Chapter 9: Buildings

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Executive summary

In 2018, the buildings sector accounted for more than 22% of global GHG emissions. These included direct emissions produced on-site, indirect emissions from electricity and heat consumed on-site and produced off-site, emissions from the use of cement, steel, as well as those from halocarbons produced by building systems and appliances (*robust evidence, high agreement*). The analysis of global scenarios illustrates that currently implemented policies lead to an increase of direct, indirect, and embodied CO_2 emissions of buildings from around 12 $GtCO_2$ yr^{-1} in 2020 to around 16 $GtCO_2$ yr^{-1} in 2050. At global level, emissions' drivers include (i) the population growth, especially in developing countries, (ii) the increase of the floor area per capita, especially in developed countries, (iii) the inefficiency of the newly constructed buildings, especially in developing countries, and existing ones, especially in developed countries, (iv) the use, number and size of appliances and equipment, especially ICT and cooling, driven by growing welfare, and (v) the slow decarbonisation of energy supply. These factors taken together are projected to continue driving GHG emissions in the building sector in the future. {9.3}

Both, illustrative pathways relying on IAMs and bottom-up models, attest that 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 GHG emissions in developing countries (*medium evidence, high agreement*). The aggregation of results from bottom-up studies also attests that the implementation of technological and non-technological measures allows mitigating at least 80% of CO_2 emissions of global buildings in 2050, as compared to their reference (*low evidence, high agreement*). {9.3}

Significant lock-in risks arise from the long lifespans of buildings and low ambitious policies. If only today's stated policies are implemented, CO_2 emissions from the building use phase that would be locked in buildings by 2050 would reach 9.3 $GtCO_2$ yr^{-1} (*robust evidence, high agreement*). {9.3, 9.6}

Advances since AR5 include an increasing understanding about the crucial role of sufficiency policies if considered at the very first step of buildings' decarbonisation strategy. Efficiency improvement alone will not be enough to offset for the increasing energy demand driven by the projected increase of floor area per capita and other drivers. Sufficiency measures are those aiming at reducing the demand for energy and materials while delivering a decent living standard for all within the planetary boundaries. These measures are included in models by reducing unnecessary floor area per capita, avoiding unnecessary energy demand, integrating multiple appliances and equipment into units delivering multiple services, and sharing them by multiple users. Scenarios considering sufficiency measures show higher mitigation potentials than those driven only by efficiency improvement of technologies and decarbonisation of supply (*medium evidence, high agreement*). {9.1, 9.2, 9.4, 9.5, 9.6, 9.9}

The development, since AR5, of integrated approaches to construction and retrofit of buildings has led to the widespread of zero energy/carbon buildings in all world relevant climate zones. The complementarity and the interdependency of measures lead to cost reduction while optimising the mitigation potential grasped and avoiding the lock-in-effect (*medium evidence, high agreement*). The potential associated with the exchange of appliances, equipment, and lights with efficient ones is below 0 USD tCO_2^{-1} (*high evidence, high agreement*). The construction of high-performance buildings is becoming a business-as-usual technology with costs below 20 USD tCO_2^{-1} (*medium evidence, high agreement*). For existing buildings, there have been many examples of deep retrofits where additional costs per CO_2 abated are not significantly higher than those of shallow retrofits. However, for the whole stock they tend to be in the range 20-50 USD tCO_2^{-1} (*medium evidence, medium agreement*). {9.6}

COVID-19 emphasised the importance of buildings for human's wellbeing. However, the lockdown measures implemented to avoid the spread of the virus has also stressed the inequalities in the access for all to suitable and healthy buildings, which provide natural daylight and clean air to their occupants. Natural ventilation with outdoor air has been the privileged option to respond to the new health requirements raised by COVID-19. Meeting these new health requirements, has also put an emphasis on preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. Moreover, the lockdown measures have led to spreading the concept of officetel (office-hotel) to many countries and to extending it to *officetel-schooling*. Therefore, the projected growth, prior to the COVID-19, of 58% of the global residential floor area by 2050 compared to the 290 billion m²/year in 2019 might well be insufficient. However, addressing the new needs for more residential buildings may not, necessarily mean constructing new buildings, but repurposing existing non-residential buildings (*low evidence, low confidence*). {9.1, 9.2}

Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential for achieving the United Nations Sustainable Development Goals. The impacts of mitigation actions in the building sector go far beyond the goal of climate action (SDG13) and contribute to further meeting fifteen other SDGs (*high evidence, high agreement*). {9.8, Figure 9.19}

Mitigation actions are needed to adapt buildings to the expected future climate and guarantee wellbeing for all. Global warming will impact cooling and heating needs but also the performance, durability and safety of buildings, especially historical and coastal ones, through changes in temperature, humidity, wind and concentrations of CO_2 and chloride. Measures to cope with climate change may increase the demand for energy and material leading to an increase in GHG emissions if not mitigated. Cooling demand is an emerging trend which is projected to continue by all scenarios. The expected higher cooling and lower heating needs may accelerate the shift of thermal needs to electrical demand, which could lead to higher emissions, if electricity generation is not decarbonised and generate higher loads and stress on power systems. Sufficiency measures will decrease the demand for cooling (*medium evidence, high agreement*). {9.7}

The decarbonisation of buildings is constrained by multiple barriers and obstacles. The building sector stands out for its high heterogeneity, with many different building types, sizes, and operational uses. Its segment representing rented property faces principal/agent problems where the tenant benefits from the decarbonisation's investment made by the landlord. A focus on decarbonisation policies to overcome barriers is not enough for effective buildings policies, and their organisational context is important as the same barrier might have hugely different organisational effects and require quite different policy responses (*high evidence, high agreement*). {9.9}

Policy packages based on the SER (Sufficiency, Efficiency, Renewables) framework could grasp the full mitigation potential estimated in different scenarios. Building energy codes is the main regulatory instrument used in several countries to reduce emissions from both new and existing buildings. Most advanced building energy codes include requirements on bioclimatic design of buildings, their energy performance as well as on the share of on-site renewable production. Some announced building energy codes extend these requirements from the use phase to the whole building lifecycle. Building energy codes are proven to be especially effective if compulsory and combined with other regulatory instruments such as minimum energy performance standard for appliances and equipment, especially if the performance level is set at the level of the best available technologies in the market (*robust evidence, high agreement*). Market-based instruments such as carbon taxes with recycling of the revenues and personal or building carbon allowances also contribute to foster the decarbonisation of the building sector (*robust evidence, high agreement*). {9.9}

Provision of financing with several effective instruments and technical assistance are of a paramount for the decarbonisation of buildings (*robust evidence, high agreement*). Institutional

capacity in particular in developing countries, global harmonisation of ambitious energy performance standards (e.g. for cooling equipment) and multilevel governance, including action at city level and citizen engagement are essential for the decarbonisation of buildings (*medium evidence, high agreement*). Thousands of policies implemented across different countries of the world drove investment into buildings’ energy efficiency, onsite renewable heat, and onsite renewable electricity as high as USD 150 billion, USD 24 billion, and at least USD billion in 2019 respectively. However, this is by far not enough to close the investment gap, given that depending on the country the incremental investment cost to decarbonise buildings is up to 3.5% of its GDP per annum for the next thirty years (*robust evidence, high agreement*). {9.9}

9.1 Introduction

In 2018, global buildings CO_2 emissions (including direct, indirect, and embodied emissions) accounted for 30-40% of global CO_2 emissions (IEA 2019a, UNEP Global Aliance for Building and Construction 2020). In terms of final energy demand, buildings accounted for 31.2% of the global energy demand and 51.0% of the global electricity demand (International Energy Agency 2019a). The final energy demand of building sector increased 26.7% from 2010 to 2018. There is a fast increase in buildings emissions in the developing world as a result of the improved of Standard of Living. Mitigation measures in building sector received much attention, because growing scientific evidence showed huge identified mitigation potential in 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; IEA 2019c).

Buildings mitigation measure are heterogeneous in many different aspects, from building components (envelope, structure, etc.) to services (shelter, heating, etc.), to building types (residential and non-residential, sometimes also called commercial and public), to building size, function, and climate zone. Mitigation measures from developed countries and developing countries vary, too.

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. 2014a). Changes since AR5 are reviewed, including: the latest development of building service and components (Section 9.2), findings of 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 emissions, potential emission reduction of these operations at global and regional level (Section 9.6), links to adaptation (Section 9.7) and sustainable development (Section 9.8), and sectoral barriers and policies (Section 9.9). All the chapter is organised around the Sufficiency-Efficiency-Renewables (SER) framework (Box 9.1).

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 technological efficiency measures to mitigate GHG emissions in the built environment, the contribution non-technological, in particular 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.

Box 9.1 SER (sufficiency-efficiency-renewables) framework

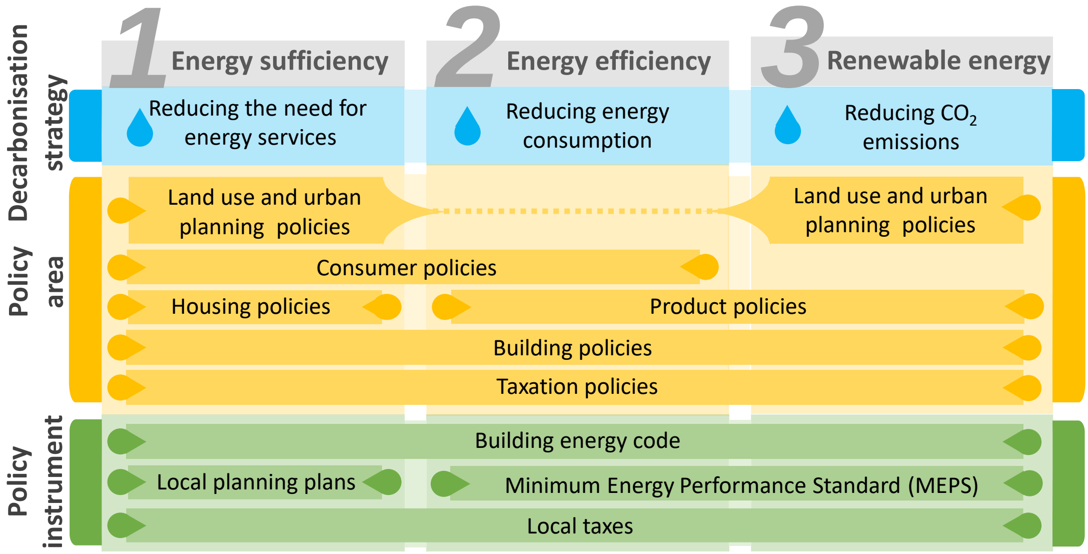
The SER framework was introduced, late nineties, by a French NGO (Negawatt) advocating for a decarbonised energy transition. In 2015, the SER framework was considered in the design of the French energy transition law. The three pillars of the SER framework include (i) sufficiency, which tackles the causes of the environmental impacts of human activities by reducing the demand for energy services, (ii) efficiency, which tackles the symptoms of the environmental impacts of human activities by reducing energy consumption, and (iii) the renewables pillar, which tackles the consequences of the environmental impacts of human activities by reducing GHG emissions.

Sufficiency is not a new concept, it was introduced in early nineties by (Sachs 1993) and further developed by (Princen 2003). Since 1997, Thailand considers sufficiency as a new paradigm for development with the aim of improving human wellbeing for all by shifting development pathways towards sustainability (Mongsawad 2012). The Thai approach is based on three principles (i) moderation, (ii) reasonableness, and (iii) self-immunity. Sufficiency goes beyond the dominant framing of energy demand under efficiency and behaviour. Sufficiency is defined as reducing the demand for materials and energy while delivering a decent living standard for all within the planetary boundaries.

Decent living standard is a set of essential material preconditions for human wellbeing which includes shelter, nutrition, basic amenities, health care, transportation, information, education, and public space (Rao and Baer 2012; Rao and Min 2018; Rao et al. 2019).

(Cézard and Mourad 2019) identified four sufficiency levers including (i) societal organisation such as the organisation of the space and human activities, (ii) the size of goods and equipment, (iii) their use, and (iv) ownership. When applied to the building sector, these four levers translate into the building typology (single-family homes vs. multifamily buildings), the size of dwellings as well as appliances and equipment, occupants' behaviour, and the share of space and equipment such as co-working places and shared laundry. (Lorek and Spangenberg 2019a) argue that combining sufficiency with efficiency allows addressing the direct rebound effect.

A systematic categorisation of policy interventions in the building sector through the SER framework (Box 9.1 Figure 1) enables identification of the policy areas and instruments to consider for the decarbonisation of the building stock, their overlaps as well as their complementarities. It also shows that sufficiency policies go beyond energy and climate policies to include land use and urban planning policies suggesting a need for a different governance which should include local authorities and a bottom-up approach driven by citizen engagement.



Box 9.1 Figure 1 SER framework applied to the building sector (Saheb et al. 2021)

COVID-19 emphasised the importance of buildings for human's wellbeing, however, the lockdown measures implemented to avoid the spread of the virus has also stressed the inequalities in the access for all to suitable and healthy buildings, which provide natural daylight and clean air to their occupants. Natural ventilation with outdoor air has been the privileged option to respond to the new health requirements raised by COVID-19. Meeting these new health requirements, has also put an emphasis on preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. Moreover, the lockdown measures have led to spreading the South Korean concept of officetel (office-hotel) to many countries and to extending it to *officetel-schooling*. Therefore, the projected growth, prior to the COVID-19, of 58% of the global residential floor area by 2050 compared to the 290 billion m^2yr^{-1} in 2019 might well be insufficient. However, addressing the new needs for more residential buildings may not, necessarily mean constructing new buildings. In fact, repurposing existing non-residential buildings, no longer in use due to the expected spread of teleworking triggered by the health crisis and enabled by digitalisation, could be the way to overcome the new needs for *officetel-schooling* triggered by the health crisis.

The four novelties introduced in this assessment link the building sector to other sectors and call for more sectoral coupling when designing mitigation solutions. Guidelines and methodologies developed in Chapters 1, 2, 3, 4 and 5 are adopted in this chapter. Detailed analysis in building GHG emissions are discussed based on Chapters 2, 3 and 4. There are tight linkages between this chapter and Chapter 6, 7, 8, 10 and 11, which are sectoral sectors. This chapter focus more on individual buildings and building clusters, while Chapter 8 discuss macro topics in urban areas. Findings of this chapter provides contribution to 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).

9.2 Services and components

This section mainly details the boundaries of the building sector; mitigation potentials are evaluated in the 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 (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.). Another classification is per ownership: owner-occupiers, landlords, and owners' association/condominiums.

Non-residential buildings have a much broader use. They include cultural buildings (which include theatres and performance, museums and exhibits, libraries, and cultural centres), educational buildings (kindergarten, schools, higher education, research centre, and laboratories), sports (recreation and training, and stadiums), healthcare buildings (health, wellbeing, and veterinary), hospitality (hotel, casino, lodging, nightlife buildings, and restaurants and bars), commercial buildings and offices (institutional buildings, markets, office buildings, retail, and shopping centres), public buildings (government buildings, security, and military buildings), religious buildings (including worship and burial buildings), and industrial buildings (factories, energy plants, warehouses, data centres, transportation buildings, and agricultural buildings).

Globally, the building stock of residential buildings grew 28% from 2005 to 2019, reaching 191.7 billion $m^2 \cdot yr^{-1}$ in 2019, and it is estimated to grow up to 46% in 2030 and up to 60% in 2050, in all considered scenarios (Figure 9.1a and Box 9.2). On the other hand, non-residential building stock grew 27% since 2005, while projections show that it will grow up to 40% in 2030 and up to 54% in 2050. The regional growth in residential building stock (Figure 9.1b) shows clear differences both between regions and between historical and estimated growth. For example, Europe shows growth both historically and in the future, while Latin America and Caribbean does not show growth in the past, while future estimations show growths of up to 100% between 2020 and 2050. Non-residential building stock (Figure 9.1c) does not show such steep growth, but still a growth between 22% (North America) and 60% (Africa).

9.2.2 Building components and construction methods

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.

(a)

(b)

(c)

Figure 9.1 Building stock: historical and illustrative pathways. (a) Global, (b) Regional for residential buildings, and (c) Regional for non-residential buildings.

Source: (Saheb et al. 2021) based on IEA WEO data

Box 9.2 Methodology to estimate future emissions and energy demand in buildings

Future emissions and energy demand are analysed using scenarios from the International Energy Agency World Energy Model (OECD / IEA 2018). The three scenarios considered include a scenario based on current policies, another one based on the stated policies and a transformative scenario aiming at decarbonising the global building stock while meeting sustainable development goals (SDGs) globally. The selection of the IEA scenarios was driven by data availability. Global scenarios submitted to IIASA database and considered for Chapter 3 analysis do not include the data needed to understand the potential pathways of the building sector. Additional scenarios will be considered for the final version of the report if owners of the scenarios submitted to IIASA database provide the data needed for the analysis.

There are some differences between IEA and IPCC aggregation of regions. IEA includes Israel, Belarus, Moldova and Macedonia in Europe while the IPCC includes Israel in Middle East and Belarus, Moldova and Macedonia in Eurasia. The other difference relates to Korea which is considered in developed Asia-Pacific by the IEA while it is included in Eastern Asia in the IPCC. For the purpose of this report, South Korea is considered in Eastern Asia. Also, for consistency South Asia and South-East Asia and Developing Pacific have been grouped into one single region as the level of disaggregation of the IEA data does not allow reconstructing these two IPCC regions separately.

There is no a global classification for the building components. Nevertheless, Figure 9.2 tries to summarise the building components found in literature (Asbjørn 2009; Ching 2014; Mañá Reixach 2000). The buildings are divided in the substructure and the superstructure. The substructure is the foundation of the building, where the footing, basement, and plinth are found. The superstructure integrates the primary elements (heavyweight walls, columns, floors and ceilings, roofs, sills and lintels, and stairs), the supplementary components (lightweight walls and curtain walls), the completion components (doors and windows), the finishing work (plastering and painting), and the buildings services (detailed in Section 9.3).

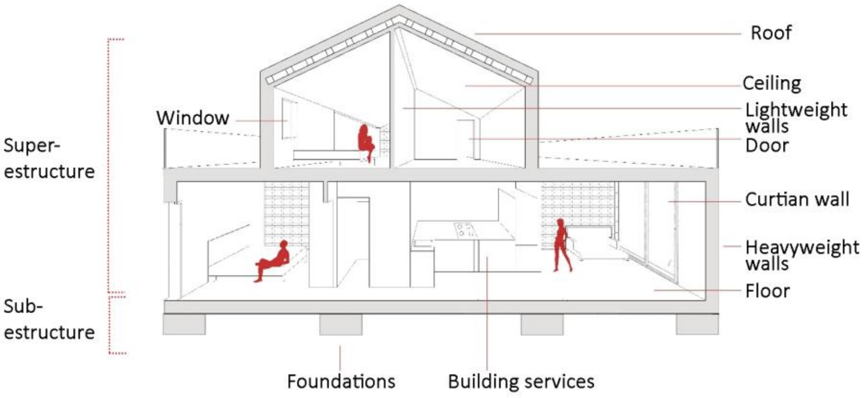


Figure 9.2 The main building components

At global level, from historical perspective (from the Neolithic to the present), building techniques have evolved, to be able to solve increasingly complex problems. Vernacular architecture has evolved over many years to address problems inherent in housing. Through a process of trial and error, populations have found ways to cope with the extremes of the weather. The industrial revolution was the single most important development in human history over the past three centuries. Previously, building materials were restricted to a few manmade materials (lime mortar, and concrete) along with those available in nature as timber, and stone. Metals were not available in sufficient quantity or consistent quality to be used as anything more than ornamentation. The structure was limited by the capabilities of natural materials; this construction method is called on-site construction. The Industrial Revolution changed this situation dramatically, new building materials emerged (cast-iron, glass structures, reinforced steel concrete, steel). Iron, steel and concrete were the most important materials of the nineteenth century (De Villanueva Domínguez 2005; Wright 2000). In that context prefabricated buildings (prefabrication also known as pre-assembly or modularisation) appeared, within the so-called off-site construction. Prefabrication has come to mean a method of construction whereby building elements, ranging in size from a single component to a complete building are manufactured at a distance from the final building location. Prefabricated buildings have been developed rapidly since World War II and are widely used all over the world (Pons 2014; Moradibistouni et al. 2018).

Recently, advances in technology have produced new expectations in terms of design possibilities. In that context, 3D printing seems to have arrived. 3D printing may allow in the future to build faster, cheaper and more sustainably. At the same time, it will introduce new aesthetics, new materials, and complex shapes that will be printed at the click of a mouse on our computers. Although 3D printing would not completely replace architectural construction, it would allow optimisation of various production and assembly processes by introducing new sustainable construction processes and tools. Nevertheless, what is clear is that 3D printing is a technology still in development, with a lot of potentials and that it is advancing quite quickly (Hager et al. 2016; Stute et al. 2018; Wang et al. 2020).

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. Moreover, building services demand differ on rural and urban population. Although rural population will not increase in the future (in 2010 the rural population was 3350 million and in 2050 it will be 3080 million), in 2050 will still be one third of the total world population (urban population will grow from 3580 million in 2010 to 6630 million in 2050) (Figure 9.33).

Building services are classified as shown in **Error! Reference source not found.**. (Illankoon and Lu 2 019) already stated that building services are indispensable for low-energy buildings and that in practice they are today considered independently while if the building and services were considered holistically, the overall energy performance would be better. **Error! Reference source not found.**5 shows schematically the means used to deliver on building energy services available in today buildings.

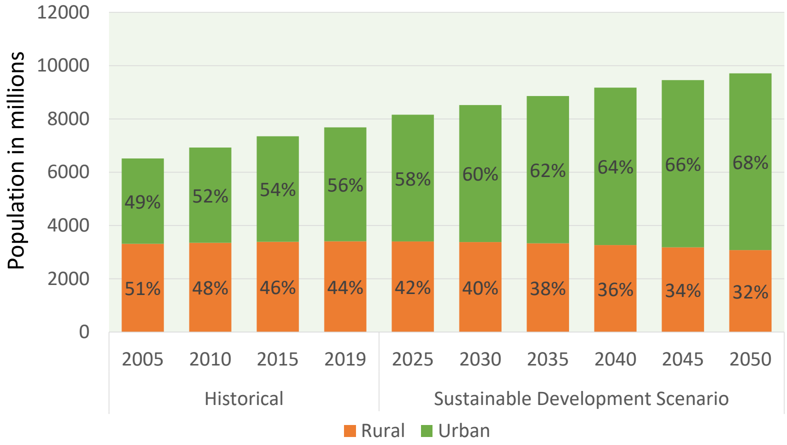


Figure 9.3 Rural and urban world shares of population. Source: based on IEA WEO data

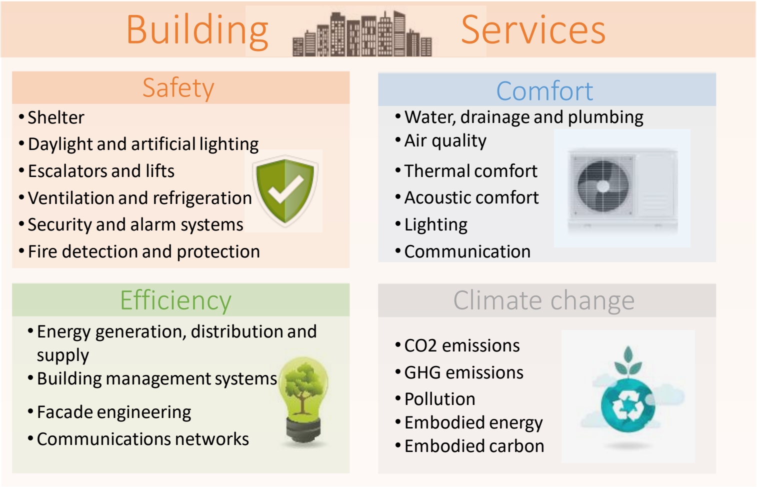


Figure 9.4 Classification of building services (Vérez and Cabeza 2021a)

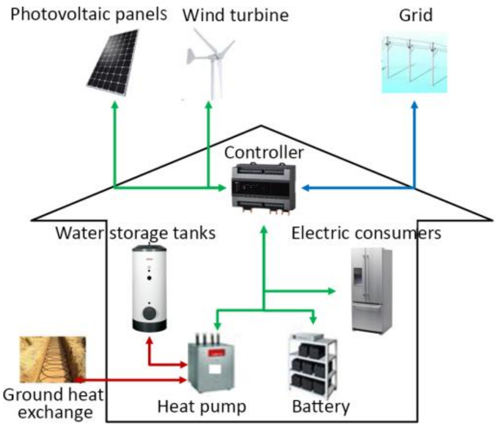


Figure 9.5 Schematic diagram of building energy services (Shcheklein et al. 2017)

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 optimise building operations and reduce cost (Kelsey Carle Schuster, Youngchoon Park 2019). Recent developments include the integration of the system with the renewable energy systems (D.Arnone, V.Croce, G.Paterno 2016), most improved and effective user interface (Rabe et al. 2018), and integrated with wireless communication (Chavan et al. 2018).

Building designs have to consider provision of adequate ventilation. Natural ventilation reduced energy consumption in buildings (Azmi et al. 2017; Taleb 2015). 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 Box 9.3). 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 (Burnett et al. 2014a), and use of common thermal storage technologies (De Falco et al. 2016) all of which are geared towards minimising 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. 2015b); use of nanoparticles for energy saving (Azmi et al. 2017) to mention some.

(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 2021b) 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, lighting, and appliances (see Section 9.4). 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) (see Section 9.4).

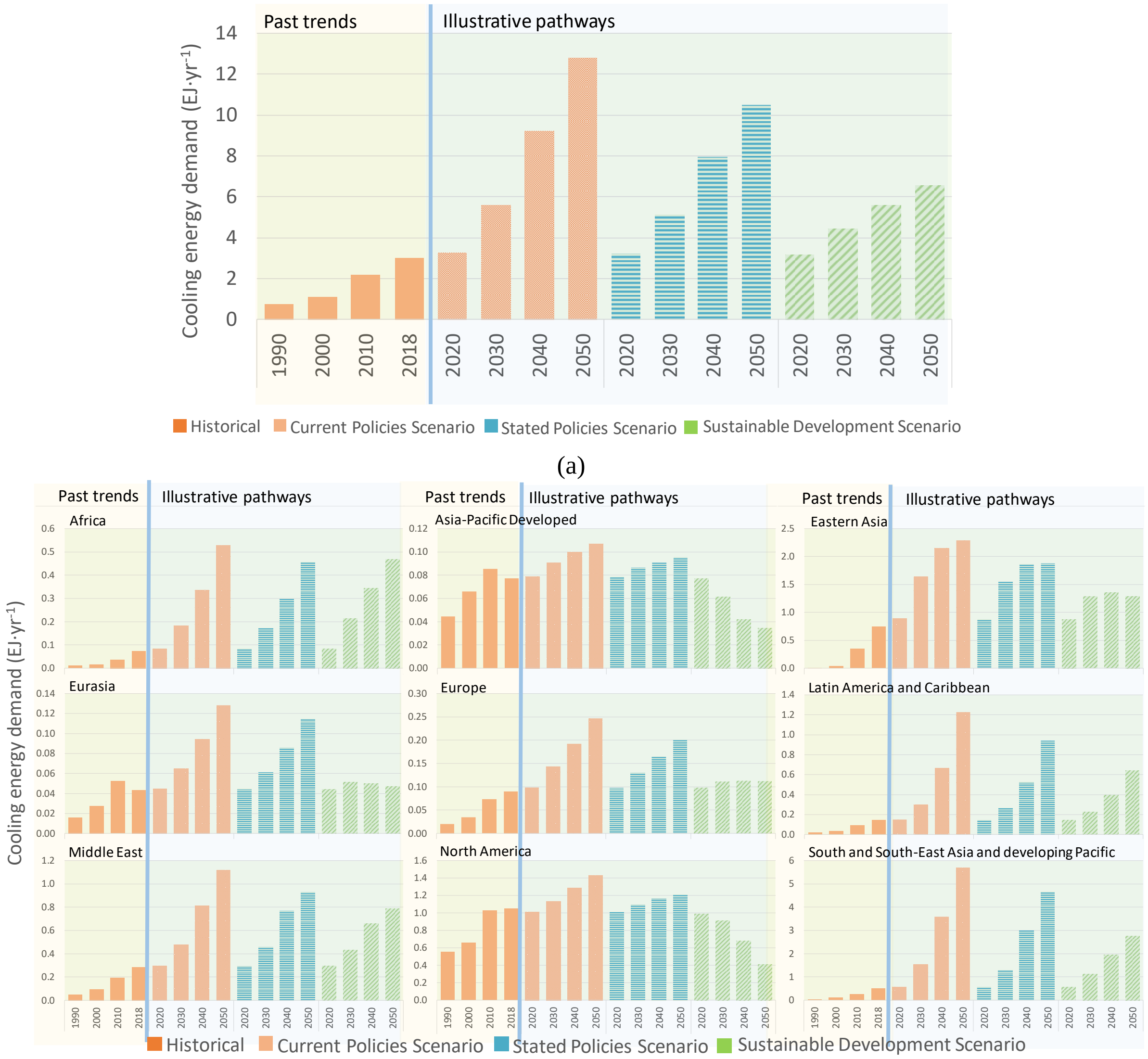
Box 9.3 Cooling energy demand in the building sector

In a warming world with a growing population and expanding middle-class, the demand for cooling is likely to increase leading to increased emissions if cooling solutions implemented are carbon intensive (Kian Jon et al. 2021; Dreyfus et al. 2020b; Santamouris 2016; Sustainable Energy for All 2018; United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020). Sufficiency measures such as building design and forms, which allow balancing the size of openings, the wall area, the thermal properties, shading, and orientation are all non-cost solutions, which should be considered first to reduce cooling demand. Air conditioning systems using halocarbons are the most common solutions used to cool buildings. According to (Dreyfus et al. 2020b; Peters 2018), up to 4 billion cooling appliances are already installed and this could increase to up 14 billion by 2050. Energy efficiency of air conditioning systems is of a paramount to ensuring the increased demand for air conditioning will be satisfied without contributing to warmer temperatures through halocarbon emissions (United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020; Shah et al. 2019, 2015; Campbell 2018). The installation of highly efficient technological solutions with low GWP, as mandated by the Kigali amendment to the Montreal Protocol, is the second step towards reducing GHG emissions from cooling. Developing solar solutions integrated to buildings is also a track to follow to reduce GHG emissions from cooling.

Over the period 2010-2018, global cooling demand increased by 40% in the residential sector (Box 9.3, Figure 1b). 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 driven by the increased ambient temperatures driven by 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.

Over the period 2020-2050, global cooling demand is projected to increase in all three IEA scenarios. However, the projected global cooling demand could be halved in the SDS compared to the CPS. In all three scenarios, the highest increase of global cooling demand is projected to occur in Africa, followed by South and South-East Asia and developing Pacific while the lowest increase is projected to occur in Eurasia (Box 9.3 Figure 1 a).



(a)

(b)

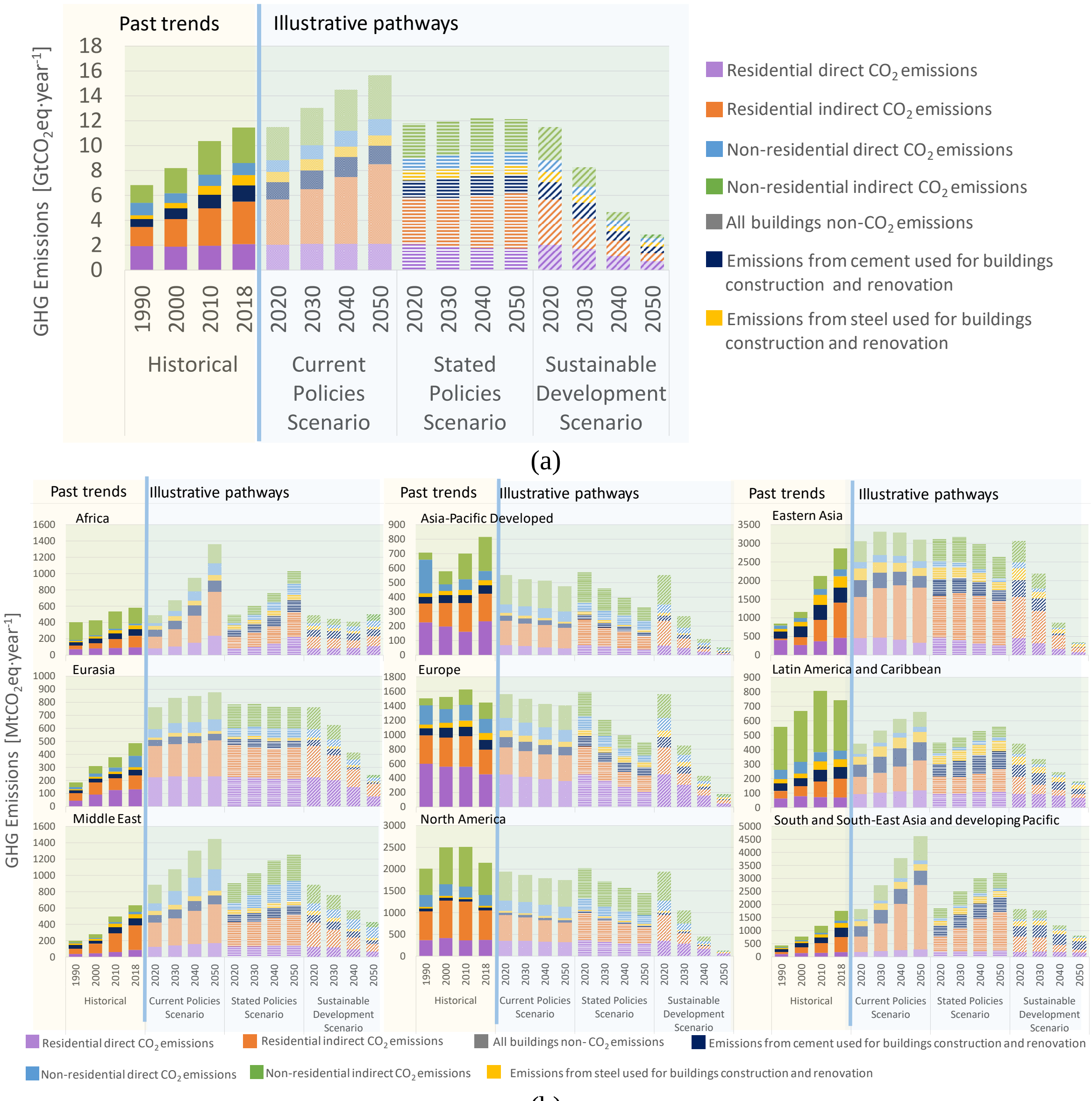
Box 9.3 Figure 1 Cooling energy demand for the residential sector: historical and illustrative pathways. (a) Global and (b) Regional.

Source: Based on IEA WEO data

9.3 New developments in emission trends and drivers

9.3.1 Past trends and future ones in illustrative pathways

Total GHG emissions in the building sector reached 13.5 Gt in 2018, out of which 46.2% were indirect emissions resulting from the use of carbonised electricity and heat, followed by 22.8% of direct emissions and 15.7% of emissions due to the production of cement and steel used for the construction and/or refurbishment of buildings (Figure 9.6a). Halocarbon emissions represented 7.5% out total emissions in 2018 and were calculated by considering that 60% of total halocarbon emissions occurred in buildings as reported by (Hu et al. 2020). Emissions from aerosols and other sources have also represented 7.5% out of total GHG emissions. Over the period 2010-2018, global GHG emissions in the building sector experienced an increase of 9.1% while the shares of GHG emissions per sub-sectors remained stable with the residential sector representing 53% out of total GHG emissions of the global building stock. Over the same period, indirect GHG emissions increased by 10% in residential buildings and 3% in non-residential ones while direct emissions increased by 6% in the former and 11% in the latter and embodied emissions for all buildings increased by 19%. Direct emissions from CH_4 and N_2O were, in 2018, negligible compared to direct CO_2 emissions with 0.03 Gt for the combined emissions from CH_4 and N_2O. Therefore, GHG emissions referred to in this section are CO_2 emissions only.



