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Decarbonisation of buildings: for climate, health and jobs

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EASAC

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Foreword

Europeans spend a very large part of their lives in buildings: working, relaxing, eating, sleeping and engaging in many other activities. So the quality of a building's indoor environment can have a large effect on the health of its occupants. It can also affect their ability to work and enjoy their activities. A potentially good indoor environment can be created by building designers and builders, but that environment cannot be realised without using energy to provide heating, cooling and ventilation. Much of that energy today is supplied using fossil fuels, which cause buildings to produce about 25% of the European Union's (EU's) total greenhouse gas (GHG) emissions and so contribute to climate change.

Action must therefore be taken urgently to reduce the energy that is needed to operate the approximately 250 million existing buildings in the EU as well as all the new buildings that may be built in the future. Existing energy supplies must also be replaced with very low carbon alternatives.

The latest analyses by the United Nations Inter-governmental Panel on Climate Change (UN IPCC) confirm the need for urgent actions (before 2030) to reduce GHG emissions so that the world can meet its Paris Agreement commitments to limit global warming to less than 1.5 or 2 °C above pre-industrial levels.

Several of the 17 UN Sustainable Development Goals (SDGs) are particularly relevant to the decarbonisation of buildings, including SDG 3 'Good health and well-being', SDG 7 'Affordable and clean energy', SDG 11 'Sustainable cities and communities' and SDG 13 'Climate action'. With these goals and commitments in mind, a group of experts, nominated by their national science academies (EASAC member academies), spent just over 12 months in 2020–21 reviewing the available options for reducing GHG emissions from buildings. This report summarises the group's analyses, conclusions and advice for policy-makers.

In agreement with many other groups of experts working in this field, EASAC confirms that there is no 'silver bullet' solution that can quickly reduce GHG emissions from buildings in the EU to nearly zero. Nevertheless, this report convincingly argues that a coordinated updating of existing policies, together with some well-targeted and innovative initiatives at EU, national and local levels, could deliver the required reductions in energy needs of existing buildings, and decarbonise the EU's energy supplies.

It recommends immediate actions during a transition period, with a focus on renovation measures that will maximise GHG emission reductions in existing buildings by 2030. It also emphasises the importance of adopting an integrated approach to the decarbonisation of electricity and heat supplies for buildings together with those for the industry and transport sectors.

It highlights the importance of reducing the embodied GHG emissions in the building materials, components and processes that are used in both the construction of new buildings and the renovation of existing buildings. This will require major investments in new production plants and facilities along the supply chains for building materials and components. It will also require the building industry to adopt a more circular business model, with a stronger focus on the re-use and recycling of building materials and components.

The decarbonisation of buildings is a challenge, but it is also an opportunity for industries and businesses to develop and produce new products and services. European industries should take advantage of the new business models facilitated by digital technologies and use them to create new high-quality and smart jobs.

It is EASAC's intention that this report and the analyses it contains should not only highlight the options for decarbonising buildings in the EU, but should also help EU policy-makers and other stakeholders to prioritise their future policies, legislation and investments for this important sector.

Christina Moberg
EASAC President

Summary

The target audiences for this report are policy-makers and those who advise them at European Union (EU), national, regional and local levels. It presents science-based advice on policies and measures for delivering the decarbonisation of buildings in the period from 2020 to 2050 in the context of the UN Sustainable Development Goals and the EU Green Deal.

The available evidence relating to the potential impacts (intended and unintended) of low greenhouse gas (GHG) emission building design and renovation options on the health and well-being of building occupants is reviewed. To facilitate occupant health and well-being, it is emphasised that all new and renovated buildings must have adequate ventilation, good air quality, no overheating, adequate access to daylight and access to outside space.

As the EU recovers from the COVID pandemic, it is noted that it will be particularly important to tackle energy poverty. This can be better addressed by supporting the renovation of rented private and social housing to very low GHG emission performance levels than by using public money to pay the energy bills of low-income households.

The report recognises the holistic nature of successful building design and the importance of teamwork involving all key actors including architects, engineers, urban planners and builders to deliver new and renovated buildings with reduced GHG emissions. It addresses the main socio-economic barriers encountered and risk mitigating measures required when reducing GHG emissions from the construction, operation, renovation, demolition and recycling of residential and non-residential buildings across the EU, Norway, Switzerland and the UK. It confirms that the rate of renovation must be increased but is impeded by a lack of information (including a need for one-stop shops), incumbent industry structures and procedures, and insufficient risk mitigation via regulation, incentives, grants and long-term financing with guaranteed low interest rates.

The report emphasises the urgent need to limit by regulation not only the operational GHG emissions of buildings, which represent about 25% of the total GHG emissions from the EU, but also the embodied GHG emissions in the materials, components and systems used in the construction of new buildings or renovations. Moreover, it highlights the need to limit the cumulative GHG emissions (operational plus embodied emissions) of building renovations to levels below the GHG emissions that would have occurred from operating the same buildings without renovation. If this limit is exceeded, then there is a serious risk that the EU will fail to deliver its Paris Agreement commitments and that the average global temperatures will increase beyond 1.5 or 2 °C above pre-industrial levels.

Some reductions in operating GHG emissions can be achieved quickly by replacing old fossil-fuelled heating and cooling systems with higher-efficiency ones. However, without decarbonising the energy supplies and implementing deep renovations to the building envelope, this will not reduce emissions sufficiently to meet EU targets and could lead to the creation of stranded assets. In terms of embodied GHG emissions, buildings have a potential role as carbon sinks, storing carbon in their structure and fabric for many decades.

The energy performance of new and renovated buildings is discussed together with the reasons for gaps between calculated and actual building energy performance. Technological options are reviewed for reducing direct GHG emissions from building operations (such as fossil-fuelled heating systems), indirect GHG emissions from electricity and district heating supplied to buildings, and embodied GHG emissions in building materials, components, construction processes and building services.

The challenge of reducing the energy consumed by improving the energy efficiency of building operation has been studied for many years, and has been regulated in the EU by an Energy Performance of Buildings Directive (EPBD) since 2002. The EPBD was recast in 2010, when requirements for nearly zero-energy buildings (NZEB) were introduced, but these requirements have not been applied in the same way by all EU Member States. The definition of NZEB and its associated requirements in the EPBD were helpful when first introduced because they addressed the need to improve the energy efficiency of buildings that were mainly using fossil-based energy sources. However, the definition of NZEB and its requirements are becoming increasingly outdated as the fraction of renewable energies in building energy consumption increases. This report discusses these challenges, then highlights the importance of focusing in future on reducing the consumption of fossil-based energy sources that cause GHG emissions from buildings.

EASAC recognises that, despite the fact that the definition of NZEB is becoming increasingly outdated, the concept of nearly zero-energy buildings is intuitively attractive and NZEB is widely used in EU policies and legislation. Consequently, now is a good time to shift the focus from energy to GHG emissions by redefining NZEB as 'nearly zero emissions buildings'.

This report recognises the potential of buildings to generate renewable electricity and heat, and to export them when they exceed on-site demands. It concludes that, to minimise the risks of confusion, such positive energy buildings and positive energy neighbourhoods should be promoted in parallel with initiatives aiming to reduce the annual GHG emissions from buildings. In particular, it should be made clear that a building that exports renewable electricity from photovoltaic systems in the summer (a common example of a positive energy building) must nevertheless be renovated to avoid having high demands for heating in the winter.

This report addresses the coupling of building energy supplies and demands with those of industry and transport, as all three sectors are increasingly electrified and as electricity supplies are decarbonised. It discusses how buildings can be integrated into the energy system, generating renewable electricity and providing electricity storage (in buildings or in associated electric vehicles) that can be used together with heat storage and heat pumps for balancing and flexibility management on the electricity grid. It also discusses the integration of buildings into district heating and cooling systems, and the storage of heat.

Barriers are explored that limit increases in the rate of building renovation. To achieve faster and deeper energy-efficient renovations of existing buildings, this report highlights a need for policies and legislation to expand, retrain and re-skill the building workforce (e.g. smart skills and competences) as well as to introduce new (more circular) business models for the long-term financing and rapid implementation of deep low-energy building renovations. It also notes the potential of using innovative products, components and systems with much lower embodied GHG emissions, including prefabricated components and industrialised building practices, and of renovating clusters of buildings to reduce transactional costs.

The report suggests that the number of new jobs in the building industry that could result from the proposed Renovation Wave would almost double the existing building workforce of 3.4 million workers. This would be much higher than the addition of 160,000 new jobs, which has been suggested by the European Commission.

To trigger renovations and increase the renovation rate, this report highlights the importance of engaging with financing institutions and promoting the use of long-term low interest loans to finance renovations with guaranteed reductions in final energy consumption and GHG emissions. The need to improve user and policy-maker confidence and expectations associated with the energy performance of buildings is also discussed, together with the need to replace primary energy consumption data on energy performance certificates with ranges of annual final energy consumption corresponding to typical variations in weather and user behaviour.

There are big variations over the year in the demands for heating and cooling in buildings, and big variations in the supplies from renewable energy sources which do not always match those variations in demand. As fossil fuels are phased out, it will therefore become increasingly important to reduce the overall and peak energy demands by renovating buildings and to use electricity and heat storage to help with the management of flexibility in electricity grids and district heating networks. At the same time, it will also be important to expand sustainable energy supplies (notably from renewable electricity generation and district heating) and to reinforce the energy supply infrastructure.

The report highlights the key role of cities in the decarbonisation of buildings, and suggests that they should take opportunities to build and renovate neighbourhoods to achieve very low GHG emission targets with integrated energy and transport systems. Cities should also maximise the use of green spaces to limit urban heat island effects. District heating and cooling systems should be constructed or upgraded to produce near-zero GHG emissions by optimised use of renewable electricity, combined heat and power (CHP), heat pumps, solar and geothermal heat, waste heat and natural cooling.

The report concludes that the decarbonisation of buildings is a very big challenge for which there is no ‘silver bullet’ solution. However, it highlights potential revisions to EU policies, directives and regulations that would help to achieve the decarbonisation goal and, in particular, to smooth the way to a successful EU building Renovation Wave.

Key messages for policy-makers aiming to decarbonise new and existing buildings in the EU are summarised below.

1. **Phase out fossil fuels by 2030**, increase integrated supplies of decarbonised electricity and heat to buildings, industry and transport, and accelerate the deployment of carbon capture and storage.

2. **Use grants and incentives** to trigger, leverage and de-risk private financing for deep energy-related building renovations.

3. **Regulate levels of embodied GHG emissions** in building materials and components, and promote recycled materials, re-used building components and renovation instead of demolition.

