLS) for all, especially in the global South and the increased penetration of new technologies in both the global North and South (*high evidence, high agreement*). DLS for all and achieving SDG targets as well as ensuring well-being for all within the planetary boundaries will not necessarily translate in higher emissions if innovative policies (see section 9.9) are put in place in all countries over the world (*low evidence, high agreement*).

The type and composition of building influence energy consumption and the associated greenhouse gases emissions *(medium evidence, high agreement).* Technological advancements in building services can lead to efficient energy use *(medium evidence, high agreement).*

Low-energy and low carbon buildings are possible today in every climate and every location worldwide (*high evidence, medium agreement*). The quantification of the mitigation potential of available technological mitigation options and strategies is not always available, clear and comparable (*high evidence, low agreement*). The available technological options (passive options to improve the building envelope, active technologies that can be implemented in the building envelope or in the building energy systems and on-site energy production) contribute to changing the building to become a small power plant, exporting surplus energy. The role of buildings in the energy system is changing towards a prosumer role, and digitalisation (smart buildings, smart meters and smart appliances) is key to decrease emissions in buildings (*low evidence, high agreement*).

Non-technological and behavioural mitigation actions are among the sufficiency measures in buildings with a great effect in energy use and GHG emissions (*robust evidence, high agreement*). These measures are also required to increase the uptake of technical mitigation measures (*robust evidence, high agreement*), and to guarantee demand-supply flexibility (*medium evidence, high agreement*). Income, climate, energy price and size are key determinants of buildings energy consumption (*robust evidence, high agreement*), so price and size mechanisms have potential to deliver mitigation solutions in buildings. Households with the adequate level of services are willing to change (*medium evidence, medium agreement*) but additional infrastructural and policy support is needed to implement the major lifestyle changes required to significantly reduce GHG emissions from buildings (*medium evidence, high agreement*). Furthermore, sufficiency measures may deliver energy savings even before they are implemented through efficiency and behaviour as sufficiency avoids energy demand at low costs (*medium evidence, high agreement*). Given the lower limit of energy sufficiency and the fact that many people around the world still lack appropriate access to energy services, energy sufficiency is not only about demand reduction but also about matters of distribution and equity (*medium evidence, medium agreement*).

Existing technologies and practices allow transforming the building sector by 2050 in a way that it would emit very low GHG emissions in developed countries (*robust evidence, high agreement*) and relatively low GHGs emissions (*medium evidence, high agreement*). This however requires an acceleration of building retrofit rates in developed countries because the retrofit rates observed are very much lower than those modelled (*robust evidence, high agreement*). This also requires an immediate introduction of very ambitious building and equipment standards in developing countries to avoid the lock-in effect due to accelerated construction rates (*robust evidence, high agreement*). The estimates of the potential and its associated costs should be treated with caution because they rely on the number of assumptions containing uncertainties (*robust evidence, high agreement*). These include stock turnover, technological limitations, e.g. in urban areas, investment costs, baseline emissions, discount rates and others. The actual investment costs are likely to be higher than the models predict (*medium evidence, medium agreement*).

Climate change impacts buildings in different ways, including impacts to building structures, building construction, building material properties and indoor thermal comfort. Adapting to these impacts, in turn, have consequences in terms of energy consumption and, thus, mitigation strategies (*high evidence, high agreement*). Eventual trade-offs between climate change adaptation and mitigation in buildings can be reduced by strengthening efficiency, sufficiency and building envelope measures. So, considering climate change in the design of new buildings in a way that they can operate in both current and future climates can avoid higher adaptation costs associated with retrofit of the existing building stock.

Mitigation actions in buildings have multiple co-benefits that result in substantial social and economic value beyond their direct impact on reducing energy consumption and GHG emissions (*robust evidence, high agreement*), contributing to the achievement of almost all the United Nation's Sustainable Development Goals (*medium evidence, high agreement*). Most studies agree that the value of these multiple benefits is greater than the value of energy savings (*medium evidence, high agreement*), while their quantification and inclusion in decision-making processes will strengthen the adoption of ambitious reduction targets and improve coordination across policy areas (*robust evidence, high agreement*).

A number of policies such as appliances standards and building codes have been adopted in OECD countries and many other large economies. These policy instruments have proven to be effective, however not sufficient to decarbonize the building sector. Police shave also fostered the adoption of on-site renewable generation. From a policy perspective the de-carbonization of the building sector implies coupling technological change in relation to energy efficiency and on-site renewable generation with the adoption of measures limiting energy consumption growth, i.e. policies and measure targeting energy conservation and sufficiency. Effective and innovative policies, which address behaviour change related to energy conservation and energy sufficiency should be designed and adopted, including carbon taxes, personal or building allowances, mandatory deep renovation of existing buildings. Financing mechanisms are essential for the transformation of the building sector.

### 9.10.2 Research Gaps

Insights from regions, sectors and communities

- Due to the dominating amount of literature from developed countries and rapidly developing Asia (China), the evidence and therefore conclusions are limited for the developing world. In particular, there is limited evidence on the potential and costs the countries of Africa and South America.
- The contribution of indigenous knowledge in the evolvement of buildings is not well appreciated. There is a need to understand this contribution and provide methodological approaches for incorporation of indigenous knowledge.
- Analysis of emissions and energy demand trends in non-residential buildings is limited due to the number of building types included in this category and the scarcity of data for each building type. The use of new data gathering techniques such as machine learning, GIS combined with digital technologies to fill in this data gap was not identified in the literature.