(a)

(b)

Figure 9.6 Building GHG emissions: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global and (b) Regional. Source: (Saheb et al. 2021)

The section further presents the potential for GHG emission reduction as identified by the World Energy Outlook (IEA 2020); the potential identified by other literature is presented in Section 9.6. It estimated that the potential for global emissions reduction in 2050 is 23% in the Stated Policy Scenario (SPS) and 83% in the Sustainable Development Scenario (SDS) compared to the Current Polity Scenario (CPS). Future CO_2 emissions would reach by 2050, 13.35 Gt in CPS against 12.1 Gt in SPS and 2.8 Gt in SDS while they were at 11.44 Gt in 2018. The same year, direct emissions are projected to contribute to global building emissions by 22% in CPS, 23% in SPS and 38% in SDS (Figure 9.6a). Overall, direct emissions are projected to be reduced by 69% in SDS compared to CPS in 2050. The contribution of indirect emissions to the global building emissions is expected to decrease, the same year, from 63% in CPS to 31% in SDS, while indirect emissions are projected to be reduced by 91% in SDS compared to CPS. The same year, embodied emissions are projected to contribute to global building emissions by 19% in SPS and 31% in SDS reflecting the expected role of embodied emissions if the zero energy/carbon building concept is applied to the use phase only (see Section 9.4.2 and Section 9.9). Direct emissions from CH_4 and N_2O are projected to remain negligible compared to CO_2 emissions. Emissions from residential buildings are expected to dominate global building emissions.

At regional level, 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 buildings in Europe with 10% decrease while in developed Asia-Pacific, the decrease of direct emissions was at 3% in residential buildings and at 3.6% in non-residential ones (Figure 9.6b).

Regarding indirect emissions, North America and Europe have both experienced a decrease of their emissions. The highest decrease was observed in North America driven by the shift from coal to gas in power generation, followed by Europe driven by the increased penetration of renewables in power generation under the implementation of the 2020 renewable energy target (see Section 9.9). Developed Asia-Pacific countries experienced an increase of 4% of non-residential buildings indirect emissions due to the use of coal for power generation. When it comes to embodied emissions, 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 in their embodied emissions (Figure 9.6b).

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) 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 economies in the region, as shown by IMF data. 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 (Figure 9.8a). 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 (Figure 9.6b).

By 2050, the potential for GHG emissions reduction in the developed world ranges from 17% in the SPS in North America to 93% in SDS in the same region. The potential for GHG emissions reduction, by 2050, in Europe and Asia-Pacific are estimated at 33% in SPS for both, while it is estimated at 87% in SDS for Europe and 80% in developed Asia-Pacific (Figure 9.6b). The highest mitigation potential is estimated in non-residential buildings, 97%, in North America under SDS, while the potential for residential buildings in the same region and under the same scenario is estimated at 79%. The highest potential for indirect GHG emissions reduction, 99%, in both residential and non-residential buildings is projected to take place in North America under SDS against 78% potential reduction for direct emissions in residential buildings and 93% in non-residential ones, Figure 9.6b).

The lowest potential for GHG emissions reduction in the developing world is projected to take place in Latin America in SPS with 12%, followed by 14% in Eurasia and 15% in Eastern Asia. The potential for emissions reduction in these regions increases strongly in SDS to 71% in Latin America and 89%

in Eastern Asia. Total mitigation potential in Africa is estimated at 24% in SPS and 72% in SDS. The highest mitigation potential is estimated in non-residential buildings, 95%, in Eastern Asia under SDS, while the potential for residential buildings in the same region and under the same scenario is estimated at 91%. The potential for GHG emissions in Africa under SDS is estimated at 76% in residential buildings and 60% in non-residential ones. South-East Asia and Developing Pacific are projected to have the lowest, 40%, potential for direct GHG emissions reduction in residential buildings while the estimated potential for indirect emissions of the region is at 95%. In Africa, the mitigation potential of indirect emissions is estimated under SDS in residential buildings at 77% and at 68% in non-residential buildings while the mitigation potential for direct emissions is estimated at 52% in residential buildings and 47% in non-residential ones (Figure 9.6b).

9.3.2 Drivers of GHG emissions

Drivers of GHG emissions in the above scenarios are assessed using the Kaya decomposition analysis (Kaya 1989) which expresses GHG emissions as a function of population, GDP and energy. Broad drivers of GHG emissions such as GDP and population are analysed in Chapter 2. The Kaya decomposition used in this chapter is the one described in Chapter 2 but with building specific identities and reflecting the three pillars of the SER framework (sufficiency, efficiency, renewables). The aim is to understand the impact of building specific drivers such as floor area per capita on building GHG emissions (Saheb et al. 2021). Previous Kaya decomposition analysing drivers of GHG emissions in the building sector have either assessed the impact of GDP and population only as drivers of GHG emissions (Lamb et al. 2021) or the impact of building specific drivers such as floor area per capita on energy demand and not on GHG emissions (Ürge-Vorsatz et al., 2015, IPCC AR5, 2014, IEA, 2020, ODYSSEE, 2020).

Due to lack of data, the decomposition analysis for non-residential buildings was limited to two pillars of the SER framework (efficiency and renewable) while for residential buildings the three pillars of the SER framework are analysed. For residential buildings, GHG emissions are decomposed as follows:

Equation 9.1 For residential buildings, GHG emissions are decomposed as follows

$$GHG\ emissions_{resid} = Population \cdot Structural\ intensity \cdot Technological\ energy\ intensity \cdot Carbon\ intensity$$

while for non-residential buildings, GHG emissions are decomposed as follows:

$$GHG\ emissions_{non-resid} = Value\ added \cdot Technological\ energy\ intensity \cdot Carbon\ intensity$$

Structural intensity reflects the sufficiency pillar of the SER framework. It is expressed in terms of floor area per capita. Technological energy intensity reflects the efficiency pillar of the SER framework (Box 9.1). It is expressed as climate corrected final energy per floor area for residential buildings and as climate corrected final energy per value added for non-residential buildings. Carbon intensity reflects the renewables pillar of the SER framework. It is expressed for both residential and non-residential buildings as GHG emissions per climate corrected final energy.

At a global level (Figure 9.7a), the historical increase of GHG emissions in residential buildings has been driven by population increase (see Chapter 2) and, importantly, by the increase of floor area per capita by 62% over the period 1990-2018 and 34% over the period 2010-2018 reflecting the absence of sufficiency policies in climate mitigation policy packages (Section 9.9), especially in the global North combined with the legitimate access to modern buildings in the global South. In the global North, aging population combined with the decrease in fertility have led to a decline in households' size and consequently to an increase of floor area and GHG emissions per capita (Ellsworth-Krebs 2020; Ivanova and Büchs 2020). Dwellings size (Huebner and Shipworth 2017) rather than occupant behaviour

(Guerra Santin et al. 2009) is the key driver of GHG emissions in residential buildings. Larger homes combined to smaller household size increase the ownership of appliance and equipment leading to more energy demand (Cabeza et al. 2018b) and consequently to increasing GHG emissions if energy supply is not decarbonised. These factors taken together will continue to drive GHG emissions in the building sector in the future. Over the period 2020-2050, floor area per capita is projected to continue to increase in all three scenarios. However, floor area per capita is projected to be 17% less in 2050 in SDS compared to CPS (Figure 9.7a).

Energy intensity expressed as climate corrected final energy per floor area is the second driver of GHG emissions in residential buildings. The improvement of energy intensity has contributed to reducing GHG emissions. However, despite an efficiency improvement of 43% over the period 1990-2018 and 17% over the period 2010-2018, the overall building stock is still inefficient. This reflects the lack of efficiency policies in the global South which has experienced the highest increase of number of square meters built (see Section 9.4 and Section 9.9) and the inadequacy of efficiency policies in the global North, which are stringent mainly for new buildings while the challenge in this region is to renovate the existing building stock (see Section 9.9). Over the period 2020-2050, efficiency improvement is projected to continue in all three scenarios. The highest improvement, 64%, is projected in SDS.

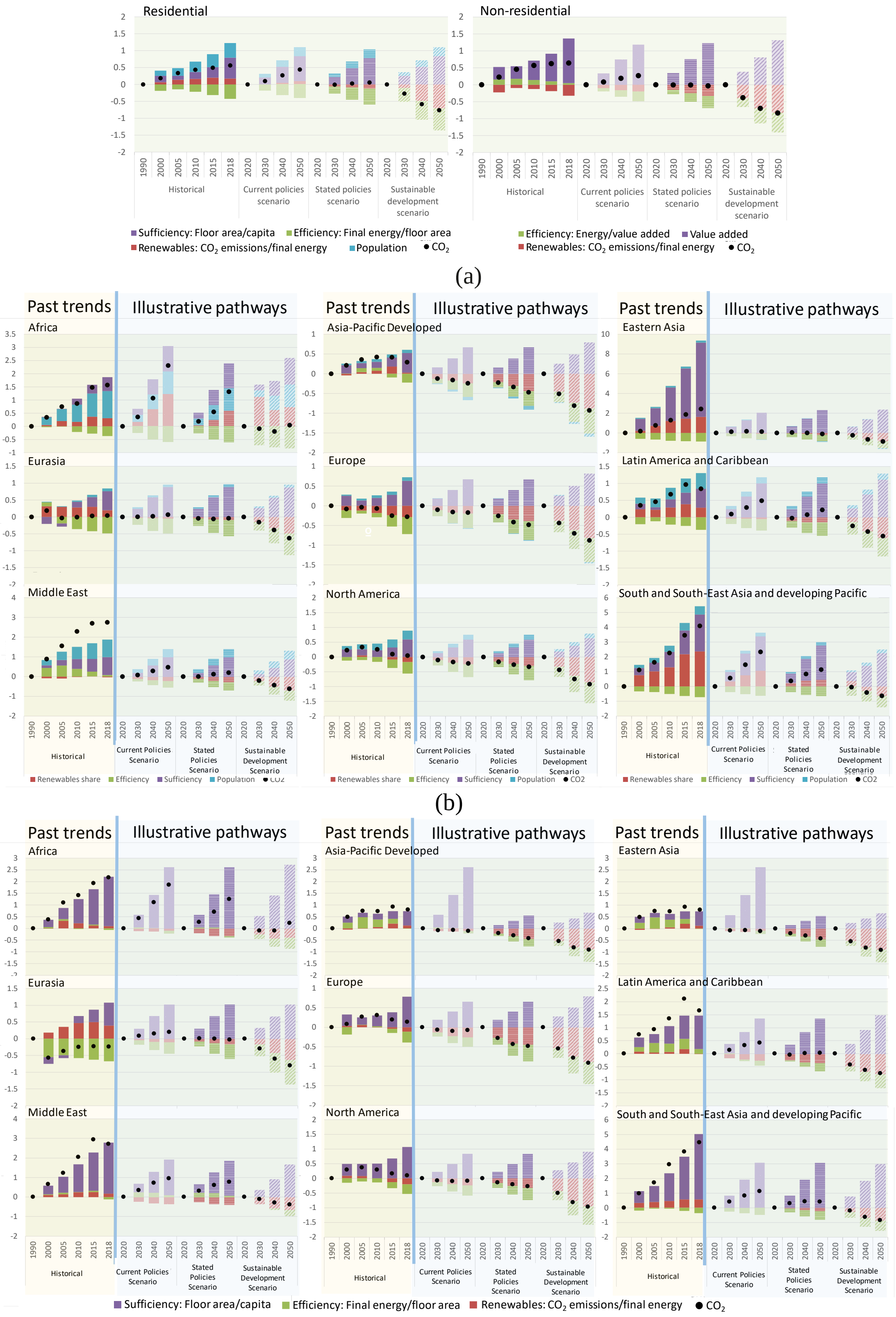


Figure 9.7 Drivers of GHG emissions: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global, (b) Regional for residential buildings, and (c) Regional for non-residential buildings Source: (Saheb et al. 2021)

Note: Floor area/capita is the indicator to assess the impact of sufficiency measures, Final energy/Floor Area is the indicator to assess the impact of efficiency measures and CO_2 emissions/Final energy is the indicator to assess the impact of renewables penetration. A positive impact of the measures compared to the reference year is represented below the X-axis.

However, this improvement will not be sufficient to offset for the increasing energy demand driven by the projected increase of floor area per capita. Similarly, in non-residential buildings, energy intensity improvement, expressed as climate corrected final energy per value added has contributed to reducing GHG emissions over the period 1990-2018. Overall, historical emissions from non-residential buildings have been driven mainly by the value added of increased activity. Over the period 2020-2050, efficiency improvement in non-residential buildings is projected to continue to improve in all three scenarios making the value added of increased activity more efficient. Thus, contributing to lowering GHG emissions from non-residential buildings (Figure 9.7a).

Carbon intensity, expressed as GHG emissions per climate corrected final energy, is the third driver of historical GHG emissions in both residential and non-residential buildings. Over the period 1990-2018, carbon intensity of residential buildings increased by 17% while the increase was at 5% in non-residential buildings. The high increase of carbon intensity in residential buildings reflects the legitimate increase of new residential buildings in the global South (Section 9.2) and the access to energy which was not necessarily supplied by clean energy sources (Section 9.8) as well as the slow decarbonisation of the energy supply in the global North. Over the period 2020-2050, carbon intensity is projected to continue to drive GHG emissions in CPS and SPS. However, SDS projects an acceleration of the decarbonisation of the energy supply leading to lower GHG emissions (Figure 9.7a).

There are great discrepancies in the drivers of GHG emissions across regions (Figure 9.7b and Figure 9.7c). Historically, population increase has been a driver of GHG emissions of residential buildings in all regions. However, over the period 1990-2018, population increase has been the main GHG emissions driver in residential buildings mainly in Africa while in the rest of the world, it is the increase of floor area per capita that has led to increasing GHG emissions. In South/South-East Asia and developing Pacific, it is the combination of floor area per capita with carbon intensity that have led to the increase of historical emissions in residential buildings. Over the period 2020-2050, population is projected, in all three scenarios, to continue to play a major role in driving emissions from residential buildings in Africa and to some extent in Middle East, developing Asia and Pacific as well as in Latin America/Caribbean. In the global North and Eastern Asia, population is projected to be a driver of GHG emissions in residential buildings only in North America.

In Africa, GHG emissions from residential buildings are projected, across all the three scenarios, to be driven by the increase of population, the legitimate access to modern buildings which will lead to an increase of floor area per capita as well as the projected access to energy, which is not projected to be necessarily delivered by renewable (Sections 9.8 and 9.9). Efficiency improvement is projected across all three scenarios, to contribute to decreasing GHG emissions in residential buildings (Figure 9.7b).

Over the period 1990-2018, historical GHG emissions in non-residential buildings were driven by the increased value added in all regions and in the developing world by the increased access to energy, which was not necessarily delivered by renewable energy sources. In the developing world, the lack of efficiency improvement has also contributed to increasing historical emissions while in the developed world efficiency improvements has contributed to decreasing GHG emissions in non-residential buildings. Over the period 2020-2050, efficiency improvement and decarbonisation of energy supply are projected to offset the increase of GHG emissions driven by the increased activity in the global North, under SDS. In the global South, efficiency improvement and the decarbonisation of energy supply will not be enough, even under SDS, to compensate for the increase of GHG emissions driven by the increased activity (Figure 9.7c).

9.3.3 Energy demand trends

9.3.3.1 Energy demand based on energy carriers

During 2010-2018, global energy demand of buildings increased by 10% (Figure 9.8a). The highest increase was observed in non-residential buildings, with 13% increase against 8% in residential energy demand. By 2050, the potential for energy demand reduction in SDS compared to CPS, is projected to be at 43% in non-residential buildings and 39% in residential ones. However, over the period 2020-2050, energy demand is projected to increase in non-residential buildings by 60% in CPS, 45% in SPS while it would remain constant in SDS. At a global level, biomass was the most used energy carrier in residential buildings and electricity the most used one in non-residential buildings (see Box 9.8). The use of electricity is projected to increase in both residential and non-residential buildings across the three scenarios driven by the increased electrification of thermal end uses such as water heating (see Box 9.6) as well as the increase penetration of connected and small appliances (see Box 9.5) (Figure 9.8a). Finally, hydrogen shows only a minor role in the building sector in the future (see Box 9.4).

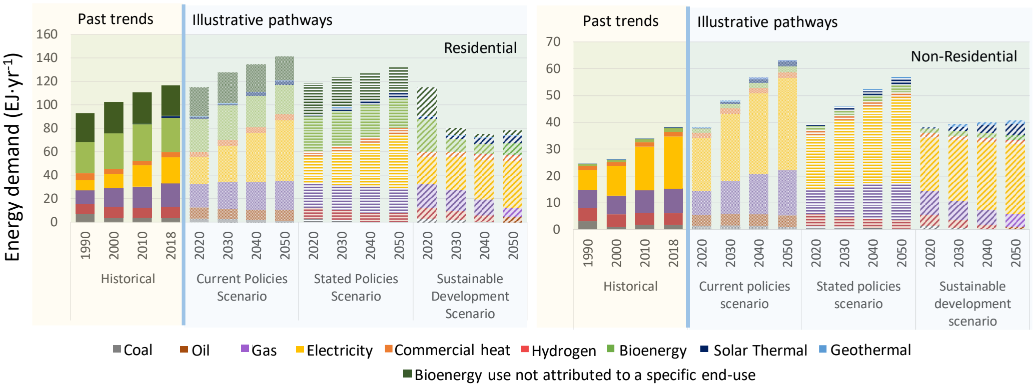
Box 9.4 Hydrogen in the building sector

Hydrogen emerged in the policy debate as an important energy carrier for the decarbonisation of the energy system. In the case of the building sector, depending on how hydrogen is sourced (see Chapter 12, Box 12.3), converting gas grids to hydrogen might be an appealing option to decarbonise heat without putting additional stress on the electricity grids. However, according to (Elements energy Ltd 2018; Broad et al. 2020; Frazer-Nash Consultancy 2018; Gerhardt et al. 2020) the delivered cost of heat from hydrogen would be much higher than the cost of delivering heat from heat pumps, which could also be used for cooling (see Box 9.3). According to (Gerhardt et al. 2020), hydrogen-based low-temperature heating systems consume 500–600% more renewable energy than heat pumps and are less efficient if all losses are considered. Repurposing gas grids for pure hydrogen networks will also require system modifications such as replacement of piping and replacement of gas boilers and cooking appliances, a factor cost to be considered when developing hydrogen roadmaps for buildings. Moreover, (Frazer-Nash Consultancy 2018) points out to safety and performance concerns with domestic hydrogen appliances given hydrogen’s propensity to leak through joints and tendency to disperse and dilute more readily than gas.

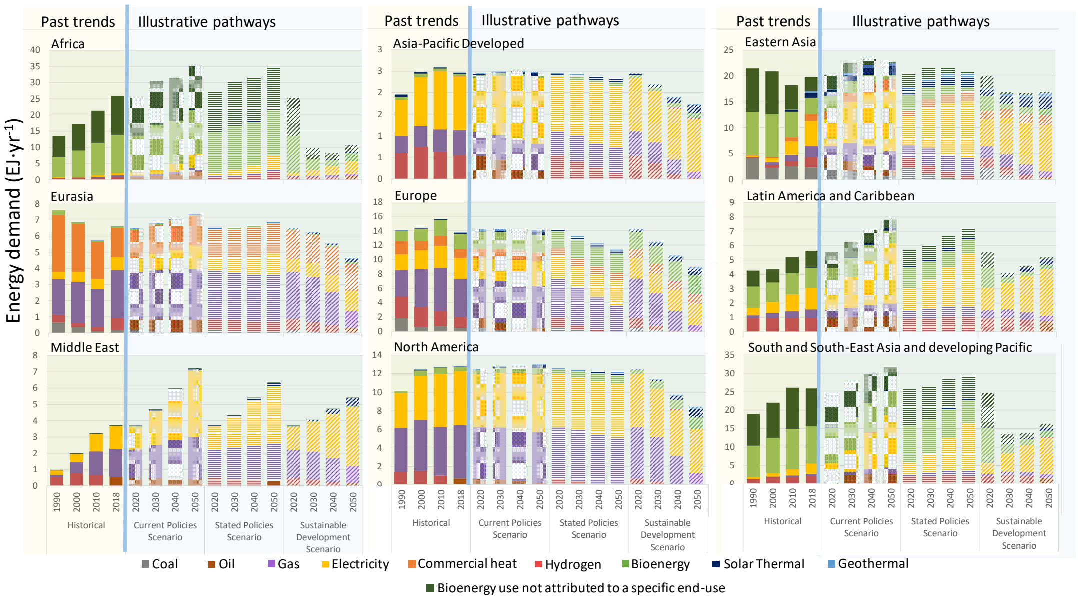
Over the period 2010-2018, hydrogen was not used in the building sector and illustrative pathways show a modest role for its use in the future. IEA sustainable development scenario shows a penetration of hydrogen, mainly in Europe and Eastern Asia, in buildings starting from 2030. However, the projected contribution of hydrogen is ranging from 0.1% in 2030 to 0.4% by 2050 out of total energy demand.

At regional level, 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 latter (Section 9.3). The highest increase of residential energy demand was observed in Eastern Asia, with 26% increase followed by Africa which has experienced an increase of 26%, reflecting the increase of square metres built (See Section 9.3). Middle East and Eurasia have both experienced an increase of 15% in their residential energy demand over the same period while North America experienced an increase of 1% of its residential energy demand despite the increase of residential floor area by 11% (Figure 9.8b). The increase of energy demand in residential buildings was driven by the high penetration of appliances, especially connected and small appliances (see Box 9.5) and room air conditioners (see Box 9.3). Biomass has been the dominant energy source used in residential buildings in the developing countries while electricity was the main energy source used in developed countries in Asia-Pacific and gas was the dominant energy source in Europe, used mainly for heating and hot water. The dominance of electricity in residential buildings is projected, over the three scenarios, to continue in developed Asia-pacific and to increase Middle East and North America. Biomass is projected to continue to play a major role in residential buildings in Africa, South, South-East and developing Pacific. Overall, energy demand in non-residential buildings is projected to increase across all regions in the three scenarios (Figure 9.8b).

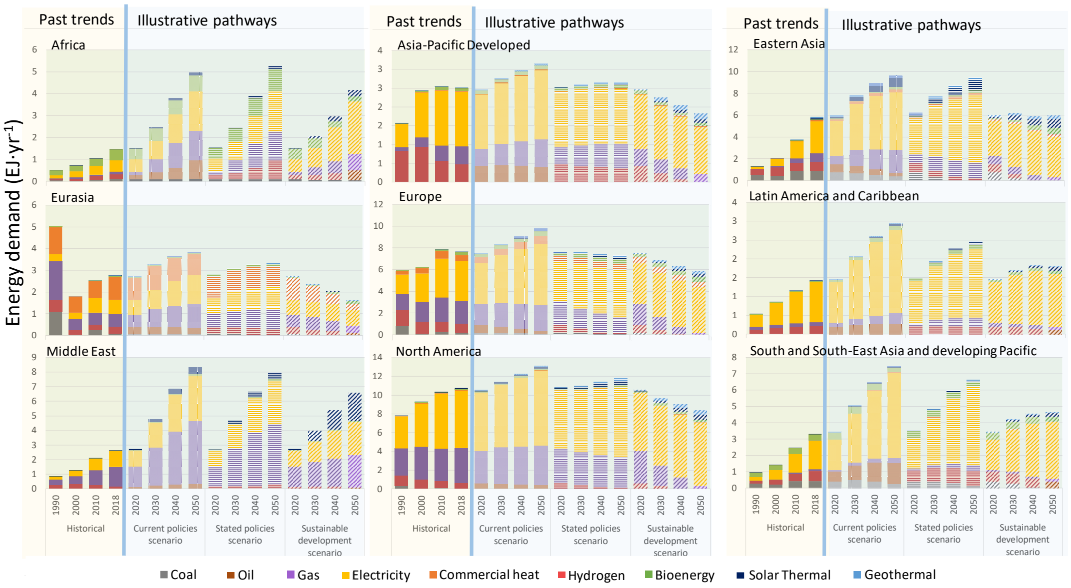
In non-residential buildings, the increase of energy demand was driven by Eastern Asia with 55% increase, followed by Africa with 43% and the region of South and South-East Asia and developing Pacific which has experienced an increase of 34% (Figure 9.8c). Energy demand of non-residential buildings in 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. Over the period 1990-2018, electricity was the main energy source used in non-residential buildings in all regions, except in Africa where it was equal to biomass. Gas is the second energy source used in non-residential buildings, mainly for heating, except in Latin America and Caribbean. Over the period 2020-2050, electricity is projected to become the main energy source used in non-residential buildings in all three scenarios, followed by gas, in the developed world, Middle East and Eastern Asia. In developing countries, across all scenarios, biomass is projected to continue to be used in Africa while oil is projected to continue to be used in South and South-East Asia as well as in developing pacific (Figure 9.8c).



(a)



(b) Recheck the data for Africa under SDS



(c)

Figure 9.8 Energy demand per energy carrier: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global, (b) Regional for residential buildings, and (c) Regional for non-residential buildings. Source: (Saheb et al. 2021) based on IEA WEO data

9.3.3.2 Energy demand based on end-use

Over the period 2010-2018, space heating was the dominant end-use at a global level, followed by water heating and cooking (Figure 9.9a). However, energy demand for space heating experienced a decrease of 16 percentage points. Lighting was the other end-use experiencing a decrease of its energy demand over the same period while energy demand for all other end-uses experienced an increase. Energy demand from connected and small appliances experienced the highest increase (see Box 9.5), followed by space cooling (see Box 9.3). There are great differences in the contribution of energy demand from each end-use to the regional energy demand (Figure 9.9b). In 2018, the share of energy demand from space heating out of total represented in Eurasia and Europe 66% and 62% respectively while there was no demand for space heating in Middle East, reflecting differences in climatic conditions. To the contrary, the share of energy demand from cooking out of total represented 53% in the Middle East against 6% in Eurasia and 5% in Europe reflecting societal organisations. The highest contribution of energy demand from connected and small appliances to the regional energy demand was observed in 2018 in the developed Asia Pacific, 24%, followed by the region of Southern Asia, South East Asia and Developing Pacific, with 17%. Energy demand from cooling was at 9% out of total energy demand of Southern Asia, South East Asia and Developing Pacific and at 8% in both Middle East and North America while it was at 1% in Europe in 2018.

The decline of energy demand from space heating is projected to continue over the period 2020-2050 across the three IEA scenarios with the highest decrease for heating projected to occur in the SDS driven by climate change and the expected improvement of building design and technologies. Energy demand from connected and small appliances (see Box 9.5) as well as from space cooling (see Box 9.3) are both projected to continue to increase, even in the SDS scenario while the energy demand from lighting is projected to continue to decrease. At regional level, there will be almost no change on space heating energy demand in the CPS and SPS in Eurasia and Europe while in SDS an additional drop of ten more percentage points is projected to occur. In all scenarios, Asia Pacific developed is projected to continue to lead in the energy demand from connected and small appliances, followed by Middle East and north America. Similarly, Southern Asia, South East Asia and Developing Pacific will continue to lead in the energy demand for cooling, followed by Middle East and Latin America/Caribbean.

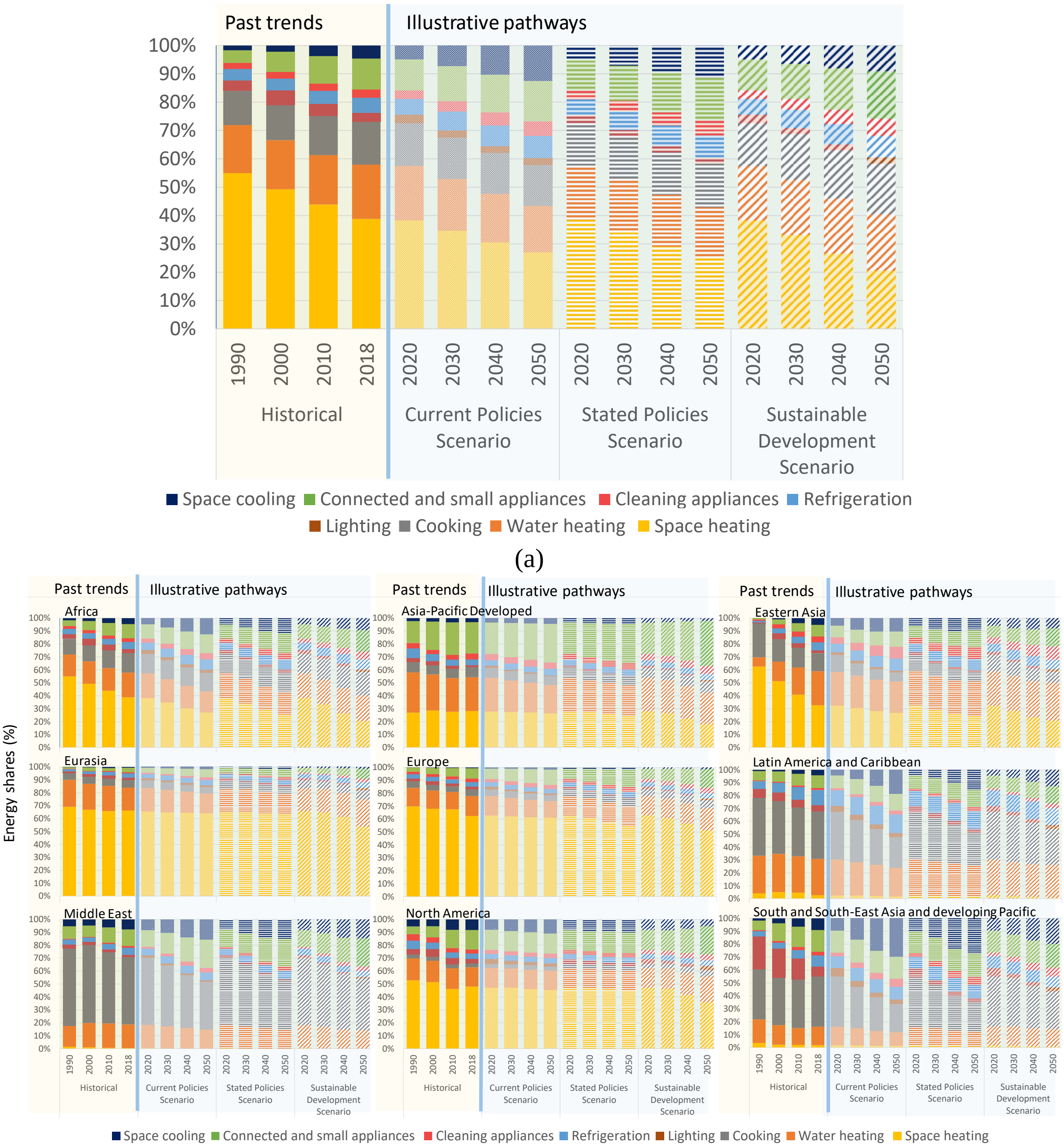
9.4 Mitigation technological options and strategies towards zero carbon buildings

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. 2020). It should be highlighted that when assessing the literature, it is clear that a lot of new research is focussed on 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 summarised, following with a summary of the technological developments since AR5, specially focussing on residential buildings.

9.4.1 Key points from AR5 and special reports

AR5 Chapter 9 on Buildings (Ürge-Vorsatz et al. 2014b) 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 examples of costs at building level. A key point highlighted is the fact that the conventional process of designing and constructing buildings and its systems is largely linear, losing opportunities for the optimisation 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.



(a)

(b)

Figure 9.9 Energy demand per end-use: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global, (b) Regional for residential buildings. Source: (Saheb et al. 2021)

9.4.2 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 2019b); but other building frames should be considered to include worldwide building construction practice, such as rammed earth and bamboo (Cabeza et al. 2021).

The most prominent materials used following these 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 are finding new interest in developed ones (Cabeza et al. 2021).

The literature evaluating the embodied energy in building materials is extensive, but that considering embodied carbon is much more scarce (Cabeza et al. 2021). 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). A summary of the embodied energy and embodied carbon cradle to gate coefficients reported in the literature are found in Figure 9.10 (Cabeza et al. 2021; Alcorn and Wood 1998; Birgisdottir et al. 2017; Cabeza et al. 2013; De Wolf et al. 2016; Symons 2011; Moncaster and Song 2012; Omrany et al. 2020; Pomponi and Moncaster 2016, 2018; Crawford and Treolar 2010; Vukotic et al. 2010). Steel represents the materials with higher embodied energy, 32-35 $MJ \cdot kg^{-1}$; embodied energy in masonry is higher than in concrete and earth materials, but surprisingly, wood has the highest embodied energy. On the other hand, earth materials and wood have the lowest embodied carbon, with less than 0.01 kg CO_2 per kg of material (Cabeza et al. 2021). The concept of buildings as carbon sinks raise from the idea that wood stores considerable quantities of carbon with a relatively small ratio of carbon emissions to material volume and concrete has substantial embodied carbon emissions with minimal carbon storage capacity (Churkina et al. 2020a; Sanjuán et al. 2019).

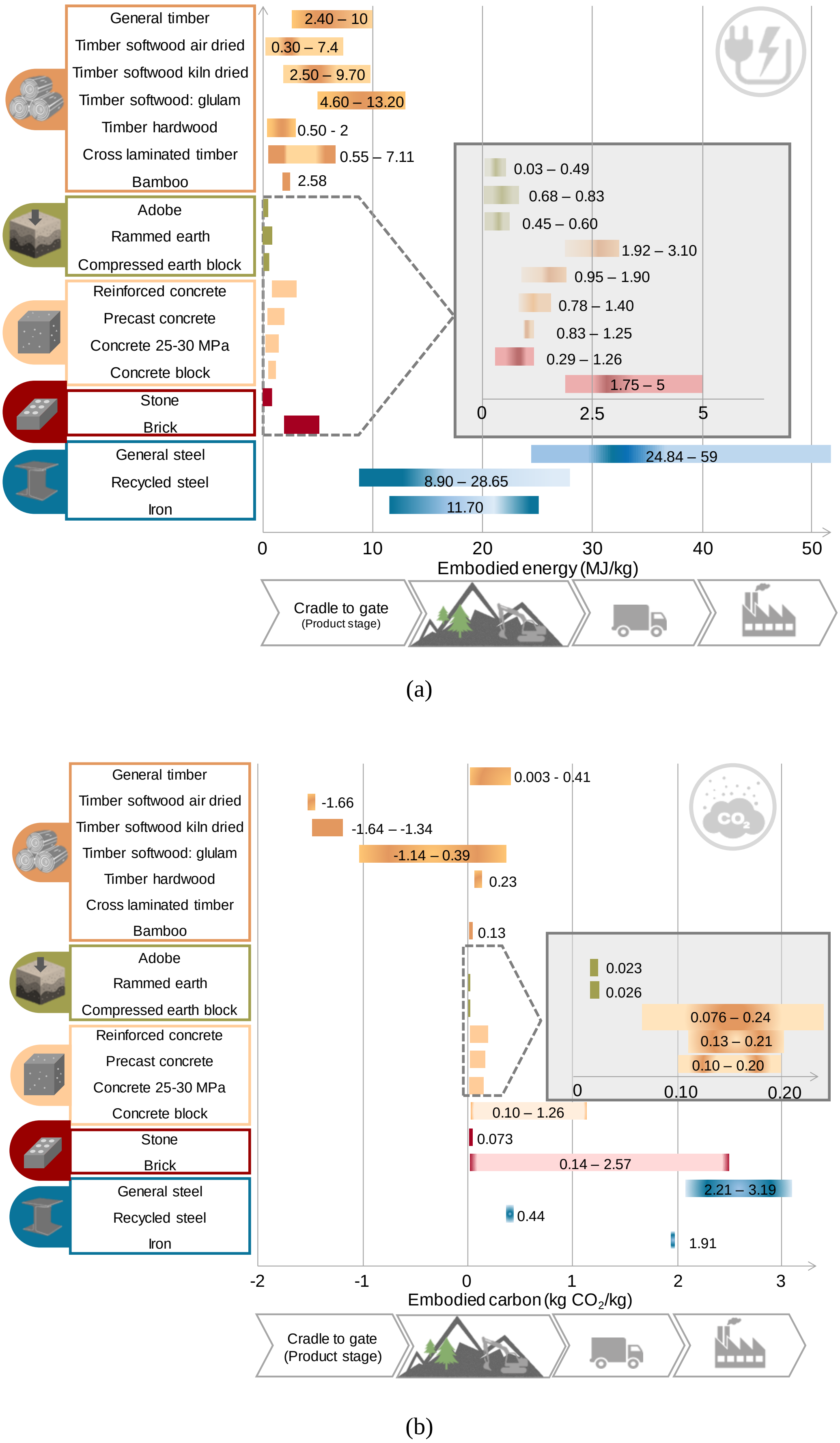


Figure 9.10 Building materials (a) embodied energy and (b) embodied carbon (Cabeza et al. 2021).

9.4.3 Technological developments since AR5

9.4.3.1 Overview of technological developments

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 to achieving carbon zero buildings are less present in the literature. Common technologies available to achieve zero energy buildings were summarised in (Cabeza and Chàfer 2020) and are presented in Tables SM9.1 to SM9.3 in detail, where Figure 9.11 shows a summary.