4. **Refocus building regulations, certification schemes and incentives** to deliver new and renovated buildings that operate with nearly zero GHG emissions.

5. **Promote health and well-being** to double or triple rates of renovations that improve air quality, increase access to daylight, and avoid draughts and overheating as well as reducing GHG emissions.

6. **Champion public authorities and cities,** facilitate and support their commitments to decarbonise buildings and reduce energy poverty.

7. **Expand and modernise the building industry** to operate using circular business models with 3 million more jobs (including high-quality jobs) to deliver new and renovated buildings with nearly zero GHG emissions.

8. **Improve access for building owners and professionals to certified data** on the embodied GHG emissions of building materials and components, and on the energy and GHG emission performance of new and renovated buildings.

9. **Update EU legislation** (Energy Performance of Buildings Directive (EPBD), Energy Efficiency Directive (EED), Renewable Energy Directive (RED), Emissions Trading System (ETS), Construction Products Directive (CPD), Taxonomy) using an integrated approach to phase out fossil fuels, increase renewable energy supplies and reduce cumulative GHG emissions from buildings.

1 Introduction

1.1 The challenge of decarbonisation

There is broad agreement across the European Union (EU) that decarbonisation of the EU economy to net-zero is necessary by 2050 to mitigate climate change, comply with the Paris Agreement (UNFCCC 2015) and avoid increasing global temperatures by more than 1.5 or 2 °C above pre-industrial levels (IPCC 2019). Although that objective is clear, and an ambitious programme of work has begun to develop and implement a European Green Deal (EC 2019a, 2020h, 2020k), it is less clear 'how' the 2050 goal will be achieved.

In 2019, EASAC produced a report on the decarbonisation of transport (EASAC 2019c) and, since then, has been working on the decarbonisation of buildings. Greenhouse gas (GHG) emissions from the operation of existing buildings are produced directly today on site by the combustion of fossil fuels to provide heating and hot water. They are produced indirectly when buildings use district heating and grid electricity generated by fossil-fuel-driven power plants for heating, lighting, appliances, cooling and other equipment. When new buildings are constructed and existing buildings are renovated and demolished, GHG emissions are produced by the processes involved in extracting and processing construction materials, manufacturing components, transporting them to site, constructing buildings, using them over their entire lifetime, and finally in their demolition (Good 2016; Good *et al.* 2016; Birgisdottir *et al.* 2017; Kristjansdottir *et al.* 2018; Nwodo and Anumba 2019).

Total GHG emissions from buildings	=	GHG emissions from building operation	+	Embodied GHG emissions in building materials and components	+	GHG emissions produced during construction, renovation. and demolition

To deliver EU commitments to the Paris Agreement, GHG emissions from buildings must urgently be reduced to nearly zero. Nearly zero fossil-based energy consumption is relatively straightforward to achieve technically for new buildings, but more challenging to achieve by renovating existing buildings.

Most (85–95%) of Europe's approximately 250 million existing buildings will still be in use in 2050 (EC 2020a), and the rate of constructing new buildings is low. So the biggest potential for reducing GHG emissions from the EU building sector lies in reducing the use of energy from fossil fuels in existing buildings through increasing the depth and rate of energy-efficient building renovations.

An average renovation rate of almost 3% would be required for 30 years to address the estimated 85–95% of existing buildings in the EU that will still be in use in 2050 (JRC 2019a; EC 2020a), although the actual requirement is likely to lie between 2% and 2.5% because some existing buildings already have good energy performance. Given that renovation rates in the EU are currently around 1% (EC 2019f), these would need to be increased by a factor of 2–3 (depending on the Member State) to deliver decarbonisation of the whole EU building sector by 2050.

Specifically for the residential building sector, in 2019 there were about 195 million households in the 27 Member States of the EU (Eurostat 2020c). So to renovate by 2050 only the 75% of residential buildings that are estimated to have poor energy performance (JRC 2019a) would require 146 million renovations in only 30 years, which is equivalent to a renovation rate for the total EU residential building stock of approximately 2.2%. Concretely, this implies a need to renovate more than 90,000 homes per week across the EU.

Nearly zero GHG emission buildings are typically very well insulated and have low air infiltration rates. Their high air tightness requires well-controlled natural or mechanical ventilation, often with heat recovery in Northern Europe. They have high-performance windows, low GHG emission systems for water heating, energy-efficient space heating and cooling with advanced controls, and self-generated renewable electricity and heat. They may also use on-site heat and electricity storage (Magrini *et al.* 2020).

Some reductions in the use of energy (and its associated GHG emissions) from fossil fuels in buildings can be made at relatively low cost by improving the energy efficiency and controls of heating, ventilation and air conditioning systems (HVAC) and by adding insulation (especially in Northern Europe) to reduce heat losses and/or shading devices to reduce overheating. Such interventions that typically offer good short-term financial returns in the form of energy cost savings are often referred to as 'picking low-hanging fruits'.

However, much 'deeper' building-specific renovations are needed to reduce GHG emissions of buildings to nearly zero. Such deep renovations may

- involve significantly higher investment costs;
- provide much lower rates of return over longer periods of time;
- be likely to require building-specific design work;

- employ more highly skilled construction workers and smart-skilled technicians;
- include more advanced technologies; and
- be particularly challenging to achieve in heritage buildings for which changes are legally restricted.

The potential for a building to have a low energy use is largely determined by the design, materials and components used and the quality of construction. However, actual energy performance can be very strongly influenced by external weather conditions (Thomas and Rosenow 2020) and occupant behaviour. The latter is also influenced by the number of occupants, their lifestyle and periods of occupancy (Yohanis *et al.* 2008). For example, when a building becomes too hot, then its occupants are likely to open doors or windows if that is easier for them to do than to adjust (or correctly set) the heating system controls. Such behaviour increases energy use, and must therefore be discouraged by ensuring that a design objective to enable occupants to readily enjoy a comfortable indoor environment is placed at the heart of the design process both for new buildings and for the renovation of existing buildings (Naylor *et al.* 2018). In this way, the actual GHG emissions from the operation of the building should remain low throughout the building's lifetime.

In addition to reducing the energy needs of individual buildings or groups of buildings through energy efficiency measures, the fossil energy consumption of the building sector can be reduced by integrating solar electricity generators (photovoltaics) into the structure of buildings or mounting photovoltaic generators beside them to supply some of their own energy needs and to export any excess renewable energy to the grid (i.e. positive energy buildings (PEBs) and positive energy neighbourhoods (PENs)).

Both PEBs and PENs are potentially valuable contributors to the EU's future integrated energy system and, especially in Southern Europe where buildings have high electricity demands for cooling in the summer, they can reduce the required capacity of electricity supply networks. However, it is important to note that the most common example of a PEB in Central and Northern Europe consists of a photovoltaic generator, which exports electricity to the grid during the summer and is mounted on a building that has a substantial demand for heating energy in the winter. When investing in deep building renovations in Central and Northern Europe, priority should therefore be given to reducing the annual demand for fossil-based energy. The addition of renewable electricity generators and energy storage to buildings in these regions can then be optimised from an economic perspective by comparing the costs with those of importing renewable electricity from the grid and of investing in large-scale stand-alone solar photovoltaic farms and energy storage, which may benefit more from economies of scale than photovoltaic systems integrated into buildings.

Europe has a rich diversity of energy systems, building types and forms, climates and weather conditions, industry structures, political systems, norms and regulations. These can all influence social values and cultural understandings of what 'good' buildings should look and feel like. Considerable experience with improving the energy efficiency of buildings has already been gained and applied, and there are strong commitments to decarbonisation at both EU and national levels. However, there is no 'silver bullet' solution – no single innovative technology – that can be deployed to decarbonise the EU building sector. Instead, large-scale decarbonisation of EU buildings will require a transition during which public opinion becomes better informed, a very large number of regulations, directives, codes and standards at EU and national levels are updated, and actors in the building industry introduce innovative technologies and new business practices and business models. Building users and owners will need to work closely with energy experts and energy suppliers and share best practices to deliver the EU's decarbonisation objectives.

1.2 EU building stock (residential and non-residential)

Information on the energy performance of the existing building stock is needed by EU, national and local policy-makers when they are making plans and establishing budgets for the decarbonisation of buildings and for the future development of energy supplies. However, the gathering of reliable data on the energy use in existing buildings is complicated by the evolving status of the building stocks and the historic reliance on estimates of energy consumption based on when the building was built. The availability of data on the EU building stock is being improved with the help of the online EU Building Stock Observatory database (EU 2020a), but this is a slow process.

Across all Member States, residential buildings constitute approximately 75% of the floor area, with the remainder being non-residential buildings. However, the share of residential buildings varies considerably, from around 60% in Slovakia, The Netherlands and Austria to more than 85% in Cyprus, Malta and Italy. The average final energy consumption per square metre of floor area for all EU building types in 2016 was approximately 200 kilowatt-hours (kW h) per year, but non-residential buildings were about 60% more energy intensive than residential buildings (300 kW h/m^2 per year compared with 170 kW h/m^2 per year) (Odyssee-Mure 2018); so approximately one-third of building energy consumption occurred in non-residential buildings and two-thirds in residential buildings across the EU Member States.

Information collected by the European Commission from EU Member States suggests that only around 1% (depending on the country) of the EU building stock is renovated each year (EC 2018) and, at present, about 35% of the EU's buildings are over 50 years old (EC 2020a).

1.3 Closing the gap between GHG emissions from buildings and future EU goals

As part of its Green Deal, the EU is committed to reducing all GHG emissions (including emissions from buildings) by 55% by 2030 as a milestone in a trajectory to achieving close to zero GHG emissions by 2050. To make this change as cost-effectively as possible, steps must be taken in a coordinated way to do the following:

- reduce energy use in new buildings by design, and in existing buildings by renovation;
- decarbonise all energy supplies to buildings;
- optimise the use of renewable energies in buildings; and
- minimise embodied GHG emissions in materials, components and processes used to construct new buildings and to renovate existing buildings.

The first step, reducing energy use, is important because it will lessen not only the total amount of decarbonised energy needed by the building sector but also its peak demands, thereby potentially reducing the size of the investments needed in very low GHG emission energy supplies, notably for renewable electricity generation. It is also important to manage the first step carefully because some investments in 'shallow' building renovations (i.e. 'picking low-hanging fruits') may provide an attractive short-term economic return, but can lead to stranded assets in the future if policies, market conditions, technological innovation and financing options change to enable the implementation of deeper renovations. For example, to install a new gas boiler may reduce short-term energy costs, but that boiler would need to be replaced when bans on the use of gas in buildings come into force.