Measures, potentials and costs

- There is a lack of scientific reporting of case studies of exemplary buildings, specially from developing countries. Also, there is a lack of identification of researchers on technologies with the mitigation potential of such technologies, bringing a lack in quantification of that potential.
- There is limited evidence on sufficiency measures including those from behavioural energy saving practices: updated categorizations, current adoption rates and willingness to adopt.
- There is limited evidence on circular and shared economy in buildings, including taxonomies, potentials, current adoption rates and willingness to adopt
- Most of the literature on climate change impacts on buildings is focused on thermal comfort. There is need for further research on climate change impacts on buildings structure, materials and construction and the energy and emissions associated with those impacts. Also, more studies that assess the role of passive energy efficiency measures as adaptation options are needed. Finally, regional studies leave out in depth analyses of specific regions.

Feasibility and policies

- Applications of human centred profiles for targeted policy making and considering stages of diffusion of innovation, that is: what works (motivation) for whom (different stakeholders, not only households) and when (stages of market maturity)
- The multiple co-benefits of mitigation actions are rarely integrated into decision-making processes. So, there is a need to further develop methodologies to quantify and monetize these externalities as well as indicators to facilitate their incorporation in energy planning.
- Policies for sufficiency have to be further analysed and tested in real situation, including ex ante simulation and ex-post evaluation. The same is also valid for Personable (tradable) Carbon Allowances.

Methods and models

- There is limited literature on the integration of behavioural measures and lifestyle changes in modelling exercises
- Mitigation potential resulting from the implementation of sufficiency measures is not identified in global energy/climate and building scenarios despite the growing literature on sufficiency. At the best, mitigation potential from behaviour change is quantified in energy scenarios; savings from structural changes and resource efficiency are not identified in the literature on global and building energy models.
- The actual costs of the potential could be higher to rather optimistic assumptions of the modelling literature, e.g. assuming 2-3% retrofit rate versus the current 1%. The uncertainty ranges of potential costs are not well understood.

## Frequently Asked Questions

### FAQ 9.1: To which GHG emissions do buildings contribute?

**A**: GHG emissions from buildings include CO2 emissions, CH4 emissions, N2O emissions and F-gas emissions. However, CH4 and N2O direct emissions from buildings are negligible compared to CO2 emissions. F-gas emissions include those related to aerosols, fire extinguishers, soundproof windows and the use of HVAC (heating, ventilation and air conditioning) equipment. Emissions from power generation and heat production are counted as indirect emissions from buildings and embodied emissions in construction material are also attributed to buildings, although the literature on the latter is limited.

**FAQ 9.2: How much could behavioral measures contribute to ambitious climate targets and what would be the costs of such measures?**

**A**: Behavioural change is a key requirement in all sort of mitigation interventions, and includes "curtailment" behaviour which are everyday practices such as turning off unnecessary lights, "efficiency" behaviour, which are one-time decisions to adopt low carbon solutions such as installing solar panels, "flexibility" behaviour which refers to increased tolerance to comfort variations and automation, and "acceptance" behaviour which are social, institutional and organizational issues seen as either barriers or enablers, at different levels, of the technical mitigation measures. The information on the costs of such measures is however limited and often merged with the cost of a technological intervention that would trigger behavioural change, for instance the cost of a mobile application that provides feedback on energy behaviour, or the cost of a smart home energy management system for integration of solar panels and batteries.

**FAQ 9.3: Are there any trade-offs and synergies between mitigation and adaptation in buildings?**

A: Adaptation interacts with mitigation because measures to cope with climate change impacts can increase energy consumption, which may lead to higher GHG emissions. For instance, increased storms and rainfall may create mould problems in building materials and components that would need to be renovated, with the corresponding increased energy consumption for producing and installing the new components. Nevertheless, many mitigation alternatives related to energy efficiency, building envelope and behavioural changes can reduce the energy needs for adapting to climate changes.

**FAQ 9.4: To what extent the co-benefits and trade-offs of mitigation actions in buildings could influence their effectiveness and cost-effectiveness?**

A: Mitigation actions in buildings generate multiple co-benefits (e.g., health benefits due to the improved indoor and outdoor conditions, productivity gains in non-residential buildings, creation of new jobs particularly at local level, improvements in social wellbeing etc.) beyond their direct impact on reducing energy consumption and GHG emissions. Most studies agree that the value of these multiple benefits is greater than the value of energy savings and their inclusion in economic evaluation of mitigation actions may improve substantially their cost-effectiveness. On the other hand, the buildings sector in several cases is characterized by strong rebound effects, as for many households the reduction in energy costs resulting from improved energy efficiency leads to acquisition of better energy services, which may affect significantly the net effectiveness of the climate mitigation actions and eventually their overall economic performance.

**FAQ 9.5: Which are the most effective policies to decarbonize the building sector?**

**A**: There is not a single policy, but a range of policy instruments ranging from regulatory, to market based (including financing) to information. What is important to consider to decarbonise the global building stock is the combination of sufficiency and efficiency with the supply from renewable energy sources.

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