9.4.3.2 Appliances and lighting

Electrical appliances have a significant contribution to household electricity consumption (Pothitou et al. 2017). Ownership of appliances, the use of appliances, and the power demand of the appliances are key contributors to domestic electricity consumption (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)(Chu and Bowman 2006; Spiliotopoulos 2019) . At the same time, household energy-related behaviours are also a driver of energy use of appliances (Khosla et al. 2019) (see Section 9.5). Trends show that appliances account for an increasing amount of building energy consumption (see Box 9.5). Appliances used in developed countries consume electricity and not fuels (fossil or renewable), which often have a relatively high carbon footprint. The rapid increase in appliance ownership (Cabeza et al. 2018c) can affect the electricity grid. Moreover, energy intensity improvement in appliances such as refrigerators, washing machines, TVs, and computers has counteracted the substantial increase in ownership and use since the year 2000 (International Energy Agency 2019a).

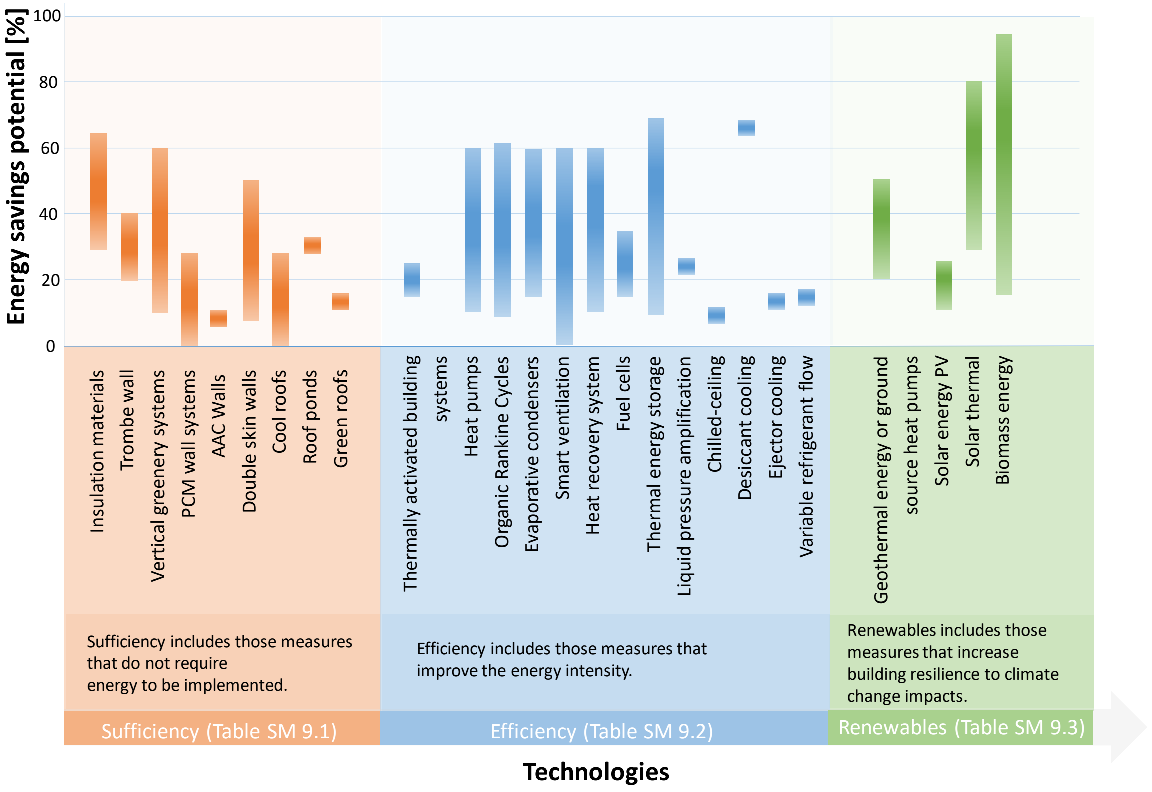


Figure 9.11 Energy savings potential of technology strategies for climate change mitigation in buildings. Adapted from (Bojić et al. 2014; Luo et al. 2017; Bevilacqua et al. 2019; Coma et al. 2017; Djedjig et al. 2015; Chen et al. 2013; Haggag et al. 2014; Khoshbakht et al. 2017; Saffari et al. 2017; Seong and Lim 2013; Radhi

2011; Pomponi et al. 2016; Andjelković et al. 2016; Rosado and Levinson 2019; Costanzo et al. 2016; Spanaki et al. 2014; Coma et al. 2016; Yang et al. 2015; Cabeza et al. 2010; Kameni Nematchoua et al. 2020; Annibaldi et al. 2020; Varela Luján et al. 2019; Jedidi and Benjeddou 2018; Capozzoli et al. 2013; Asdrubali et al. 2012; Irshad et al. 2019; Cabeza and Chàfer 2020; Prívara et al. 2011; Sourbron et al. 2013; Ling et al. 2020; Peng et al. 2020; Zhang et al. 2020; Dong et al. 2020; Harby et al. 2016; Liu et al. 2019; Vakiloroaya et al. 2014; Mahmoud et al. 2020; Romdhane and Louahlia-Gualous 2018; Gong et al. 2019; de Gracia et al. 2013; Navarro et al. 2016; Fallahi et al. 2010; Mujahid Rafique et al. 2015; Soltani et al. 2019; Imanari et al. 1999; Yu et al. 2020; Lee et al. 2018; Sarbu and Sebarchievici 2014; Hohne et al. 2019; Zhang et al. 2019a; Omara and Abuelnour 2019; Alam et al. 2019)

But appliances also are a significant opportunity for energy efficiency improvement. Research on energy efficiency for different appliances worldwide showed that this research started in different time frames in different countries (Figure 9.12) (Cabeza and Vérez 2021). 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 to highlighted 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 (such as digital television or smart phones).

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 (Wiel and McMahon 2005). IEA TCP 4E (IEA-4E 2014) shows that the first labels for refrigerated appliances in EU appeared in 1992 and are mandatory, while in USA appeared in 1993 and are voluntary, 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.

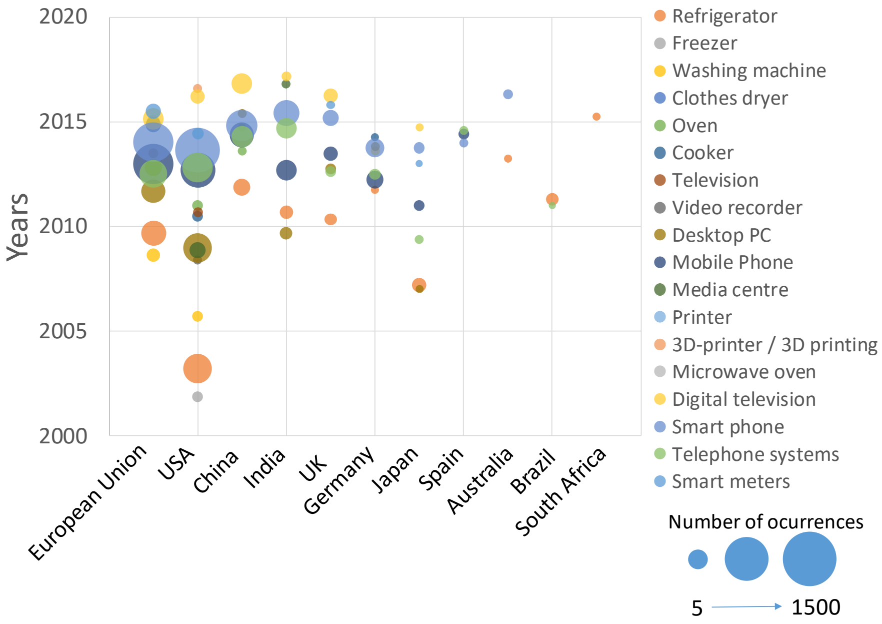


Figure 9.12 Energy efficiency in appliances research. Year and number of occurrences of different appliances in each studied country/territory.

Source: (Cabeza and Vérez 2021)

Lighting energy accounts for around 19% of global electricity consumption (Attia et al. 2017; Enongene et al. 2017; Baloch et al. 2018). Many studies have reported the correlation between the decrease in energy consumption and the improvement of the energy efficiency of lighting appliances (Table 9.1). Today, the new standards recommend the phase out of incandescent light bulbs, linear fluorescent lamps, and halogen lamps and their substitution by more efficient technologies such as compact fluorescent lighting (CFL) and light-emitting diodes (LEDs) (see Box 9.5). Due to the complexity of these systems, simulation tools are used for the design and study of such systems, which can be summarised 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 9.1 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^{-1}]	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

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 of 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. 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).

9.4.4 Case studies

9.4.4.1 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 customisation 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, 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.

9.4.4.2 Historical and heritage buildings

Historical buildings, defined as those built before 1945, are usually low-performance buildings by definition from the space heating point of view 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.

9.4.4.3 Positive energy or energy plus buildings

The integration of energy generation on-site means further contribution of buildings towards decarbonisation (Ürge-Vorsatz et al. 2020). Integration of renewables in buildings should always come after maximising the reduction in the demand for energy services through sufficiency measures and maximising efficiency improvement to reduce energy consumption, but the inclusion of energy generation would mean a step forward to distributed energy systems with high contribution from buildings, becoming prosumers (Sánchez Ramos et al. 2019). Decrease price of technologies such as PV and the integration of energy storage (De Gracia and Cabeza 2015) are essential to achieve this objective. Other technologies that could be used are photovoltaic/thermal (Sultan and Ervina Efzan 2018), solar/biomass hybrid systems (Zhang et al. 2019b), solar thermoelectric (Sarbu and Dorca 2018), and solar powered sorption systems for cooling (Shirazi et al. 2018).

9.4.4.4 District energy networks

District heating networks have evolved from systems where heat was produced by coal or waste and storage was in the form of steam, to much higher energy efficiency networks, integrating different forms of energy sources, including renewables (i.e. geothermal, PV, large solar thermal, biomass) or industry surplus heat or power-to-heat concepts, and heat storage including seasonal heat storage (Lund et al. 2018). Latest developments include the inclusion of smart control and AI (Revesz et al. 2020). Authors show carbon emissions reduction up to 80% compared to the use of gas boilers. District cooling networks are more novel technology less widespread.

9.4.5 Low- and net-zero energy buildings – exemplary buildings

Nearly zero energy (NZE) buildings or low-energy buildings are possible in all world relevant climate zones (Ürge-Vorsatz et al. 2020; Mata et al. 2020b) (Figure 9.13). 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 9.2 lists several exemplary low- and NZE buildings with some of their feature.

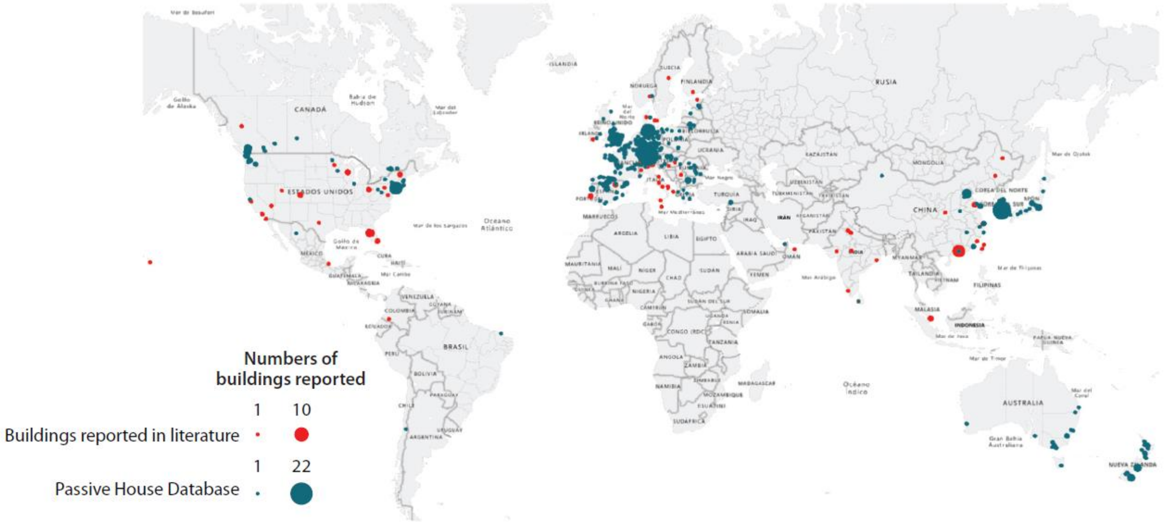


Figure 9.13 Regional distribution of documented low-energy buildings.
Source: (Ürge-Vorsatz et al. 2020)

Table 9.2 Selected exemplary low- and net-zero- energy buildings worldwide
(Adapted from (Ürge-Vorsatz et al. 2020; Mørck 2017; Schnieders et al. 2020))

Building name and organisation	**Location**	**Building type**	**Energy efficiency and renewable energy features**	**Measured 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 • Energy-efficient air conditioning and leveraged load diversity across categorised spaces: comfort air conditioning (workstations, rooms), critical load conditioning (server, hub, UPS, battery rooms), ventilated areas (restrooms, electrical, transformer rooms), and pressurised areas (staircases, lift wells, lobbies) • 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 • 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; • 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 • Active designs such as energy-efficient lighting, air-conditioning systems, building management system with sensors and solar panels • 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^{-1}

			- Hybrid (combination of natural and controlled ventilation) ventilation for thermal comfort, air quality, user acceptance and energy efficiency - Integrated photovoltaic plant and wood pellet driven combined heat and power generation - Classrooms are oriented to the south to enable efficient solar shading, natural lighting and passive solar heating - 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 maximises 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 - 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 - Underfloor ventilation with demand-controlled dedicated outside air system (DOAS) - Roof-mounted photovoltaic system and adjacent parking structures covered with PV panels	EPI of 110 kWh/m$_2$ yr^{-1} with a project area of 222,000 ft^2 with the goal the largest commercial net-zero energy building in the country
Mohammed Bin Rashid Space Centre (Schnieders et al. 2020)	United Arab Emirates, Dubai	Non-residential, offices	- Exterior walls U-value = 0.08 W/m^2·K - Roof U-value = 0.08 W/m^2·K - Floor slab U-value = 0.108 W/m^2·K - Windows UW = 0.89 W/m^2·K - PVC and aluminium frames, triple solar protective glazing with krypton filling - Ventilation = MVHR, 89% efficiency - Heat pump for cooling with recovery of the rejected heat for DHW and reheating coil	Cooling and dehumidification demand = 40 kWh/m^2·year sensible cooling + 10 kWh/m^2·year latent cooling Primary energy demand = 143 kWh/m^2·year
Sems Have (Mørck 2017)	Roskilde, Denmark	Multi-family residential (Retrofit)	- Pre-fabricated, light weight walls - Low-energy glazed windows, basement insulated with expanded clay clinkers under concrete - Balanced mechanical ventilation with heat recovery - PV	Final Energy Use: 24.54 kWh/m^2 Primary energy use: 16.17 kWh/m^2

9.4.6 Buildings emerging issues

Highlighting emerging issues are digitalisation (see Box 9.5) and the increase of electrical energy demand in the building sector (see Box 9.6).

Box 9.5 Digitalisation of the building sector

European Union (2019) and Witthoeft and Kosta (2017) identified seven digital technologies already in use in the building sector. These technologies include (i) Building Information Modelling/Management (BIM), (ii) additive manufacturing, also known as 3D printing, (iii) robots, (iv) drones, (v) 3D scanning, (vi) sensors, and (vii) Internet of Things (IoT). BIM supports decision making in the early design stage and allows assessing a variety of design options and their embodied emissions

(Röck et al. 2018; Basbagill et al. 2013). 3D printing reduces material waste and the duration of the construction phase as well as labour accidents (Dixit 2019). Coupling 3D printing and robots allows for increasing productivity through fully automated prefabricated buildings. Drones allow for a better monitoring and inspection of construction projects through real-time comparison between planned and implemented solutions. Coupling drones with 3D scanning allows predicting building heights and energy consumption (Streltsov et al. 2020). Sensors offer a continuous data collection and monitoring of end-use services (i.e. heating, cooling, and lighting), thus allowing for preventive maintenance while providing more comfort to end-users. Coupling sensors with IoT, which connects to the internet household appliances and devices such as thermostats, enable demand-response, and flexibility to reduce peak loads (IEA - International Energy Agency 2017; Lyons 2019). Overall, connected appliances offer a variety of opportunities for end-users to optimise their energy demand by improving the responsiveness of energy services (Nakicenovic et al. 2019; IEA - International Energy Agency 2017) through the use of digital goods and services (Wilson et al., 2020) including peer-to-peer electricity trading (Morstyn et al. 2018).

Energy demand from connected and small appliances reached at a global level 7.14 EJ in 2018, this is 27% increase compared to 2010. Over the period 2010-2018, the highest increase was observed in Eastern Asia where energy demand from connected and small 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 from connected and small appliances experienced an increase of 42% in Africa and less than 10% in Europe and North America. The only region where a decrease in the energy demand from connected and small appliances was observed is the developed Asia-Pacific. The increase of energy demand from connected and small appliances does not necessarily follow the increase in ownership of such products. While Eastern Asia experienced the highest increase in energy demand from connected and small appliances, the increase of ownership in this region was at 16%. This suggests that the use of digital appliances (see Section 9.5) is an important driver in the increase of energy demand from these appliances. The highest increase in ownership of connected 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 connected 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 end-user's digital technologies. Global energy demand from connected and small appliances is projected in the IEA current policy scenario to reach 14.5 EJ in 2050, this is more than double the energy demand observed in 2018 (Box 9.5 Figure 1). Future energy demand is expected to occur in the developing world given the projected rate of penetration of household appliances and devices (Wolfram et al. 2012). Over the period 2020-2050, the highest increase is projected to occur in all IEA scenarios in Africa, followed by South and South-East Asia and developing Pacific, reflecting the combination of rising incomes, income distribution and the S-curves of ownership rates (Gertler et al. 2016). However, (Grubler et al. 2018) projects a lower energy demand from connected and small appliances by assuming multiple appliances and equipment will be integrated into units delivering multiple services and sharing them by multiple users.

Energy demand from digitalisation occurs in datacentres, which are dedicated buildings or part of buildings for accommodating large amount of IT equipment such as servers, data storage and communication devices, and network devices. Data-centres are responsible for about 2% of global electricity consumption (Diguet and Lopez 2019; Avgerinou et al. 2017). Energy demand from datacentres arises from the highly packaging IT equipment, which is up to 100 times higher than a standard office accommodation (Chu and Wang 2019). Chillers combined with air handling units are, usually, used to provide cooling in datacentres. Given the high cooling demand of datacentres, some additional cooling strategies, such as free cooling, liquid cooling, low-grade waste heat recovery, absorption cooling, etc., have been adopted. In addition, heat recovery can provide useful heat for industrial and building applications. More recently, datacentres are being investigated as a potential resource for demand response and load balancing (Zheng et al. 2020; Koronen et al. 2020). Supplying datacentres with renewable energy sources is increasing (Cook et al. 2014) and is expected to continue to increase (Koomey et al. 2011).

Estimates of energy demand from digitalisation (connected and small appliances, data centres, and data networks) combined vary from 5% to 12% of global electricity use (Ferreboeuf 2019; Gelenbe and Caseau 2015; Malmodin and Lundén 2018; Diguet and Lopez 2019). According to (Ferreboeuf 2019) the annual increase of energy demand from digitalisation could be limited to 1.5% against the current 4% if sufficiency measures are adopted along the value chain.

(a)

(b)

Box 9.5. Figure 1 Energy demand from connected and small appliances in residential buildings: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global, (b) Regional. Source: (Saheb et al. 2021)

9.5 Non-technological and behavioural mitigation options and strategies

The section is set out to first understand non-technological options and strategies aiming at reducing buildings energy demand and emissions (Section 9.5.2); then to list non-technological actions to reduce GHG emissions in the building sector (Section 9.5.3); finally, to understand how to get these actions implemented. 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.

Non-technological measures are key for a low-carbon building sector (Figure 9.14), but still attract less attention than technological measures (Ruparathna et al. 2016; Vence and Pereira 2019; Cabeza et al, 2020; (Creutzig et al. 2016; Creutzig, F, Roy, J, Lamb 2018; Mundaca et al. 2019; Mata et al. 2021b).

Box 9.6 Electricity energy demand in the building sector

Electricity is used in buildings for plug-in appliances (i.e. refrigerators, cleaning appliances, connected and small appliances (see Box 9.5), lighting but also for thermal energy services (cooking, water and space heating).

Over the period 2010-2018, global electricity demand from buildings increased by 25% driven by the combination of rising incomes, income distribution and the S-curve of ownership rates (Wolfram et al. 2012; Gertler et al. 2016) (Box 9.6 Figure 1a). The highest increase (97%) was observed in Eastern Asia, 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 experienced a decrease in their electricity demand of 5% and 7% respectively (Box 9.6 Figure 1b). This reflects the policies implemented in these regions (see Section 9.9) which have led to a high penetration of efficient technologies (see Section 9.4). North America is the only developed region with an increase (1%) of electricity demand.

An important emerging trend in electricity demand is the use of electricity for thermal energy services (cooking, 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 (Box 9.6 Figure 1b).

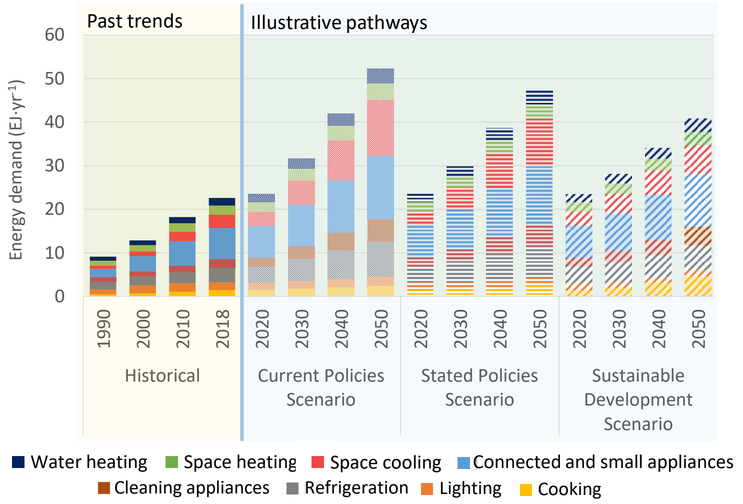
Over the same period, electricity demand from water heating increased by 24% driven by the increase of the demand in Eastern Asia, South and South-East Asia and developing Pacific, where it has almost doubled. Africa, Middle East and Eurasia experienced an increase of more than 30% in water heating electricity demand 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 water heating electricity demand (Box 9.6 Figure 1b).

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 end-use. The highest increase was observed in the region of South and South-East Asia and developing Pacific where it has more than doubled, followed by Eastern Asia where an increase of 79% was observed. Europe experienced a 26% decrease of space heating electricity demand (Box 9.6 Figure 1b). Heat pumps used either individually or in conjunction with heat networks can provide heating in cold days and cooling in hot ones. (Lowes et al. 2020) suggests electricity is expected to become an important energy vector to decarbonise heating. However, the use of heat pumps will increase halocarbon emissions (United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020). (Bloess et al. 2018; Barnes and Bhagavathy 2020; Connolly 2017) argue for electrification of heat as a cost effective decarbonisation measure, if electricity is supplied by renewable energy sources. However, the electrification of the heat supply in the buildings sector will lead to additional electricity demand and consequently additional investment in new power plants. (Thomaßen et al. 2021) identifies flexibility as a key enabler of larger heat electrification shares. Importantly, heat pumps work at their highest efficiency level in highly efficient buildings and their market uptake is likely to require incentives due to their high up-front cost (Hannon 2015; Heinen et al. 2017).

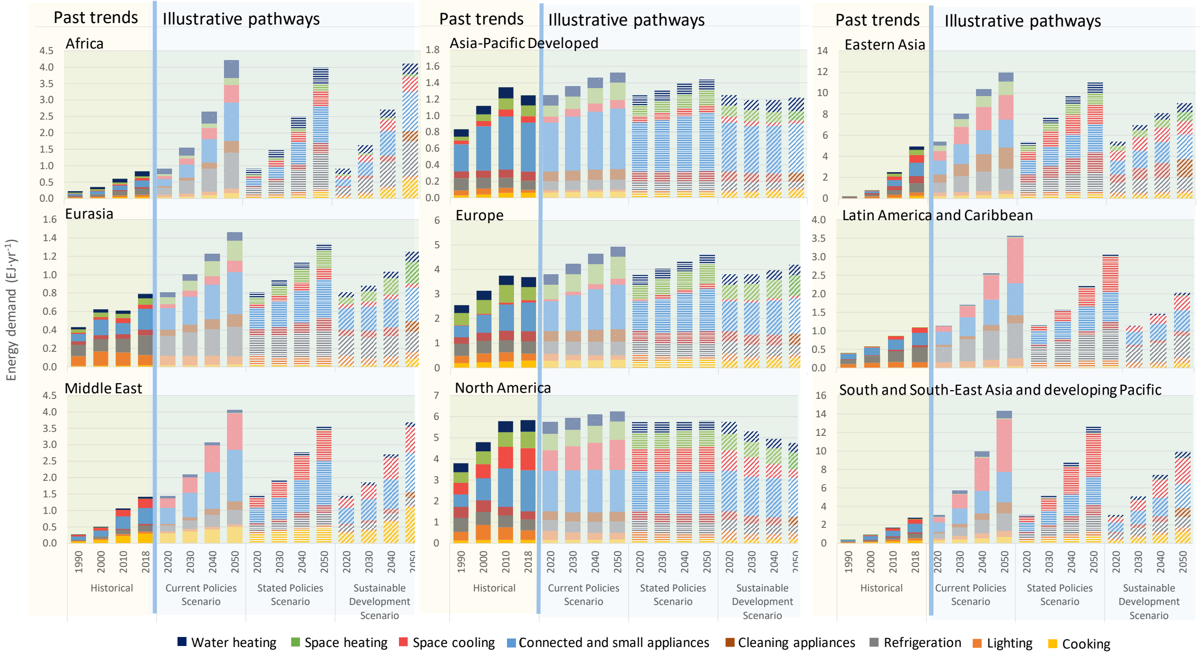
Electricity demand from cleaning appliances has also experienced, an increase in all regions except North America which has experienced a decrease of 3%. The highest increase was observed in Eastern Asia, with 81% increase, while the lowest increase was experienced in Europe with 8.4% increase over the period 2010-2018 (Box 9.6 Figure 1b).

Lighting is the only end use which has experienced a decrease in its electricity demand 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 driven by 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, driven by the shift to LEDs, with a 46% decrease, while the lowest decrease was observed in Middle East with a 2% decrease over the same period (Box 9.6 Figure 1b).

By 2050, global electricity demand will more than double under the IEA current policies scenario and almost double under the IEA sustainable development scenario driven by the increased access to electricity of the population, currently, deprived for this modern energy service (see Section 9.8). The highest increase is projected to occur in Africa, followed by South and South-East Asia and developing Pacific. From end-use perspective, the highest increases are projected to occur in electricity demand from water heating and cooking while lighting is projected to experience a decrease in all regions except Africa and South and South-East Asia and developing Pacific (Box 9.6 Figure 1b).



(a)



(b)

Box 9.6 Figure 1 Electricity energy demand for the residential sector: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. (a) Global and (b) Regional.

Source: (Saheb et al. 2021)

9.5.1 Non-technological determinants of energy demand and carbon emissions

GDP or income, energy price and climate are unequivocal drivers of buildings energy demand and GHG emissions, followed by other indicators of size such as population or buildings floor area (Mata et al. 2021b).

9.5.1.1 Climate and physical environment

Outdoor temperature, sunshine hours, and rainfall are highly determinant of energy demand (Harold et al. 2015b; Rosenberg 2014b; Lindberg et al. 2019b). Density, compacity, and spatial effects define the surrounding environment and relate to urbanisation. Building and urban typologies implicitly assume single family houses and rural areas as less compact than apartment buildings and urban areas. Urban households consume more electricity than rural households, as urban residents usually have a relatively affluent lifestyle, but less energy for heating (Huang 2015a; Niu et al. 2012; Rafiee et al. 2019b; Ayoub 2019b; Oh and Kim 2019b).

Climate variability and extreme events may drastically increase energy consumption (Mashhoodi et al. 2019). Climate change effects on future energy demand and GHG emissions, are discusses in Section 9.7, and effects of temperature on health and productivity, in Section 9.8.

9.5.1.2 Characteristics of the building

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 (Fosas et al. 2018; Morganti et al. 2019; Manzano-Agugliaro et al. 2015). Affluence is embedded in these variables as higher-income households have larger homes and lots. Residential consumption increases with the number of occupants but consumption per capita decreases proportionally to it (Serrano et al. 2017). Vintage has a negative correlation as recently built buildings must comply with increasingly strict standards (Brounen et al. 2012a; Kavousian et al. 2015b). Only for electricity consumption no significant correlation is observed to building age (Kavousian et al. 2013a). As buildings are being renovated, the renovation year is instead a key indicator of the building status (Mangold et al. 2016; Österbring et al. 2016).

9.5.1.3 Socio-demographic factors

Income has generally a positive correlation to energy demand (Kavousian et al. 2015a; Hansen 2016; Singh et al. 2017; Bissiri et al. 2019; Sreekanth et al. 2011; Couture et al. 2012).

Mixed effects are found for household size, age, gender, ethnicity, education levels and tenancy status (Hansen 2016; Rafiee et al. 2019; Engvall et al. 2014; Arawomo 2019). Single-parent and elderly households consume more gas and electricity, and gender has no significant effect (Harold et al. 2015; Brounen et al. 2012; Huang 2015). Similarly, larger families are found to use less electricity per capita (Huang et al. 2015; Bedir et al. 2013; Kavousian et al. 2013b, 2015b). High-income households tend to use more efficient appliances and are likely to be more educated and environmentally sensitive, but their higher living standards require more electricity and gas (Hidalgo et al. 2018; Harold et al. 2015b). Heating expenditure tends to be higher for owners than for renters, despite the formers' tendency to have more efficient appliances (Gillingham et al. 2012; Meier and Rehdanz 2010; Harold et al. 2015b) (Davis, 2012; Kavousian et al. 2015b; Huang 2015).

9.5.2 Insights from non-technological and behavioural interventions

Occupant behaviour (Figure 9.14), e.g. the frequency of use of heating and cooling appliances and temperature settings, sharing, using non-electricity using mechanisms to achieve thermal comfort, and cultural practices correlate with energy consumption (Li et al. 2019; Khosla et al. 2019). Households consume more on weekends and 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. 2015a; Hidalgo et al. 2018). At the same time, occupants behaviour has less relevance, in absolute energy consumption, in more efficient buildings (Grove-Smith et al. 2018; Pitts 2017).

9.5.2.1 Passive and active management and operation

Passive management refers to adjustments in human behaviour that do not consume energy, such as the manual operation of the building envelope, adapted clothing, and the allocation of activities in the rooms of the building to minimise the energy use (*green schedule*) (Rafsanjani et al. 2015; Klein et al. 2012). In non-residential buildings, 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, reduce energy demand (Talele et al. 2018; O'Brien and Gunay 2014; Taniguchi et al. 2016). 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 minimise losses during cold nights; optimise natural lighting by opening blinds and curtains during the day (Rijal et al. 2012; Volochovic et al. 2012). Quantitative modelling of such measures is most common for non-residential buildings. Additional small savings are available through design, such as placing refrigerator away from the oven, the radiators or the windows (Christidou et al. 2014a).

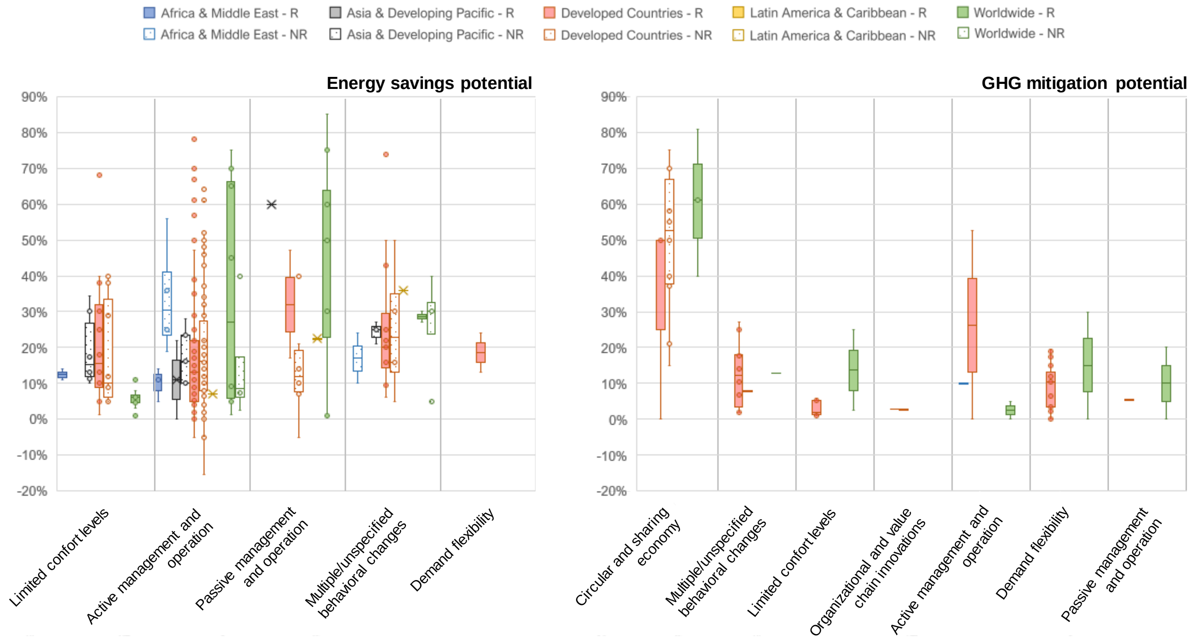


Figure 9.14 Energy saving and GHG mitigation potentials for categories of non-technological interventions. Based on a review of 28 references published since 2011 (Mata et al. 2021c)

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, e.g. using small lighting support for focused tasks and turning off unnecessary lights, can effectively reduce summer peak demand (Dixon et al. 2015a; Taniguchi et al. 2016). On the contrary, the application of the Daylight-Saving Time in the US increases up to 7% lighting consumption (Rakha et al. 2018). Efficient cooking practices for cooking (e.g. fit size of cooking pan to the heating plate; use pressure cooker and, for small quantities, microwaves oven), appliance use (e.g. avoid stand-by regime, select eco-mode), or for hot (e.g. shorter showers, turning off taps while washing and shaving) 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; Dixon et al. 2015; Christidou et al. 2014; Reichert et al. 2016). High behavioural control is so far proven difficult to achieve (Ayoub et al. 2014b; Sköld et al. 2018).

Technical measures to that could trigger passive management and automated management solutions are addressed in Section 9.4.

9.5.2.2 Limited demands for services

Adjustment in the temperature of the heating in winter and the cooling in summer results in savings between 5% and 25% and vary due to occupant behaviour (Ayoub et al. 2014a; Christidou et al. 2014; Sun and Hong 2017; Taniguchi et al. 2016;).

As presented in Section 9.3, the increase of floor area per capita is an important driver of GHG emissions. A series of recent works study a cap on the living area (van Sluisveld et al. 2016; Millward-Hopkins et al. 2020; Annette Jenny, Barbara Wegmann and Noëmi Cerny 2013; Toulouse et al. 2017; Virage-Energie Nord-Pas-de-Calais. 2016; Brischke et al. 2015). These studies are promising (Figure 9.15) but of limited complexity, in terms of rebounds to other sectors and services, interactions with other measures, and business models, and require further investigation. Professional assistance and training on these issues is limited (Maxwell et al. 2018).

Willingness to adopt is only found for certain measures (full load to laundry appliances, lid on while cooking, turning lights off, defer electricity usage and HVAC systems, adjust set-point temperature by 1°C) but negative not for others (appliances on standby, using more clothes, avoid leaving the TV on while doing other things, defer ovens, ironing or heating systems, adjust set-point temperature by 1°C, move to a low energy house or smaller apartment) (Brown et al. 2013a; Sköld et al. 2018; Yohanis 2012; Li et al. 2017). A positive synergy with digitalisation and smart home appliances is identified, driven by a combination of comfort requirements and economic interest, confirmed by a willingness to defer electricity usage in exchange for cost savings (Ferreira et al. 2018; Mata et al. 2020c).

9.5.2.3 Flexibility of demand and comfort requirements

In a “flexible” behaviour, the desired level of service is the same, but it can be shifted over time, typically allowing automated control and increased digitalisation. There are substantial economic, technical, and behavioural benefits from implementing flexibility measures (Mata et al. 2020c).

With demand side measures (DSM), such as shifting demand a few hours, peak net demand can be reduced up to 10-20% (Stötzer et al. 2015), a similar potential is available for short-term load shifting during evening hours (Aryandoust and 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 and Pascucci 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 and Alvehag 2014). Behavioural 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). Real-time monitoring and behavioural change could influence 40% of the building energy use in terms of savings (Kamilaris et al. 2014).