The task of reducing the need for energy use in the existing EU building stock is undoubtedly huge, with around 75% of the stock probably being energy inefficient (JRC 2019a). However, this is difficult to quantify with confidence because the available information is largely based on data from energy performance certificates (EPCs), which are not only of variable quality but are unfortunately not directly comparable within or between Member States—see chapter 8.

According to the carbon inventories compiled by the European Environment Agency (EEA 2020), the GHG emissions from residential and commercial (non-residential) buildings in the EU account for approximately 36% of energy-related GHG emissions or about 25% of the total GHG emissions from the EU. Of the 36%, approximately 12% are produced directly by burning fossil fuels for heating in buildings and the rest are produced indirectly through the consumption of heat from district heating systems and of grid electricity for lighting, cooling, hot water supply, ventilation, air conditioning and other appliances. The contributions of these direct and indirect GHG emissions vary between Member States, depending mainly on the mix of energy (and fuels) used for heating, cooling and hot water, the degree of electrification of the building sector and the degree of decarbonisation of the grid electricity.

The direct GHG emissions from buildings can be expected to decrease in the future as the burning of fossil fuels in buildings is phased out, and the indirect GHG emissions from buildings will decrease as grid electricity is decarbonised. The construction of energy-efficient new buildings and the deep low-energy renovation of existing buildings are critical to reducing future energy consumption in buildings.

In addition, both in new and in renovated buildings, the GHG emissions embodied in building materials and components by the energy used for their extraction, transport, processing and fabrication must be limited. This is necessary to ensure that the cumulative operational and embodied GHG emissions from buildings do not contribute unduly to increasing global temperatures by more than 1.5 or 2 °C above pre-industrial levels (see chapter 6).

It follows that to close the gap early enough to deliver the EU's commitments to the Paris Agreement will require an updated EU policy framework for the building and energy sectors, supported by similar policy frameworks in the Member States, together with substantially increased levels of public and private investment. Much of what is needed has been highlighted by the European Commission in its documents on the EU Green Deal (EC 2019a) and the proposed Renovation Wave (EC 2020a).

2 Meeting the needs of building occupants

2.1 Occupant-centred planning and building design

Buildings are usually designed to meet the main needs of people who will live, work and perform their day-to-day activities in them. However, in future, buildings must also be designed to produce far lower GHG emissions than they do today. To trigger investments in new buildings and renovations with nearly zero GHG emissions, it makes sense to offer also improved levels of health, well-being and amenity to occupants.

All members of building design teams, including architects, engineers, urban planners as well as the builders themselves, need to work together to deliver an occupant-focused approach, and to take the health, well-being and human comfort of future building occupants into account when making each design and construction decision. Such an inclusive approach is not new, but is being revived through the EU Bauhaus Initiative (EC 2021). An earlier example from the World Health Organization's Healthy Cities Initiative, which dates from the early 1990s, is illustrated in Figure 1. This highlights why the potential impacts of climate change, the growing needs of ageing populations and the importance of minimising energy poverty (see section 2.5) should all be addressed from the earliest stages of the planning and design processes.

2.2 Health and well-being

Building occupants require a good indoor environment for their health and well-being. So designers of new buildings and of existing buildings that are to be renovated to nearly zero GHG emission performance standards must give special attention to those factors that directly affect the quality, comfort and amenity provided by an indoor environment, including temperature, air quality, lighting, humidity and acoustics (IEQ 2020).

Buildings with a poor indoor environment, including dampness or mould, darkness, noise or cold, are often linked to building-related health problems. Children living in homes with one of these four risk factors are 1.7 times more likely to report poor health. Children who are exposed to all four factors in their homes are, strikingly, 4.2 times more likely to report poor health (Gehrt *et al.* 2019).

In offices, uncomfortable thermal conditions or poor air quality have been shown to decrease cognitive performance and productivity (Lan *et al.* 2011; Satish *et al.* 2012; Wargocki and Wyon 2017).

The following design features are particularly important for ensuring the health and well-being of building occupants.

Adequate heating and cooling are essential for the health and well-being of building occupants. These must be provided using systems and controls that are designed to be easily understood by users as, unfortunately, innovations in buildings can be misused by occupants when they are not readily understood. This can lead to higher energy use and GHG emissions, as well as a poor indoor environment (Zhao and Carter 2020). The best way to avoid such problems is not to expect users to behave differently, but rather to design equipment controls so that their operation is intuitive because this will help to avoid their misuse (Naylor *et al.*

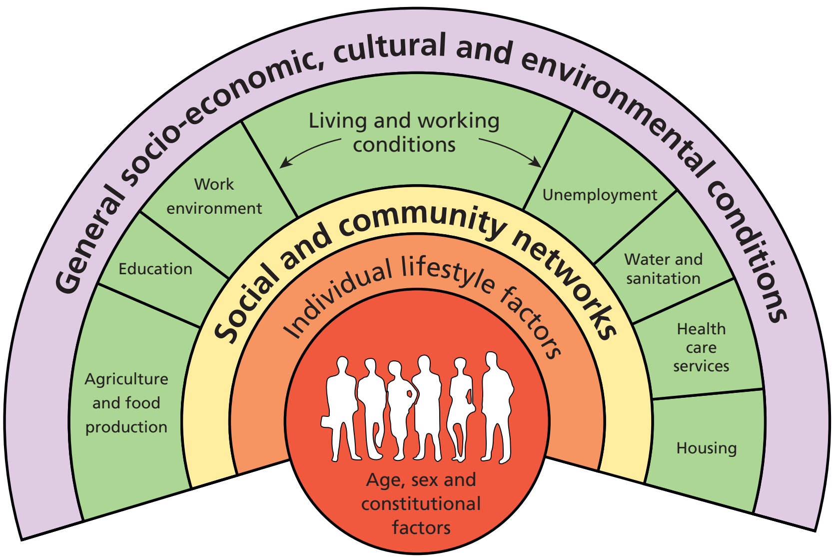


Figure 1 Key interrelationships in healthy cities (adapted from Dahlgren and Whitehead 1991).

2018; Bavaresco et al 2019; Park *et al.* 2019), and/or to use building system controls that intelligently learn user preferences and adapt settings to their behaviour (Peng *et al.* 2018, 2019).

Adequate ventilation is needed to maintain good air quality and protect the health and well-being of building occupants because, for example, some materials emit chemical compounds to the air when the temperature and/or moisture content rises, and airborne particles may be generated by human activities or penetrate the building envelope (WHO 2010). For example, phthalate emissions from plastic building materials have been found to increase with indoor relative humidity (Hsu *et al.* 2017). Similarly, formaldehyde emissions from timber-based boards used in timber-frame constructions may increase with indoor relative humidity (Hens 2012).

In some parts of Europe, there are risks that radon gas, which causes lung cancer and can enter buildings from the ground or from some building products, may accumulate in buildings that are inadequately ventilated (JRC 2020). Detailed advice on how to avoid problems with radon gas in buildings in specific areas of Europe are available in national building regulations.

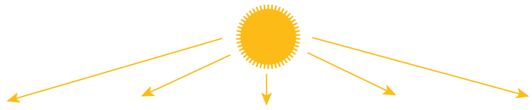
A lack of ventilation can raise the humidity of indoor air which, if high enough, can facilitate the growth of moulds and bacteria on surfaces. Condensation will occur when the relative humidity at surfaces reaches 100%, which may increase the risk of rot and mites (Arlian and Platts-Mills 2001; Weschler 2009; Potera 2011; Bekö *et al.* 2013; Karottki *et al.* 2015).

Specifications for nearly zero GHG emission performance in new and renovated buildings typically include more airtight building envelopes (i.e. less air infiltration), with therefore an increased risk of insufficient ventilation unless appropriate and reliable mechanical or natural ventilation devices are installed to provide the occupants with fresh air (Bornehag *et al.* 2005; Bekö *et al.* 2010). Too little ventilation may be insufficient to remove pollutants from indoor sources. In contrast, too much ventilation, without modification (e.g. filters and humidity control), may damage the indoor environment by bringing in outdoor pollution (Artiola *et al.* 2019). Extreme heat increases the content of air pollutants such as ozone and particles, which increases the burden on health (Orru *et al.* 2013). Guidance on ventilation rates for non-residential buildings is given in European Committee for Standardization (CEN) standard EN 13779:2007.

Although mould allergy is relatively uncommon, it has been found that asthma and respiratory symptoms are 30–50% more common in moist buildings (Fisk *et al.* 2007). Children are particularly vulnerable to poor indoor air quality, because their airways are still developing and their intake of indoor air per unit of body weight is considerably higher than for adults (Bateson and Schwarts 2007; Salvi 2007). Children can spend up to 100% of their earliest years in their home or daycare facility, where exposures may cause increased risk of airway symptoms, such as cough, wheeze and asthma, inflammations and allergic reactions (Bornehag *et al.* 2005; Landrigan 2017). In schools, poor air quality, inadequate temperature control, insufficient daylight or noise result in decreased learning, which may have many individual and societal consequences (Hens and De Meulenaer 2007; Wargocki and Wyon 2007; Bako-Biro *et al.* 2012; Sleegers *et al.* 2013; Sullivan and Osman 2015).

The incidence of non-specific building-related ill health has been reported in some cases to be higher in air-conditioned buildings than in naturally ventilated buildings (Seppänen and Fisk 2004). This could be because poorly designed or poorly maintained air conditioning can increase the concentration of indoor pollutants unless adequate air change rates and filtering are deployed, or because low air change rates have been selected to reduce energy consumption or energy costs. In buildings with variable occupancy levels, such as conference centres, schools or universities, and large indoor spaces such as shopping centres, demand-controlled ventilation may be used. This typically involves monitoring carbon dioxide (CO_2) concentrations and/or humidity levels, and using the measured data to adjust the ventilation rates to meet the needs of the occupants (Metelskiy 2011; Sowa and Mijakowski 2020).

Adequate daylighting reduces the energy used for artificial lighting during the day as well as being important to the health and well-being of building occupants (Norton 2020). Bringing daylight into buildings can, even with overcast skies, provide sufficient illumination for the majority of activities during most of the day and is thus a critical part of building design. However, the need for daylight must be balanced against the risks of overheating, because buildings with large areas of glazing on east, west or south façades can quickly become overheated on sunny days, and therefore need adequate external shading devices, thermal storage capacity in the building fabric and ventilation so that occupants can maintain comfortable indoor temperatures (Bertolino *et al.* 1991). The multiple benefits of adequate daylight are summarised in Figure 2, although it must be noted that not all wavelengths of daylight are transmitted equally through glass, and that glasses with different transmission characteristics are used in buildings. Consequently, access to outside space is important for building users to be able to produce vitamin D by exposing their skin to ultraviolet-B radiation from the sun because most of the sun's ultraviolet-B is not transmitted by glass.