9.5.2.4 Circular economy

The built environment is the world largest consumer of raw materials (World Economic Forum 2016). Circular economy solutions include reuse and recycling of buildings and materials, e.g. 3D-printing, reuse of structural steel, and insulation with recycled content, replacing primary with secondary materials, reusing buildings including disabling, rethinking building materials, densification (Pomponi and Moncaster 2017; Mercado 2018; ARUP 2018; Hertwich et al. 2020;Cantzler et al. 2020; Mata et al. 2021c). The recycling principle is however limited by nature, material complexity, and abuse (Ghisellini et al. 2016).

9.5.2.5 Sharing economy

The sharing economy generates an increased utilisation rate of products or systems by enabling or offering shared use, access or ownership of products and assets that have a low ownership or use rate. Measures include conditioned spaces (accommodation, facility rooms, offices) as well as tools and transfer of ownership (i.e., second-hand or donation) (Rademaekers et al. 2017; Harris et al. 2021). The evidence on the link between user behaviour and net environmental impacts of sharing options is still limited (Laurenti et al. 2019; Mata et al. 2020a; Harris et al. 2021).

9.5.2.6 Value chain innovations

Organisational changes that require cooperative efforts are necessary to improve the energy efficiency of buildings (Masuda and Claridge 2014; Ruparathna et al. 2016; Kamilaris et al. 2014). Inter-disciplinary understanding of organisational culture, occupant behaviour, and technology adoption is required to set up occupancy/operation best practises (Janda 2014). Buildings owned by non-profit groups are less energy efficient compared to private buildings, or management changes for and establishing operational best practises (Azar and Menassa 2014; Peterman et al. 2012). Building commissioning helps to reduce energy consumption by streamlining the systems, but benefits are not persistent.

For instance, non-technological challenges include training and software costs (tailored learning programs, learning-by-doing, human capital mobilisation), client and market demand (service specification, design and provision; market and financial analysis) and potential legal issues (volatile energy prices, meeting regulation); and partnership, governance and commercialisation, are identified for Building Information Modelling (Rahman and Ayer 2019; Oduyemi et al. 2017), for PV industry (Triana et al. 2018), Smart Living (Solaimani et al. 2015), or circular economy (Vence and Pereira 2019).

9.5.3 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 (Table 9.3). Mixed effects are found for technical issues, attitudes and values. In spite of proven positive environmental attitudes and willingness to adopt low-carbon solutions, these are outweighed by financial aspects all over the world (Mata et al. 2021). Adopters in developed countries are more sensitive towards disruptions in their quality of life in terms of finance, thermal comfort or habits; whereas in other world regions techno-economic concerns prevail. Private consumers seem ready to support stronger governmental action, whereas non-private interventions are hindered by constraints in budgets and profits, institutional barriers and complexities (Curtis et al. 2017a; Zuhaib et al. 2017; Tsoka et al. 2018a; Kim et al. 2019).

It is clear that the needs of consumer groups are diverse, and a variety of specific interventions targeted to heterogeneous decision makers is needed (Liang et al. 2017; Soland et al. 2018; 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 and empirical studies investigating investment decisions need to be taken further through a multidisciplinary approach to energy consumption patterns and market maturity (Boyd 2016; Marzano et al. 2018; Heiskanen and Matschoss 2017a; Baumhof et al. 2018; Wilson et al. 2018).

9.5.3.1 *Building envelope*

In North America and Europe, personal attitudes and values, and existing information and support are the most and equally important reasons for improving the building envelope. Consumers have some economic concerns and little technical concerns, the later related to the performance and maintenance of the installed solutions (Mata el al, 2021c). In other world regions the literature is limited.

Motivations are triggered by contextual needs, such as after moving in, driven by urgent comfort or replacement needs. 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 (Haines and Mitchell 2014;Bright et al. 2019). 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. 2017b; Zuhaib et al. 2017; Tsoka et al. 2018b; Maxwell et al. 2018). For instance, if energy renovations of the buildings' envelope are not normative, cooperative ownership may be a barrier in apartment buildings (Miezis et al. 2016). Similarly, product information and labelling may be helpful or overwhelming (Ozarisoy and Altan 2017; Curtis et al. 2017; Lilley et al. 2017; Bright et al. 2019). The decisions are correlated 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).

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).

9.5.3.2 *Adoption of efficient HVAC systems and appliances*

We find mixed willingness to adopt efficient technologies (Figure 9.15). While developed countries are positive towards building envelope technologies (draught proofing, insulation), appliances such are A-rated appliances, condensing boiler, are negatively perceived (Yohanis 2012). In contrast, adopters in Asia are positive towards energy saving appliances in general (Liao et al. 2020; Spandagos et al. 2020).

Table 9.3 Reasons for adoption of climate mitigation solutions. The sign represents if the effect is positive (+) or negative (-), and the number of signs represents confidence level (++, many references; +, few references). Based on data extracted from 287 references published after 2011 (Mata et al. 2021a)

	Climate mitigation solutions buildings						
	Building envelope	**Efficient technical systems**	**On-site renewable energy**	**Performance standards**	**Low-carbon materials**	**Smart home and digitalisation**	**Circular and sharing econ.**
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			-	-		--	

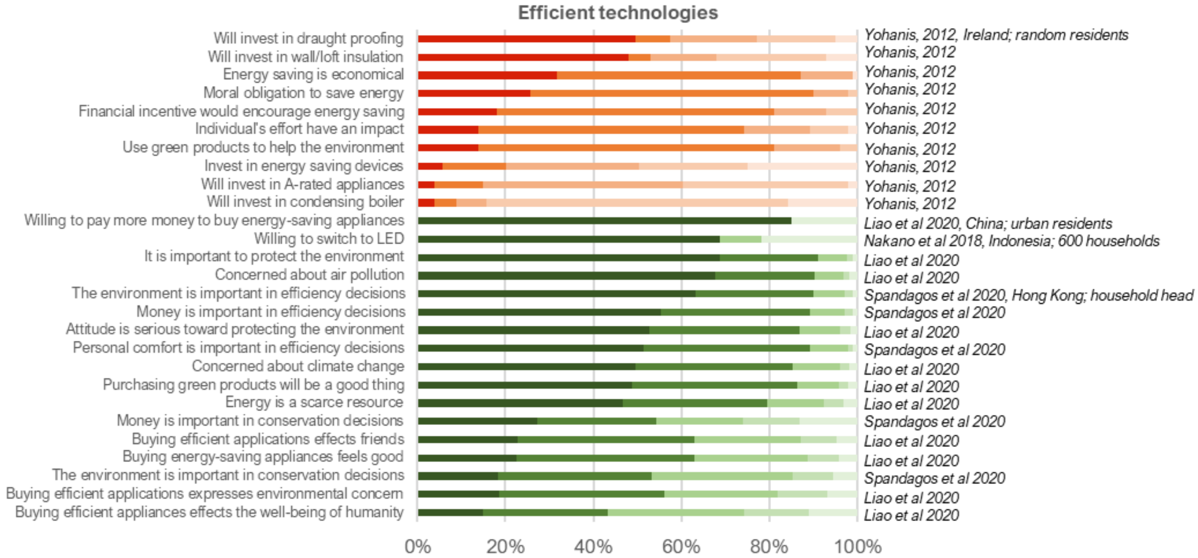


Figure 9.15 Willingness to adopt efficient HVAC systems and appliances, in developed countries (red) and Asia and developing Pacific (green)
(Mata et al. 2021a)

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). The most relevant aspects for efficient technical systems are those concerning availability, or lack, of information and support from different stakeholders in different geographical contexts (Heiskanen and Matschoss 2017b; Clancy et al. 2017; Tumbaz and Moğulkoç 2018; Christidou et al. 2014b; Bright et al. 2019; Hernandez-Roman et al. 2017; Chun and Jiang 2013; Chu and Wang 2019; Ketchman et al. 2018; Curtis et al. 2018).

Among high-income countries (Europe, USA, Japan and Australia), economy aspects have positive effects, specially reductions in energy bills and financial incentives or subsidies (Mortensen et al. 2016; Clancy et al. 2017; Christidou et al. 2014b; Chun and Jiang 2013; Ketchman et al. 2018; Curtis et al. 2018). Having complementary technologies required for adoption already in place was found to have a positive effect in adoption (Zografakis et al. 2012; Clancy et al. 2017) but concerns about the performance and maintenance issues are identified as barriers (Qiu et al. 2014). The solutions are positively perceived as high-technology innovative, to enhance status, and are supported by peers and own-environmental values (Ketchman et al. 2018; Mortensen et al. 2016; Heiskanen and Matschoss 2017b).

9.5.3.3 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.

Investments in residential PV are realised by comparatively rich homeowners who expect reasonable high and secure return on investments (Hampton and Eckermann 2013; Schaffer and Brun 2015) but costs are decreasing fast and installations in bigger buildings are becoming attractive (Jäger-Waldau 2019; Jager-Waldau et al. 2018). 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). Regional neighbourhood effects are observed that point at the importance of specified craft skills and/or intermediary agents (Schaffer and Brun 2015). Finally, previous experience with similar solutions increases environmental behaviour (Bach et al. 2020; K 2018; QURAISHI and AHMED 2019; Reindl and Palm 2020).

9.5.3.4 Low carbon materials

Studies investigating the adoption of low-carbon material focus on the adoption of wood-based building system and prefabricated housing construction, mostly in high-income countries, as the majority of the resource (as in sustainable managed forestry) and technology (as in factories for prefabricated housing) availability are concentrated in such regions and countries (Mata el al, 2021c).

High level decision-making is most relevant, e.g. political will and the environmental values of society play have a positive effect on the adoption rate of low-carbon materials (Lien and Lolli 2019), whereas lobbying by traditional materials industries are identified as barriers for adoption, in combination with the short-term political decision making (Tozer 2019). Concerns over technical performance, risk of damage, and limited alternatives available are also hinders for wood-based building systems (Thomas et al. 2014). In contrast, low investment costs if compared to traditional material and building solutions are drivers for adoption (Lien and Lolli 2019; Steinhardt and Manley 2016). Finally, if prefabricated buildings become more streamlined, the potential for participative ownership and new ownership models can favour their adoption (Steinhardt and Manley 2016).

9.5.3.5 Digitalisation, value-chain innovations and demand-supply flexibility

Demand-supply flexibility measures are experimentally being adopted in North America, Europe and Asia-Pacific Developed regions. The current regulatory framework would need to change to facilitate participation based on trust and transparent communication (Wolsink 2012; Nyborg and Røpke 2013; Mata et al. 2020b). However, governments and energy utilities are assumed by consumers as responsible drivers of the transition (Seidl et al. 2019).

Three types of challenges exist: economic challenges such as unclear business models and disadvantageous market models and high costs of advanced smart metering; technical challenges such as constraints for HPs and seasonality of space heating demands; social challenges in which consumers seem to display a lack of awareness of real-time price information and inadequate technical understanding. 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). Risks identified include higher peaks and congestions in low price-hours and difficulties in designing electricity tariffs because of conflicts with CO_2 intensity, and potential instability in the entire electricity system cause by tariffs coupling to wholesale electricity pricing.

New market players 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 would make their storage system available as balancing load for the grid operator, the acquisition of new batteries by a 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).

9.5.3.6 Circular and sharing economy

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 (EPA 2009). The circular and sharing economy begins to be perceived as organisational and technologically innovative, with the potential to provide superior customer value, response to societal trends, and positive marketing (Cantzler et al. 2020; L.K et al. 2020; Mercado 2018).

Government support is needed an initiator but also to decrease construction rates, reinforce building retrofit targets and promote more stringent energy and material standards for new constructions (Hongping 2017; Fischer and Pascucci 2017; Patwa et al. 2020). Taxes have a clear effect as incentives for waste reduction and recycling (Ajayi et al. 2015a; Rachel and Travis 2011; Volk et al. 2019). In developing countries, broader, international, market boundaries can allow for a more attractive business model (Mohit et al. 2020).

Attitudes and values can also be highly relevant, as a survey applied to construction site workers in Lebanon shows that improved construction waste management are highly influenced by attitude, past experience, and social pressure; but training is needed as a basic requirement (Amal et al. 2017). The reuse of building elements has been a traditional practice within communities and has been replaced by a culture of waste (Mohit et al. 2020; Hongping 2017; Ajayi et al. 2015).

9.6 Global and regional costs and potentials drivers

Section 9.4 illustrates how existing technological options and practices allow constructing and retrofitting individual buildings to produce very low GHG emissions during the building operation phase. The section illustrated that since AR5, we have observed a growing number of such buildings in all parts of the world. A growing amount of literature calculates GHG emission reduction potential at national level for different countries if such buildings will penetrate at scale. The analysis of these figures shall be cautious, because they rely on a number of assumptions containing uncertainties and feasibility constrains. The present section assesses the potentials reported at national level and aggregates these into regional and global figures. It complements Section 9.3 which provides potentials using top-down model based on the illustrative pathways classification provided in Chapter 3. It also discusses the determinants of the potential and its costs. The novelty of the section is that many national studies rely on the application of integrated approaches to construction and retrofit of buildings, as compared to only few such national studies identified in AR4 and AR5. We also see a new trend of bottom-up modelling non-technological potentials at national and global level, including the application of sufficiency approach. The estimate of embodied emission reduction at national scale is the next novelty in literature.

9.6.1 Review of literature calculating potentials of different world countries

Error! Reference source not found. presents the review of literature published since AR5, which q uantifies the potential for GHG mitigation in the buildings sector at national level for different countries. It focuses on studies using a technology-reach, bottom-up approach. The studies tend to rely on the following mitigation strategies: improvement of energy efficiency of thermal envelopes in new and existing buildings; improvement of energy efficiency in building systems, equipment, and appliances; as well as fuel switch to low carbon energy carriers including buildings-integrated renewables. The growing amount of studies consider these measures as an integrated package due their technological complementarity and interdependence, and therefore ranking of individual measures in terms of size or cost is not as relevant as in case of incremental improvements. The results address only the measures integrated in buildings, and therefore exclude the impact of decarbonisation of electricity supply from the grid. The figure reports the reduction of both, direct and indirect emissions of buildings.

Europe and North America have the richest amount of literature, which has grown since AR5 and AR4, though it was also available that time. In line with their commitments and due to declining baseline emissions, the potential in some European countries is provided versus a base year. The literature attests that by 2050, countries on these continents may reduce up to 90% of their baseline emissions or emissions in the base year (between 2010 and 2020). Germany (Markewitz et al. 2015), Switzerland (Iten et al. 2017), and Greece (Mirasgedis 2017) illustrated these opportunities heading to buildings carbon neutrality in 2050.

The amount of literature on potentials in Eurasia, Eastern Asia, Southern Asia, South-East Asia, and Developing Pacific has increased significantly since AR5 and AR4. The studies from these continents estimate the GHG emission reduction potential of up to 80% and even more as compared to their baseline emissions in 2050. African, Middle East, and South American countries have still little amount of literature assessing the sector potential. They report possible emission reductions up to 70%. These emission reductions of all these regions, except Eurasia are estimated against sharply growing baselines.

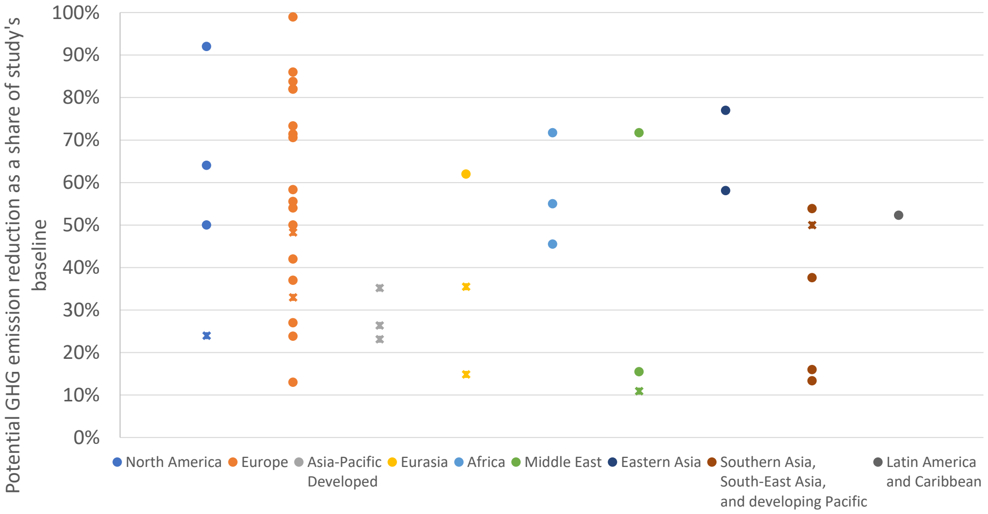


Figure 9.16 Potential GHG emission reduction in the buildings sector at national level in different world countries grouped by region, 2050

Note: × indicates the potential in year 2030.

Sources: (Camarasa et al. 2019; Chaichaloempreecha 2016; Climate Action Tracker 2019a, 2018a, 2019b, 2018b; Csoknyai et al. 2016; de la Rue du Can et al. 2019; Energetics 2016; Fotiou et al. 2019; Gagnon, Peter, Margolis, Robert, Melius, Jennifer, Phillips, Saleb, Elmore 2016; González-Mahecha et al. 2019; Horváth et al. 2016; Hrabovszky-Horváth et al. 2013; Kamal et al. 2019a; Krarti 2019; Kusumadewi and Limmeechokchai 2015, 2017; Langevin et al. 2019; Markewitz et al. 2015; Mata et al. 2018; Nadel 2016; Novikova et al. 2018a,b, 2020; Ostermeyer, Y.; Camarasa, C.; Naegeli, C.; Saraf, S.; Jakob, M.; Hamilton, I; Catenazzi 2018; Chaichaloempreecha et al. 2017; Ostermeyer, Y.; Camarasa, C.; Saraf, S.; Naegeli, C.; Jakob, M.; Palacios, A, Catenazzi 2018; Ostermeyer et al. 2018; Bienge et al. 2019; Radpour et al. 2017; Subramanyam et al. 2017a,b; Tan et al. 2018; Timilsina et al. 2016; Toleikyte et al. 2018; Trottier 2016; Vaillancourt et al. 2017; Vijay and Hawkes 2017; Wilson et al. 2017; Yeh et al. 2016; Yu et al. 2018; Zhou et al. 2018; Iten et al. 2017; Department of Environmental Affairs 2014; Oluleye et al. 2018a,b; Oluleye and Smith 2016; Wakiyama and Kuramochi 2017; SUGIYAMA et al. 2020; Bashmakov 2017; Mirasgedis 2017)

9.6.2 Assessment of the potentials and costs at global level

The assessment of potential using both top-down and bottom-up approaches may suggest a range of estimates, improving its accuracy. Box 9.7 describes the methodology used to derive bottom-up estimates of the potential from technological energy efficiency and buildings integrated renewable energy reported in the chapter. Chapter 3 describes the methodology and estimates according to the top-down approach (IAMs) and Section 9.3 summarises them for the buildings sector.

Figure 9.17 presents these ranges for each world region in 2050, in comparison with the baseline emissions in 2020 and 2050. The potential is broken down in energy efficiency and building-integrated renewables and in measures reducing direct and indirect emissions. The figure illustrates that the potential at regional level as a share of baseline emissions in 2050 ranges between 50% to 75%. No single study assessing the technological potential considers energy wasteful behaviour of building users. In other words, the potentials are usually calculated to allow for meeting health standards and other requirements, but not exceeding them. This means that a part of the non-technological potential is assumed as being realised by the technological potential estimates. The potential for energy efficiency must be realised prior to that of renewable energy. This will allow meeting the remaining energy demand of buildings with the a wide range of energy supply options that is important in urban areas with limited areas for onsite installations of renewable energy production (Horváth et al. 2016). Top-down estimates provided by IAMs of Chapter 3 are not sufficiency clear and this is why we did not integrate them in Figure 9.17 yet (will be the last column).

Box 9.7 Methodology to estimate the global potentials of CO_2 mitigation in buildings

The bottom-up regional estimates are provided as a share of baseline emissions in 2050 for 10 IPCC regions. They represent an aggregation of estimates reported by national bottom-up studies. Only studies covering a comprehensive range of measures were considered. They include comprehensive improvements of thermal envelopes of new and existing buildings, including HVAC and controls; efficient equipment and appliances including cooking and lights; and renewable energy production integrated in buildings. Often, these improvements implied an integrated approach. When several bottom-studies were identified for a region, either a rounded average or a rounded median figure was taken, giving the preference to the one which is closer to the potential estimates of countries with very large contribution to regional baseline emissions in 2050 (for instance, to China in Eastern Asia). To report the absolute potential, the estimates as % of baseline were multiplied with baseline emissions, as reported by the current policy scenario of World Energy Outlook 2019 (International Energy Agency 2019c). The potentials of buildings in 2030 reported in Chapter 12 are interpolated estimates targeting the 2050 figures.

Figure 9.17 Potential GHG emission reduction in the buildings sector broken down in energy efficiency and building-integrated renewable energy measures (up) and measures reducing direct and indirect emissions (bottom), 2050 (the potential in Asia Pacific developed is to revise, need more studies)

The tendency of studies to apply the integrated approach made the ranking of individual technological options in terms of the potential size and costs less relevant as compared to the approach applying incremental improvements.

Table **9.4** presents the prioritisation of the potential by region as identified by studies, to the extent that it was possible to disaggregate.

A novelty since AR5 is a new trend of attempts to account for opportunities to drastically reduce energy consumption and emissions applying non-technological approaches, in particular sufficiency.

Figure 9.14 in Section 9.5 provides an assessment of individual non-technological options in different countries. Whereas total non-technological potentials are usually assessed by top-down models similar to (van Sluisveld et al. 2016b), there are three very detailed models relying on bottom-up approaches. The Low Energy Demand Scenario modelled for the world by (Grubler et al. 2018) assessed the impact of the changes in quantity and types of energy services, as well as their energy intensity to reach low energy demand. Their approach results in buildings final energy demand in 2050 at 62 EJ; this is 67% lower than that of the WEO current policy scenario (International Energy Agency 2019c). The Decent Living Energy scenario of (Millward-Hopkins et al. 2020) estimated even higher possible reduction in energy demand xx% (available for buildings in January 2021), if the world is to minimise energy use without scarifying decent living. Similarly, (Levesque et al. 2019) assessed demand reduction scenarios implementing both technological and non-technological potential and found that in 2050 a 45% energy demand reduction is possible.

Table 9.4 Prioritisation of measures in terms of the amount of potential in 2050 as identified by studies

Region	Priority 1	Priority 2	Priority 3	Priority 4	Priority 4
North America	HVAC (heat pumps)*	Envelope improvement (renovation)*	Envelope improvement (new)*	Efficient appliances	Renewable energy production onsite

Europe	Envelope improvement (new)*	HVAC (heat pumps)*	Envelope improvement (new)*	Other HVAC incl. fuel switch, often to renewables onsite	Efficient appliances
Asia-Pacific Developed	Efficient appliances	Envelope improvement (renovation)	Renewable energy production onsite	Envelope improvement (new)	Non-technological measures
Eurasia	Renewable energy production onsite	Envelope improvement + HVAC (renovation)*	Envelope improvement + HVAC (new)*	Efficient appliances	
Africa	Envelopes (new buildings)	Renewable energy production onsite	Efficient appliances excluding cooking	Cooking appliances	
Middle East	Envelope improvement (renovation)	Renewable energy production onsite	Envelope improvement (new)	Efficient appliances	
Eastern Asia	Envelope improvement (new)	HVAC*	Fuel switching from coal	Efficient appliances	Renewable energy production onsite
Southern Asia, South-East Asia and developing Pacific	Envelope improvement (new)	Efficient appliances incl. HVAC excl. cooking	Cooking appliances	Envelope improvement (renovation)	Renewable energy production onsite
Latin America and Caribbean	Renewable energy production onsite	Efficient appliances, esp. cooking appliances	HVAC	Envelope improvement (renovation)	Envelope improvement (new)

Notes: HVAC in combination with the envelope.

Figure 9.18 presents the potential at global level integrating the potential delivered by technological energy efficiency and renewable energy measures, as reported in Figure 9.17 and the potential of non-technological approaches and technological energy efficiency, as estimated by (Grubler et al. 2018). The figure was corrected for an overlap between potentials, relying on the estimates in Section 6.3. The figure argues that it is possible to mitigate at least 80% of emissions of global buildings. About 30% of this potential could be realised by non-technological approaches such as the change in energy service and its amount delivered. The next 40% of potential could be realised by technological energy efficiency. Finally, at least additional 12% could be delivered by renewable energy technologies integrated in buildings. We will make an attempt to integrate sufficiency in Figure 9.17 in FGD.

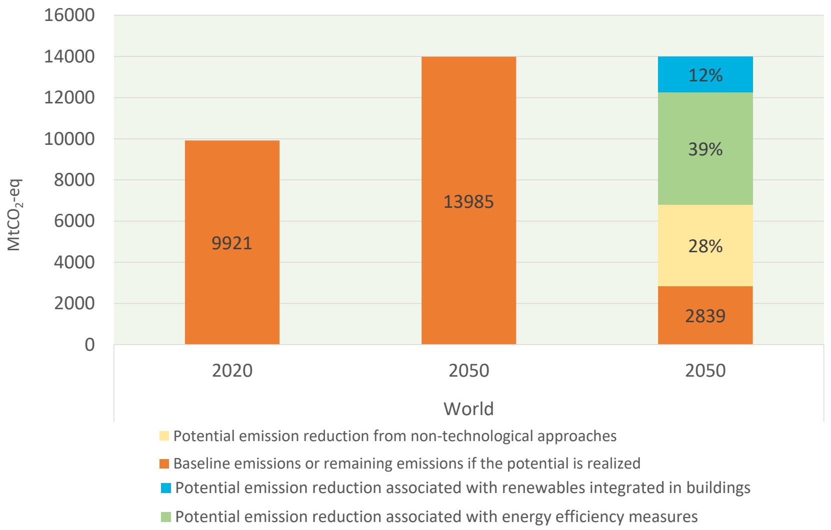


Figure 9.18 Potential GHG emission reduction (direct and indirect) in buildings at global level, 2050

9.6.3 Determinants of the potentials

All potential reported assume a widespread diffusion of a particular set of low-carbon technologies, in a manner similar to disruptive innovation. The chance to achieve such high penetration is a subject to feasibility uncertainties which will encourage or constrain the realisation of technologies and thus potential at scale. The feasibility constrains applicable to the buildings sector are discussed in detail in Section 9.10 and in the Supplementary Material Table SM9.5. From the technological point of view, the key determinants are stock turnover, speed of technological improvement, and cost learning.

9.6.3.1 Stock turnover

Buildings have a long lifetime and the feasibility of transforming them towards low carbon depends on its construction, demolition, and retrofit rates. As Figure 9.1 illustrates, high construction rates and high building replacement rates in developing countries offer an opportunity to realise a large amount of the potential in new buildings, introducing ambitious building energy codes, as discussed in Section 9.9. As shown in Section 9.3.2, a large amount of the energy savings realised due to energy efficiency improvement is however right away offset by an increase of floor area per capita. The construction rates are sometimes high even in countries with a large share of vacant buildings, for example in developing Europe (Novikova et al. 2018b). Therefore, one of critical determinants is policies supporting the realisation of sufficiency in terms of floor area per person above particular thresholds especially in developed countries where this resource is abundant, in addition to increasing the share of high-performance construction. Sufficiency does not necessarily mean a much lower service, but an alternative service. For instance, (Ivanova and Büchs 2020) illustrates that the per capita emission reduction of sharing a households with an additional member is 24% for European households Consideration of sufficiency in floor area per capita and integrating its estimates in the models is a novelty in literature since AR5.

Once a building is there, we observe a lock-in effect of energy consumption and GHG emission levels for many decades ahead, because a building is a large and complex technology with a long lifetime. Given low demolition rates in Europe, North America, and OECD Pacific, models assume high renovation rates to decarbonise the buildings stock as soon as possible. The studies reviewed assume renovation of the stock between 2.0% and 10% per annum, a speed which has never seen before. (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. Numerous barriers constrain the renovation of building as discussed in Section 9.9, in particular in urban areas (Seto et al. 2016; Ürge-Vorsatz et al. 2018; Khosla and Janda 2019). Therefore, without strong policies supporting these renovations, the feasibility to realise such potential is rather low.

9.6.3.2 Appliances, equipment, lights, renewable energy integrated

Similar, the potential energy savings from efficient appliances depends on their saturation rate and replacement rate. The size and lifetime of appliances and office equipment is much shorter than that of buildings, it is therefore more feasible to enable their quicker replacement than replacement or renovation of buildings (Chu and Bowman 2006; Spiliotopoulos 2019).

Whereas the data records a permanent energy efficiency improvement of individual devices (Cabeza and Vérez 2021), the demand for new services and devices offsets energy savings delivered by this improvement. (Grubler et al. 2018) provided an example how redefining an energy services and devices delivering it may help. The authors illustrated the reduction of energy demand by factor 30 to substitute over 15 different end-use devices with one integrated digital platform. Sufficiency approaches to appliances and equipment, with such drastic improvement have never been assessed at such large scale before and this is a novelty since AR5. This allows articulating that the sufficiency potentials in services delivered by appliances, equipment, and lights have not well being explored before and their consideration may help make the sector transformation more feasible.

9.6.3.3 Energy efficiency improvement

The other novelty since AR5 is that a growing amount of literature assessing potential at national scale rely on the application of integrated approaches to the construction and retrofit of buildings considering measures as interdependent and complementing. This approach allowed understanding the unprecedented scale of potential in several European countries and China heading towards climate neutrality, as illustrated by studies reported in Section 9.6.1. Even though the studies already report a very large potential, it is still likely to be an underestimate. The reason is that all studies reviewed considered only the application over the next 30 years of today's mature commercialised or near to commercialisation technologies. This assumption disregards the fact that efficiency of technologies is being constantly improved (Lovins 2018). Therefore, the potential is a dynamic value and the estimates assuming no technological changes are low estimates.

As said, nearly all studies assessing the technological potential also assume a change to climate cautious behaviour. Therefore, the adoption of policies promoting such behaviour is a feasibility factor of the realisation of the potential volume calculated by technological studies. Besides (Grubler et al. 2018) and (Millward-Hopkins et al. 2020) assessing the opportunities to drastically limit energy demand at global level, there have been only several non-peer-reviewed pieces of research which assess such opportunities at national and regional scale (IGES et al. 2019; Negawatt 2017). Therefore, whereas it is a promising trend, it leaves many questions behind such as what is the potential at national level in different countries and how to operationalise its realisation (Lovins 2018).

9.6.3.4 Embodied emissions

With the declining amount of energy and emissions during the building operation stage, the importance of embodied emissions in buildings grows (Cabeza et al. 2021; Peñaloza et al. 2018) (Section 9.2). This is reflected in the emerging literature, which assesses lifecycle emissions embodied in buildings at national level.

9.6.4 Determinants of costs

9.6.4.1 Integrated design approach vs incrementality

The growing consideration of integrated approach to construction of new buildings and renovation of existing buildings results in a lower relevance of breaking down the potential into cost categories, because to deliver deep energy and cost savings technologies and approaches shall be applied together in an integrated and interdependent manner. The construction of high-performance buildings is becoming a business-as-usual technology soon around the world (Ürge-Vorsatz et al. 2020): nearly 40% of new buildings in China had green certification in 2018 (Shen and Faure 2020), whereas the European Union legislation requires new public buildings to be nearly Zero Energy Buildings since 2018 and new commercial and residential buildings – since 2021. Based on the review of 79 case studies, (Erhorn-Kluttig et al. 2019) 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. This learning allowed to reduce their costs of energy conserved below the costs of energy or slightly higher that it in most countries (Ürge-Vorsatz et al. 2020) that translated to the mitigation cost below 20 USD/tCO_2.

For existing buildings, there have been many examples of deep retrofits which additional costs per CO_2 abated are not significantly higher than those of shallow retrofits (Filippi Oberegger et al. 2020), however for the whole stock they tend to be higher than those of new buildings, in the range of 0-20 USD/tCO_2.

Nearly all publications argue that it is critical, to define the right timing of building renovation integrating it as much as possible with business-as-usual renovation, to save costs. Thus, a review of studies (Neuhoff et al. 2011) reporting costs of buildings renovated to a high level of performance illustrated that the share of the latter costs exceeds significantly the share of incremental energy efficiency investment. Therefore, the rate of business-as-usual renovations is also an important determinant of deep renovations because it helps save a very high share of costs. In case of low business-as-usual retrofit rates, it is unlikely feasible to achieve high deep renovation rates.

Literature agrees that potential associated with the replacement of appliances, equipment, and lights with more efficient is lies below 0 USD/tCO$_2$ (Molenbroek et al. 2015). Integrated photovoltaic solar energy application costs are already near the level of electricity costs (Chapter 6). For the production of solar heat, it is likely that benefits will not balance the costs today, but they will with expected further cost reductions (Conti et al. 2019). Integrated renewable energy technologies are often a part of construction or retrofit packages rather than an individual measure that creates a synergy of costs.

9.6.4.2 Cost learning

Studies rarely consider the integration of cost learning into the potential cost figures which leads to their overestimation. Among the studies analysed there was no single study doing so. For a few comparable European studies, which conducted an assessment of the sector transformation aiming at emission reduction by 80-90% in 2050 as compared to 1990, the annual incremental investment need is estimated between 1% and 3.5% of GDP assuming constant prices (Kjell Bettgenhäuser and Andoni Hidalgo 2013; Markewitz et al. 2015). More research is needed to assess how far it is possible to enable cost learning and integrate it into the assessments. As of today, two such examples are known. First, the Dutch Energiesprong programme contracted the retrofits of 111,000 homes by 2020 (64) targeting energy savings of 45–80%. By developing innovative building prefabrication systems and project delivery models, the retrofit costs were reduced from EUR 130,000 down to EUR 65,000 (Ürge-Vorsatz et al. 2020). Second, the French Observatory of Low Energy Buildings found that the deep renovations of most buildings in France were cost-effective, and these were because they were conducted in one step using a holistic approach, a cap was set for absolute primary energy consumption to achieve after renovation, and a cap was set for the budget to deliver the targeted absolute primary energy consumption, and all available public finance was bundled (Saheb 2018).

9.7 Links to adaptation

Buildings are capital-intensive and long-lasting assets designed to perform under a wide 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 (Hallegatte 2009; de Wilde and Coley 2012; Wan et al. 2012) and, as such, adaptation measures will be necessary.

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 and their respective adaptation strategies interact with GHG mitigation in the buildings sector in different ways.

9.7.1 Climate change impacts and adaptation in buildings

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. 2012; 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. 2012; Li et al. 2012; Andrić et al. 2019). If not met, this higher demand for thermal comfort can impact health, sleep quality and work productivity, having disproportionate effects on vulnerable populations and exacerbating energy poverty (Falchetta and Mistry 2021; Biardeau et al. 2020) (see Section 9.8).

Increasing temperatures can lead to higher cooling needs and, therefore, energy consumption (Wan et al. 2012; Li et al. 2012; Andrić et al. 2019; Schaeffer et al. 2012; Clarke et al. 2018; International Energy Agency 2018) 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 to maintain the same indoor temperature will be higher (Andrić et al. 2019). These first two effects are often measured by cooling degree days[1] (CDD) and there is a vast literature on studies at the global (Atalla et al. 2018; Clarke et al. 2018; Biardeau et al. 2020; Mistry 2019; Isaac and van Vuuren 2009) and regional level (Bezerra et al. 2021; Falchetta and Mistry 2021; Zhou et al. 2014). 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; Biardeau et al. 2020; 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) (see Box 9.3). Warmer climates can induce higher ownership of cooling equipment, especially in developing countries (Pavanello et al. 2021).

The impacts of increased energy demand for cooling can have systemic repercussions (Ralston Fonseca et al. 2019; Ciscar and Dowling 2014), which in turn can affect the provision of other building's energy services. For instance, space cooling can be an important determinant of peak demand, especially in periods of extreme heat (International Energy Agency 2018). Warmer climates and higher frequency and intensity of heat waves can lead to higher loads (Dirks et al. 2015; Auffhammer et al. 2017), increasing the risk of grid failure and supply interruptions.

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 (Wan et al. 2012; Li et al. 2012). 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). In addition, climate change may affect the economic feasibility of district heating systems, for which demand density is a key parameter, and continuous starts and stops 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 increase the risk of overheating in a warming climate (Dodoo and Gustavsson 2016; Fosas et al. 2018) (see Section 9.4). 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).

Changes in cloud formation can affect global solar irradiation and, therefore, the output of solar photovoltaic panels, possibly affecting on-site renewable energy production in building (Burnett et al. 2014b). The efficiency of solar photovoltaic panels decreases with higher temperatures (Simioni and Schaeffer 2019), which may impact their economic feasibility and power generation potential. However, studies have found that such effect can be relatively small (Totschnig et al. 2017), making solar PV a robust option to adapt to climate change (Shen and Lior 2016; Santos and Lucena 2021) (see Section 9.4).