Functions of daylight	Re ection of the environment	Reduce risk of myopia	Bone health, immune system	Major zeitgeber	Anti-depressant
Realised via	Visual system	Eye development	Skin	Circadian system	Multiple systems
Content	Vision	Myopia	Vitamin D synthesis	Circadian entrainment	Mood

Figure 2 Health and well-being benefits of daylight (adapted from Wirz-Justice et al. 2020).

Daylight gives important signals to the human circadian pacemaker, which is crucial to the healthy regulation of hormonal rhythms. The design of building apertures to provide daylight thus has a significant impact on cognitive performance (Altenberg-Vaz and Inanici 2020). Daylight has much broader and more complex long-term impacts on human well-being that are only now beginning to be understood (Knoop *et al.* 2020). For example the lower annual cumulative solar exposure experienced by people living at higher latitudes appears to be associated with negative health effects, such as a significant association with earlier onset of multiple sclerosis. Insufficient exposure to daylight also appears to be contributing to high levels of myopia in many countries (Spillmann 2020). As more people receive insufficient vitamin D from their diet and limited exposure to sunlight, their immunity to several diseases becomes reduced (Hart 2012).

2.3 Building resilience: prepared for extreme weather conditions and effects of climate change

Building design and renovation increasingly have to take into account the need to be resilient in the face of the growing frequency of extreme weather conditions and other effects of climate change.

Heat waves are becoming increasingly important as a consequence of climate change. According to the EEA, it is expected that the frequency, length and intensity of heatwaves will increase, leading to increased premature mortality, unless adaptation measures are taken (EASAC 2019a). Indoor temperatures can be considerably higher than outdoors during heatwaves and, combined with particles and other pollutant emissions, pose an increased health risk. Passive measures to avoid overheating, such as solar shading, heat storage in building fabrics and night ventilation, should be a first step, although, even with such passive measures, increased use of high-efficiency air conditioning to cool the indoor air may become unavoidable. However, waste heat from air conditioning contributes to the urban heat island effect and will increase both electricity consumption and GHG emissions until EU electricity supplies are fully decarbonised (Salamanca *et al.* 2014).

Urban heat islands arise from the physical structure of the built environment in cities, and the use of materials that store heat during the day and emit heat during the night (Leal *et al.* 2017; Mohajerani *et al.* 2017) exposes city dwellers to higher heat stress. This effect can be reduced to some extent when new urban developments are being planned by limiting the density of the built environment, using reflective low slope roof finishes, and introducing green spaces and water. However, it can be difficult to address urban heat islands when renovating existing urban areas. Urban heat may affect other aspects of the indoor environment in combination with air quality (Haines *et al.* 2006; Bell *et al.* 2008). For example, concentrations of outdoor air pollution can rise during heatwaves and cause higher air pollution in buildings without air conditioning owing to the opening of windows.

Flooding can be caused by several mechanisms, including increased intensity of precipitation, sea level rise and glaciers melting in parts of Europe (EASAC 2019a). The first line of defence against this should be to create green spaces in which water can infiltrate into the ground, while temporary storage of rainwater in buildings may also be used or the size of sewerage systems increased where necessary.

Water damage and moisture in buildings is likely to become more common owing to more extreme rainfall and flood events (Nik *et al.* 2015), with homes being built too close to rivers, lakes and the sea despite expected increases in flooding as a consequence of climate change (Steenbergen *et al.* 2012; Mallen *et al.* 2019; Siegel 2020).

2.4 Accommodating the needs of ageing populations and vulnerable occupants

Ageing populations require a mix of residential buildings, including larger homes for families with children and smaller homes without staircases for the elderly. A growing number of people of all age groups live alone in the EU, so do not require large family houses.

Maximising flexibility is therefore an increasingly important issue when building new or renovating existing residential buildings, so that they can be readily adapted to meet the evolving needs of an ageing population (Giamalaki and Kolokotsa 2019). Particular challenges are to provide adequate sound insulation between different units in multi-family dwellings and to adapt existing buildings, given their traditional construction and the tendency of older people to stay in their own houses, but without the financial resources or motivation needed to renovate them. For example, there is little economic motivation to invest in a building if the return period for that investment is longer than the remaining life expectancy of the owner. However, the elderly and people living alone have been shown to be especially vulnerable to heatwaves, so priority should be given to preparing their homes for the effects of climate change (Maller and Strengers 2011).

2.5 Energy poverty

Energy poverty (also known as fuel poverty) remains a complex issue that interacts with policies on energy use, family welfare, social housing, social care, housing tenure, income support and economic development (Thomson *et al.* 2017; Castaño-Rosa *et al.* 2019; EC 2020d). It constitutes a major challenge for many underprivileged and vulnerable groups in society, including single parents, the unemployed, chronically sick, handicapped, disabled and low-paid workers. Many such people typically do not own the buildings in which they live, so others must invest to make it possible for them to reduce their energy consumption or costs and thereby rise out of energy poverty.

Energy poverty levels are particularly high in Central, Eastern and Mediterranean EU countries (BPIE 2014). Income inequality, gross domestic product per head and the number of heating degree days have all been found to be statistically significant predictors of the percentage of people unable to heat their homes. In locations where a particularly large proportion of such households are unable to heat their homes, income inequality is typically the primary reason (Galvin 2019). As well as energy efficiency, relevant macroeconomic policies therefore also need to be addressed to reduce the numbers of cold homes during European winters.

Investing in the deep renovation of buildings whose occupants are suffering from energy poverty could be a better use of public funds than to pay, via social welfare interventions, the high energy bills of poor households in energy-inefficient homes over extended periods because, for a similar overall cost, it may offer a win–win solution for the environment and for the households involved. In the case of social housing, where investments are normally paid for by a social housing organisation, it may be feasible to recover renovation costs over time by increasing the rent without increasing the overall costs for the householders because they will benefit from reduced energy bills.

When preparing policies for addressing energy poverty, it is important to recognise that, in some cases, the energy consumption per square metre of floor area can give misleading indications because the density of occupancy can be higher when residential buildings are occupied by poor families. Both the energy consumption per square metre and the energy consumption per head should therefore be quantified when assessing renovation requirements for buildings occupied by low-income groups (von Platten 2020).

3 Designing buildings for low greenhouse gas emissions

3.1 Overview

GHG emissions from buildings are produced by the use of energy from fossil fuels for their operation, and by embodied energy from fossil fuels in the materials, components and processes used for their construction, maintenance, renovation and eventual demolition (see chapter 6). The main operational energy uses in buildings have traditionally been for space heating in Northern Europe, for space cooling in Southern Europe and for hot water and electrical appliances in both. However, as thermal insulation levels have improved and the use of electrical appliances has increased, heating demands have fallen, cooling demands have grown and electricity demands in buildings have become an increasingly important fraction of total building energy use.

Direct GHG emissions produced by burning fuels for heating vary over the day and over the year with the weather conditions (external ambient temperature, solar radiation levels, wind speeds, etc.), with the activities performed in the building (e.g. commercial, industrial, educational, health care, residential) and with the internal temperatures demanded by the occupants. In buildings such as school classrooms, lecture theatres, cinemas and conference halls, the demand for heating (and cooling) and therefore the production of GHG emissions are strongly dependent on the number of people present in the building as each person produces a heating output that depends on their level of activity. The energy consumption of buildings is also influenced by the equipment and appliances being used, such as lighting, computers, printers, refrigerators, cookers, etc., and by behavioural decisions such as the settings selected on heating and cooling system controls and the level of natural ventilation, which can be substantial when, for example, occupants open windows, doors or other natural ventilating devices.

Indirect GHG emissions produced by district heating systems and by generating electricity also vary over the day and the year, and depend on the use of heating, cooling and ventilation systems, lighting, household appliances, and information and communication technologies. The efficiency of electricity-consuming products and appliances in buildings is important not only because it affects electricity consumption, but also because it affects the cooling load caused by heat released by those products and appliances when they are operating.

To deliver the required reductions in GHG emissions, new and renovated buildings must therefore be designed so that they will need nearly zero amounts of energy from fossil fuels for heating and cooling, while providing a pleasant and comfortable indoor environment with appropriate temperature control, adequate ventilation for humidity and indoor air quality control, and good daylighting.

Delivering energy-efficient buildings requires effective quality control during the building construction process. The energy performance of a poorly constructed building is likely to be lower than was foreseen at the design stage. The commissioning process, to assure the quality of building performance, should therefore start at the design stage, and then continue into the end-use stage of the building. This process, called continuous commissioning, includes regular inspections and monitoring of the building (Jagemar and Olsson 2007). If its costs can be reduced, current developments in building information modelling present opportunities for integrating the design, construction and operation of energy-efficient buildings by coordinating decision-making on operational and embodied energy use and GHG emissions on a life cycle basis (Eleftheriadis *et al.* 2017) (see also chapter 6).

When developing policies for the renovation of the approximately 250 million existing buildings in the EU, it is useful to note that around two-thirds of building energy in the EU is consumed in residential buildings. There are six main end-uses of energy in residential buildings, of which space heating is by far the largest, but this can be expected to decrease as buildings are renovated. However, there will be a growing demand for electricity in buildings as heating systems are electrified, and as climate change increases the demand for cooling. Indirect GHG emissions from the consumption of electricity in buildings are currently substantial, but these should be reduced as EU electricity generation is decarbonised, largely by replacing fossil-fuelled electricity generators with renewable or other low GHG emission generators.

The total final energy consumption by EU households in 2018 was approximately 245 million tonnes of oil equivalent (Eurostat 2020d). The mix of fuels used for residential space heating in the 27 Member States of the EU in 2018 was dominated by gas (see Figure 3), but the use of gas and other fossil fuels must be reduced to nearly zero as buildings are decarbonised.