Climate change can also affect the performance, durability and safety of buildings and their elements (facades, structure, etc.) through changes in temperature, humidity, wind, and chloride and CO_2 concentrations (Bastidas-Arteaga et al. 2010; Bauer et al. 2018; Rodríguez-Rosales et al. 2021; Chen et

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FOOTNOTE [1] 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.

al. 2021). Historical buildings and coastal areas tend to be more vulnerable to these changes and are receiving more attention from researchers (Huijbregts et al. 2012; Mosoarca et al. 2019; Cavalagli et al. 2019; Rodríguez-Rosales et al. 2021).

Temperature variations affect the building's envelope, e.g. with cracks and detachment of coatings (Bauer et al. 2016, 2018). Higher humidity fastens deterioration of bio-based materials such as wood and bamboo (Brambilla and Gasparri 2020), also deteriorating indoor air quality and affecting users' health (Huijbregts et al. 2012; Grynning et al. 2017; Lee et al. 2020). Higher frequency and intensity of wind-driven rain can lead to more moisture accumulation, resulting in damages in buildings' facades, especially in historical buildings (Köliö et al. 2014; Nik et al. 2015; Orr et al. 2018).

Climate change can reduce reinforced concrete structures' durability, performance and safety due to the increase of chloride ingress (Bastidas-Arteaga et al. 2010) and the concentration of CO_2, which increase the corrosion (Stewart et al. 2012; Peng and Stewart 2016; Chen et al. 2021). Corrosion rates are higher in places with higher humidity and humidity fluctuations (Guo et al. 2019), and degradation could be faster with combined effects of higher temperatures and more frequent and intense precipitations (Bastidas-Arteaga et al. 2010; Chen et al. 2021).

Higher frequency and intensity of hurricanes, storm surges and coastal flooding can escalate economic losses to civil infrastructure, especially when associated with population growth and urbanisation in hazardous areas (Bjarnadottir et al. 2011; Lee and Ellingwood 2017; Li et al. 2016). Climate change, along with urban development, should also increase the risk and exposure to flood damage (de Ruig et al. 2019) and sea level rise (Bove et al. 2020; Zanetti et al. 2016; Bosello and De Cian 2014).

9.7.2 Links between mitigation and adaptation in buildings

Adaptation options interacts with mitigation efforts because the measures to cope with climate change impacts can increase energy and material consumption, which may lead to higher GHG emissions (Kalvelage et al. 2014; Davide et al. 2019; Sharifi 2020). Energy consumption is required to adapt to all impacts discussed in the previous section. Mitigation measures, in turn, influence the degree of vulnerability of buildings to future climate change and, thus, the level of adaptation required.

Studies have assessed the increases in energy demand to meet indoor thermal comfort under future warmer climate (de Wilde and Coley 2012; Li et al. 2012; Andrić et al. 2019; Clarke et al. 2018). It can be expected that higher cooling and lower heating needs may induce increases and shifts to electrical demand (Wan et al. 2012; Li et al. 2012), which could lead to higher emissions, when electricity generation is fuelled by fossil-fuels (International Energy Agency 2018; Biardeau et al. 2020), and generate higher loads and stress power systems (Dirks et al. 2015; Auffhammer et al. 2017). In this regard, increasing energy efficiency of space cooling appliances can reduce the amount of energy needed to fulfil cooling needs and limit additional growth in emissions and pressures on power systems (Davide et al. 2019; Bezerra et al. 2021) (see Section 9.4, Figure 9.11 and Tables SM9.1 to SM9.3). This can also be achieved with on-site renewable energy production, especially solar PV for which there is a timely correlation between power supply and cooling demand, improving load matching in energy producing buildings (Salom et al. 2014; Grove-Smith et al. 2018).

Mitigation alternatives through passive approaches may increase resilience to climate change impacts on thermal comfort by reducing the cooling needs associated with higher temperatures (Wan et al. 2012; Andrić et al. 2019; González Mahecha et al. 2020; Rosse Caldas et al. 2020; van Hooff et al. 2016). However, climate change may reduce their effectiveness (Ürge-Vorsatz et al. 2014a), in which case increased use of active cooling could be required (Yildiz 2015). Nevertheless, combining different passive measures can help counteracting climate change driven increases in energy consumption for achieving thermal comfort (Huang and Hwang 2016).

In cold climates, high energy performance buildings (e.g. ZEB, Passivhaus, etc.) use increased insulation and airtightness to reduce heat losses, which can potentially increase the risk of overheating in a warming climate (Gupta and Gregg 2012). In such situations, the need for active cooling technologies may arise, along with higher energy consumption and GHG emissions (Gupta et al. 2015). However, while overheating may occur as a result of poor insulation design, better insulation may actually reduce overheating when properly projected, meaning that the apparent trade-off between mitigation through building insulation and higher overheating risk can be overcome by clever designs (Fosas et al. 2018).

Strengthening building structures to increase resilience and reduce exposure to the risk of extreme events can be partially achieved by improving building standards and retrofitting existing buildings (Bjarnadottir et al. 2011). However, future climate is not yet considered in parameters of existing building energy codes (Steenbergen et al. 2012). While enhancing structural resilience would lead to GHG emissions (Liu and Cui 2018), so would disaster recovery and re-building. This emissions trade-off needs to be further assessed.

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. 2012; de Rubeis et al. 2020) and emissions (Liu and Cui 2018). Building energy codes and regulations are usually based on historical climate data, which can lead to the poor design of thermal comfort in future climate (Hallegatte 2009; de Wilde and Coley 2012; Pyke et al. 2012) and non-efficient active adaptive measures based on mechanical air conditioning (De Cian et al. 2019) (see Section 9.4, Figure 9.11 and Tables SM9.1 to SM9.3). However, 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; González Mahecha et al. 2020) and in developing countries.

The impacts on buildings durability and life span can lead to higher maintenance needs and the consequent embodied environmental impacts related to materials production, transportation and end-of-life, which account for a relevant share of GHG emissions in buildings life cycle (Rasmussen et al. 2018). Climate change induced biodegradation is especially important for bio-based materials such as wood and bamboo (Brambilla and Gasparri 2020) which are important options for reducing emissions imbued in buildings' construction materials (Peñaloza et al. 2016; Churkina et al. 2020b).

Although there can potentially be conflicts between climate change mitigation and adaptation, these can be dealt with proper planning, actions and policies. The challenge is to develop multifunctional solutions, technologies and materials that can mitigate GHG emissions while improving buildings' adaptive capacity. Solutions and technologies should reduce not only buildings' operational emissions, but also embodied emissions from manufacturing and processing of building materials (Röck et al. 2020). For instance, some building materials, such as bio-concrete, can reduce life cycle emissions of buildings and bring benefits in terms of building thermal comfort in tropical and subtropical climates (Rosse Caldas et al. 2020). Also, energy efficiency, sufficiency and on-site renewable energy production can help to increase building resilience to climate change impacts and reduce pressure on the energy system.

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. 2017; IEA 2014; US EPA 2018; Kamal et al. 2019; Bleyl et al. 2019). In other words, the implementation of these actions 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, in both developed and developing economies, which can be categorised into the following types (Reuter et al. 2017; Ürge-Vorsatz et al. 2016; IEA 2014; US EPA 2018; Nikas et al. 2020; Thema et al. 2017; Ferreira et al. 2017a): (i) health impacts due to better indoor conditions, energy/fuel poverty alleviation, better ambient air quality and elimination of the heat island effect; (ii) environmental benefits such as reduced local air pollution and the associated impact on ecosystems (acidification, eutrophication, etc.) and infrastructures, reduced sewage production, etc.; (iii) improved resource management including water and energy; (iv) impact on social well-being, including changes in disposable income due to decreased energy expenditures and/or distributional costs of new policies, fuel poverty alleviation and improved access to energy sources, rebound effects, increased productive time for women and children, etc.; (v) microeconomic effects (e.g., productivity gains in non-residential buildings, enhanced asset values of green buildings, fostering innovation); (vi) macroeconomic effects, including impact on GDP driven by energy savings and energy availability, creation of new jobs, decreased employment in the fossil energy sector, long-term reductions in energy prices and possible increases in electricity prices in the medium run, possible impacts on public budgets, etc.; and (vii) energy security implications (e.g., access to modern energy resources, reduced import dependency, increase of supplier diversity, smaller reserve requirements, increased sovereignty and resilience).

Key point: Achieving SDG targets requires implementation of ambitious climate mitigation policies which include sufficiency measures to align building design, size and use with SDGs, efficiency measures to ensure high penetration of best available technologies and supplying the remaining energy needs with renewable energy sources

Figure 9.19 Contribution of mitigation policies of the building sector to meeting sustainable development goals

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 mitigation 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 9.5 reviews and updates 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 sufficiency and efficiency improvements as well as improved access and fuel switch to modern low carbon energy, contribute to achieving 16 out of a total of 17 SDGs. Following the seven-point scale proposed by (Nilsson et al. 2016), the interactions between mitigation options and the SDGs have been evaluated and presented also in Table 9.5, highlighting that mitigation actions in buildings interact positively with 15 SDGs (with a score of greater than +1 for 12 SDGs), while some rather minor negative interactions (score -1) were identified with 8 SDGs. The second part of Table 9.5 presents more detailed analysis on how the various dimensions of mitigation actions (i.e., the basic types of multiple impacts defined previously) generate impacts across multiple SDG targets, further explained in the comments accompanying Table 9.5.

Table 9.5 Aspects of mitigation actions in buildings and their contributions to the 2030 Sustainable Development Goals

Dimensions of climate change mitigation in buildings	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
Type of interventions																	
Building sufficiency	+2	+1	+3	0	0	+2	+3	+2/-1	+2/-1	+1	+2	+2	+2	0	0	+1	0
Energy efficiency improvements	+2/-1	+2	+3/-1	+1	+1	+2	+3	+3/-1	+2/-1	+1/-1	+2	+2/-1	+3	0	+2	+2	+1
Improved access and fuel switch to lower carbon and renewable energy	+2/-1	+2/-1	+3	+1	+1	+2/-1	+3	+2/-1	+2/-1	+1/-1	+3	+2	+3	0	+2	+2	+1
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 well-being	X	X	X	X	X	X	X	X		X	X				X	X	
Microeconomic effects					X			X	X		X	X					
Macroeconomic impacts								X		X	X						
Energy security							X		X								

Notes: The strength of interaction between mitigation actions and SDGs is described with a seven-point scale (Nilsson et al., 2016) Also, the symbol X shows the interactions between co-benefits/risk associated with mitigation actions and the SDGs. **SDG1**: Sufficiency and efficiency measures result in reduced energy expenditures and other financial savings that further lead to poverty reduction. Access to modern energy forms will largely help alleviate poverty in developing countries as the productive time of women and children will increase, new activities can be developed, etc. The distributional costs of some mitigation policies promoting energy efficiency and lower carbon energy may reduce the disposable income of the poor. **SDG2**: Energy sufficiency and efficiency measures result in lower energy bills and avoiding the "heat or eat" dilemma. Improved cookstoves provide better food security and reduces the danger of fuel shortages in developing countries; under real-world conditions these impacts may be limited as the households use these stoves irregularly and inappropriately. Improving energy access enhances agricultural productivity and improves food security; on the other hand, increased bioenergy production may restrict the available land for food production. **SDG3**: All categories of mitigation actions result in health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect. Efficiency measures with inadequate ventilation may lead to the sick building syndrome symptoms. **SDG4**: Energy efficiency measures result in reduced school absenteeism due to better indoor environmental conditions. Also, fuel poverty alleviation increases the available space at home for reading. Improved access to electricity and clean fuels enables people living in poor developing countries to read, while it is also associated with greater school attendance by children. **SDG5**: Efficient cookstoves and improved access to electricity and clean fuels in developing countries will result in substantial time savings for women and children, thus increasing the time for rest, communication, education and productive activities. **SDG6**: Reduced energy demand due to sufficiency and efficiency measures as well as an upscaling of RES can lead to reduced water demand for thermal cooling at energy production facilities. Also, water savings result through improved conditions and lower space of dwellings. Improved access to electricity is necessary to treat water at homes. In some situations, the switch to bioenergy could increase water use compared to existing conditions. **SDG7**: All categories of mitigation actions result in energy/fuel poverty alleviation in both developed and developing countries as well as in improving the security of energy supply. **SDG8**: Positive and negative direct and indirect macroeconomic effects (GDP, employment, public budgets) associated with lower energy prices due to the reduced energy demand, energy efficiency and RES investments, improved energy access and fostering innovation. Also, energy efficient buildings with adequate ventilation, result in productivity gains and improve the competitiveness of the economy. **SDG9**: Adoption of distributed generation and smart grids helps in infrastructure improvement and expansion. Also, the development of "green buildings" can foster innovation. Reduced energy demand due to sufficiency and efficiency measures as well as an upscaling of RES can lead to early retirement of fossil energy infrastructure. **SDG10**: Efficient cookstoves as well as improved access to electricity and clean fuels in developing countries will result in substantial time savings for women and children, thus enhancing education and the development of productive activities. Sufficiency and efficiency measures lead to lower energy expenditures, thus reducing income inequalities. The distributional costs of some mitigation policies promoting energy efficiency and lower carbon energy as well as the need for purchasing more expensive equipment and appliances may reduce the disposable income of the poor and increase inequalities. **SDG11**: Sufficiency and efficiency measures as well as fuel switching to RES and improvements in energy access would eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor). Helpful if in-situ production of RES combined with charging electric two, three and four wheelers at home. Buildings with high energy efficiency and/or green features are sold/rented at higher prices than conventional, low energy efficient houses. **SDG12**: Energy sufficiency and efficiency measures as well as deployment of RES result in reduced consumption of natural resources, namely fossil fuels, metal ores, minerals, water, etc. Negative impacts on natural resources could be arisen from increased penetration of new efficient appliances and equipment. **SDG13**: Please see sections 9.4-9.6. **SDG15**: Efficient cookstoves and improved access to electricity and clean fuels in developing countries will result in halting deforestation. **SDG16**: Building retrofits are associated with lower crime. Improved access to electric lighting can improve safety (particularly for women and children). Institutions that are effective, accountable and transparent are needed at all levels of government for providing energy access and promoting modern renewables as well as boosting sufficiency and efficiency. **SDG17**: The development of zero energy buildings requires among others capacity building, citizen participation as well as monitoring of the achievements.

Sources: (Alawneh et al. 2019; Balaban and Puppim de Oliveira 2017a; Barnes and Samad 2018; Bailis et al. 2015; Baimel et al. 2016; Berrueta et al. 2017; Bleyl et al. 2019; Boermans et al. 2015; Brounen and Kok 2011; Burney et al. 2017; Cajias et al. 2019a; Camarinha-Matos 2016; Cameron et al. 2016; Cedeño-Laurent et al. 2018; De Ayala et al. 2016; Deng et al. 2012; EU 2016; Fuerst et al. 2015, 2016; Fricko et al. 2016; Galán-Marín et al. 2015; Goldemberg et al. 2018; Grubler et al. 2018; Hanna et al. 2016; Hasegawa et al. 2015; Hejazi et al. 2015; Högberg 2013; Holland et al. 2015; Hyland et al. 2013; Jensen et al. 2016; Jeuland et al. 2018a; Kahn and Kok 2014; Koirala et al. 2014; Levy et al. 2016; Liddell and Guiney 2015; P. et al. 2018; Maidment et al. 2014; Markovska et al. 2016; Marmolejo-Duarte and Chen 2019; Mastrucci et al. 2019; Mattioli and Moulinos 2015; McCollum et al. 2018; Mehetre et al. 2017b; Mirasgedis et al. 2014; Mofidi and Akbari 2017; Mzavanadze 2018a; Niemelä et al. 2017; Ortiz et al. 2017; Payne et al. 2015; Rao et al. 2016; Rao and Pachauri 2017; Rosenthal et al. 2018; Saheb et al. 2018b,a; Scott et al. 2014; Smith et al. 2016; Steenland et al. 2018; Tajani et al. 2018; Teubler et al. 2020; Thema et al. 2017; Thomson et al. 2017a; Tonn et al. 2018; Torero 2015; Ürge-Vorsatz et al. 2016; Van de Ven et al. 2020; Venugopal et al. 2018; Wierzbicka et al. 2018a; Willand et al. 2015; Winter et al. 2015; Zheng et al. 2012; Liu et al. 2015a; Nikas et al. 2020; Sola et al. 2016; Song et al. 2016; Zhao et al. 2017)

Despite wider recognition of the multiple benefits of investing in energy sufficiency and efficiency as well as low carbon and RES 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 (Ürge-Vorsatz et al. 2016) and (Payne et al. 2015) showed that the size of multiple benefits of mitigation actions 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 mitigation actions was equal or greater than the value of energy savings. Even in these studies, several effects have not been measured and consequently the size of multiple benefits of mitigation actions may be even higher. Quantifying and if possible, monetising, these wider impacts of climate action would facilitate their inclusion in cost-benefit 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 impacts of mitigation actions in the buildings sector, with a view to providing methods, quantitative estimates (in physical or monetary terms) that can be utilised in the decision-making process, and information on their contribution to relevant SDGs.

9.8.2 Climate mitigation actions in buildings and health impacts

9.8.2.1 Lack of access to clean energy

In 2017, approximately 3 billion people worldwide, most of whom live in Asia, Africa, and the Americas, still use polluting fuels, such as fuelwood (see Box 9.8), charcoal, dried crops, cow dung, and kerosene in low-efficiency stoves for cooking and heating, generating household air pollution (HAP), which adversely affects the health of the occupants of the dwellings, especially children and women (IEA et al. 2019; World Health Organization 2016; Quinn et al. 2018; Rahut et al. 2017; Mehetre et al. 2017b; 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, strokes, cancers, acute lower respiratory injections in 2016 (World Health Organization 2018). It is acknowledged that integrated policies are needed to address simultaneously universal energy access, limiting climate change and reducing air pollution (World Health Organization 2016; Rafaj et al. 2018) showed that a scenario achieving these SDGs in 2030 will imply in 2040 two 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).

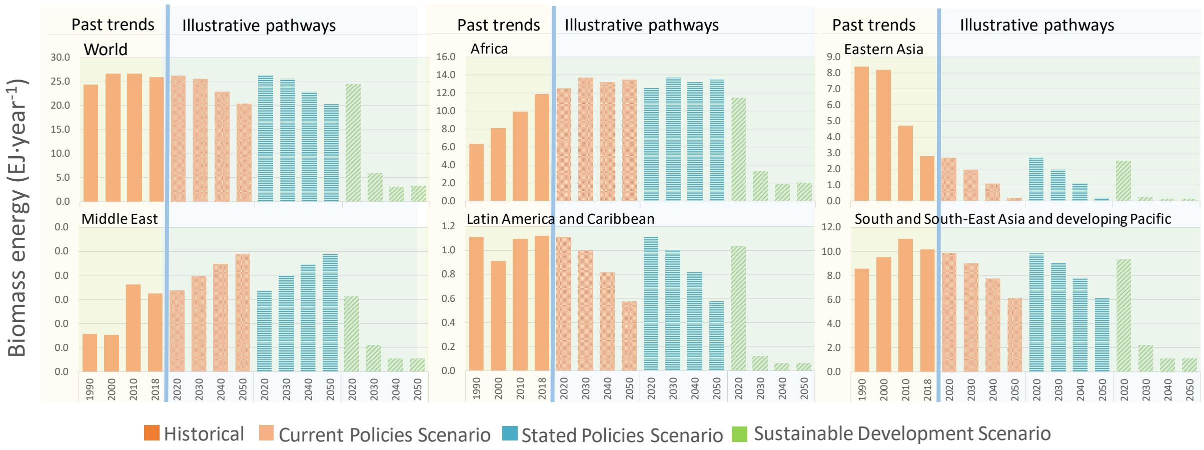
At the core of these policies is the promotion of improved cook-stoves and the use of cleaner fuels by poor households in developing countries (Figure 9.20). Most studies agree that the use of cleaner energy options such as LPG, ethanol, biogas, and electricity is more effective in reducing the health 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). A number of 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)), while some others claim 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. 2018b; Malla et al. 2011)). The evaluation of the improved biomass burning cook-stoves under real-world conditions has shown that they have lower than expected, and in many cases, limited long-run health and environmental impacts, as the households use these stoves irregularly and inappropriately, fail to maintain them, and their usage decline over time (Hanna et al. 2016; Wathore et al. 2017; Patange et al. 2015; Aung et al. 2016). In this context, the various improved cook-stoves programs should consider the mid- and long-term needs of maintenance, repair, or replacement to support their sustained use (Schilmann et al. 2019; Shankar et al. 2014).

Box 9.8 Biomass in the building sector

Biomass is used, if the wood is available locally, either for constructing buildings or for providing end-use services such as cooking and heating. According to (Stark et al. 2019), the use of biomass in the form of wood to construct buildings, in countries with high availability of timber and no competition for land with food production, contributes to reducing GHG emissions by storing carbon and displacing carbon intensive construction materials such as cement, bricks, and steel. Embodied emissions of wooden buildings are lower than those of concrete buildings given the low embodied impact factor of wood products, which ranges between 0.29 and 1.02 kg CO_2-eq·kg^{-1} compared to the embodied impact factor of material for concrete, which ranges between 0.05 and 5.15 kg CO_2-eq·kg^{-1} (Basbagill et al. 2013)

In developed countries, biomass is used for generating heat and power leading to reduction of indirect emissions from buildings (Ortwein 2016)(Ericsson and Werner, 2016). However, according to (International Energy Agency 2019d) despite the mitigation potential of biomass, its use remains low in developed countries. Biomass is also used for efficient cook stoves and for heating using modern appliances such as pellet-fed central heating boilers. In developing countries, traditional use of biomass is characterised by low efficiency of combustion (due to low temperatures) leading to high levels of pollutants and CO output, as well as low efficiency of heat transfer. The traditional use of biomass is associated with public health risks such as pre mature deaths related to inhaling fumes from cooking (International Energy Agency 2019d; Dixon et al. 2015b; Van de Ven et al. 2019; Taylor et al. 2020). According to (Hanna et al. 2016) policies failed in improving the use of biomass in the long run in India.

Over the period 2010-2018, the global use of biomass decreased by 3%. The highest decrease in the use of biomass was observed in Eastern Asia, with 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 biomass, with a 20% increase, over the period 2010-2018, followed by Latin America and Caribbean countries with an increase of 3% in the use of biomass (Box 9.8 Figure 1). Traditional use of biomass occurs also in some developed countries such as in Turkey where more than 14 % of the heat produced is derived from traditional use of biomass (Toklu 2017); Greece and Portugal where traditional use of biomass is mentioned as one of the potential source for heat production (Michopoulos et al. 2014; Ferreira et al. 2017b). Illustrative pathways based on the IEA scenarios show a continuation of the use of biomass in developing countries (Box 9.8 Figure 1). However, in the scenario aiming at meeting sustainable development goals, notably SDG 7, by 2050, the use of biomass is projected to be 84% lower than in the current policy scenario. In the sustainable development scenario, by 2050, biomass will no longer be used in Middle East while it will decrease by 90% in Latin America and Caribbean countries and by 85% in Africa.



Box 9.8 Figure 1 Global and regional biomass energy in the residential sector: historical based on IEA statistics data and illustrative pathways based on IEA WEO data. Source: (Saheb et al. 2021)

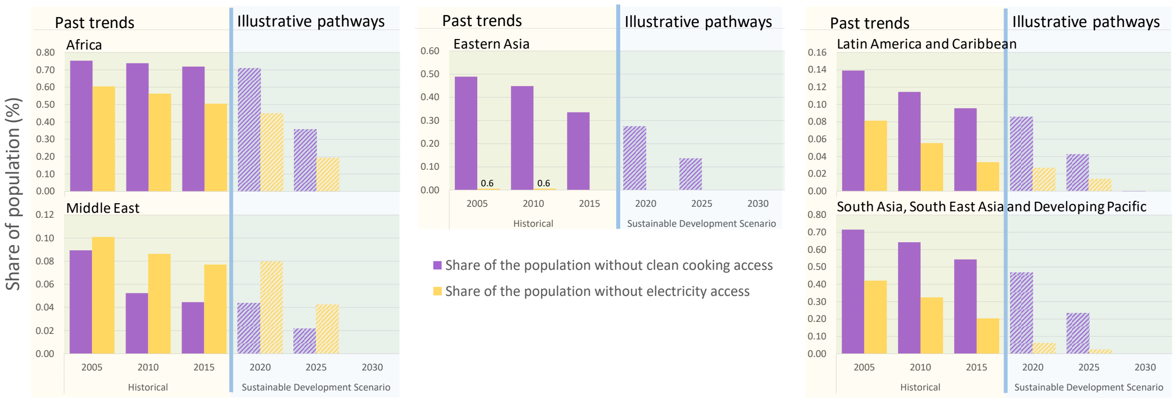


Figure 9.20 Trends on energy access: historical based on IEA statistics data and illustrative pathways based on IEA WEO data.
Source**:** (Saheb et al. 2021)

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/fuel 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 2018b) 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. 2017b; Nunes 2019). 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 the 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 (see also Section 9.7), with the poorest, who cannot afford to install air conditioning to keep them cool, and older adults (Nunes 2020) to be the most vulnerable.

Improved energy efficiency in buildings contributes in fuel poverty alleviation and 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 fuel 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 fuel poverty target the most socially vulnerable households (Lacroix and Chaton 2015; Camprubí et al. 2016), highlighting the importance of identifying energy-poor households. (Mzavanadze 2018a) 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. 2018b; 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, mould, 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).

The health benefits of mitigation actions in buildings are significant and their quantification may improve decision making processes. (Tonn et al. 2018) quantified a great variety of health-related benefits attributed to the two weatherisation 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.

9.8.2.3 Outdoor air pollution

According to (World Health Organization 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 2017b; Karlsson et al. 2020). Several studies have monetised the health benefits attributed to reduced outdoor air pollution due to the implementation of mitigation actions 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; Joyce et al. 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 2018b), while some negative effects cannot be excluded (e.g., (Dylewski and Adamczyk 2016)).

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 monetised 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 maximising recycling of old appliances.

Mitigation actions aiming to reduce the embodied energy of buildings through using local and sustainable building materials can be used to leverage new supply chains (e.g., for forestry products), which in turn bring further environmental and social benefits to local communities (Hashemi et al. 2015; Cheong C and Storey D 2019). 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 well-being

9.8.4.1 Energy/fuel poverty alleviation

In 2017 almost 0.84 billion people in developing countries didn't have access to electricity, while approximately 3 billion people relied on polluting fuels and technologies for cooking (World Health Organization 2016; IEA,IRENA,UNSD,World Bank 2018; IEA et al. 2019). 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 fuel 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 fuel poverty rates in Japan reached 8.4% in 2013. In the US, in 2015, 17 million households (14.4% of the total) received an energy disconnect/delivery stop notice and 25 million households (21.2% of the total) had to forgo food and medicine to pay energy bills (Bednar and Reames 2020).

The implementation of well-designed climate mitigation measures in buildings can help to reduce energy/fuel 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 mitigation 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 fuel poverty across the EU lies between 5.17 and 8.26 million. To capture these benefits, mitigation 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 fuel poverty, the application of different measurement methodologies often leads to divergent results, while several of these approaches do not account the depth of fuel poverty and/or the frequency of feeling cold/warm, capturing the problem imperfectly, and providing limited information for identifying energy-poor households (Deller 2018; Ntaintasis et al. 2019; Waddams Price et al. 2012), which is a prerequisite for developing targeted and effective policies to tackle the problem (Baker et al. 2019). A number of studies (e.g., (Herrero 2017; Deller 2018; Ntaintasis et al. 2019)) argue against single-indicator fuel poverty metrics and advocate multiple-indicator approaches or other dynamic metrics, the development of which needs further research. In this context, it is recognised that fuel poverty should be analysed as a multidimensional social problem (Thomson et al. 2017b; Mashhoodi et al. 2019), as it 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, disposable income, etc. In addition, the geographical dimension can have a significant impact on the levels of fuel poverty and should be taken into account when formulating response policies (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 (World Health Organization 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 (World Health Organization 2016; Mehetre et al. 2017a). 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. 2017a; World Health Organization 2016).

Expanding access to clean household energy for cooking, heating and lighting will largely help alleviate these burdens (Rosenthal et al. 2018; World Health Organization 2016; Lewis et al. 2017). (Jeuland et al. 2018b) 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 $ per household per 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, socialise, and be more productive during the evening, while it is also associated with greater school attendance by children (Barnes and Samad 2018; 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 maximising the social benefits of electrification.

9.8.5 Economic implications of mitigation actions

9.8.5.1 Buildings-related labour productivity

Low-carbon 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 monetisation 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 Ürge-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 retro-fitted 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. A review of 15 studies from 12 different countries showed 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 (the detailed results of this review are presented in Table SM9.4 included in the Supplementary Material). 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 realised 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 SM9.4 of Supplementary Material) show that energy efficiency and green features have also a positive effect on rental prices of dwellings (Cajias et al. 2019b; 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).

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). On the other hand, in Australia, a review study showed mixed evidence regarding price differentials emerged as a function of energy performance of office buildings (Acil Allen Consulting 2015).

More generally, (Giraudet 2020) based on a meta-analysis of several studies, showed that the capitalisation of energy efficiency is observed in building sales and rental (even in the absence of energy performance certificates), but the resulting market equilibrium can be considered inefficient as rented dwellings are less energy efficient than owner-occupied ones.

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 Gross Value Added (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 maximised when the related investments are realised in periods of economic recession (Ürge-Vorsatz et al. 2014b; 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) (Figure 9.20). As many of these programs are carried out with foreign assistance funds, it is essential that the funds be spent 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 (Cambridge Econometrics 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 subsidising 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 thermal energy uses; and (iii) enhancing distributed generation through the incorporation of RES and other clean and smart technologies in buildings. Increasing sufficiency, energy efficiency and penetration of RES 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). The electrification of thermal energy uses 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 (Couder and Verbruggen 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. 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). 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 are not taking place as expected by rational economic behaviour is critical to design effective policies for decarbonise the building sector, as noted by (Cattaneo 2019; Cattano et al. 2013). Barriers to energy efficiency in buildings have been investigated and categorised by different scholars in different categories (Reddy 1991; Weber 1997; Sorrell et al. 2000; Reddy 2002; Sorrell et al. 2011). More recently (Cagno et al. 2012) classified barriers according to the type of actors, their role in energy efficiency projects and the economic, social and policy structures. (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; sector and contextual level (institutional framework, regulations, policies, etc.). More recently, barriers have been analysed by (Bagaini et al. 2020) and classified in three main categories. (Zhang and Wang 2013) has identified major barriers to promoting energy efficiency in buildings in China classified as: legal; administrative; financial; market; social. (Song et al. 2020) analysed the barriers of investment risks, monitoring capacity and policies intermittency in the building sector in China. (Khosla et al. 2017) and (Gupta et al. 2017) classified barriers in building energy efficiency in India 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. Among the barriers for rooftop solar installation in buildings, the lack of clear and reliable information to end-users together with of skills of the installers (Do et al. 2020; Dutt 2020). In most of the research on barriers the end user behaviour is identified as a key barrier. A better understanding of barriers, in particular behavioural barriers (Frederiks et al. 2015) is therefore essential to design effective policies to decarbonise the building sector. Many barriers impede the energy refurbishment existing buildings (Palm and Reindl 2018; Bertoldi 2020), from information gap to financing to split incentives. Energy efficiency policy for buildings face two additional problems. First, the sector is highly heterogeneous, with many different building types, sizes and operational uses. Second, rented property faces principal/agent problems where the tenant benefits from the energy efficiency investment by the landlord.

Energy efficiency policy has focused on overcoming barriers. However, a problem with this approach is that decisions about energy efficiency investments do not take place in isolation but in competition with other priorities and as part of a complex, protracted investment process (Cooremans 2011). Subsequent research showed that a focus on overcoming barriers is not enough for effective policy. Organisational context is important because the same barrier might have very different organisational effects and require very different policy responses (Mallaburn 2018).

9.9.2 Rebound effects

In the buildings sector energy efficiency improvements and promotion of cleaner fuels can lead to all types of rebound effects, while sufficiency measures lead only to indirect and secondary effects (Chitnis et al. 2013).

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 (Galvin and Sunikka-Blank 2017). 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 usually implicated in high rebound effects upon retrofitting (Galvin and Sunikka-Blank 2017; Teli et al. 2016; Calì et al. 2016). The access for all to modern energy services such as heating and cooling is one of the wellbeing objectives governments aim for. However, ensuring this access leads to an increase of energy demand which is considered as a rebound effect by (Teli et al. 2016; Berger and Höltl 2019; Poon 2015; Seebauer 2018; Sorrell et al. 2018; Chitnis et al. 2013; Orea et al. 2015). (Aydin et al. 2017) found that in the Netherlands the rebound effect for the lowest wealth quantile is double compared to the highest wealth quantile. Similar, energy access in developing countries leads to an increase consumption compared to very low baselines which is considered by some authors as rebound (Copiello 2017). On the other hand, in households whose members have a higher level of education and/or strong environmental values, the rebound is lower (Seebauer 2018).

Rebound effects in the building sector could be a co-benefit, in cases where the mechanisms involved provide faster access to affordable energy and/or contribute to improved social well-being, or a trade-off, to the extent that the external costs of the increased energy consumption exceed the welfare benefits of the increased energy service consumption (Galvin and Sunikka-Blank 2017; Sorrell et al. 2018). In cases where rebound effects are undesirable, appropriate policies could be implemented for their mitigation.

Several studies examined in the context of this assessment (see Table 9.6) showed that direct rebound effects for residential energy consumption, which includes heating, are significant and range between 9-91% in Europe, 0-30% in the US, and 66-236% in China. The direct rebound effects for energy services other than heating may be lower (Sorrell et al. 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 (Calì 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% and 80% (Table 9.6). 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 utilised, the period of analysis and the geographical area in consideration (Gillingham et al. 2016; International Risk Governance Council 2013; Galvin 2014). In tertiary buildings the rebound effects may be smaller, as the commercial sector is characterised 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).

9.9.3 Policy packages for the decarbonisation of buildings

In public policy, and, in particular, in environmental policy, there is no single policy 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). Policy packages includes a range of different policy instruments to enhance robustness against risks and uncertainties jeopardising the success of the measures, in both short and long-term and addressing the different stakeholder perspectives (Forouli et al. 2019; Nikas et al. 2020; Doukas and Nikas 2020). As highlighted in literature there is not a single energy efficiency policy (Wiese et al. 2018) able to decarbonise the building sector. This is. due to: the several barriers; the different types of buildings (residential, non-residential, single family, etc.); the different socio economic groups of the population (social housing, informal settlement, etc.); the country development status; the local climate (predominance of cooling and/or heating), ownership structure (tenant or owner), the age of building. Several studies have highlighted the role of effective policy packages for the de-carbonisation of the building sector (Kern et al. 2017; Rosenow et al. 2017; Wiese et al. 2018), including mandatory targets, codes, the provision of information, financing and technical assistance for end-users). (Rosenow and Bayer 2017) analysed packages of policy instruments for building energy efficiency in EU Member States. Important element related to policy packages is whether the policies reinforce each other or diminish the impact of individual policies, this is often the situation when there is policy "overcrowding". As example, the EU policy package for energy efficiency in buildings is presented in the Supplementary Material (Section SM9.3).

Table 9.6 Estimates of the direct and indirect rebound effects for households

Rebound effects		Range	Mean	Median	References
Direct	Including thermal uses	9-236%	44%	36%	(Galvin 2015; Galvin and Sunikka-Blank 2016; Teli et al. 2016)(Calì et al. 2016; Copiello and Gabrielli 2017; Aydin et al. 2017; Cayla and Osso 2013; Terés-Zubiaga et al. 2016; Madonna et al. 2017; Sandberg et al. 2017; Holzmann and Schmid 2018)(Bardsley et al. 2019; Hens et al. 2010; Chitnis et al. 2013; Thomas and Azevedo 2013; Wang et al. 2014; Lin and Liu 2015)(Brøgger et al. 2018)
	Electric uses	3-14%	7%	5%	(Chen et al. 2018; Chitnis et al. 2013; Schleich et al. 2014)
Indirect		1.8-23.5%	10%	11%	(Cellura et al. 2013; Thomas and Azevedo 2013; Chitnis et al. 2013; Santos et al. 2018; Walzberg et al. 2020)
Direct and indirect		4.5-80%	32%	27%	(Scheer et al. 2013; Qiu et al. 2019; Murray 2013; Orea et al. 2015)

Example of policy package are the current policies addressing split incentives in the building sector including 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 (Bird and Hernández 2012; Economidou and Bertoldi 2015; Castellazi et al. 2017). This includes 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.

In developed countries policy packages are investigated to increase the number of existing building refurbishment and the depth of the refurbishments. Most of the policies suggested in this section are also effective for developing countries, in particular when these include regulatory measures (and incentives (grants), while the carbon tax could be more problematic unless there is a strong recycling of the revenues. In addition, specific policy addressing life cycle analysis and reduction of embedded CO_2 emissions in building construction material are still to further be investigated and developed. Building energy codes and building labels could be based on LCA emissions, rather than energy consumption during the use phase of the buildings. Finally, policy packages should also combine renewable energy and energy efficiency instruments for buildings, for example the most advanced building energy codes already include minimum requirements for the use of renewable energy in buildings.

9.9.3.1 Sufficiency and efficiency policies

Recently the concept of energy sufficiency as a complementary strategy to energy efficiency has been introduced in policy making. (Bertoldi 2020; Hewitt 2018; 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 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 (Brischke et al. 2015; Thomas et al. 2019), in particular on ways to introduce sufficiency in policy making. (Lorek and Spangenberg 2019b) 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 a heuristic sufficiency policy tool. (Lorek and Spangenberg 2019b) 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 energy codes (IEA, 2013) (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 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. Policies for sufficiency include land-use and urban planning policies sufficiency requirements in building energy codes (International Energy Agency 2013) and also consumer policies.

Several scholars have identified and classified energy efficiency policies needed to address the "energy efficiency gap" (Hirst and Brown 1990; Jaffe and Stavins 1994) and eliminate, overcome, or reduce the barriers. Based on the categorisation of environmental policies in three broad category by (Opschoor and Vos 1989) and (Christidou et al. 2014b) to classify energy efficiency policies in three broad categories: the command and control (e.g. mandatory building energy 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.). More recently, (Shen et al. 2016) proposed three categories: mandatory administration instruments, economic incentive instruments and voluntary schemes. He 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.

Based on the EU Energy Efficiency Directive, Article 7 (Rosenow et al. 2017; Bertoldi 2020), the MURE database and the IEA energy efficiency policy database (Bertoldi and Mosconi 2020; M. Economidou and Bertoldi 2015) proposed six policy categories: regulatory, financial and fiscal; information and awareness; qualification, training and quality assurance; market-based instruments: voluntary action. The categorisation of energy efficiency policies used in this chapter is aligned with the taxonomy used in Chapter 13, sub-section 13.6.1 (i.e. economic or market-based instruments, regulatory instruments, and other policies). However, the classification used here is more granular in order to capture the complexity of end-use energy efficiency and buildings (several types, e.g. residential, commercial, single family, etc., in very different regions and climates).

Sufficiency and efficiency instruments could be regulatory and/or information instruments and are, usually complemented to market-based instruments.

Regulatory instruments

Building energy codes

Several scholars highlighted the role of mandatory building energy codes and minimum energy performance requirements for buildings (Enker and Morrison 2017). (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 urbanisation content in China". Building energy codes can also include minimum requirements for renewable energy in buildings. As compliance with building energy codes is assessed before the construction of the building, i.e. when the building permits are issue, there is the need to strengthen the compliance checks with energy efficiency requirements when the building is in operation. (Evans et al. 2017) highlights the need for enforcement of building energy codes in order to achieve the estimate energy and carbon savings, the authors recommend some steps to improve enforcements, including institutional capacity and adequate resources (Evans et al. 2018). (Yu et al. 2018, 2017) shows the role of building energy codes in reducing energy consumption of the building stock in India and the contribution to the India NDC. (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 et al. 2015) indicating that stringent building energy codes and equipment efficiency standards are cost-effective policies to reduce energy consumption in buildings and greenhouse gas emissions. Progressive building energy codes include requirements on efficiency improvement but also on sufficiency measures and the share of renewables (Brown et al. 2013b) and on embodied emissions (Schwarz et al. 2020).

Another important issue to be addresses by policies is the 'Energy Performance Gap' (EPG), i.e. the gap between design and policy intent and actual outcomes. Regulatory and market support regimes are based on predictive models (Cohen and Bordass 2015) and general assumptions about building types, the way they might be used and are not covering all energy consumption. In the perspective of moving towards net zero carbon, it is important that policy capture and address the actual in-use performance of buildings (Gupta et al. 2015; Gupta and Kotopouleas 2018).

In countries with low rate of new construction, it is important to consider mandatory building energy codes or minimum energy performance requirements for existing buildings. Policies include mandating energy retrofits for low performances existing buildings, when sold or rented (or conversely the impossibility to sell or rent a low performance building). In the UK since 2018 it is not allowed by law the rental of low performance buildings/apartments in the lowest two efficiency classes. In countries with increasing building stock, in particular in developing countries, policies are more effective when targeting new buildings (Kamal et al. 2019b).

NZEBs definitions are presented and discussed among other in (Marszal et al. 2011; Deng and Wu 2014; Zhang and Zhou 2015; Wells et al. 2018; Williams et al. 2016);), covering different geographical areas, developing and developed countries, and both existing buildings and new buildings. California has also adopted a building energy code mandating for NZEBs for new residential buildings in 2020 and 2030 for commercial buildings (Feng et al. 2019). Several countries as reported by (Feng et al. 2019) have adopted targets, roadmaps or mandatory building energy codes requiring net zero energy buildings (NZEBs) for some classes of new buildings.

Minimum Energy Performance Standards (MEPSs)

Mandatory minimum efficiency standards or requirements for building technical equipment (e.g. HVAC, appliances, ICT, lighting, etc.) is a very common well-tested and successful policy in most of the OECD countries (e.g. EU, US, Canada, Australia, etc.). is a or improving energy efficiency in energy using products over the last 30 years (Wu et al. 2019; Scott et al. 2015; Brucal and Roberts 2019; Sonnenschein et al. 2019) have shown that efficiency standards do reduce product price. (McNeil et al. 2019) highlights how efficiency standards will help developing countries to reduce the power peak demand by a factor of two, this reducing large investment costs in new generation, transmission and distribution networks. Mandatory standards have been implemented also 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).

Regulatory instruments

Energy Performance Certificates (EPCs)

(Li et al. 2019b) reviews the EU experience in the mandatory Energy Performance Certificates for buildings adopted in the EU under the EPBD, the authors propose several measures to make the EPC more effective to drive the markets towards low consumption buildings. Some authors have indicated that the EPC based on the physical properties of the buildings (asset rating) may be misleading due to occupancy behaviour (Cohen and Bordass 2015) and calculation errors (Crawley et al. 2019). Control authorities can have a large impact on the quality of the label (Mallaburn 2018). There is good evidence on the impact of EPC on property value and on the rental level. While (Olaussen et al. 2017, 2019) and (Hårsman et al. 2016) showed that there is no impact, a large number of authors (Chegut et al. 2016; Brounen and Kok 2011; Cajias and Piazolo 2013; Fuerst et al. 2015; Hyland et al. 2013; De Ayala et al. 2016; Cajias et al. 2019a; Bisello et al. 2020; Chegut et al. 2020; Kok and Jennen 2012), 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 powerful policy instrument in particular for non-residential buildings (Trencher et al. 2016) and could be more accurate than energy audits; (Gabe 2016) shows that mandatory disclosure is more effective than voluntary disclosure.

Energy audits

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 subsidised energy audit for residential building since 2010 (Boucher et al. 2018).

Energy labelling

Mandatory 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 P. 2019). 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.

Information campaign

Provision of information (e.g. public campaigns, targeted technical information, etc.) is a common policy instrument to change end-user behaviour. 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). An effective approach" integrates the social norm as the basis for information and awareness measures on energy behaviour (Gifford 2011; Schultz et al. 2007). Information is more successful when it inspires and engages people: how people feel about a given situation often has a potent influence on their decisions (Slovic and Peters 2006). The message needs to be carefully selected and kept as simple as possible focusing on the following: entertain, engage, embed and educate! (Dewick and Owen 2015).

Energy consumption feedback with smart meters, smart billing and dedicated devices is another instrument recently exploited to reduce energy consumption (Zangheri et al. 2019; Karlin et al. 2015; Buchanan et al. 2018) very often coupled with contest-based interventions or norm-based interventions (Bergquist et al. 2019). (Hargreaves et al. 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 et al. 2018), technology alone will not be enough to achieve the desired energy savings due to the rebound effect. 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 and Bertoldi 2018) highlight the current limitations of policies for energy conservation and suggests complementary policy approach based on social practices theories.

Martket-based instruments

Carbon allowances

A number of recent papers (Wadud and Chintakayala 2019; Fan et al. 2016; Raux et al. 2015; Marek et al. 2018; Li et al. 2015, 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; Bristow et al. 2010; Fawcett 2010; Starkey 2012; Raux and Marlot 2005; Ayres 1995). 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 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 allowances could also be auctioned) to each person the 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). 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 (Burgess 2016; Wang et al. 2017).

The concept of a "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 (closed in 2019) or the Tokyo Metropolitan Carbon and Trade Scheme (Bertoldi et al. 2013a). The Republic of Korea implemented from 2015 onwards an Emission Trading Scheme, which covers the building sector. Under the scheme energy saving and greenhouse gas reduction in buildings are being implemented in order to secure emission reductions (ERs) (Park and Hong 2014; Narassimhan et al. 2018; Lee and Yu 2017).

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. 2013b; 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 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).

Energy efficiency obligations

Energy efficiency obligations (including energy efficiency resource standards or tradable certificates) have been introduced in some EU Member States, in several US States, Australia, South Korea and Brazil (Bertoldi et al. 2013a; Aldrich and Koerner 2018; Wirl 2015; Choi et al. 2018a; Palmer et al. 2013; Brennan and Palmer 2013; Rosenow and Bayer 2017; Fawcett and Darby 2018; Fawcett et al. 2019). Energy efficiency obligations are a market based instruments. 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 2014) and UAE (Friedrich and Afshari 2015). Another similar market based instrument is the energy saving auction mechanism implemented in some US States, Switzerland, and in Germany (Thomas and Rosenow 2020; Langreder et al. 2019; Rosenow 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 or carbon taxation

Energy and/or carbon taxation is a well-investigated climate and energy efficiency policy, which can help in reducing energy consumption (Sen and Vollebergh 2018) and manage the rebound effect where its effects are clearly more negative than positive (Peng et al. 2019; Bertoldi 2020; Font 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) . There is high agreement that carbon taxes are effective policies to reduce CO_2 emissions (IPCC 2018; Hájek et al. 2019; Andersson 2017). It is hard to define the optimum level of taxation in order to achieve the desired level of energy consumption or CO_2 emission reduction (Weisbach et al. 2009). 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. (Bourgeois et al. 2019) show that using carbon tax revenue to finance energy efficiency investment reduces fuel poverty and increases cost-effectiveness. In particular, revenues could be invested in frontline services that can provide a range of support - including advising householders on how to improve their homes, helping them understand and manage household finances, negotiating with energy suppliers, signposting to other social services, etc. 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. In literature, this is known as double dividend (Murtagh et al. 2013; Freire-González and Ho 2019). Urban economic researches (Rafaj et al. 2018; Creutzig 2014; Borck and Brueckner 2018) have highlighted that higher carbon price would translate in incentives for citizens to live closer to the city centre, which often means less floor space, less commuting distance and thus reduced emissions. (Xiang and Lawley 2019) estimated the impact of the carbon tax in British Columbia substantially reduced residential natural gas consumption. (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. (Lin and Li 2011) indicate 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, which can be mitigated by excluding it in return of energy efficiency commitments. (Solaymani 2017) studied carbon and energy taxation in Malaysia, showing that a carbon tax result in higher emission reduction that an energy tax. (Solaymani 2017) shows that with tax revenue recycling the carbon tax increases in the welfare of rural and urban households. (van Heerden et al. 2016) explored economic and environmental effects of the CO_2 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. National circumstances shall be taken into consideration in setting up energy taxes.

Taxes could also be used to penalise inefficient behaviour and favour the adoption of efficient behaviour and technologies, considering the local taxation and energy prices context with regard to sustainable development, justice and equity. 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.

9.9.4 Financing mechanisms and new business models for reducing energy demand

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).

Loans provide liquidity and direct access to capital, which can be more relevant for energy efficiency measures attached to high upfront costs, especially in deep renovation projects (Rosenow et al. 2014). There is empirical evidence (Giraudet et al. 2019), that banks make large profits on personal loans for renovation purposes. To address some barriers (limitation of funding for energy renovation, high transition costs) international financing institutions (IFIs) and national governments provided subsidies in public-private partnerships so that financial institutions can offer customers loans with attractive terms (Olmos et al. 2012). Combination of grants and subsidised loans financed by IFIs could be suitable and effective instrument together with guarantees. Potential issues with subsidies is the limited availability of public financing, the stop and go due to annual budget and the competition with commercial financing.

An energy efficient mortgage is a mortgage that credits a home's energy efficiency 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 energy efficiency 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 household. In the EU the EeMAP Initiative aims to create a standardised energy efficient mortgage template (Bertoldi et al. 2021).

On-bill financing is a mechanism that reduces first-cost barriers by linking repayment of energy efficiency investments to the utility bill and thereby allowing customers to pay back part or all costs of energy efficiency 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 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 and Bennear 2014). While this model after some difficulties has finally taken off in the US, it has not yet applied elsewhere (Bertoldi et al. 2021). Loan guarantees are effective in reducing intervention borrowing costs (Soumaré and Lai 2016). This scheme can facilitate the provision of affordable and sufficient financing for energy service companies (ESCOs) (Bullier and Milin 2013) and households. 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 allows reducing investment requirements and enhancing energy efficiency investment impacts by recovering and reinvesting the savings generated (Setyawan 2014). Revolving fund could make retrofit cost-neutral in the long term and could also dramatically increase low carbon investments, including in developing countries (Gouldson et al. 2015).

Carbon finance, started under the Kyoto Protocol with the flexible mechanisms and further enhanced under the Paris Agreement (Michaelowa et al. 2019), is an economic measure aimed at contributing to solving the climate problem and it is an activity based on “carbon emission rights” and its derivatives (Liu et al. 2015a). Carbon finance can promote low-cost emission reductions (Zhou and Li 2019). Banks involved in carbon financing rely on Carbon Development Mechanisms (CDMs) as intermediaries in China, and focus on credit investment, financing, facing some risks (Zhang and Li 2018). With the increasing popularity of Emission Trading Schemes, 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 organisations such as banks (Miller and Carriveau 2018). Typically, it involves internet-based platforms that link savers directly with borrowers (European Union 2015). It can play a significant role at the start of a renewable and sustainable energy projects (Dilger et al. 2017).

The One Stop Shop (OSS) service providers for buildings energy renovations are organisations, 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 (Mahapatra et al. 2019). OSSs are transparent and accessible advisory tools from the client perspective and new, innovative business models from the supplier perspective (Boza-Kiss and Bertoldi 2018).

Energy Performance Contracting (EPC) is an agreement between a building owner and Energy Services Company (ESCO) for energy efficiency 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 and Rozhkova 2018). According to (Giraudet et al. 2018), energy performance contracting is effective at reducing information problems between contractors and investors. It can however encourage unintended behaviour by building users, especially in the residential sector.

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, renewable technologies still face barriers due to the upfront investment costs, despite the declining price of some technologies such as PV, 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) in particular for built-in photovoltaic (Agathokleous and Kalogirou 2020). Traditional energy efficiency policies such as building energy codes could include mandatory renewable targets and NZEBs target require renewable energies to meet the remaining energy demand.

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. It is important to stress that in addition to the above policy instruments there are specific policies for renewable heating and cooling such as investment grants, soft loans, RES heat obligations, RES heat tariffs, use obligations etc. (Connor et al. 2013). In 2014, the UK introduced the Renewable Heat Incentive (RHI) a support scheme, in a form of tariff mechanism designed to meet the specific characteristics of renewable thermal energy and based on the energy output (Balta-Ozkan et al. 2015; Connor et al. 2015). Similarly, to the renewable electricity feed-in tariff, the RHI guarantee a fixed payment per unit of heat generated by a renewable heat technology for a specific contract duration (Yılmaz Balaman et al. 2019).

Many authors indicate that most common implemented policy instruments are the feed-in tariffs (FiT) and the Renewable Portfolio Standards (RPS) (Alizada 2018; Xin-gang et al. 2017a). More than 60 countries and regions worldwide have implemented one of the two policies (Sun and Nie 2015). FIT is a price policy (fixing the price but not the quota), guaranteeing the purchase of energy generation at a specific fixed price for a fixed period (Xin-gang et al. 2020; Barbosa et al. 2018). RPS is a quantitative policy (fixing the desired output but not the price), which impose mandatory quota of renewable energy generation to power generators (Xin-gang et al. 2020) .

A flat rate feed-in tariff (FiT) is a well-tested financial incentive adopted in many jurisdictions (e.g. Germany, France, German, Italy, Portugal, UK, Australia, several US states, Belgium, Japan, Brazil, China, South Korea, etc.) to encourage end-user to generate electricity from renewable sources using rooftop photovoltaic systems and on-site PV systems (Pacudan 2018). Both FITs and capital subsidies have been employed to promote the adoption of PV. More recently, 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 and Quirion 2019) argues under uncertainty over electricity prices and renewable production costs a flat FiT results in higher welfare than a feed-in premium. One of the main concerns with FiT systems is the increasing cost of policies maintenance (Pereira da Silva et al. 2019; Roberts et al. 2019a; Zhang et al. 2018). 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 through net metering and net billing, which has a lower financial impact on electricity ratepayers compared with traditional FiTs (Vence and Pereira 2019; Roberts et al. 2019b; Pacudan 2018).

In some countries, e.g. Australia (Duong et al. 2019), South Korea (Choi et al. 2018a), 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, RPS (or Renewable Obligations) have been adopted by governments in order to reduce the subsidy costs (Zhang et al. 2018). A number of scholars (Xin-gang et al. 2017b; Li et al. 2019a; Liu et al. 2018a) have highlighted the RPSs effectiveness in reducing carbon emissions and promoting the development of renewable energy. Other authors (Requate 2015; An et al. 2015) have presented possible negative impacts of RPSs.

There is an on-going debate on the effectiveness of these two renewable energy policies. Both FIT and RPS can support the development of renewable energy. Scholars compared the effectiveness of RPSs and FITs with mix results and different opinions, with some scholars indicating the advantages of RPS (Ciarreta et al. 2017, 2014; Xin-gang et al. 2017a), while (Nicolini and Tavoni 2017) showed that in Italy FITs are outperforming RPSs and Tradable Green Certificates (TGCs). (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 positive impact on installed photovoltaic capacity. This is due to the small size of many rooftop installations and the difficulties in participating in trading schemes for residential end users. 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”. Other scholars (Couture and Gagnon 2010; Lewis and Wiser 2007; Lipp 2007; Cory et al. 2009a) concluded that FiT could create a stable investment framework and long-term policy certainty and it is better in industrial development and job creation than RPS.

(Ouyang and Lin 2014) highlight that RPS has a better implementation effect than FiT in China, where FiT level required very large subsidy. (Ford et al. 2007) showed that TGC is a market-based mechanism without the need for government subsidies. (Marchenko 2008) and (Wędzik et al. 2017) indicate that the TGCs provide a source of income for investors. (Choi et al. 2018a) 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 (Park and Kim 2018; Choi et al. 2018b). Choi concluded, based on CBA, that RPS was more efficient for PV from the government's perspective while from an energy producers’ perspective the FiT was more efficient. The opposite case was valid for other renewable sources.

Some scholars proposed a policy combining FIT and RPS (Cory et al. 2009b). del Río et al. (2017) concluded that both FiT and RPS are effective, but policy costs are higher in RPSs than FiTs. RPS, REC trading and FiT subsidy could also be implemented as complementary policies (Zhang et al. 2018).

Recent literature confirm that tenders are a fast spreading and effective instrument to attract and procure new generation capacity from renewable energy sources (Bayer et al. 2018; Bento et al. 2020; Ghazali et al. 2020; Haelg 2020; Batz and Musgens 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 (Gephart et al. 2017). There is not yet the literature a quantitative assessment of its performance. (Bento et al. 2020) indicated that tendering is more effective in promoting additional renewable capacity comparing to other mechanisms such as FiTs. 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 provided by end-users include storage, energy productions, peer to peer 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). Under the EU Renewable Energy Directive (2018) Energy Communities can access suitable energy markets directly or through aggregation. In addition, the Directive on the Internal Market for Electricity Directive (2019) defines “Citizen Energy Communities”, which have as primary purpose to provide environmental, economic or social community benefits. Energy Communities may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders. Renewable or local energy communities can increase public acceptance, mobilise private funding and provide flexibility to electricity markets.

Aggregators are also important players for demand response (Zancanella et al. 2017), and to group energy sales from prosumers to obtain a better price. (Klein et al. 2019) explore the policy options for aligning prosumers with the electricity wholesale market, through price and scarcity signals.

Financing mechanisms for renewable energies are particularly needed in developing countries. Most of the common supporting mechanisms (FiT, RPSs, PPA, auctions, net metering, etc.) can and have been implemented in many development countries (Donastorg et al. 2017). Stable policies and fiscal tools for renewable energies (for example in the form of targets) and an investment-friendly environment are essential to overcome financing barriers and attract investors (Donastorg et al. 2017). (Kimura et al. 2016) identified the following elements as essential for fostering renewable energies in developing countries: innovative business models and financial mechanisms/structures; market creation through the implementation of market-based mechanisms; stability of policies and renewable energy legislation; technical assistance to reduce the uncertainty of renewable energy production; electricity market design, which reflects the impact on the grid capacity and grid balancing; improved availability of financial resources, in particular public, and innovative financial instruments, such as carbon financing (e.g. CDMs (Park et al. 2018; Kim and Park 2018; Lim et al. 2013); green bonds; public foreign exchange hedging facility for renewable energy financing, credit lines; grants and guarantees).

9.9.6 Investment in building decarbonisation

As Section 9.6.4.2 points out, the incremental investment cost to decarbonise buildings at national level is up to 3.5% GDP per annum during the next thirty years (the global GDP in 2019 was USD 88 trillion). As the following figures illustrate, only a very small share of it is currently being invested, leaving a very large investment gap still to address. The incremental capital expenditure on energy efficiency in buildings grew since AR4 to reach USD 150 billion in 2019; Europe was the largest investing region, followed by the USA and China (Figure 9.21). The total capital expenditure on renewable energy heat vice versa declined to USD 24 billion in this year; the leading investor was China, followed by Europe (ibid). The total capital expenditure on distributed small-scale (less than 1MW) solar systems in 2019 was USD 52.1, down from the peak of USD 71 billion in 2011; most of this capacity is installed in buildings (Frankfurt School - UNEP Centre/BNEF 2020). The US is the largest country market with USD 9.6 billion investment; notably USD 5 billion was deployed in the Middle East and Africa (ibid).

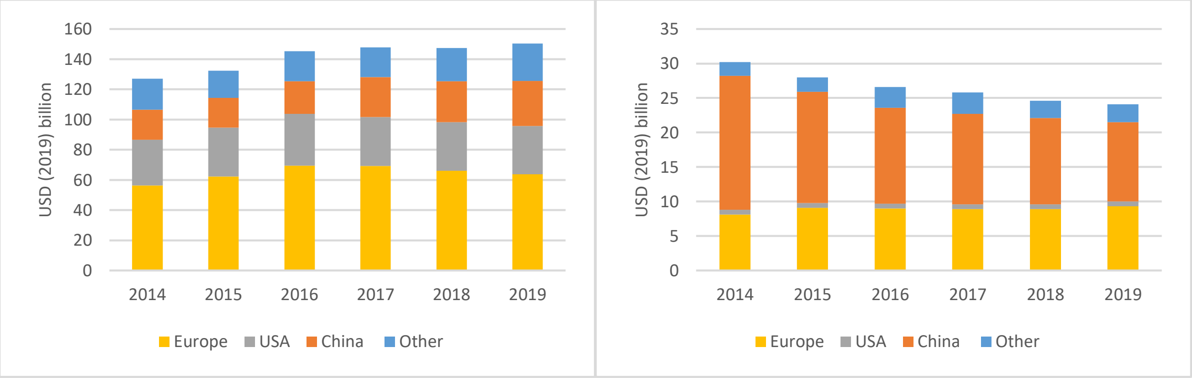


Figure 9.21 Incremental capital expenditure on energy efficiency investment in buildings (left) and total capital expenditure on renewable heat in buildings, 2015-2019
(International Energy Agency 2020).

Several countries of the world developed the so-called landscapes of climate finance, which follow financial flows along their lifecycles, from the original source of financing, through financial intermediaries, their deployment in the form of financial instruments, and the recipients of finance (Buchner et al. 2011). The landscapes for Germany in 2016, France in 2019, Czechia in 2018, Latvia in 2019, and Belgium in 2013 identified energy efficiency investment in buildings in the amount of EUR 6.9 billion, ca. EUR 17 billion, ca. EUR 0.4 billion, EUR 0.2 billion, and EUR 1.1 billion respectively (Novikova et al. 2016; Hainaut et al. 2019; Valentova et al. 2019; Kamenders et al. 2019; Rademaekers et al. 2016). It is important to note, that all these studies cover different portions of investment. Notably only the German study attempts to address strictly the incremental share of investment, with other studies taking different shares of total investment, all higher than it is typically assumed as incremental in decarbonisation models of these countries, including those reviewed in Section 9.6.1. Recently, the European Union issued a taxonomy of sustainable activities, which regulates expenditure that could be counted as sustainable, in particular in the area of mitigation (EU Technical Expert Group on Sustainable Finance 2020). Still its “sustainable” threshold is much more relaxed (at least 30% reduction in primary energy demand after renovation) as compared to the definition of incremental costs calculated by global and national decarbonisation models. These facts reveal that the estimates reported by countries on their investment in decarbonisation are too optimistic and therefore the investment gap is larger than that reported.

Despite different methodologies, still interesting observations could be made on how these countries finance decarbonisation of buildings. In all countries except Latvia, the largest shares of investment flows from private actors, however they are to the largest extent supported by financial incentives provided from public budgets. Concessionary debt onlended through local branches of private banks plays a large role in financing energy transition in Germany; diffuse instruments - including bonds, concessional loans directly disbursed by government-owned financial institutions, subsidies, commercial debt, balance sheet financing, and others are used - in France; whereas Czechia and Latvia rely mostly on grants. These facts illustrate the importance of policies, in particular financial incentives, in driving the energy efficiency market.

9.9.7 Governance and Institutional Capacity

9.9.7.1 Governance

Multilevel and polycentric governance is essential for implementing energy efficiency and renewable energies policies, which could be combined (for example through the inclusion of renewable energy in building energy codes) and implemented in coordination with each other and with climate policies (Oikonomou et al. 2014) at different levels of government and decision making (international, national, regional and local). Policies for building have be adopted at national level (Enker and Morrison 2017), at state or regional level (Fournier et al. 2019), or at city level (Trencher and van der Heijden 2019). (Zhao et al. 2019) find that national policies are instrumental in driving low carbon developments in cities, including buildings.

International agreements and conventions (Kyoto, Montreal/Kigali, Paris, etc.) play an important role in establishing national and regional energy-efficiency and renewable energy policies in several countries as reflected in the NDCs (Dhar et al. 2018; Bertoldi 2018). Under the Paris Agreement, some National Determined Contributions (NDCs) contain emission reduction targets for subsectors, e.g. buildings, specific policies and measures for subsectors and energy efficiency and/or renewable targets. In the EU since 2007 climate and energy policies are part of the same policy package. EU Member States have prepared energy efficiency plans every three years (Economidou et al. 2020). Under the new Energy and Climate Governance Regulation EU Member States have submitted at the end of 2020 integrated National Energy and Climate Plans, including energy efficiency and renewable 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; reduce the manufacturers design and compliance costs. International standards could also be applied to developing countries when specific enabling conditions exist, particularly in regard to technology transfer, assistance for capacity buildings and financial support. This would also reduce the dumping of inefficient equipment in countries with no or lower efficiency requirements. An example is the dumping of new or used inefficient cooling equipment in developing countries, undermining national and local efforts to manage energy, environment, health, and climate goals. For example, developing countries would see energy savings of over 60% by replacing old refrigerators with more efficient equipment. Specific regulations can be put in place to avoid such environmental dumping, beginning with the simplest one: i.e. “prior informed consent” as seen in the Rotterdam Convention and a later stage with the adoption of minimum efficiency requirements for appliances (ANDERSEN et al. 2018; United Nations Environment Programme (UNEP) 2017). (Dreyfus et al. 2020a) indicates that global policies to promote best technologies currently available for efficient and climate-friendly cooling have the potential to reduce climate emissions from air conditionings and refrigeration equipment by 210–460 $GtCO_2$-eq by 2060, resulting from the phasing out of HFC and from improved energy efficiency of cooling equipment. The use of bulk purchasing both through government procurement and through private “buyers’ clubs” can improve efficiency of cooling equipment, ensure low GWP refrigerants, and drive down price. Another example of a governance initiative is the commitment by heads of state and government in promoting improvements in energy efficiency of cooling equipment in parallel with the phasedown of HFC refrigerants enshrined in the Biarritz Pledge for Fast Action on Efficient Cooling signed in 2019. The policy development and implementation costs will 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 to be used in offsets markets 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 energy codes, which could be more challenging than national codes, constructions permits, urban planning. 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 stringent efficiency requirements for new buildings. Another possible policy at local level is the climate friendly building certification system. In Korea, there is a green architecture certification system operated by the government. However, based on this, Seoul has enacted Seoul's eco-friendly building standard, which includes more stringent requirements. Where it is impossible to retrofit existing 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, sufficiency, and renewable policies and measures will have a large impact on different stakeholders: citizens as building owner or building users; construction companies; equipment manufacturers; utilities, etc. it has been highlighted in literature the importance of stakeholder consultation and active participation in policy making and policy implementation (Vasileiadou and Tuinstra 2013; Ingold et al. 2020), 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.

9.9.7.2 Institutional capacity

Institutional capacity often implies a broader focus of empowerment, social capital, and an enabling environment, as well as the culture, values and power relations that influence us" (Segnestam et al. 2003). The concept of capacity is increasingly connected with the issue of public governance, emphasising the broad institutional context within which individual policies are adopted. Institutions are durable and are sources of authority (formal or informal) structuring repeated interactions of individuals, companies, civil society groups, governments and other entities. Thus, institutional capacity also represents a broader "enabling environment" which forms the basis upon which individuals and organisations interact. In general terms, capacity is "the ability to perform functions, solve problems and set and achieve objectives" (Fukuda-Parr et al. 2002). Institutional capacity is an important element for regional sustainable development (Farajirad et al. 2015).

The role and importance of institutional capacity is fundamental in implementing the decarbonisation of the building sector. Central and local governments, regulatory organisations, financial institutions, standardisation bodies, test laboratories and stakeholders are key players in supporting the implementation of energy efficiency, sufficiency and renewable policies and measures.

Governments at all levels (from national to local) planning to introduce energy efficiency and energy renewable policies needs technical capacity to set economic wide or sectoral targets, design policies, carry our impact assessments and cost-benefits analysis, and introduce verifiable, effective and enforceable policies with adequate structure, laws and resources for their implementation. Policies, which are discussed and possibly agreed with stakeholders and are based on details and impartial impact assessments, have a higher possibility of success.

In particular, the enforcement of policies needs attention. For example, policies on appliance energy standards have to establish criteria for random checks and tests of compliance, establish penalties and sanctions for non-compliance. In the case of building energy code compliance there is the need to verify compliance after construction to verify the consistence with building design (Vine et al. 2017). 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 energy codes for safety and other important issues.

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

International support for institutional capacity for policy development implementation and 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, evaluation experts. Thus, in development support, addition to technology transfer, also capacity buildings for national and local authorities should be provides. The Paris Agreement (Article 11 on capacity building) aims at enhancing the capacity of decision-making institutions in developing countries to support effective implementation.

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. The literature argues for the need 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. Policy developments are observed following this trend, but they are clearly insufficient so far.

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 in combination with a still unestablished decoupling between GHG emissions and wealth in the developed countries. This increase is expected to continue in the coming years driven by achieving Decent Standard of Living (DLS) for all, especially in the developing countries, and the increased penetration of new technologies (*high evidence*, *high agreement*). Technological and non-technological measures could ensure DLS, SDG targets, and well-being for all within the planetary boundaries without increasing GHG emissions in the building sector if innovative and comprehensive policies (see section 9.9) are put in place worldwide (*low evidence*, *high agreement*).

The type and composition of building influence energy consumption and the associated GHG 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 design, active for the building envelope, and energy systems, as well as on-site renewable energy production) can turn buildings in small power plants that could export surplus energy. The role of buildings in the energy system is changing towards a prosumer role, and trends of increased digitalisation could favour such transition (smart buildings, smart meters and smart appliances) is key to decrease emissions in buildings (*low evidence, medium agreement*).

Non-technological and behavioural mitigation actions are among the sufficiency measures that can substantially reduce building 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 GHG mitigation in buildings. Private consumers seem ready to support stronger governmental action, whereas the business sector identifies many organisational constraints (*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 to emit very low GHG emissions in developed countries (*robust evidence*, *high agreement*) and relatively low GHGs emissions in developing ones (*medium evidence*, *high agreement*). However, this requires an acceleration of building retrofit rates in developed countries and 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*). Current estimates of potentials and costs for mitigation should be treated with caution because they rely on a number of uncertain assumptions (*robust evidence*, *high agreement*). Uncertainties include stock turnover, technological limitations, e.g. in urban areas, investment costs, baseline emissions, discount rates and others.

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 agreement, high evidence*). Eventual trade-offs between climate change adaptation and mitigation in buildings can be reduced by strengthening efficiency, sufficiency and on-site energy production (*high agreement, low evidence*). Considering climate change uncertainties in the design of new buildings and retrofitting strategies 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 SDGs (*medium evidence*, *high agreement*). 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 effective policies such as appliances standards and building energy codes have been adopted in OECD countries and many other large economies, they are however not sufficient to decarbonise the building sector (*robust evidence, high agreement*). A particular success is observed in the increased adoption of on-site renewable generation with financial incentive and market based instruments. From a policy perspective the de-carbonisation 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 (*robust evidence, high agreement*).

Reaching deep decarbonisation levels throughout the life cycle of buildings will depend on the multidimensional feasibility of mitigation measures, including criteria related to geophysical, environmental-ecological, technological, economic, socio-cultural and institutional dimensions. An assessment the feasibility of mitigation measures in the buildings sector indicates whether a specific factor, within broader dimensions, acts as a barrier or helps enabling such mitigation measures (Table 9.7 and Supplementary material Table SM9.5 and Table SM9.6). Although mitigation measures are aggregated in the assessment of Table 9.7 and feasibility results can differ for more specific measures, generally speaking, the barriers to mitigation measures in buildings are few, sometimes including technological and socio-cultural challenges. However, many co-benefits could help enable mitigation in the buildings sector. For instance, many measures can have positive effects on the environment, health and well-being, and distributional potential, all of which can boost their feasibility. The feasibility of mitigation measures varies significantly according to socio-economic differences across and within countries.

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.