The challenge of reducing GHG emissions by reducing the energy consumption of buildings is greater in some Member States than others, as can be seen from Figure 4, which shows the energy demands per square metre in residential and non-residential buildings for EU Member States and the UK (EU 2016a). Figure 4 should not be interpreted as meaning that little needs to be done to the buildings in those countries that currently

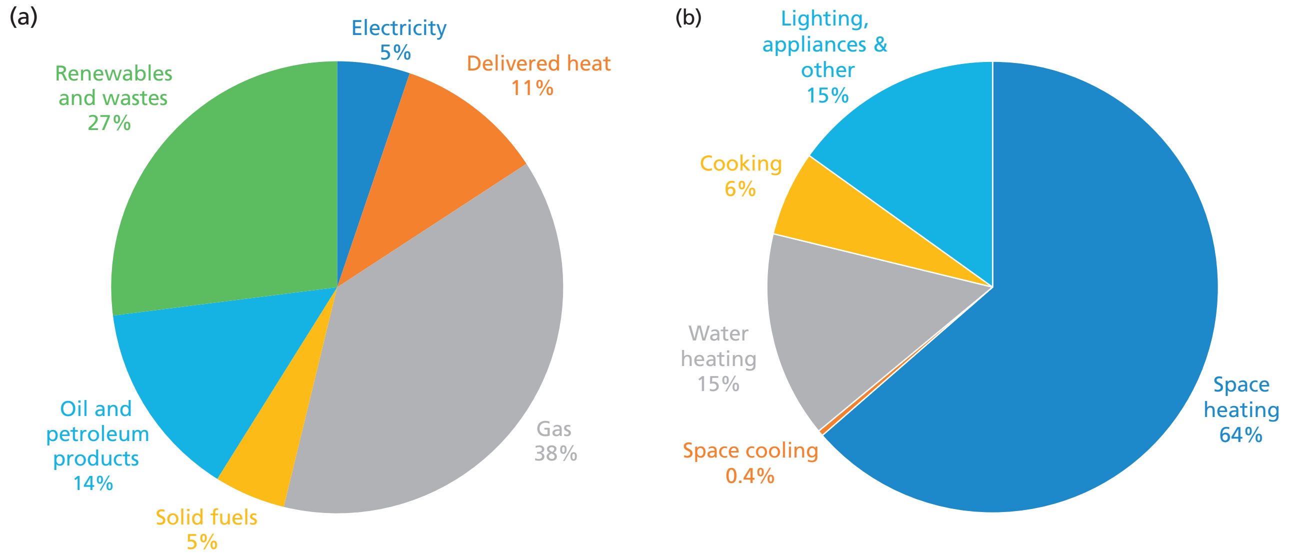


Figure 3 Final energy consumption in the EU residential sector (2018) (adapted from Eurostat 2020a, 2020b): (a) by fuel type for space heating; (b) by application.

have relatively low energy consumptions, because in many of them the demand for space cooling is growing. In all EU countries, it is important to improve the energy performance of building envelopes and HVAC systems to reduce GHG emissions.

3.2 Build new or renovate old buildings?

The option to demolish existing buildings and rebuild from scratch instead of renovating them should be strongly discouraged by policy-makers. This is because higher overall levels of GHG emissions result, largely from the embodied GHG emissions in the materials and components used in the construction of new buildings. Of course, some old buildings can have such severe problems, for example from moisture damage or land subsidence, that demolition is the only feasible option. However, for most existing buildings, the added value of renovating instead of demolishing and rebuilding is well known to architects, as can be seen for example through the RetroFirst campaign (Hurst 2020). Strong policies are therefore needed to influence, convince and eventually oblige building owners to accept the renovation option.

Moreover, priority should be given to minimising embodied GHG emissions when selecting materials, components and systems to be used for renovations, such that the cumulative GHG emissions (operating emissions plus additional embodied emissions from renovations) by 2030 will be less than would have ensued if the renovations had not taken place (see chapter 6).

3.3 Energy demand of buildings

Many physical factors influence the energy demand and consequent GHG emissions of a building, including the context and orientation of the building resulting from urban planning constraints and decisions, the form and layout of the building, the airtightness of the envelope, how the building is ventilated, the thermal mass of the building fabric, the thermal insulation installed, and the glazing used.

3.3.1 Urban planning

Until the world's energy supplies have been fully decarbonised, the construction of new buildings will always produce embodied GHG emissions, and future building use in the EU is likely to produce further GHG emissions. So the first question for urban planners should be whether the demand for new buildings reflects a real need. Renovating existing buildings generally produces less GHG emissions than building new ones, so renovation options should be explored before new buildings are planned.

The planning of developments involving more than one building can have major impacts on the energy demands of the buildings and on the quality of the indoor and outdoor environments created for their occupants. Spacings between buildings can affect their access to sunlight and therefore influence demands for artificial lighting, heating and cooling. For example, buildings might be situated quite close together in Southern Europe to optimise solar shading, while in Northern Europe they might be more widely spaced with access roads running from east to west to optimise potential access to useful solar gains, especially in winter. In urban areas where land is costly, there has been a clear preference for many years for apartment buildings and terraced housing, both of which can relatively easily be made energy efficient. However, experience during the COVID-19 pandemic has highlighted the value of having access to private outside

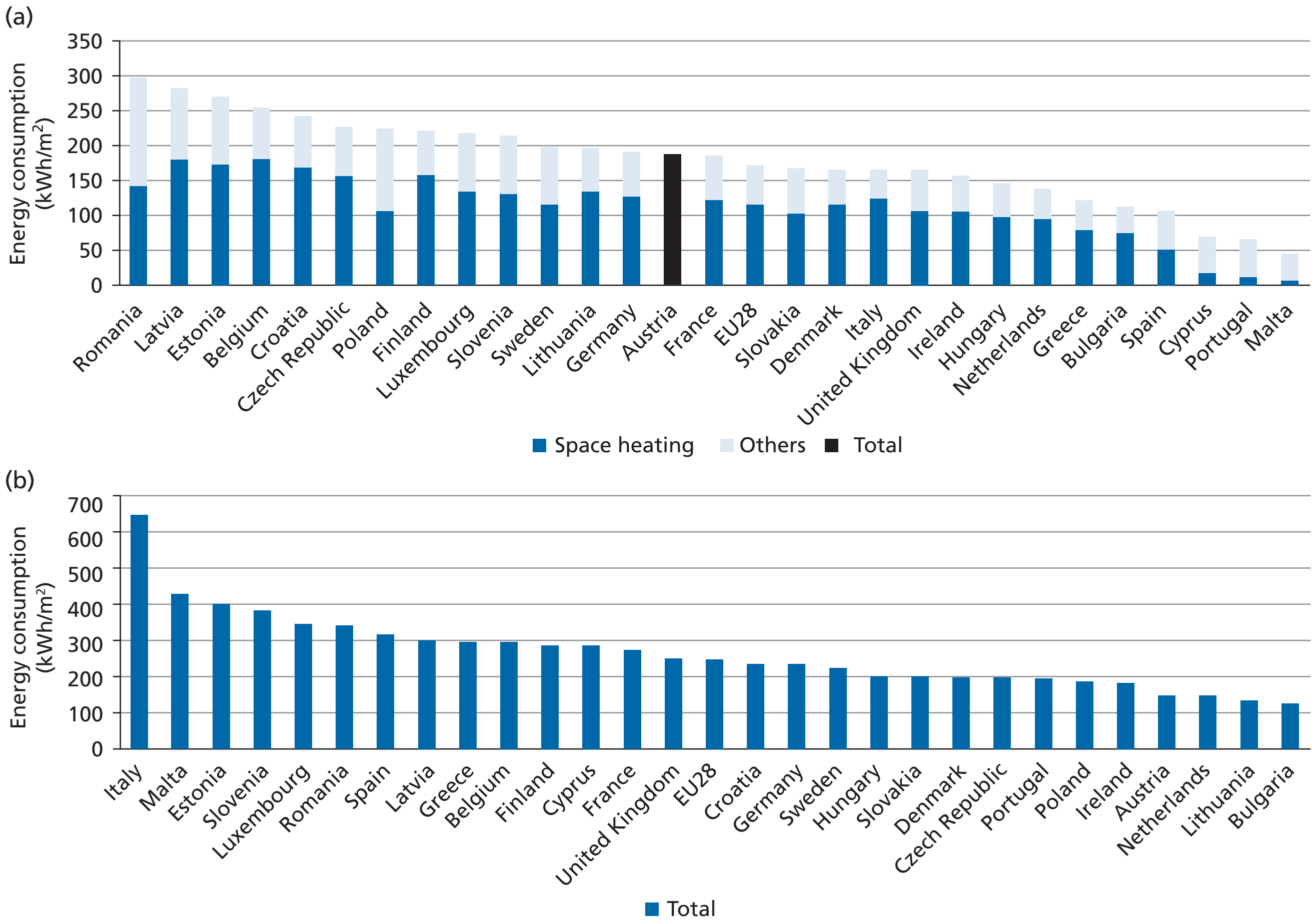


Figure 4 Energy consumption in 2014 in EU Member States: (a) in residential buildings; (b) in non-residential buildings. (Adapted from EU 2016a.)

space (Norton 2020), so this experience is likely to be reflected in urban planning guidance in the coming years.

Also important from a development planning perspective is the distance between groups of industrial and commercial buildings and the nearest groupings of residential buildings, because this distance must be commuted by workers and other occupants, and commuting usually produces GHG emissions. This effect has been studied in relation to the development of cities, and is included, for example, in a definition for zero emission neighbourhoods, which addresses mobility together with building energy use (Wiik *et al.* 2018). In addition, clustering of industries together can provide opportunities for improved overall energy efficiency through the integration of their energy systems.

Planners can reduce the GHG emissions from a new development by using district heating and cooling systems and mixing different building types so that a potential surplus of energy in one building (e.g. from a building needing cooling) can be recovered and used in another nearby building that needs heating.

Planners should also address the local microclimate that they create. Urban heat islands reduce heating energy demand but increase cooling energy demand (Li *et al.* 2019). The potential for creating urban heat islands can be minimised by providing open water (lakes or ponds), planting vegetation and using appropriate external surfaces (Gago *et al.* 2013). Water, locally planted vegetation, green roofs and green walls influence the local microclimate and help to reduce the cooling energy needed. In response to the changing climate, planners should also make other provisions, for example to address increased rain infiltration and storage, and to control flash flooding, although these are outside the scope of this report.

Studies continue to explore the potential for minimising the energy supplied to groups of buildings at neighbourhood level by integrating 'positive energy buildings' into a cluster of buildings. With this approach, some buildings would produce more energy than they need and supply it to others in the same cluster. One option, which is widely discussed and being demonstrated, is to install photovoltaic generators on the roofs of some buildings and to share the solar electricity produced with others (Magrini *et al.* 2020).

3.3.2 Building form and layout

To deliver Europe's commitment to decarbonisation, all new buildings should be designed as nearly zero GHG emission buildings or better (e.g. PEBs). This requires attention being given to achieving nearly zero GHG emission performance by the building design team from the outset, because important contributions to delivering successful, low-emission building designs come from the choice of building form (size and shape of building footprint and the height of the building), its orientation (especially the layout of fenestration), the depth of the building plan, the thermal quality of the envelope, and the selection and right sizing of building services systems (HVAC) (Butler 2020). An integrated energy design, assessment and certification process is therefore needed, such as the PassivHaus approach that was initially promoted in Germany, BREEAM that was initially promoted in the UK, and Minergie that was initially promoted in Switzerland (Passive House Institute 2015; BREEAM 2020; Minergie 2020). The most widely used sustainable building certification schemes in the EU are the UK's BREEAM, the French HQE, the German DGNB and the American LEED (Ecorys 2014).