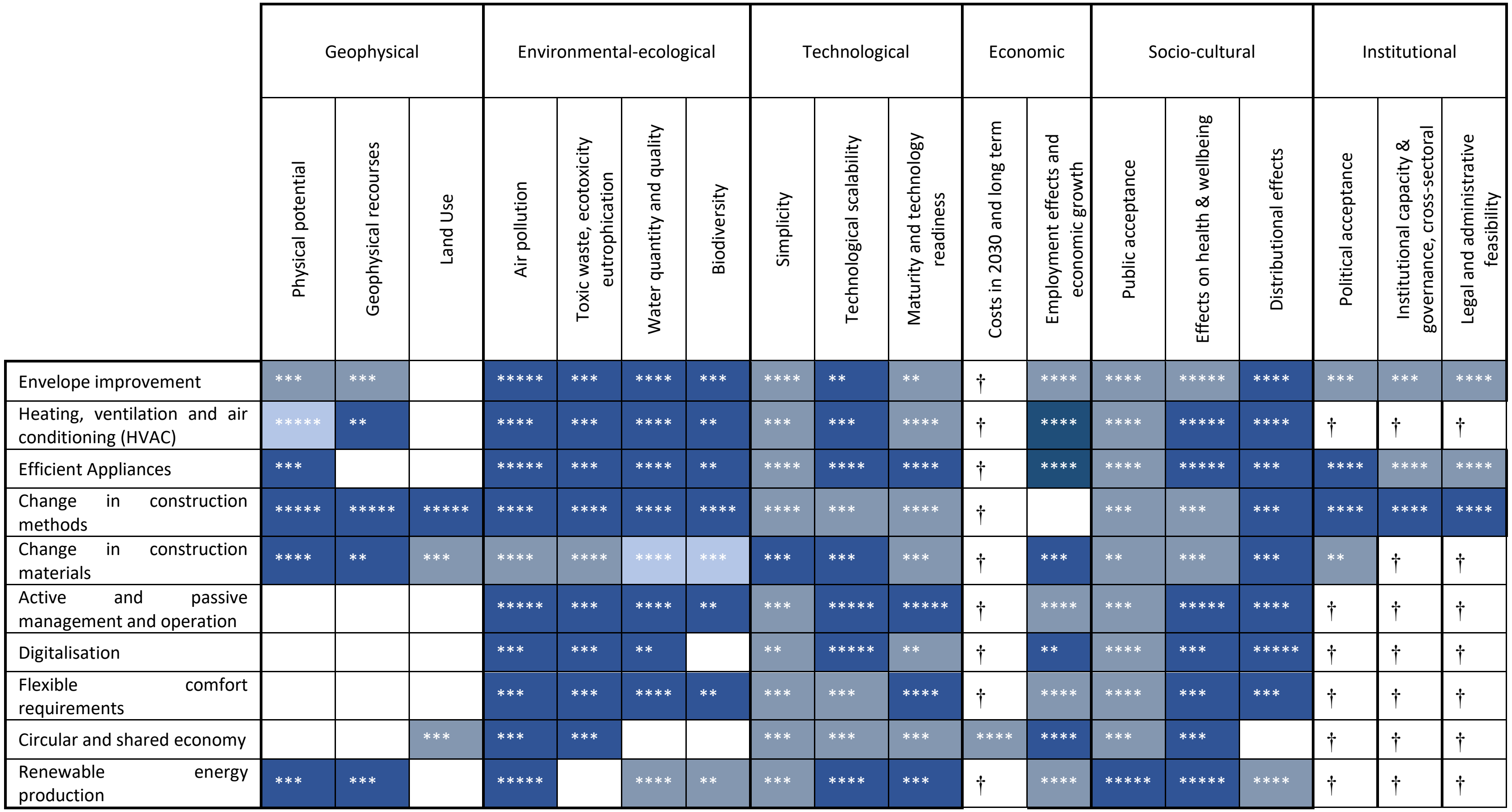
Measures, potentials and costs

- 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 categorisations, 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.

Table 9.7. Feasibility of mitigation measures for the building sector (based on Supplementary material Table SM9.5 and Table SM9.6)



	Geophysical			Environmental-ecological				Technological			Economic		Socio-cultural			Institutional		
	Physical potential	Geophysical recourses	Land Use	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity	Simplicity	Technological scalability	Maturity and technology readiness	Costs in 2030 and long term	Employment effects and economic growth	Public acceptance	Effects on health & wellbeing	Distributional effects	Political acceptance	Institutional capacity & governance, cross-sectoral	Legal and administrative feasibility
Envelope improvement	▨ ***	▨ ***		■ *****	■ ***	■ ****	■ ***	▨ ****	■ **	▨ **	†	▨ ****	▨ ****	▨ *****	■ ****	▨ ***	▨ ***	▨ ****
Heating, ventilation and air conditioning (HVAC)	░ *****	■ **		■ ****	■ ***	■ ****	■ **	▨ ***	■ ***	▨ ****	†	■ ****	▨ ****	■ *****	■ ****	†	†	†
Efficient Appliances	■ ***			■ *****	■ ***	■ ****	■ **	▨ ****	■ ****	■ ****	†	■ ****	▨ ****	■ *****	■ ***	■ ****	▨ ****	▨ ****
Change in construction methods	■ *****	■ *****	■ *****	■ ****	■ ****	■ ****	■ ****	▨ ****	▨ ***	▨ ****	†		▨ ***	▨ ***	■ ***	■ ****	■ ****	■ ****
Change in construction materials	■ ****	■ **	▨ ***	▨ ****	▨ ****	░ ****	░ ***	■ ***	■ ***	▨ ***	†	■ ***	▨ **	▨ ***	■ ***	▨ **	†	†
Active and passive management and operation				■ *****	■ ***	■ ****	■ **	▨ ***	■ *****	■ *****	†	▨ ****	▨ ***	■ *****	■ ****	†	†	†
Digitalisation				■ ***	■ ***	■ **		▨ **	■ *****	▨ **	†	■ **	▨ ****	■ ***	■ *****	†	†	†
Flexible comfort requirements				■ ***	■ ***	■ ****	■ **	▨ ***	▨ ***	■ ****	†	▨ ****	▨ ****	■ ***	■ ***	†	†	†
Circular and shared economy			▨ ***	■ ***	■ ***			▨ ***	▨ ***	▨ ***	▨ ****	■ ****	▨ ***	■ ***		†	†	†
Renewable energy production	■ ***	■ ***		■ *****		▨ ****	▨ **	▨ ***	■ ****	■ ***	†	▨ ****	■ *****	■ *****	▨ ****	†	†	†

Overall assessments	
■	Positive impact
▨	Mixed evidence
░	Negative impact
□	N/A or no evidence

†: in progress

Level of confidence	
1	* (Lowest)
2	**
3	***
4	****
5	***** (highest)

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 monetise 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?

There are three categories of GHG emissions from buildings:

i. direct emissions which are defined as all on-site fossil fuel or biomass-based combustion activities (i.e. use of biomass for cooking, or gas for heating and hot water) and F-gas emissions (i.e. use of heating and cooling systems, aerosols, fire extinguishers, soundproof)

ii. indirect emissions which occur off-site and are related to heat and electricity production

iii. embodied emissions which are related to construction material and goods used in buildings

In terms of gases, GHG emissions from buildings include carbon dioxide, (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gas (F-gas). However, data on CH_4 and N_2O and F-gas are scare.

FAQ 9.2: How important are the co-benefits and trade-offs of mitigation actions in buildings?

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 characterised by strong rebound effects, which may lower the economic performance of mitigation actions. All these are characterised by several uncertainties as mitigation actions will be implemented in a changing climate. Climate change impacts can increase energy consumption, which may lead to higher GHG emissions and greater need for mitigation. Also, increased storms and rainfall under future climate may impact building materials and components that would need to be renovated, resulting in increased energy consumption and household expenditure for producing and installing the new components and renovations.

FAQ 9.3: Which are the needed and most effective policies and measures to decarbonise the building sector?

Several barriers (information, financing, markets, behavioural, etc.) still prevents the decarbonisation of buildings stock, despite the several co-benefits, including large energy savings. Solutions include investments in technological solutions (e.g. insulation, efficient equipment and on-site renewables) and life style changes. In addition, the concept of sufficiency shall be promoted and implemented through policies and information, as technological solutions will be not enough to decarbonise the building sector. Due to the different types of buildings, occupants and development stage there is not a single policy, which alone will reach the decarbonisation target. A range of policy instruments ranging from regulatory measures such as building energy code for NZEBs and appliance standards, to market based instruments (carbon tax, personal carbon allowance, renewable portfolio standards, etc.), and information. Financing (grants, loans, performance base incentives, pays as you save, etc.) is another key enabler for energy efficiency technologies and on-site renewables. Finally, effective governance and strong institutional capacity are key to have an effective and successful implementation of policies and financing.

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Chapter 9: Buildings – Supplementary material

SM9.1 Supplementary information to Section 9.4

Figure 9.11 shows a summary of the available technologies with climate change mitigation potential in buildings. Here, an extended list of such technologies are presented (Table SM9.1 to Table SM9.3).

Table SM9.1. Technology strategies contributing to sufficiency aspects. Adapted from (Cabeza and Chàfer 2020a; Bojić et al. 2014; Bevilacqua et al. 2019a; Coma et al. 2017; Djedjig et al. 2015a; Chen et al. 2013a; Haggag et al. 2014a; Khoshbakht et al. 2017; Saffari et al. 2017a; Seong and Lim 2013a; Radhi 2011; Pomponi et al. 2016a; Andjelković et al. 2016; Rosado and Levinson 2019; Costanzo et al. 2016; Spanaki et al. 2014; Coma et al. 2016a; Yang et al. 2015; Cabeza et al. 2010; Kameni Nematchoua et al. 2020; Annibaldi et al. 2020; Varela Luján et al. 2019; Jedidi and Benjeddou 2018; Capozzoli et al. 2013; Asdrubali et al. 2012)

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Passive strategies for walls				
Insulation materials	- These materials can be used in the different buildings envelope parts (floor, wall, ceiling and roof) - They have a clear impact on improving the u-value of historic buildings (retrofitting) - Proper installation of insulation using energy-efficient materials reduces the heat loss or heat gain, which leads to the reduction of energy cost as the result	- Conventional insulation materials are derived from petrochemical substances - New organic/sustainable materials are more expensive than conventional materials - If the insulation barrier is broken or without a correct design, thermal bridges may appear (Jedidi and Benjeddou 2018; Capozzoli et al. 2013; Asdrubali et al. 2012)	28-37% in winter 45 – 64% in summer (Cabeza et al. 2010)	Conventional insulation materials (PUR; MW, XPS) Mediterranean continental climate Experimentally tested
			Up to 30% of cooling energy reduction (Kameni Nematchoua et al. 2020)	Conventional insulation materials + PCM Tropical climate Simulation
			Up to 38.83% reduction in the heating season (Annibaldi et al. 2020)	Calcium silicate in heritage buildings Mediterranean climate Simulation
			Reduced energy losses by 57% and energy gains by 39% (Varela Luján et al. 2019)	External Thermal Insulation Composite Systems (ETICS) in existing buildings Mediterranean continental climate Experimentally tested
Trombe wall	- Capability to be integrated with new technologies such as PV systems. - Reduction of building's energy consumption, and decrease of moisture and humidity of interior spaces in humid regions. - The indoor temperatures are more stable than in most other passive systems. Prevention of excessive sunshine penetration into the inhabited space. - Installation is relatively inexpensive, where construction would normally be masonry, or for retrofitting existing	- In regions with mild winters and hot summers, over heating problems may outweigh the winter benefits. - In a climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink. - 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. - The amount of gained heat is unpredictable due to changes occur in solar intensity. - Trombe walls are aesthetically appealing	20% (Bojić et al. 2014)	Annual heating – Mediterranean climate Simulation
			18.2% and 42.2% (Bevilacqua et al. 2019b)	Heating cold climate and cooling cold climate Simulation

	buildings with uninsulated massive exterior walls. - 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. - 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			
Vertical Greenery Systems (Green walls / Green facades)	- Enhancing building aesthetics. - Improving the acoustic properties. - Reduction of heat gains and losses. - Ability to be integrated with existing buildings.	- Providing a living environment for mosquitoes, moths, etc. - Requiring significant, and consistent maintenance measures. - Water drainage can be involved in complexities, and difficulties.	58.9 % Green wall 33.8 % Green facade (Coma et al. 2017)	Cooling season warm climate Experimental study
			37.7% and 50% (Djedjig et al. 2015b)	Hot climate Cold climate Cooling Savings Simulation
			12% (Chen et al. 2013b)	Cooling savings Tropical climate Experimental
			20.5 % (Haggag et al. 2014b)	Cooling savings Hot climate Experimental
PCM Wall systems	- Availability at different temperatures - High volumetric energy storage	- Low thermal conductivity - Flammability - Low thermal and chemical stability	19 – 26% (Khoshbakht et al. 2016)	Heating savings Mediterranean climate Experimental
			0 up to 29% (Saffari et al. 2017b)	Heating savings in different climates Simulation
			9.28% (Seong and Lim 2013b)	Annual cooling savings Temperate climate Simulation
AAC Walls (Autoclaved aerated concrete)	- High volumetric energy storage - AAC walls are light weight concrete, and fire resistance.	- Production cost per unit is higher than other ordinary concretes - It is not as strong as conventional concrete - The process of autoclaving concrete requires significant energy consumption	7% (Radhi 2011)	Annual Dry desert climate Experimental and simulation

Double Skin Walls	- Provision of sufficient visual connection with the surroundings - Facilitation of entering a large amount of daylight without glare - Offering attractive aesthetic values - Promotion of natural ventilation and thermal comfort without any electricity demand - Acoustic insulation	- Higher cost for designing, construction, and maintenance compared to traditional single facades - Increase weight of building structure - Risk of overheating during sunny days - Additional maintenance and operational costs - Increased airflow velocity inside the cavity - Potential issues associated to fire propagation	28-33% (Pomponi et al. 2016b)	Heating savings Cooling -- Average of reviews
			8 – 9% (Andjelković et al. 2016)	Heating Cooling -- Moderate climate -- Simulation
			51 % and 16% (Khoshbakht et al. 2016)	Annual savings of temperate and subtropical climate Simulation
Passive strategies for roofs				
Cool Roofs	- Reduction of the solar heat gain in the building increasing the solar reflectance of the roof surface - 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 - Not appropriate in cold climates	0.3 – 27 % (Rosado and Levinson 2019)	Cooling season Warm climate Simulation
			17 – 25% (Costanzo et al. 2016)	Cooling season Mediterranean climate Simulation
Roof ponds	- Processes indirect evaporative cooing and/or radiant cooling are combined to provide passive cooling - They can also be used for passive heating in winter - Knowledge available on design and operation of the systems - Useful in arid and temperate climates; can be used in humid climates - Performance is not affected by building orientation - They do not increase indoor humidity	- Increase weight of building - Only to be used in flat roofs - Affection of accessibility of roof for other uses - Potential leakage and contamination of water - Only useful for one- or two-story buildings	30% (Spanaki et al. 2014)	Annual savings Mediterranean climate Simulation
	- Enhancing building aesthetics. - Improving the acoustic properties.	- Increase weight of building	7-16% (Coma et al. 2016b)	Cooling season Mediterranean climate

Green roofs	- Reduction of heat gains and losses. - Ability to be integrated with existing buildings. - Reducing greenhouse gas emissions, air pollution and urban heat island effects in highly populated areas	- Maintenance		Experimental
			15.2% (Yang et al. 2015)	Cooling season Sub-tropical climate Experimental

Table SM9.2 Technology strategies contributing to efficiency aspects. Adapted from (Cabeza and Chàfer 2020a; Prívara et al. 2011; Sourbron et al. 2013; Ling et al. 2020; Peng et al. 2020; Zhang et al. 2020b; Dong et al. 2020; Harby et al. 2016; Liu et al. 2019; Vakiloroaya et al. 2014a; Mahmoud et al. 2020; Romdhane and Louahlia-Gualous 2018; Gong et al. 2019; de Gracia et al. 2013; Navarro et al. 2016b; Fallahi et al. 2010; Mujahid Rafique et al. 2015; Soltani et al. 2019; Imanari et al. 1999; Yu et al. 2020; Lee et al. 2018; Sarbu and Sebarchievici 2014; Irshad et al. 2019; Luo et al. 2017; Hohne et al. 2019; Zhang et al. 2019; Omara and Abuelnour 2019; Alam et al. 2019)

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Thermally activated building systems (TABS)	- Reduce energy and cost operation	- TABS with high thermal mass, as hollow core slabs or active concrete core, have significant slow response time. - 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 - Monitoring
			15% (Sourbron et al. 2013)	- Ceiling radiant heating panels - Simulation
Heat Pumps	- Low maintenance system - Low cost (ASHP) - Three technologies available (Air-source heat pump (ASHP), ground source heat pumps (GSHP), water source heat pumps (WSHP))	- High space requirements. - Complex control optimisation algorithm to achieve maximum energy savings.	17 – 25 % (ASHP) (Ling et al. 2020)	- Case study
			10 % cooling (Peng et al. 2020)	---
			-18.43% to 14.78% (Zhang et al. 2020b)	---
			60 % (Mi et al. 2020)	- Last case coupled with PVT
Organic Rankine Cycles	- Significant energy recovery - Reduction of peak demand - Efficient as heat recovery system	- High space requirements. - High capital cost	41% in the cooling season, 63% in the heating season, 9% in the intermediate season (Dong et al. 2020)	- High-rise apartment building
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 - Simulation
Smart ventilation	- Reduces energy consumption and costs - 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 - High efficiency, especially in temperate climates	- Difficult to integrate depending of the type of heat recovery system - Larger than conventional air-handling units - Expensive both in capital and operation costs	8% (Vakiloroaya et al. 2014a)	- Annual - Humid climate - Experimental
			60.6% (Mahmoud et al. 2020)	- 4.8 COP of the proposed district heating
Fuel cells	- Can use hydrogen as energy fuel - Allows micro-CHP - Can be used in all climates - Reduced CO_2 emissions - No noise during operation	- High capital cost - High space requirements	35% (Romdhane and Louahlia-Gualous 2018)	- Single-family house in France - PEMFC
			15% (Gong et al. 2019)	- PEMFC and SOFC
Thermal energy storage	- Significant reduction of electricity costs - Required smaller ducts - Increase in flexibility - Three technologies available (sensible, latent and thermochemical energy storage)	- COP lower than conventional vapour compression systems - Expensive both in capital and operation costs - More complex systems	12-37% (Alam et al. 2019) (Omara and Abuelnour 2019)	- Latent heat storage system
			19-26% (de Gracia et al. 2013) 30-50% (Navarro et al. 2016a)	- Active façade with PCM - Cooling and heating - Arid climates - Activated concrete slab with PCM - Cooling and heating - Arid climates
			21% to 26% in summer and from 41% to 59% during winter (Fallahi et al. 2010)	- Sensible TES with concrete thermal mass with mechanical or natural ventilation
			40-70% (Fallahi et al. 2010)	- Aquifer TES (ATES) - Large scale TES

Strategies for cooling				
Direct evaporative cooling	- Reduction of pollution emissions - Life cycle cost effectiveness - Reduction of peak demand - Cheap	- Not good when ambient humidity >40% - Humidity Increase	70% (Mujahid Rafique et al. 2015)	- Hot and dry climate
Indirect evaporative cooling	- Higher air quality than direct evaporative cooling - No humidity increase - More efficient than vapour compression systems	- Installation and operation more complex than direct evaporative systems	50% (Mujahid Rafique et al. 2015)	- Hot climate
Liquid pressure amplification	- Significant energy savings	- Energy savings potential limited to low ambient temperatures - More expensive than conventional vapour compression systems	25.3% (Vakiloroaya et al. 2014b)	-Simulation
Ground-coupled	- Less noise and GHG emissions than conventional vapour compression systems	- Requirements of earth surface - Very high upfront costs - Expensive both in capital and operation costs	50 % (Soltani et al. 2019)	- Ground-coupled heat pump system
Chilled-ceiling	- Less refrigeration use due to use of cooled water instead of chilled water	- Unable to moderate indoor humidity - Risk of condensation at cold surface	10% (Imanari et al. 1999)	- 70% of the ceiling surface covered by radiant ceiling panels
Desiccant cooling	- Humidity control is improved when coupled with conventional systems	- Corrosive materials - Large response time - Crystallisation of materials maybe a problem - Expensive both in capital and operation costs	77% (Mujahid Rafique et al. 2015)	-Dunkle cycle
Ejector cooling	- More simple installation, maintenance and construction than conventional compression systems	- Need of a heat source >80ºC - Lower COP than conventional compression systems	14.52% (Yu et al. 2020)	-Simulation -R236ea Refrigerant
Variable refrigerant flow	- Efficient in part load conditions	- Requirement of extra control systems - Cannot provide full control of humidity	17% (Lee et al. 2018)	-Simulation -Building temp set-point 24ºC

Table SM9.3 Technology strategies contributing to renewables. Adapted from (Cabeza and Chàfer 2020a; Irshad et al. 2019; Luo et al. 2017)

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Geothermal energy or ground source heat pumps	- Abundant and clean - Provides year around low cost heating and cooling using district energy technology - Not affected by climate	- Expensive start-up and maintenance due to corrosion - Risk of toxic emissions - Subsidence, landscape change, and polluting waterways - Long construction time - Hard to assess resource - High cost	cooling 30–50% heating 20–40% (Sarbu and Sebarchievici 2014)	Warm-climate region, Atlanta (cooling-dominated climate) -- Simulation
Solar energy PV	- Abundant supply - Less environmental damage compared to other renewable options - Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers - Medium – high cost depending of the system used	- Storage and backup issues - Not constant supply	22 % (Irshad et al. 2019)	Energy saving potential -- PV integrated with the TE (thermoelectric technologies)
			12 – 25 % (Luo et al. 2017)	Double skin façade using photovoltaic blinds (PV-DSF) -- Changsha, Hunanprovince, China -- Summer conditions
Solar thermal	- Abundant and clean supply - Less environmental damage compared to other renewable options - Significant energy savings	- Storage and backup issues - Not constant supply	30% (Ahmadi et al. 2021)	Simulation HEAT4COOL
			Winter 75.8%, summer 51.5%. (Hohne et al. 2019)	Hybrid solar Electric water heater

Biomass energy	- Abundant with a wide variety of feedstock and conversion technologies - Indigenous fuel production and conversion technology in developing countries - Low cost	- May release GHGs during biofuel production - Landscape change and deterioration of soil productivity	94.98% (Zhang et al. 2019)	Hybrid solar-biomass
			16 – 94 % (Pardo et al. 2020)	

SM9.2 Supplementary information to Section 9.8

Table SM9.4 summarises the results of 17 studies from 12 different countries showing the price premium of energy efficient dwellings.

Table SM9.4 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
			C / D	5.1%		

			E / D	-5.4%		the advertising requirement implemented by 1 July 2010
			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 energy codes / No		23.3%	The existence of the codes IECC2003 through IECC2006 for American households is evaluated in this study

SM9.3 Supplementary information to Section 9.9

Box SM9.1 presents an example of a policy package, to complement, Section 9.9.

Box SM9.1 EU policy package for energy efficiency of buildings

Buildings consume 40% of final energy in the EU and are responsible for 36% of the EU CO_2 emissions (Renovation Wave, 2020). The majority of buildings are already built, with several buildings between 50 and 20 old, built before energy performance requirements were part of building energy codes, therefore having poor energy performances. The current energy renovation rate is 1% per year, with many renovations only marginally improving the energy performances. At the current renovation rate, the target to decarbonise the building stock by 2050 will be largely missed.

The EU has developed over the years a comprehensive policy package of several policy instruments, aiming at reducing energy consumption, integrating renewable energies and thus mitigating GHG emissions from buildings (Economidou et al. 2020).

In 1992, a first EU law (Save Directive) encouraged EU Member States (MSs) to adopt energy performance standards in building energy codes, this resulted in mix action by MSs, with only a few adopting stringent energy performances requirements. To reinforce the action by MSs and align it, in 2002 the EU adopted the Energy Performance Buildings Directive (EPBD, 2002), requiring MSs to adopt minimum efficiency performance standards for buildings according to a common methodology both for new and existing buildings, when undergoing major renovation (Bertoldi P. 2019). The EPBD is a regulatory measure, with its implementation left to individual MSs. This has resulted in very different levels of stringency among MSs. In addition, the enforcement of control on the application of the energy performance requirements is left to national authorities and finally delegated to local authorities, who may lack the technical knowledge or manpower to check compliance with legal requirements. This has resulted in low compliance with normative requirements in many MSs. The 2002 EPBD has also introduce the obligation to show an energy performance certificate when a building is sold or rented (information policy) (Li et al. 2019). In 2010, the EPBD was amended by introducing the requirements for MSs to set the national energy requirement for new and existing buildings at the cost-optimal level and providing a common methodology for calculating it (Zangheri et al. 2018; Corgnati et al. 2013).The 2010 EPBD introduced the requirement for all new buildings to be nearly zero energy (nZEBs) by 2021, however definitions of nZEB are left to EU Member States, which have different requirements for energy consumption limits and contribution of renewables (D'Agostino and Mazzarella 2019; Attia et al. 2017; Grove-Smith et al. 2018; Economidou et al. 2020). The latest 2018 amendment of the EPBD introduced the requirements for MSs to prepare a Long Term Renovation Strategies (LTRSs) with an overarching decarbonisation target of the national building stock by 2050.

The 2012 Energy Efficiency Directive (EED) requested MSs: to adopt smart meters and smart billing and to charge consumers on their real heating energy consumption; to remove the split-incentive barriers; to foster energy efficient procurement by public authorities; to renovate each year at least 3% of the building stock of central governments. Article 7 of the EED established the obligation for MSs to set up mandatory obligation for energy companies to save at least 1.5% of their energy sales by implementing energy efficiency actions in end-users, including measure on buildings (Fawcett and Parag 2017) or alternative policy measures delivering the same amount of energy savings (Rosenow and Bayer 2017). The EED encourages the setting up of financing programmes for the renovation of buildings. MSs have implemented a number of financial mechanisms such as low interest loans, grants, guarantees funds, revolving funds etc. (Bertoldi 2020). Moreover, the EU Regional and Cohesion Funds are also used by MSs for the renovation of existing buildings. Some of the instruments used at national level to finance the renovation of dwellings occupied by low-income families result from the auctioning of allowances under the EU Emissions Trading Scheme, which is used in some MSs.

The EU has an overall binding economy-wide domestic emission reductions target of at least 55% by 2030 compared to 1990 and, for sectors of the economy not covered by the EU Emission Trading System, the Effort Sharing Regulation (2018) set a target to reduce emissions by 30% by 2030 compared to 2005 (this target will include only buildings direct emissions), with specific mandatory targets for individual MSs.

In addition, there is an overall mandatory EU energy saving target set at reducing primary energy by 32.5% against a BaU scenario, each MSs must contribute to reaching this target (but no mandatory individual targets for MSs). As results, in order to contribute to the EU target, individual MSs have adopt a range of national policies and measures for the building sector in addition to the EU EPBD requirements as described in the National Energy and Climate Plans of 2020.

To complement measures for the overall performance of buildings, regulatory measures focuses on the building equipment and technical services such as air conditioners, boilers, lightings, domestic appliances. In the EU minimum energy performance requirements for appliances and equipment are adopted at EU level under the EcoDesign Directive (2005) The energy efficiency requirements are the same for all the MSs and now all the major building technical equipment are covered by dedicated regulation under the Ecodesign. As example the removal from sale of incandescent and halogen lamps has been implemented under the Eco-design Directive.

In the EU over 10000 cities taking part in the Covenant of Mayors initiative (Palermo et al. 2020) have adopted building measures as part of the city planning or city building permits.

Despite the comprehensiveness of the EU policy package, the monitoring of the progress made in reducing GHG from the EU building stock shows that the EU would miss its buildings' decarbonisation target for 2050. The following issues were identified as major obstacles to Europe's decarbonisation strategy of the building stock. The inconsistencies between the overarching target of a decarbonised building stock by 2050 and the energy requirement in case of major renovation of existing buildings. Both requirements are included in the EPBD. As of today, there is enough evidence about the lock-in effect of the renovation requirements included in the EPBD. The complexity, and sometimes the impossibility, of bundling public finance targeting GHG mitigation of buildings, with private finance. The Smart Finance for Smart Building (SFSB) initiative addresses this issue only partially. The lack of rigorous MV&E for both buildings (including the Energy Performance Gap) and appliances performances, which reduce the level of expected savings. There is no concrete measure to avoid the direct rebound effect and the current energy prices are relatively low. In addition, there are no specific policies and measures at EU level to address energy sufficiency. Regulations and technical standards do not include the life cycle CO_2 emissions in the performance of the buildings. The complexity of the governance structure at different levels (EU, National, Regional and Local), with many options left to individual MSs, for example the definition of Near Zero Energy Buildings. The complexity of managing several instruments, often dealt by different national ministries and departments (industry, environment, construction, urbanisation, etc.) and, finally, the disconnect between high-level EU targets and the lack of ambition of individual policies, which makes the decarbonisation of the EU building stock more challenging. The recently adopted Renovation Wave Communication addresses the above issues, in particular on financing renovation of buildings.

SM9.4 Supplementary information to Section 9.10

Table SM9.5 details the feasibility assessment presented in Table 9.7. Table SM9.6 provides the references used for the feasibility assessment.

1 **Table SM9.5. Feasibility Assessment of Mitigation Options in the Buildings Sector**

Mitigation Options	Envelope improvement		Heating, ventilation and air conditioning (HVAC)		Efficient Appliances		Change in construction methods		Change in construction materials	
Indicators	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal
Geophysical										
Physical potential	LoA=5|LoC=3	Not applicable in historical /heritage buildings where modifications to facade are difficult / transparent insulation materials (TIM) provide the advantages of insulation materials including also the advantages of being able to use daylight / Green Roofs: in some regions new buildings is compulsory to implement green roof & Enhancing building aesthetics & Reduction of heat gains and losses / Thermal mass is not always beneficial in relation to thermal comfort and energy consumptions/ PCMs reduce the internal temperature fluctuations in the building, providing better thermal comfort to the occupants / Trombe walls are aesthetically appealing and In region with mild winters and hot summers, overheating problems may outweigh the winter benefits	LoA=5|LoC=5	High space requirements in buildings	LoA=4|LoC=3	There are technical limitations to energy efficiency, but there is much room for improvement, especially in developing countries	LoA=5|LoC=5	* It is expected that in advanced construction methods (e.g. BIM (Building Information Modeling, Industrialisation and rationalisation, Design for Deconstruction/Disassembly, Digital fabrication and Design for performance) there will be a reduction in the consumption of raw materials and natural resources. The design for deconstruction/disassembly allows an increase of the reuse potential of building materials and elements. When these products are reused there are avoided impacts related to the consumption of virgin resources and end-of-life of wastes. This will decrease pressure for geophysical resources and land use.	LoA=4|LoC=4	Some low carbon construction materials are already used in civil construction. The physical availability of materials (e.g. wood, bamboo, bio-concretes, earth, concrete with limestone and supplementary cementitious materials and limestone calcined clay cement) is abundant, although there may be some regional scarcity and depends on the scale of adoption.
Geophysical resources	LoA=5|LoC=3	Conventional insulation materials are derived from petrochemical substance. New sustainable insulation materials have been developed / To consider green roofs as an environmentally friendly technology, the selection of efficient and sustainable components is extremely important. Green walls is still controversial / Regarding improvement of thermal inertia, this can be achieved with the use of materials with high density, such as concrete or rammed earth / or with the use of phase change materials (PCM) / The process of autoclaving concrete requires significant energy consumption	NA		NA		LoA=5|LoC=5	see *	LoA=4|LoC=4	Some low carbon construction materials are already used in civil construction. The physical availability of materials (e.g. wood, bamboo, bio-concretes, earth, concrete with limestone and supplementary cementitious materials and limestone calcined clay cement) is abundant, although there may be some regional scarcity and depends on the scale of adoption.
Land use	NA		NA		NA		LoA=5|LoC=5	see *	LoA=3|LoC=3	For bio-based materials, feedstock can be developed in degraded areas. However, land competition with agriculture, food and other industrial uses (e.g. cellulose) can happen.

Mitigation Options	Envelope improvement		Heating, ventilation and air conditioning (HVAC)		Efficient Appliances		Change in construction methods		Change in construction materials	
Indicators	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal
Environmental-ecological										
Air pollution	LoA=4|LoC=5	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	LoA=4|LoC=4	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	LoA=4|LoC=5	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	LoA=4|LoC=4	"** The use of Building Information Modeling (BIM) together with the Life Cycle Assessment (LCA) methodology allows a faster, holistic and more assertive assessment of the potential environmental impacts of a building project, allowing to reduce impacts throughout the project life cycle. It is expected that advanced construction methods will induce a reduction in the consumption of raw materials and natural resources. Then, a reduction in the environmental impacts during the production of these materials is expected. In addition, it is expected a decrease in waste generation. However, some trade-offs between environmental impacts (e.g. reduction of air pollution and increase the water consumption, etc.) can occur, depending on type of product/process. "	LoA=4|LoC=4	Engineered wood/bamboo products normally use petroleum-based adhesives. These adhesives can release toxic gases (e.g. formaldehyde and Volatile Organic Compounds - VOCs). Life cycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with SCM replacing cement or clinker is less polluting.
Toxic waste, ecotoxicity and eutrophication	LoA=3|LoC=3	As a result of the reduced consumption of natural resources and reduced air pollution levels.	LoA=3|LoC=3	As a result of the reduced consumption of natural resources and reduced air pollution levels.	LoA=3|LoC=3	As a result of the reduced consumption of natural resources and reduced air pollution levels.	LoA=4|LoC=4	see **	LoA=4|LoC=4	Some biomass treatment processes uses toxic materials and substances. The use of fertilisers in forestry activities can increase eutrophication. Life cycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with SCM replacing cement or clinker is less polluting.