The form of the building envelope should be designed to suit the local climate. For example, in the colder climates of Central and Northern Europe, and in mountainous regions, priority should be given to maximising the benefits of solar gains for daylighting and for heating (i.e. passive solar heating) in winter. In contrast, in the hotter climates of Southern Europe, priority should be given to minimising cooling demands by solar shading and natural ventilation (including night ventilation and passive cooling) while maintaining adequate daylighting for the health and well-being of the occupants. Attention should also be given to structural issues, following the rules of the Eurocodes, when designing new buildings and renovations, especially in areas with seismic actions (JRC 2019c).

The future efficiency and effectiveness of energy conservation measures may be increasingly affected by climate change. For example, in southern Spain it has been estimated that global warming will increase the average percentage of indoor thermal discomfort hours during the summer by more than 35% (Escandon *et al.* 2019). Therefore particular attention should be given to the resilience to global warming of the overall building design (Ascione *et al.* 2017). Extreme future weather data have been synthesised for this purpose (Pernigotto *et al.* 2020), and it is important to note that although bigger and more complex HVAC systems can deliver low GHG emission performance, they are not the only option when designing to minimise GHG emissions (Tschümperlin *et al.* 2016).

3.3.3 Airtightness of the building envelope and ventilation

Many existing buildings are poorly sealed and need to be made much more airtight to achieve nearly zero GHG emission performance. In contrast, it is common for most new buildings to have high levels of airtightness. In both cases, ventilation is needed to maintain good indoor air quality for the occupants by removing CO_2, fine particles, volatile organic compounds and odours. Appropriate levels of ventilation are also needed to avoid humid conditions which can lead to mould growth on surfaces inside buildings and consequently fabric damage. For example, buildings fitted with modern airtight windows must be complemented either by mechanical ventilation or by trickle ventilators and, wherever possible, the option of window opening should be provided.

Air change rates (also known as ventilation levels) need to be set to suit the activities in the ventilated space: for example, modest rates in residential living rooms and bedrooms, and higher rates in kitchens and bathrooms. Detailed advice on ventilation rates for specific applications can be obtained from the relevant European Committee for Standardization (CEN) standard (EN 16798-2:2019) or from building services engineers or experts, such as those working with the IEQ Global Alliance (IEQ 2020). The selected air change rates impact directly on the heating and cooling demands of the building and therefore on the building's GHG emissions unless provision is made for recovering heat from the exhaust air, for example by installing heat (and cooling) recovery systems that use plate heat exchangers or thermal wheels.

Depending on the climate in which the building is operating and the activities inside it, it may be necessary not only to cool the air in the building but also to control its humidity. Humidification may be needed in really cold climates, where heating and ventilating may force the relative humidity inside to drop below 20%, while a value between 40% and 60% is typically recommended. Dehumidification in turn may be needed in hot and humid climates, where cooling and ventilation can push the relative humidity above 80%. Regardless of the climate, humidity control is always needed in some specific environments such as clean rooms, operating theatres, intensive care units and museums. Humidity levels are expected to increase as a result of climate change, and their control requires additional energy and therefore causes additional GHG emissions.

Recent experience during the COVID-19 pandemic has led to new advice on ventilation from the European Centre for Disease Prevention and Control (ECDC 2020), which highlighted the need to upgrade ventilation air filters (where appropriate) and follow maintenance instructions for the cleaning and changing of filters.

The Centre has also given updated advice on increasing ventilation rates and controlling relative humidity levels in different types of air-conditioned space.

3.3.4 Thermal mass of the building fabric

The thermal capacity of the building fabric and the structure and location of thermal insulation are very important to the delivery of nearly zero GHG emission buildings. The thermal mass of a building, as much as possible of which should be located inside the thermal insulation of the building envelope (unless the building has only very intermittent occupancy), can have an important impact on the heating and cooling demands of a building (Johra *et al.* 2019). Thermal mass stores heat, so a building with high levels of thermal mass can maintain stable thermal comfort conditions despite variations in weather conditions over the day and variations in heating supplies, for example from variable renewable sources (Hens 2016). In hot weather, night ventilation can be used to cool off thermal mass so that it is ready to absorb heat gains again during the following day, for example in office buildings.

3.3.5 Thermal insulation

Thermal insulation levels for new buildings to deliver national building energy performance requirements are usually specified in national building regulations either in terms of U-values for individual building elements or overall calculated coefficients for the building envelope. Insulation can be easily integrated into new building elements, and high insulation levels can be achieved with a wide range of material combinations (Jeziersk *et al.* 2021). However, adding extra insulation brings diminishing returns in terms of U-values, so attention must also be paid to the extra embodied energy involved (Hens 2016)—see chapter 6. In contrast, adding thermal insulation during building renovations is more complex—see section 4.3.4. Very well insulated buildings can have a cooling demand even in northern parts of Europe (depending on building type and use), so integrated energy design is needed to minimise the building's energy use and related GHG emissions.

3.3.6 Glazing

Although it can be used to create a pleasant internal ambience or to highlight a specific artefact or feature, artificial lighting should not normally be needed during the daytime if a building is designed with adequate glazing for daylighting. However, solar gains from daylighting as well as heat from artificial lighting systems both contribute to the space heating of buildings (Sepúlveda *et al.* 2020), and can therefore create additional demands for space cooling with its related GHG emissions (Hens 2016).

As discussed in chapter 2, access to sunlight is important for human health, and is especially important for the development of children's eyesight and certain bodily rhythms. Daylighting should therefore be used in place of artificial lighting wherever possible, not only to minimise energy demands and GHG emissions but also to maximise the health and well-being of building occupants.

Daylighting can be provided by windows, or by roof lights or light tubes passing through multi-storey buildings. However, these last two design options do not bring the health and well-being benefits of being able to see nice views outside. Unfortunately, daylighting from vertical windows is only possible within a few metres of the windows, depending on the glazing materials and the room and window heights. Special attention should therefore be given to the depth of the building plan (shallow or deep) and to the provision of open spaces (atria or quadrangles) within building clusters so that the occupants can not only access the energy saving benefits of natural daylight but also enjoy the health benefits of being able to see 'outside' (Knopp *et al.* 2020). As discussed in chapter 2, this is important because unhappy occupants are more likely to interfere with building system controls and to use windows and doors in ways that increase the overall energy demand and its related GHG emissions.

The quality of the glazing used can significantly influence building energy demand and noise transmission. For example, in cold climates, low heat loss through glazing systems can be achieved by (1) suppression of convection in the air between the panes of double or triple glazing and (2) instead of dry air, having an inert gas or vacuum between the panes to reduce or eliminate convective heat transfer, although separators are needed between the glass panes when a vacuum is used and these reduce performance. In all these systems, low emissivity coatings can reduce the radiative heat transfer. Low-heat-loss glazing systems with glass panes separated by aerogels, which are mainly translucent but not transparent (not see through), are also emerging onto the market. High-performance glazing allows large areas of a building façade to be glazed without large attendant heat losses. However, particularly in hotter climates, glazing systems may need to be fitted with shading devices to avoid overheating caused by excessive solar gains as well as to control glare. A variety of techniques can do this, including external fixed and movable shading, internal blinds (less effective than external devices) or newer switchable transparency glazings such as electrically actuated electrochromic, liquid crystal with suspended particle devices, or non-electrically actuated thermochromic, thermotropic and gasochromic systems (Ghosh and Norton 2018).

External shading of glazing is particularly important in the hot climates of Southern Europe to avoid overheating and to control glare (Norton and Lo 2020), but is also becoming increasingly important for combatting overheating in many other parts of Europe as the weather conditions become more extreme because of climate change. Adjustable shading can be valuable to occupants, especially in multi-storey buildings, because it allows them not only to avoid glare and overheating when the sun is shining directly onto their windows, but also to enjoy the health benefits of a clear view to the outside at other times.

Multiple glazing systems can also reduce the transmission of noise, and thereby improve internal comfort conditions. The ability of multiple glazing systems to reduce noise depends largely on the spacing between the glass sheets, with larger spacings typically providing better noise attenuation (Tadeu *et al.* 2001). Solutions that are specifically designed for noise attenuation include dual frame windows, multiple pane designs using glass panes of different thicknesses, and multiple glazing units in which one pane is laminated with a synthetic intermediate layer and the gap is filled with a more viscous, better damping gas than dry air.

3.4 Prefabricated building components and industrialised building practices

Buildings with nearly zero GHG emission performance require advanced building designs, high-quality building components, and much higher quality control of construction and installation practices (including quality assurance procedures) than are typically adopted when most of the work is performed on site. By standardising the designs and construction of prefabricated components, important economies of scale can be achieved during manufacture, and much higher levels of quality control can be achieved when components are made in a factory than are possible when using conventional construction practices on site. Savings in both installation time and costs can also be achieved when compared with conventional building solutions (BPIE 2019b), and levels of embodied GHG emissions can typically be reduced. Prefabrication in a factory also provides year-round job opportunities for people who do not wish to work outdoors on site, and who do not have conventional building skills.

The structural elements of prefabricated building components can be made using concrete and metal structures, or structural timber or engineered wood products, which typically have low embodied GHG emissions. Prefabricated components can be made using innovative insulation technologies, and building services (pipework, ductwork, wiring, etc.) can be integrated into them during manufacture, thereby reducing the risks of the most common installation problems encountered when they are installed on site.

Heating, ventilating and cooling systems can be prefabricated and installed as complete units in pitched roof spaces together with large-scale prefabricated roofing, which itself can include integrated photovoltaic electricity generators. Photovoltaic generators can also be integrated into prefabricated walling, although this should only be used where the walls are not shaded from the sun. However, unless the service life of the photovoltaic generators can be guaranteed to be similar to that of the other roof or façade materials, then the designs must allow for photovoltaic modules to be replaced without damage to the adjacent elements.

3.5 GHG emissions from building heating systems

Heating systems in most buildings today are either hydronic (using water-filled radiators or convectors) or air based, with the heat delivered either by burning gas, oil, coal, or electricity on site or by a heat exchanger coupled to district heating (see section 5.6). Building heating systems with low-temperature heat exchangers (wall-mounted radiators or underfloor pipework) allow the efficient use of low-temperature heat sources, such as heat pumps, solar and geothermal heating, and the use of waste heat, all of which can be distributed using district heating. However, underfloor heating is not always well accepted or understood by users and can provide comfort conditions that are perceived differently by different occupants (Hens 2016; Karmann *et al.* 2017).

3.6 GHG emissions from building cooling systems

Most of the cooling systems in European buildings use electricity to power either air-to-air heat pumps (room air conditioners) or water-to-air heat pumps, and the demand for cooling in buildings is growing (Pezzutto *et al.* 2017). There is also an emerging use of district cooling which circulates cold water from nearby rivers or aquifers to remove heat from buildings. The International Energy Agency published a report in 2020 on the worldwide progress being made with cooling of buildings (IEA 2020a), which highlights the need for tighter requirements for the efficiency of cooling equipment. It also recognises the added value of combining high-efficiency air conditioning plant with passive design approaches, such as green roofs and walls. EU requirements for energy-efficient cooling systems are given in the relevant parts of the Ecodesign Directive (EU 2016b). However, although system efficiency is of course very important, to substantially reduce the GHG emissions from these systems, it is also necessary to decarbonise the electricity supplies (see chapter 5).

3.7 GHG emissions from water heating systems

For domestic hot water, the heating energy required increases with the temperature of the hot water demand, and is somewhat higher in winter than in the summer because of variations in the temperature of the cold water supply. The heating power required for water heating can be significantly reduced by installing a hot water storage tank, but it is the overall energy demand for water heating that is important for determining GHG emissions.

Solar water heaters can significantly reduce the energy demand that has to be supplied from other sources, and electric heat pumps will offer an increasingly attractive option as grid electricity is further decarbonised. An example of this is in Cyprus, where 93% of all houses are equipped with a thermosiphon solar water heater that offers significant energy savings (Kalogirou 2014). The use of electric heat pumps for water heating offers the additional advantage that it allows hot water tanks in buildings to act as a means of storing excess variable renewable electricity from the grid when wind or solar generators would otherwise have to be curtailed. Energy demands for water heating can be marginally reduced by recovering heat from grey wastewater and using it to preheat the incoming cold water (e.g. in hotels or commercial buildings), although the energy savings in most residential buildings (e.g. houses and apartments) are relatively small.

Attempting to save energy by storing sanitary hot water at temperatures below 60 °C can have serious adverse health consequences because it encourages the growth of *Legionella* bacteria. Sanitary hot water storage at temperatures below 60 °C is therefore generally prohibited by regulations. Instead, if required, low-temperature sanitary hot water can be provided by using mixer taps or in-line heaters located close to the point of use (Ji *et al.* 2017).

3.8 GHG emissions from lighting and other electrical appliances and equipment

Energy-efficient lighting systems such as LEDs (light-emitting diodes) have helped to reduce electricity consumption in buildings over recent years (Mardaljevic 2009; UNEP 2017), and this has been reflected in reductions in demands for cooling. Nevertheless, lighting can still create a significant electricity demand, especially in some non-residential buildings. So it is important to deploy building automation and control systems (BACS) to control and optimise the use of artificial lighting and shading systems in relation to occupancy levels in different parts of the building.

Efficient electrical appliances, including computers, printers, copiers, washing machines, dish washers, cookers, freezers and refrigerators, that comply with the Ecodesign Directive (EU 2016b) can help to reduce electrical loads in buildings and thus contribute to reductions in demands for space cooling and corresponding reductions in GHG emissions.

3.9 Reducing GHG emissions by using BACS

Building automation and control systems (BACS) are important because heating or cooling may only be needed to maintain internal temperatures and comfort conditions in buildings for limited periods during the day, for example:

- during working hours for offices, schools, and other places of work;
- early mornings and evenings in the homes of working families;
- all day with night set-backs for old people's homes, hospitals and some work places.

The digitisation of building energy systems through BACS can be used not only to control internal building temperatures, but also lighting levels, air change rates, and humidity levels (in some cases) over the day, the week and the year, all of which can lead to energy savings and GHG emission reductions.

Energy consumption and GHG emissions can also be reduced by using BACS to monitor the performance of boilers and other heating and cooling system components, to ensure that they are adequately maintained and working properly. For these reasons, legislation addressing the energy and GHG emission performance of buildings should include a range of provisions for the deployment and use of BACS (EC 2018; Waide 2019).

Among the different digital systems, some have been developed to manage the energy needed to deliver adequate levels of comfort in buildings. However, because people are different, occupying themselves in different ways in the same building, it is important to recognise that the occupants must also be given tools that allow them to control the internal environment in which they live and work. If simple controls (such as thermostatic radiator valves or room thermostats) are not provided for occupants, then there is a strong likelihood that some occupants will override their energy management systems (Naylor 2018).

Overall, it is important that building controls should be of very good quality (reliable) and properly set up. They should also be easily understood (intuitive and user friendly) by untrained householders in residential buildings and by users of non-residential buildings (see chapter 2). Otherwise there is a high risk that the control system will be misused or even abused (e.g. sensors removed or taped up) and then it will malfunction and cause unnecessary energy demands and poor indoor environmental conditions. In addition, BACS should have a low self-consumption (Kräuchi *et al.* 2017) and low embodied GHG emissions.

Building occupants generate heat (typically 100–300 watts per person, depending on activity level), which can reduce the heating demands or increase the cooling demands of a building, especially if there are large numbers of occupants per square metre of floor area, for example in schools, theatres and meeting rooms. In addition, the occupants can increase the energy demand, even in well-designed buildings, if they do not operate the building and its services wisely. For example, more heating or cooling will be needed if windows or doors are left open, or if temperature controls are set too high or too low. Such increases in energy demand may not lead to increased GHG emissions if the building is supplied only with low GHG emission energy (e.g. green electricity), but the availability of low GHG emission energy is likely to be limited for some years to come. Consequently, smart controls and monitoring systems (e.g. to switch off the heating or cooling system when windows are opened) are needed to minimise the risks of unnecessary user-created energy demands, while still giving users the freedom and tools to control the conditions in which they live or work.

4 Reducing greenhouse gas emissions by renovating existing buildings

4.1 Overview

Many of the ways of designing buildings to reduce GHG emissions, which were addressed in chapter 3, are also applicable to renovations. However, there is usually less freedom of choice for designers and additional considerations need to be taken into account by policy-makers, as discussed in this chapter.

A supportive policy and regulatory framework is needed to tackle the key socio-economic barriers to renovating large numbers of buildings, notably by helping building owners to obtain the required financing. In addition, a supportive framework can help to accelerate building renovation rates by encouraging the implementation of deep energy-efficient renovations that at the same time maximise the non-energy benefits of renovations: for example, by including targeted requirements for daylighting and ventilation that will improve the health and well-being of building users by creating a better indoor environment.

The EU's Renovation Wave could be helped by facilitating renovations wherever possible at a neighbourhood scale, rather than building by building, because this brings opportunities for sharing responsibility for GHG emission reductions between building owners, energy suppliers, builders and financiers. For example, economies of scale are being demonstrated at all stages of the process in a growing number of zero emission neighbourhoods (Wiik *et al.* 2019) or positive energy districts (Shnapp *et al.* 2020).

It would also be helpful to monitor, evaluate and publish the energy performance improvements resulting from building renovations, especially for those renovations that are supported by public money.

4.2 Using empirical data to design site-specific and optimal renovation measures

Each building renovation has a specific geographical context, because each building is set in an urban or rural environment with its own construction history and its own occupants. Using similar renovation measures on different buildings therefore carries the risk of making investments that deliver different results (better or worse). Digitised tools, models and on-site assessment techniques exist, which can be used together with recently measured energy consumption data to determine the most cost-effective options for renovating a given building. These can also be used to optimise the allocation of available funding (EPRS 2016).

The key to selecting the best renovation measures for a specific building lies in assessing its context with empirical data that have been measured on site. Developments in affordable sensors, open-source hardware and software (Ali *et al.* 2016; Frei *et al.* 2020) and wireless data transmission through the Internet (4G/5G) increasingly facilitate data gathering on site with reduced effort and costs. Unlike building management systems, which are installed in commercial buildings and require a substantial undertaking, simple sensor kits can now be deployed for short durations (e.g. a couple of weeks) to gather just enough data to inform the renovation design. After the renovation, they can be used again, for quality control and calibration. Typically, the sensors used include temperature, humidity, U-value, indoor CO_2, lighting and contact sensors (operation of doors, windows) as well as electricity meters. They can be largely powered by batteries and wirelessly connected to a transmission hub, which directly sends data to cloud storage for subsequent analysis.

Such data can be used to inform future building design decisions, but also in many other ways. Firstly, they can be used to identify low-effort options to improve the operational efficiency of heating systems (Papafragkou *et al.* 2014). Measurements of temperatures of the interior space and the heating system, for example, can be used to adjust the thermostats and heating curves for better adaptation to outside temperatures, and the operating schedules of heating systems can be improved by adjusting for absence and presence, for example day and night, weekday and weekend. Secondly, the data can be used to determine specific user preferences, for example the temperatures and ventilation levels desired in different parts of the building. Thirdly, and most importantly, the data can be used to calibrate thermal building models for greater accuracy and even for developing bespoke bottom-up thermal models (Li *et al.* 2015; Lozinsky and Touchie 2018; Hong and Lee 2019; Deb *et al.* 2020). Such models can be used to explore the thermal behaviour of a building and its potential responses to renovation measures. Combined with environmental and cost databases for materials and systems, such models can be used to customise renovations for a building, to optimise the utilisation of available funds and to reduce the risks of poor performance or undesired effects.

Additionally, data from smart electricity meters can be used to quantify the load patterns of electricity-consuming equipment in the building, for example by using disaggregation techniques (Deb *et al.* 2019). A better understanding of the electricity consumption patterns of a building allows overall consumption to be reduced by optimising its timing. For example, electrical loads can be shifted to match the available variable renewable electricity, and heating and cooling profiles can be adapted to reflect occupancy and user behaviour (Anand *et al.* 2019).

In summary, future policies to increase the effectiveness of renovations should encourage the upfront empirical assessment of buildings because this can be used to design targeted renovation measures that will deliver the most effective use of funds together with the best possible reduction of emissions. Data from such assessments should also be recorded in EPCs (see section 8.4.4) and in smart readiness indicators (see section 8.4.6). Generating and assessing data in the context of a building renovation must, of course, respect all relevant aspects of privacy and data security, and its use needs to be restricted to the assessment of the specific renovation by qualified assessors.