Mitigation Options	Envelope improvement		Heating, ventilation and air conditioning (HVAC)		Efficient Appliances		Change in construction methods		Change in construction materials	
Indicators	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal
Water quantity and quality	**LoA=4|LoC=4**	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.	**LoA=4|LoC=4**	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy producton facilities.	**LoA=4|LoC=4**	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy producton facilities.	**LoA=4|LoC=4**	see **	**LoA=3|LoC=4**	An increase in water demand can be observed during the forest activities
Biodiversity	**LoA=3|LoC=3**	Green roofs and walls, particularly if they are connected to other green spaces enhance urban biodiversity. Reduced air pollution levels due to mitigation actions improves biodiversity.	**LoA=3|LoC=2**	Reduced air pollution levels due to mitigation actions improves biodiversity.	**LoA=3|LoC=2**	Reduced air pollution levels due to mitigation actions improves biodiversity.	**LoA=4|LoC=4**	see **	**LoA=3|LoC=3**	Normally monoculture production is encouraged and can put pressure on native forest areas
Technological										
Simplicity	**LoA=5|LoC=4**	There different envelope measure with different levels of simplicity. Building integrated concepts (such as insulation or PCM) are very simple. Other concepts such as greenery systems can be more complicated	**LoA=3|LoC=3**	Different criteria depending on the technology. Evaporative cooling systems have higher simplicity than heat pumps and ground-coupled systems.	**LoA=4|LoC=4**	Simple efficiency improvements are available in many regions. However, increasing appliance efficiency can be complex in countries with already high efficient standards.	**LoA=3|LoC=4**	Many advanced construction methods are common and widespread in the market in mainly developed countries. There is a need for a change of thinking during the project design, especially indicated for complex building design and shapes. Prescriptive standards need to be modified so that products and processes achieve the final performance required for a given situation/need.	**LoA=4|LoC=3**	Bio-concretes use available materials and similar infrastructure of conventional concrete production. However, more research is needed. Biomaterials are widely used and have a variety of applications in residential, commercial and industrial buildings. However, attention is needed for fire protection and biological durability. Other materials such as earth, concrete with limestone and supplementary cementitious materials and limestone calcined clay cement use available materials with adequate performance and similar infrastructure of Portland cement production
Technology scalability	**LoA=5|LoC=2**	From a facade to a building to a multifamily house	**LoA=5|LoC=3**	It is widely implemented at all scales. for example vehicles, houses, buildings, warehouses.	**LoA=4|LoC=4**	Can be easily scaled up.	**LoA=3|LoC=3**	Construction methods can be applied for a building component, façade or to a whole building. However, it tends to be more difficult to apply in larger scale projects.	**LoA=4|LoC=3**	Biomaterials can be applied to furniture, façade and to the whole building in general. Bio-concrete can be used to produce construction elements that not require high mechanical performance

Mitigation Options	**Envelope improvement**		**Heating, ventilation and air conditioning (HVAC)**		**Efficient Appliances**		**Change in construction methods**		**Change in construction materials**	
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Maturity and technology readiness	**LoA=4|LoC=2**	Insulation is very well known technology, however sustainable materials need future research / A step forward is the use of transparent insulation materials (TIM) for building energy savings and daylight comfort / VGS are still being controversial depending on the climate and materials / PCM can be organic or inorganic, each type with their advantages and disadvantages	**LoA=5|LoC=4**	It is a widely implemented technology. In the same way, efforts continue to be allocated to R&D to improve i.e. energy efficiency	**LoA=4|LoC=4**	Many efficient appliances are technologically mature. Moreover, efforts continue to be allocated to R&D to improve i.e. energy efficiency	**LoA=3|LoC=4**	Some technologies are well known, however their market applicability varies from country to county. There are some isolated cases of projects using highly advanced construction methods (e.g. Building Information Modeling, Design for Deconstruction/Disassembly, Digital fabrication and Design for performance) in pilot and research projects.	**LoA=4|LoC=3**	Some bio-based (wood and bamboo) materials are well known and widespread used, however its applicability in varies from country to county. Some bio-concretes (e.g. hempcrete) are already available on the market. However, it is still not widespread in the construction industry. Other bio-concretes are still in the research phase. The use of limestone in large quantities still needs to be further researched. Earth materials and some supplementary cementitious materials are already used commercially, such as soil-cement bricks and fly ash, respectively. However, others are still in research development stage
Economic										
Costs in 2030 and long term	**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**	
Employment effects and economic growth	**LoA=4|LoC=4**	Positive and negative direct and indirect effects associated with lower energy energy demand and possible reductions in energy prices, energy efficiency investments, lower energy exoenditures, and fostering innovation. Improvements in labour productivity.	**LoA=4|LoC=4**	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy exoenditures, and fostering innovation. Improvements in labour productivity.	**LoA=4|LoC=4**	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy exoenditures, and fostering innovation. Improvements in labour productivity.	NE		**LoA=4|LoC=3**	Potential positive effect along the value chain (job creation and added value)

Mitigation Options	**Envelope improvement**		**Heating, ventilation and air conditioning (HVAC)**		**Efficient Appliances**		**Change in construction methods**		**Change in construction materials**	
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Socio-cultural										
Public acceptance	**LoA=4|LoC=4**	Perceived as increased confort and status, with limited concerns for heritage or aesthetic values in regions with higher living standards.	**LoA=4|LoC=4**	Perceived as increased confort and status, with limited concerns for lack of space for installation in regions with higher living standards.	**LoA=4|LoC=4**	Perceived as increased confort and status, with limited concerns for technical issues and durability in regions with lower living standards.	**LoA=4|LoC=3**	Although many stakeholders see advantages in new construction methods, especially in terms of sustainable construction, there are social barriers, such as information interaction between software, insufficient technical training for employees, cultural resistance, etc.	**LoA=3|LoC=2**	Bio-based materials, such as wood, can be well accepted for being a natural and aesthetically pleasing material. However, in some cases (mainly in developing countries) it is associated with low quality buildings. There is not enough information about other materials.
Effects on health and wellbeing	**LoA=4|LoC=5**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect. Envelope improvement with inadequate ventilation may lead to the sick building syndrome symptoms.	**LoA=4|LoC=5**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect	**LoA=4|LoC=5**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect	**LoA=4|LoC=3**	Biomass based materials, such as wood and bamboo, has aesthetic advantages and brings the concept of biophilia. However, the preservatives and glues used in the production can bring health problems related to the presence of VOCs	**LoA=3|LoC=3**	Bio-based materials, such as wood and bamboo, has aesthetic advantages and brings the concept of biophilia. However, the preservatives and glues used in the production can bring health problems related to the presence of VOCs
Distributional effects	**LoA=4|LoC=4**	Result in lower energy bills and avoiding the"heat or eat" dilemma. Also, in energy/fuel poverty alleviation and in improving energy security.	**LoA=4|LoC=4**	Result in lower energy bills and avoiding the "heat or eat" dilemma. Also, in energy/fuel poverty alleviation and in improving energy security.	**LoA=3|LoC=3**	Improved cookstoves provide better food security and reduces the danger of fuel shortages in developing countries (under real world conditions these impacts may be limited). Result in lower energy bills and avoiding the"heat or eat" dilemma. Also, in energy/fuel poverty alleviation and in improving energy security.	**LoA=3|LoC=3**	Biomass based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities	**LoA=3|LoC=3**	Bio-based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities

Mitigation Options	Envelope improvement		Heating, ventilation and air conditioning (HVAC)		Efficient Appliances		Change in construction methods		Change in construction materials	
Indicators	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal
Institutional										
Political acceptance	LoA=3|LoC=3	Not perceived as a priority policy for energy effciency in buildings by many policy makers in particular in warm climate and in develping countries. Policy makers are neutral to the technology implemented to improve the building energy performances. Incentives are often used to promote insulation in residential buildings	LoA=|LoC=		LoA=4|LoC=4	Some governments have encouraged the use of new construction methods. Industrialisation and rationalisation are considered a cleaner construction method that facilitates sustainability in the construction industry in many countries. Normally, there are public policies that encourage industrialisation and rationalisation of construction	LoA=4|LoC=4	Some governments have encouraged the use of new construction methods. Industrialisation and rationalisation are considered a cleaner construction method that facilitates sustainability in the construction industry in many countries. Normally, there are public policies that encourage industrialisation and rationalisation of construction	LoA=4|LoC=2	Bio-based materials, such as wood and bamboo, have been pointed as important alternatives for the construction sector in low-carbon policies in some countries.
Institutional capacity and governance, cross-sectoral coordination	LoA=3|LoC=3	Very often building performance and envelopment improvents require very specific technical capabilities. In some countries building energy codes are established at local level, with gaps in governance and coordination between different levels of government	LoA=|LoC=		LoA=4|LoC=4	There are cross-sectorial actions between different stakeholders (government, designers, building companies, material manufacturers, research centers, etc.)	LoA=4|LoC=4	There are cross-sectorial actions between different stakeholders (government, designers, building companies, material manufacturers, research centers, etc.)	LoA=|LoC=	
Legal and administrative feasibility	LoA=4|LoC=4	"Building energy codes are difficult to enforce, often compliance is based on design and no check is carried out when in use. In use energy may be much higher than calculated energy. Envelop improvement in particular fo existing building are difficult to verify also in the case on public subsidies"	LoA=|LoC=		LoA=4|LoC=4	In many countries, there are public policies that encourage industrialisation and rationalisation of construction.	LoA=4|LoC=4	In many countries, there are public policies that encourage industrialisation and rationalisation of construction.	LoA=|LoC=	

Mitigation Options	**Active and passive management and operation**		**Digitalisation**		**Flexible comfort requirements**		**Circular and shared economy**		**Renewable energy production**	
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Geophysical										
Physical potential	NE		NA		NA		NA		LoA=5|LoC=3	Large unatped potential for most technologies / Rural areas have a great potential of renewable energy sources
Geophysical resources (incl geologica storage capacity)	NA		NA		NA		NA		LoA=4|LoC=3	Most technologies not limited by materials
Land use	NA		NA		NA		LoA=4|LoC=3	Implications for wood products depend on material accounting methods	NA	
Environmental-ecological										
Air pollution	LoA=4|LoC=5	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	LoA=3|LoC=3	Support interventions that can eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor). However, it should be taken into account that smart controls and connected devices result in increased electricity consumption.	LoA=4|LoC=3	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	LoA=3|LoC=3	Reduced environmental impact depends on solutions and materials. Potential rebound for reduced ownership.	LoA=4|LoC=5	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)

Mitigation Options	**Active and passive management and operation**		**Digitalisation**		**Flexible comfort requirements**		**Circular and shared economy**		**Renewable energy production**	
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Toxic waste, ecotoxicity and eutrophication	**LoA=3|LoC=3**	As a result of the reduced consumption of natural resources and reduced air pollution levels.	**LoA=3|LoC=3**	As a result of reduced consumption of natural resources and air pollution levels.	**LoA=3|LoC=3**	As a result of the reduced consumption of natural resources and reduced air pollution levels.	**LoA=3|LoC=3**	Reduced environmental impact depends on solutions and materials	NA	
Water quantity and quality	**LoA=4|LoC=4**	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy producton facilities.	**LoA=4|LoC=2**	Smart meters give the opportunity to monitor and reduce water consumption in households	**LoA=4|LoC=4**	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy producton facilities.	**NE**		**LoA=4|LoC=4**	An upscaling of RES usually results in reducing water demand for thermal cooling at energy producton facilities. Improved access to electricity is necessary to treat water at homes. In some situations the switch to bioenergy could increase water use compared to existing conditions.
Biodiversity	**LoA=3|LoC=2**	Reduced air pollution levels due to mitigation actions improves biodiversity.	NA		**LoA=3|LoC=2**	Reduced air pollution levels due to mitigation actions improves biodiversity.	**NE**		**LoA=4|LoC=3**	Reduced air pollution levels due to mitigation actions improves biodiversity. Bioenergy production may have both positive and negative impact in biodiversity.
Technological										
Simplicity	**LoA=5|LoC=3**	There is a wide range of possibilities; ranging from very simple measures (turning off lights and water when not necessary, closing windows while cooking, keep refrigerator door closed, using washing machine in ecomode) to more complex ones (buy energy saving devices, sensors, timers). Still individual factors such as identity, environmental values and circumstances can make adoption more complex under specific conditions.	**LoA=5|LoC=2**	Ranges from very simple monitoring sensors, or simple concepts to smart cities	**LoA=4|LoC=3**	Behaviour diffusion occurs via peer pressure and social norms, and can be easily fostered among social groups with homogenous values. Behaviour changing feedback devices and automation technology can be used to drive behavour change. Yet, the collision between environmental collectivist values and individual identity and goals can present barriers to diffusion.	**LoA=3|LoC=3**	Circular solutions (reduced waste, materials reuse and recycling) have varying technological complexity, whereas sharing solutions need only ICT support for communication and business models.	**LoA=4|LoC=3**	Most technologies are simple. However, supply of technical support at the local scale can be a barrier / Hybridisation beetwen several technologies can achieve better results both for energy production and for power generation.

Mitigation Options	Active and passive management and operation		Digitalisation		Flexible comfort requirements		Circular and shared economy		Renewable energy production	
Indicators	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal	Feasibility barriers or enablers	Role of context, scale, time, temperature goal
Technology scalability	LoA=4|LoC=5	High potential for scalability. The simple measures can be upscaled easily via information campaigns, enhanced by the fact that there is a high willingness to adopt. Even the more complex measures have this strong willingness due to the potential to reduce energy and water bills. Nevertheless, cultural values and local physical conditions can affect the scalability of measures that affect comfort and well-being directly. ICT tools, peer effects and rewards could help foster scalability;, keeping in mind potential barriers such as perception of control, concerns over information sharing and privacy and expectancies in terms of effort and benefits.	LoA=4|LoC=5	High scalability	LoA=3|LoC=3	Highly scalable among heterogenous social groups. Location-specific environmental realities may become barriers, e.g. regions facing heatwaves.	LoA=3|LoC=3	Circular solutions are not yet implemented at scale. Requires improved design for flexibility and deconstruction, improved procurement and prefabrication and off-site construction, improved standardisation and dimensional coordination, with differences among solutions..	LoA=5|LoC=4	Most technologies can be scaled up to most regions.
Maturity and technology readiness	LoA=5|LoC=5	The simple measures require no technology development, while more complex measures are already widely available, still with potential for improvement	LoA=5|LoC=2	It is a recent concept that emerged with the boom of digital technologies, important efforts are allocated to R&D	LoA=5|LoC=4	Feedback technology exists for many energy uses at households (TVs, air conditioners, lighting, heating). It has existed for a while although in lower scale (e.g. air conditioners that display temperature).	LoA=3|LoC=3	Technological improvements are expected (waste reduction and management, recycling and upgrade of materials and products), together with additional improved compatibility with existing design, tools and technologies. Limitations on share of recicled materials in concrete, problem shifting to other sectors, with regional and sectorial differences.	LoA=4|LoC=3	Most technologies are mature. Moreover, efforts continue to be allocated to R&D to improve.
Economic										
Costs in 2030 and long term	LoA=|LoC=		LoA=|LoC=		LoA=|LoC=		LoA=3|LoC=4	Potential cost-competitiveness and (lower life cycle costs, green/quality premium), but still uncertain large-scale investors due to perceived higher investment costs.	LoA=|LoC=	
Employment effects and economic growth	LoA=4|LoC=4	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, and lower energy exoenditures.	LoA=3|LoC=2	Digitalisation of energy resuls in increased productivity and efficiency. Smart meters result in creation of new businesses and jobs in manufacturing.	LoA=4|LoC=4	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, and lower energy exoenditures.	LoA=4|LoC=4	Potential positive effect along the value chain (job creation, bussines value, networking), including synergies with digitalisation	LoA=4|LoC=4	Positive and negative direct and indirect effects associated with lower demand for fuels and possible reductions in energy prices, RES investments, improved energy access and fostering innovation. Improvements in labour productivity.

Mitigation Options	**Active and passive management and operation**		**Digitalisation**		**Flexible comfort requirements**		**Circular and shared economy**		**Renewable energy production**	
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Socio-cultural										
Public acceptance	**LoA=3|LoC=3**	Perceived as environmental and technological friendly, with concerns for lack of control in regions with higher living standards. Little literature in regions with lower living standards.	**LoA=5|LoC=4**	Perceived as environmental and technological friendly, with concerns for costs and lack of control in regions with higher living standards. Little literature in regions with lower living standards.	**LoA=4|LoC=4**	Perceived as environmental friendly, with concerns for lack of confort and control in regions with higher living standards. Little literature in regions with lower living standards.	**LoA=4|LoC=3**	Perceived as environmental friendly, with concerns for costs, lack of confort and control in regions with higher living standards. Favoured by digitalisation. Little literature in regions with lower living standards; extended life of products seems specially appreciated in emerging economies.	**LoA=5|LoC=5**	Perceived as environmental and technological friendly
Effects on health and wellbeing	**LoA=4|LoC=5**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect	**LoA=4|LoC=3**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect	**LoA=4|LoC=3**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect	**LoA=4|LoC=3**	Superior customer value	**LoA=4|LoC=5**	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect
Distributional effects	**LoA=4|LoC=4**	Result in lower energy bills and avoiding the "heat or eat" dilemma. Also, in energy/fuel poverty alleviation and in improving energy security.	**LoA=4|LoC=5**	Result in lower energy bills and avoiding the"heat or eat" dilemma. Also, in energy/fuel poverty alleviation and in improving energy access and energy security (assuming a very high level of consumer involvement). Smart meters support the introduction of new and dynamic tariff schemes that allow price benefits for the end-users.	**LoA=4|LoC=3**	Result in lower energy bills and avoiding the"heat or eat" dilemma. Also, in energy/fuel poverty alleviation.	NE		**LoA=4|LoC=4**	Improving energy access ehnances agricultural productivity and improves food security. On the other hand, increased bioenergy production may restrict the available land for food production. Result in energy/fuel poverty alleviation and in improving energy security.
Institutional										
Political acceptance	**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**	
Institutional capacity and governance, cross-sectoral coordination	**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**	
Legal and administrative feasibility	**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**		**LoA=|LoC=**	Business models still to be deployed at large scale, though some succesfull examples exist.	**LoA=|LoC=**	

LoA: Level of Agreement	1=low, 5= full
LoC: Level of confidence	1=low 5 = high
🟨	+ The indicator has a positive impact on The feasibility of The option
🟧	± Mixed evidence: the indicator has mixed positive and negative impacts on the feasibility of the option
🟫	-The indicator has a negative impact on the feasibility of the option
⬜	The indicator does not affect the feasibility of the option
⬛	NA Criterion is not applicable for the option
🟦	NE No evidence available
▨	LE Limited evidence available
🟥	Assessment still in progress

Table SM9.6 References for the Feasibility Assessment of Mitigation Options in the Buildings Sector

	Geophysical			Environmental-ecological				Technological		
Mitigation Options	**Physical potential**	**Geophysical recourses**	**Land Use**	**Air popultion**	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**	**Simplicity**	**Technological scalability**	**Maturity and technology readiness**
Envelope improvement	(Cabeza et al. 2018; Cabeza and Chàfer 2020b), (Sun et al. 2018a; Cabeza et al. 2020) (Lidelöw et al. 2019; Cascone et al. 2018; Pérez et al. 2014; Olsthoorn et al. 2017; Bhamare et al. 2019; Navarro et al. 2016a; Belussi et al. 2019; Omrany et al. 2016)	(Aditya et al. 2017; Charoenkit and Yiemwattana 2016; Cascone et al. 2018; Laborel-Préneron et al. 2016; Irshad et al. 2019; Tatsidjodoung et al. 2013; Kalnæs and Jelle 2015; Shafigh et al. 2018)	NA	(MacNaughton et al. 2018; Levy et al. 2016; Balaban and Puppim de Oliveira 2017; Thema et al. 2017)	(Mzavanadze 2018; Thema et al. 2017)	(Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Mayrand and Clergeau 2018; Joimel et al. 2018; Hui and Chan 2011; Mzavanadze 2018; Thema et al. 2017)	(Aditya et al. 2017; Wang et al. 2018; Sun et al. 2018b; Riley 2017; Pérez et al. 2014; Omrany et al. 2016; Raji et al. 2015; Drissi et al. 2019; Tatsidjodoung et al. 2013; Belussi et al. 2019; Laborel-Préneron et al. 2016; Irshad et al. 2019; Shafigh et al. 2018)	(Aditya et al. 2017; Pérez et al. 2014; Omrany et al. 2016; Raji et al. 2015)	(Aditya et al. 2017; Wang et al. 2018; Sun et al. 2018b; Riley 2017; Mavrigiannaki and Ampatzi 2016; Soares et al. 2013; Noro et al. 2014; Khadiran et al. 2016; Silva et al. 2016; Reddy et al. 2018)
Heating, ventilation and air conditioning (HVAC)	(Prívara et al. 2011; Ling et al. 2020; Dong et al. 2020; Peng et al. 2020; Gong et al. 2019; Zhang et al. 2020a; Mi et al. 2020)	(Abas et al. 2014; Dilshad et al. 2020; Bamisile et al. 2019)	NA	(Levy et al. 2016; Balaban and Puppim de Oliveira 2017; MacNaughton et al. 2018; Thema et al. 2017)	(Mzavanadze 2018; Thema et al. 2017)	(Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Mzavanadze 2018; Thema et al. 2017)	(Harby et al. 2016; Mujahid Rafique et al. 2015; Peng et al. 2020; Zhang et al. 2020a; Ling et al. 2020; Soltani et al. 2019)	(Chen et al. 2021; Cvok et al. 2020; Teja S and Yemula 2020; Sha and Qi 2020; Talkar et al. 2020)	(Choe 1973; Lo Basso et al. 2021; Pahinkar et al. 2020; Husin et al. 2020; Chen et al. 2021; Hadjadj et al. 2020)
Efficient Appliances	(Singh et al. 2019; Saheb et al. 2018; González Mahecha et al. 2020; González-Mahecha et al. 2019)	NA	NA	(Rosenthal et al. 2018; Steenland et al. 2018; Goldemberg et al. 2018; Levy et al. 2016; Balaban and Puppim de Oliveira 2017; MacNaughton et al. 2018; Thema et al. 2017)	(Mzavanadze 2018; Thema et al. 2017)	(Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Mzavanadze 2018; Thema et al. 2017)	(Himeur et al. 2020; Singh et al. 2019) (Wang et al. 2021; Mariano-Hernández et al. 2021; Kaur and Bala 2019; Rajagopal et al. 2019)	(Ma et al. 2016; Singh et al. 2019) (Mariano-Hernández et al. 2021; Zhang et al. 2016)	(Himeur et al. 2020; Singh et al. 2019; Cabeza et al. 2018) (Hopkins et al. 2020; Joshi et al. 2020)

	Geophysical			Environmental-ecological				Technological		
Mitigation Options	Physical potential	Geophysical recourses	Land Use	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity	Simplicity	Technological scalability	Maturity and technology readiness
Change in construction methods	* Agustí-Juan et al. (2017), Agustí-Juan et al. (2017a), Ahmed and Tsavdaridis (2018), Alhumayani et al. (2020), Brambilla et al. (2019), Huang et al. (2021), Diyamandoglu and Fortuna (2015), Eckelman et al. (2018), Habert et al. (2020), Kuzmenko et al. (2020), González Mahecha et al. (2020), Saade et al. (2020), Santos et al. (2020), Soust-Verdaguer et al. (2017)		Agustí-Juan et al. (2017), Agustí-Juan et al. (2017a), Ahmed and Tsavdaridis (2018), Alhumayani et al. (2020), Brambilla et al. (2019), Huang et al. (2021), Diyamandoglu and Fortuna (2015), Eckelman et al. (2018), Habert et al. (2020), Kuzmenko et al. (2020), González Mahecha et al. (2020), Saade et al. (2020), Santos et al. (2020), Soust-Verdaguer et al. (2017)					Agustí-Juan et al. (2017), Agustí-Juan et al. (2017a), Ahmed and Tsavdaridis (2018), Alhumayani et al. (2020), Brambilla et al. (2019), Huang et al. (2021), Diyamandoglu and Fortuna (2015), Eckelman et al. (2018), Habert et al. (2020), (Kuzmenko et al. 2020), González Mahecha et al. (2020), Saade et al. (2020), Santos et al. (2020), Soust-Verdaguer et al. (2017)		

	Geophysical			Environmental-ecological				Technological		
Mitigation Options	Physical potential	Geophysical recourses	Land Use	Air popultion	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity	Simplicity	Technological scalability	Maturity and technology readiness
Change in construction materials	Peñaloza et al. (2016), Pomponi et al. (2020), Churkina et al. (2020), Soust-Verdaguer et al. (2020), Zea Escamilla and Habert (2014), Zea Escamilla et al. (2016), Escamilla et al. (2018), Chang et al. (2018), Ruggieri et al. (2017), Pittau et al. (2018), Rosse Caldas et al. (2020), Arrigoni et al. (2018), Ben-Alon et al. (2019), Alhumayani et al. (2020), Van Den Heede and De Belie (2012), Nakic (2018), Cancio Díaz et al. (2017), Pillai et al. (2019)			Peñaloza et al. (2016), Pomponi et al. (2020), Churkina et al. (2020), Soust-Verdaguer et al. (2020), Zea Escamilla and Habert (2014), Zea Escamilla et al. (2016), Escamilla et al. (2018), Chang et al. (2018), Ruggieri et al. (2017), Pittau et al. (2018), Rosse Caldas et al. (2020), Arrigoni et al. (2018), Ben-Alon et al. (2019), Alhumayani et al. (2020), Van Den Heede and De Belie (2012), Nakic (2018), Cancio Díaz et al. (2017), Pillai et al. (2019), Widder (2017), Teixeira et al. (2016)				Peñaloza et al. (2016), Pomponi et al. (2020), Churkina et al. (2020), Soust-Verdaguer et al. (2020), Zea Escamilla and Habert (2014), Zea Escamilla et al. (2016), Escamilla et al. (2018), Chang et al. (2018), Ruggieri et al. (2017), Pittau et al. (2018), Rosse Caldas et al. (2020), Arrigoni et al. (2018), Ben-Alon et al. (2019), Alhumayani et al. (2020), Van Den Heede and De Belie (2012), Nakic (2018), Cancio Díaz et al. (2017), Pillai et al. (2019), Widder (2017), Teixeira et al. (2016), PBMC (2018)		
Active and passive management and operation	NE	NA	NA	(Levy et al. 2016; Balaban and Puppim de Oliveira 2017; MacNaughton et al. 2018; Thema et al. 2017)	(Mzavanadze 2018; Thema et al. 2017)	(Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Mzavanadze 2018; Thema et al. 2017)	(Christidou et al. 2014; Osunmuyiwa et al. 2020; Dane G Kim DJ 2020; Sadeghi et al. 2016; TL 2020)		

	Geophysical			Environmental-ecological				Technological		
Mitigation Options	**Physical potential**	**Geophysical recourses**	**Land Use**	**Air pollution**	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**	**Simplicity**	**Technological scalability**	**Maturity and technology readiness**
Digitalisation	NA	NA	NA	(Sovacool et al. 2020; Yang et al. 2019; Inetrnational Energy Agency 2017)	(Sovacool et al. 2020; Yang et al. 2019; Inetrnational Energy Agency 2017)	(Yang et al. 2019)	NA	(Serrano 2021; Al-Shareefi et al. 2021; Khan 2019; Wan and Bai 2021; Pigliautile et al. 2021)	(Del Río Castro et al. 2021; Sabarish et al. 2021; Strenger and Frerich 2021; Ardito et al. 2021)	(Del Río Castro et al. 2021; Gavrila Gavrila and de Lucas Ancillo 2021; Dornberger and Schwaferts 2021)
Flexible comfort requirements	NA	NA	NA	(Thema et al. 2017)	(Mzavanadze 2018; Sovacool et al. 2020; Thema et al. 2017)	(Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Mzavanadze 2018; Sovacool et al. 2020; Thema et al. 2017)	(Miezis et al. 2016; Osunmuyiwa et al. 2020)		
Circular and shared economy	NA	NA	(Nußholz et al. 2020) (Niamir et al. 2017)	(Cabeza et al. 2014; Geyer et al. 2016; Mata et al. 2020a; Ingrao et al. 2014; Ortiz et al. 2009; Vadenbo et al. 2017; Junnila et al. 2018; Nußholz et al. 2020)	(Cabeza et al. 2014; Geyer et al. 2016; Mata et al. 2020a; Ingrao et al. 2014; Ortiz et al. 2009; Vadenbo et al. 2017; Junnila et al. 2018; Nußholz et al. 2020)	NE	NE	(Volk et al. 2019; Amal et al. 2017; Mohit et al. 2020; André and Jorge 2013) (Ajayi et al. 2015; Schiller et al. 2018; Osmani 2012; Lu and Yuan 2013; Cossu and Williams 2015)		
Renewable energy production	(Capellán-Pérez et al. 2017; Calvert and Mabee 2015; Poggi et al. 2018)	(Capellán-Pérez et al. 2017; Calvert and Mabee 2015; Poggi et al. 2018)	(Capellán-Pérez et al. 2017)	(Balaban and Puppim de Oliveira 2017; Rosenthal et al. 2018; Steenland et al. 2018; Goldemberg et al. 2018; Thema et al. 2017)	NA	(Rao and Pachauri 2017; Hejazi et al. 2015; Song et al. 2016; Holland et al. 2015; Fricko et al. 2016; McCollum et al. 2018)	(Wu et al. 2018; Immerzeel et al. 2014; Correa et al. 2017; Mzavanadze 2018; Thema et al. 2017)	(Usman et al. 2020; Cabeza and Chàfer 2020b)	(Gonçalves et al. 2021; Montoya and Perea-moreno 2020; Reindl and Palm 2020; Singh et al. 2020; Shahid 2018)	(Guo et al. 2020; Ürge-Vorsatz et al. 2020)

	Economic		Socio-cultural			Institutional		
Mitigation Options	**Costs in 2030 and long term**	**Employment effects and economic growth**	**Public acceptance**	**Effects on health & wellbeing**	**Distributional effects**	**Political acceptance**	**Institutional capacity & governance, cross-sectoral coordination**	**Legal and administrative feasibility**
Envelope improvement	🟥	(Ürge-Vorsatz et al. 2016; Mirasgedis et al. 2014; Alawneh et al. 2019; Bleyl et al. 2019; European Commission 2016; Niemelä et al. 2017; Mofidi and Akbari 2017; McCollum et al. 2018; Saheb et al. 2018; Thema et al. 2017)	(Abreu et al. 2019; Allcott and Greenstone 2012; Azizi S Nair T 2019; K 2018; Bright et al. 2019; Curtis et al. 2017; Friege 2016; García-López and Heard 2015; Howarth and Roberts 2018; Ketchman et al. 2018; Kim et al. 2019; Lilley et al. 2017; Mortensen et al. 2016; Ozarisoy and Altan 2017; W.Y et al. 2016; Tsoka et al. 2018; Zuhaib et al. 2017; Miezis et al. 2016; Reindl and Palm 2020)	(Abreu et al. 2019; K 2018; Bright et al. 2019; Curtis et al. 2017; Friege 2016; Kim et al. 2019; Lilley et al. 2017; Miezis et al. 2016; Mortensen et al. 2016; Reindl and Palm 2020; W.Y et al. 2016; Tsoka et al. 2018; Zuhaib et al. 2017; Allcott and Greenstone 2012; Azizi S Nair T 2019; García-López and Heard 2015; Howarth and Roberts 2018; Ketchman et al. 2018; Ozarisoy and Altan 2017)	(Payne et al. 2015; Tonn et al. 2018; Liddell and Guiney 2015; Mastrucci et al. 2019; Thomson et al. 2017; Boermans et al. 2015; Ürge-Vorsatz et al. 2016; Alawneh et al. 2019; Saheb et al. 2018; Thema et al. 2017)	(Enker and Morrison 2020; Kwag et al. 2020; Liu et al. 2020)	(Schwarz et al. 2020; Yan et al. 2017)	(Chandel et al. 2016; Sun et al. 2016; Pérez-Bella et al. 2017)
Heating, ventilation and air conditioning (HVAC)	🟥	(McCollum et al. 2018; Ürge-Vorsatz et al. 2016; Mirasgedis et al. 2014; Alawneh et al. 2019; Bleyl et al. 2019; European Commission 2016; Niemelä et al. 2017; Mofidi and Akbari 2017; Saheb et al. 2018; Thema et al. 2017)	(Bevan et al. 2020; Clancy et al. 2017; Cunha et al. 2020; Curtis et al. 2018; Heiskanen and Matschoss 2017; Qiu et al. 2014; Si and Marjanovic-Halburd 2018; N.M and Moğulkoç 2018; Mata et al. 2021; Bright et al. 2019; Christidou et al. 2014; Mortensen et al. 2016; Azizi S Nair T 2019; Ketchman et al. 2018; TL 2020)	(Willand et al. 2015; Balaban and Puppim de Oliveira 2017; Tonn et al. 2018; Ürge-Vorsatz et al. 2016; Mzavanadze 2018; Liddell and Guiney 2015; Mastrucci et al. 2019; Thema et al. 2017).	(Månberger 2018; Tonn et al. 2018; Liddell and Guiney 2015; Ürge-Vorsatz et al. 2016; Mastrucci et al. 2019; Alawneh et al. 2019; Thema et al. 2017)	🟥	🟥	🟥
Efficient Appliances	🟥	(McCollum et al. 2018; Ürge-Vorsatz et al. 2016; Mirasgedis et al. 2014; Alawneh et al. 2019; Bleyl et al. 2019; European Commission 2016; Niemelä et al. 2017; Mofidi and Akbari 2017; Saheb et al. 2018; Thema et al. 2017)	(Bonan et al. 2017; Figueroa 2016; Hernandez-Roman et al. 2017; Johansson et al. 2015; Rey-Moreno and Medina-Molina 2020; Wang et al. 2019; Zografakis et al. 2012; Christidou et al. 2014; Reindl and Palm 2020; Mata et al. 2021; Ketchman et al. 2018)	(Balaban and Puppim de Oliveira 2017; Tonn et al. 2018; Ürge-Vorsatz et al. 2016; Mzavanadze 2018; Willand et al. 2015; Rosenthal et al. 2018; Thema et al. 2017).	(Berrueta et al. 2017; Hanna et al. 2016; McCollum et al. 2018; Ürge-Vorsatz et al. 2016; Alawneh et al. 2019; Thema et al. 2017)	(Gerke et al. 2017; McNeil et al. 2013; Singh et al. 2019)	(Rahman et al. 2015; Russo et al. 2018; Mahlia and Saidur 2010)	(Rahman et al. 2015; Russo et al. 2018; Mahlia and Saidur 2010)

Change in construction methods	🟥	NE	(Olawumi et al. 2018; Oesterreich and Teuteberg 2019; Huang et al. 2021)	(Harb et al. 2018; Xiong et al. 2019; Sotayo et al. 2020; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al. 2018b)	(Winchester and Reilly 2020; Pomponi et al. 2020; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al; 2018b)	(González Mahecha et al. 2020; Succar and Kassem 2015; Kassem and Succar 2017; Yang and Chou 2018; Li et al. 2018; Li et al. 2020)	🟥	🟥

	Economic		**Socio-cultural**			**Institutional**		
Mitigation Options	**Costs in 2030 and long term**	**Employment effects and economic growth**	**Public acceptance**	**Effects on health & wellbeing**	**Distributional effects**	**Political acceptance**	**Institutional capacity & governance, cross-sectoral coordination**	**Legal and administrative feasibility**
Change in construction materials	🟥	(Winchester and Reilly 2020; (Churkina et al. 2020; Pomponi et al. 2020; (Nambiar 2019; Zea Escamilla et al. 2016)	(Wang et al. 2014; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al. 2018b; Obiri et al. 2020; INBAR 2019)	(Harb et al. 2018; Xiong et al. 2019; Sotayo et al. 2020; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al. 2018b; Nfornkah et al. 2020)	(Winchester and Reilly 2020; Pomponi et al. 2020; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al. 2018; Obiri et al. 2020)	(Himes and Busby 2020; Kremer and Symmons 2018; Laguarda Mallo and Espinoza 2015; Nfornkah et al. 2020)	🟥	🟥
Active and passive management and operation	🟥	(McCollum et al. 2018; Saheb et al. 2018; Thema et al. 2017)	(Christidou et al. 2014; Mata et al. 2021; Rey-Moreno and Medina-Molina 2020; Sadeghi et al. 2016; TL 2020)	(Balaban and Puppim de Oliveira 2017; Tonn et al. 2018; Ürge-Vorsatz et al. 2016; Mzavanadze 2018; Mastrucci et al. 2019; MacNaughton et al. 2018; Thema et al. 2017; Saheb et al. 2018)	(Tonn et al. 2018; Ürge-Vorsatz et al. 2016; Mastrucci et al. 2019; Alawneh et al. 2019; European Commission 2016; Saheb et al. 2018; Thema et al. 2017)	🟥	🟥	🟥
Digitalisation	🟥	(Inetrnational Energy Agency 2017; Sovacool et al. 2020)	(Balta-Ozkan et al. 2014; Batalla-Bejerano J Trujillo-Baute M 2020; Jaramillo et al. 2014; Kendel and Lazaric 2015; Mata et al. 2020b; Moser 2017; Nikou 2019; Pal et al. 2019; Park et al. 2018; Poortinga et al. 2012; Safdar et al. 2019; Shih 2013; K 2019; Sundt et al. 2020; Tan et al. 2017; Vassileva and Campillo 2016; Vimpari and Junnila 2019; Zhuang and Wu 2019; Reindl and Palm 2020; Mata et al. 2021; Si	(Inetrnational Energy Agency 2017; Sovacool et al. 2020; Yang et al. 2019)	(Vallés et al. 2016; Ponce de Leon Barido et al. 2018; Inetrnational Energy Agency 2017; Sovacool et al. 2020; Yang et al. 2019)	🟥	🟥	🟥

	🟥		and Marjanovic-Halburd 2018)			🟥	🟥	🟥

	Economic		**Socio-cultural**			**Institutional**		
Mitigation Options	**Costs in 2030 and long term**	**Employment effects and economic growth**	**Public acceptance**	**Effects on health & wellbeing**	**Distributional effects**	**Political acceptance**	**Institutional capacity & governance, cross-sectoral coordination**	**Legal and administrative feasibility**
Flexible comfort requirements	🟥	(McCollum et al. 2018; Saheb et al. 2018; Thema et al. 2017)	(Allcott and Greenstone 2012; Batalla-Bejerano J Trujillo-Baute M 2020; Sundt et al. 2020; Cunha et al. 2020) (Ferreira et al. 2018; Liang et al. 2012; Mir-Artigues et al. 2018; Ruokamo et al. 2019; Seidl et al. 2019; Soland et al. 2018; Xu et al. 2018; Yoo et al. 2020)	(Sovacool et al. 2020; Saheb et al. 2018)	(Sovacool et al. 2020; Saheb et al. 2018)	🟥	🟥	🟥

Circular and shared economy	(Ferreira et al. 2015; Ghisellini et al. 2018; Hart et al. 2019; Schenkel et al. 2015; Vatalis et al. 2013; Witjes and Lozano 2016; Nußholz et al. 2020)	(Patwa et al. 2021; Nußholz et al. 2020) (Ferreira et al. 2015; Hart et al. 2019; Schenkel et al. 2015; Vatalis et al. 2013; Witjes and Lozano 2016; Nußholz et al. 2020; Ghisellini et al. 2018)	(Mata et al. 2020a; Patwa et al. 2021)	(Patwa et al. 2021; Nußholz et al. 2020) (Ferreira et al. 2015; Hart et al. 2019; Schenkel et al. 2015; Vatalis et al. 2013; Witjes and Lozano 2016; Nußholz et al. 2020; Ghisellini et al. 2018)	NE	🟥	🟥	(Nußholz et al. 2020)
Renewable energy production	🟥	(McCollum et al. 2018; Alawneh et al. 2019; Bleyl et al. 2019; European Commission 2016; Niemelä et al. 2017; Mofidi and Akbari 2017; Saheb et al. 2018; Thema et al. 2017)	(Roth et al. 2018; Radmehr et al. 2014; Overholm 2015; Lay et al. 2013; Qureshi et al. 2017; Hai et al. 2017; Kosorić et al. 2019; Jung et al. 2016; Stauch and Vuichard 2019; Jimenez et al. 2016; Sagebiel and Rommel 2014; Groote et al. 2019; Frey and Mojtahedi 2018; Wolske et al. 2018; Dong and Sigrin 2019; Torani et al. 2016; Heiskanen and Matschoss 2017; Vimpari and Junnila 2019; Abreu et al. 2019)	(Burney et al. 2017; Levy et al. 2016; Balaban and Puppim de Oliveira 2017; Tonn et al. 2018; Mzavanadze 2018; Liddell and Guiney 2015; Willand et al. 2015; Rosenthal et al. 2018; MacNaughton et al. 2018; Thema et al. 2017; Payne et al. 2015; Saheb et al. 2018; Grubler et al. 2018; Van de Ven et al. 2019; SunHorizon 2020)	(Hasegawa et al. 2015; Torero De Boeck Supérieur 2015; Leibrand et al. 2019; Ahmad and Byrd 2013; McCollum et al. 2018; Ürge-Vorsatz et al. 2016; Alawneh et al. 2019; Saheb et al. 2018; Thema et al. 2017; Sola et al. 2016)	🟥	🟥	🟥

Note:

🟥	Assessment still in progress

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