4.3 Reducing the energy demand of the building

Many different factors influence the energy demand and consequent GHG emissions of an existing building, including the context of the building, its form and layout, the airtightness of the envelope, the chosen ventilation solution, the thermal mass of the building fabric, the thermal insulation installed and the glazing used. Most, but not all, of these can be improved by implementing a deep renovation.

4.3.1 Building context and form

Existing buildings have their own local contexts in terms of climate, surroundings and use, which need to be properly assessed before renovation options are selected. If the main structure of the building is unstable or has suffered substantial moisture and humidity damage (e.g. from rising damp, rain penetration, surface or interstitial condensation, moulds or fungi), then it may be necessary to demolish the building and build a new one. However, demolition should be avoided wherever possible to minimise the embodied GHG emissions associated with new structural elements (Hurst 2020).

An attractive renovation compromise in many cases, from the perspective of GHG emissions, is to retain as many as possible of the structural elements with high embodied GHG emissions (notably concrete and steel), and then to renovate the building by introducing new thermal and acoustic insulation in the roof, walls and floor, installing low-heat-loss glazing, reducing air infiltration, improving ventilation and renovating the HVAC system.

The growing availability of lighter weight materials for use in building envelopes can lead to less heat storage capacity and therefore increase the risk of overheating. However, it also offers the opportunity to add additional floors to an existing building, which can significantly increase the value of the building and thereby cover part or all of the renovation costs.

4.3.2 Airtightness of the building envelope and ventilation

Many older buildings are not well sealed. They are naturally ventilated through leaks in the building envelope and openable windows, which can incur large heat losses that vary considerably between buildings (Miszczuk and Heim 2021). The reduction of air leakages by sealing all possible gaps in the building envelope is therefore an important energy renovation objective. This will not only improve comfort levels in the building by excluding draughts, but will also avoid unnecessary heat losses from buildings in Northern Europe or unnecessary heat gains to buildings in Southern Europe.

However, when leaks are sealed, for example to meet nearly zero GHG emission requirements, then correctly designed natural or mechanical supply, extract or balanced ventilation systems should be installed so that air change rates can be controlled. Adequate ventilation is especially important in parts of old buildings that are difficult to fully insulate or may still contain thermal bridges, because these may otherwise become a focus for the growth of moulds that were not present before the air leaks were sealed (see section 2.2).

Important challenges arise when mechanical air handling is installed as part of a building renovation to meet nearly zero GHG emission requirements in small domestic residences, because the air handling equipment (including fans, air filters and heat recovery units) can take a significant amount of space and require regular maintenance and cleaning, which was not necessary when the building relied only on natural ventilation (Zukowska *et al.* 2020). Unless the required maintenance is done regularly, especially the cleaning of filters and ductwork, then the quality of the indoor air will fall, the system may become noisy and the health of the building occupants will be put at risk. Legally enforceable regulations are therefore needed, for example similar regulations to those in place for the maintenance of gas boilers, to ensure that air handling equipment in occupied buildings is adequately maintained by suitably qualified persons.

These issues have recently been emphasised in relation to the COVID-19 pandemic by the European Centre for Disease Prevention and Control (ECDC 2020), which highlighted four measures to be used to reduce the risks of airborne transmission of the virus in closed spaces.

1. Control of COVID-19 sources—keeping people with the virus apart from those who do not have it.

2. Engineering controls—upgrade ventilation air filters (where appropriate) and follow maintenance instructions about the cleaning and changing of filters. Advice on increasing ventilation rates and controlling relative humidity levels in different types of air-conditioned space was also given.

3. Administrative controls—limit the number of people in enclosed spaces and the duration of stay.

4. Personal protective behaviour—physical distancing, hand hygiene, use of face masks.

4.3.3 Thermal mass

By adding thermal mass to the walls and floors of a building, inside the thermal insulation, the ability of the building fabric to store heat and thereby provide demand response services to energy suppliers can be significantly increased (Johra *et al.* 2019).

Temperatures change relatively slowly within buildings with high thermal mass. So, for most buildings and climates, introducing more thermal mass inside the thermal insulation improves thermal comfort and reduces the energy demand, although the reduction in energy demand is typically small (Verbeke and Audenae 2018).

For infrequently used rooms and buildings, high thermal mass may be a disadvantage because it increases the time needed to heat up a cold room or to cool down a hot one. Lightweight structures or lightweight internal cladding may be preferred for such applications.

4.3.4 Thermal insulation

Heat loss from a building envelope can be relatively easily reduced by integrating conventional thermal insulation into the building fabric, notably in the roof and in the cavities of traditional brick or block walls. However, although such improvements lead to somewhat lower GHG emissions and may offer quick returns on investment in badly insulated existing buildings, they do not on their own constitute 'deep renovations' because they do not result in nearly zero GHG emission performance. Moreover, wrongly adding insulation (e.g. interior insulation for a wall exposed to wind-driven rain) may result in frost or moisture problems, and filling old cavity walls with insulation may result in little benefit if the old cavities contain thermal bridges (Dumitrescu *et al.* 2017). So renovation project designers and product manufacturers must address thermal insulation levels within and between building components (i.e. thermal bridges), as these produce significant heat losses, reduce thermal comfort and lead to mould growth, especially around balconies.

To achieve the deep renovation of an existing building, thermal insulation levels must be much higher than can be achieved by adding cavity wall insulation. This typically requires materials to be added to the outside walls and roof, which may cause an increase to the external dimensions and a significant change to the look and character of the building. Changes to the look of the building can pose serious challenges in the case of historic or heritage buildings, but can sometimes be minimised by the use of appropriate insulation technologies (Corrêa *et al.* 2020). In some cases, historic buildings with external characteristics and features that must not be changed can be successfully fitted with internal insulation if the buildings are used only intermittently, although this may reduce internal room sizes.

To achieve nearly zero GHG emission performance, it may also be necessary to significantly increase underfloor thermal insulation levels, although the need for insulation will depend largely on what is below the floor. If the building has suspended wooden floors that are openly vented to the outside, then insulating the floor may be almost as effective as insulating the roof. On the other hand, if a slab floor is situated above a basement or unvented crawl space, then to insulate the floor may be less effective. If a solid concrete floor was laid without insulation, then the only practical solution may be to lay insulation on top of it and fix boards over that, although this would require the addition of a moisture-resistant membrane and will have the disadvantage that it will typically raise the floor level (Odgaard 2019).

The use of insulation to create building zones has been proposed to reduce overall energy demands, for example insulating between warm living rooms and cooler bedrooms; however, experience with this appears to be mixed. Instead, it is usually better to install a valve in the ventilation heat recovery unit to provide separate air loops for warmer and cooler zones.

4.3.5 Glazing

The energy performance of glazing can typically be improved by replacing existing windows with modern high-performance glazing. Depending on the local climate, such glazing may consist of double- or triple-glazed units that have low emissivity internal coatings, low conductivity gases between the glass sheets and efficient designs of insulated frames without thermal bridges to reduce heat losses.

Windows in historic or heritage buildings can be of high quality, aesthetically appealing and characteristic of a certain architectural style. To replace them with modern designs can therefore have an adverse effect on the character of the building, and on some historic buildings may not be permitted. Fortunately, the performance of many historic windows is better than commonly thought and they can be upgraded by keeping the

Figure 5 Apartment building in Estonia before refurbishment in 2015 (left) and after a low-energy refurbishment in 2018 (right) (source: Hamburg et al. 2020).

existing window and adding a new pane of glass or slim double glazing unit on the inside, with a sealed cavity between the two and possibly also adding insulating shading devices (Bakonyi and Dobszay 2016).

Further improvements may also be possible, for example to dual aspect buildings in Northern Europe by increasing the window sizes on south-facing façades and reducing window sizes on north-facing ones. In Southern Europe, further improvements may be achieved by integrating smart glazing solutions (such as electrochromic or photochromic glass) and/or movable shading devices to maximise daylighting and useful solar gains while reducing heat losses and avoiding problems with glare or overheating.

4.4 Prefabricated building components

As discussed in chapter 3, prefabricated building components offer many potential benefits in both new buildings and renovations, including higher levels of quality control, reduced installation times, and reduced disturbance and mess inside and around existing buildings. It is much easier to control the quality of prefabrication of large-scale building components in a factory than during on-site construction. Moreover, prefabricated components can be used in both new buildings and renovations, although it has been found typically easier to use them in new buildings.

In recent years, there has been an increase in the use of laser scanning to gather geometric data of existing buildings for building information modelling (BIM), and fully fledged laser scanning frameworks for geometric data acquisition have been developed for planning, surveying and data analysis (Sanhudo *et al.* 2020). Photogrammetric techniques have been integrated with infrared thermography to allow building defects to be precisely located and quantified, provided that there is a large enough temperature difference between the inside and outside of the building and that the effects of solar radiation are minimised (Macher *et al.* 2020; Shariq and Hughes 2020). Such techniques can be brought together to support a coherent renovation process, as in the P2Endure project (Piaia *et al.* 2019).

In addition, the use of the latest building scanners together with robot manufacturing technologies is now allowing prefabricated building components to be tailored to fit the actual dimensions of existing buildings, without significantly increasing the manufacturing costs.

An example of an apartment building located in Estonia, before and after renovation, is shown in Figure 5. This particular example combines the addition of insulation using prefabricated modular panels with new heating and hot water systems and the enclosure of balconies to provide additional volume to the living space.

For the refurbishment of the building shown in Figure 5, national (NZEB) criteria for a new apartment building were used for the energy performance target. The energy consumption was measured after renovation, and the refurbished building was found to have met the national minimum energy performance requirements for new apartment buildings. However, the heating energy consumption was 1.6 times higher than the national target because indoor temperatures and ventilation airflow rates were both higher than those included in the methodology for calculating heating energy. Similarly, the energy used for domestic hot water was 4.4 times higher the national target, mainly because actual hot water use was higher than the design assumption (Hamburg *et al.* 2020). These results confirm the importance of using realistic assumptions about occupant behaviour and actual building use to inform national calculation methodologies for energy performance.

4.5 Space heating and cooling and water heating

The existing systems for space heating and cooling should normally be replaced as part of a deep building renovation. They should typically be replaced by much smaller systems, which have been selected to meet the reduced needs of more energy-efficient building envelopes after renovation, and should be supplied with very low GHG emission energy, for example from a decarbonised electricity grid or district heating and cooling network. Although the demand for sanitary hot water may not be significantly reduced as a result of renovation, the water heating system should also be supplied with very low GHG emission energy.

4.6 BACS

As discussed in chapter 3, all renovations should include BACS systems which not only control internal building temperatures, but also relative humidity, lighting levels and air change rates over the day, the week and the year, because this will lead to energy savings and GHG emission reductions. The quality and user interface of BACS are both crucial to the future performance of a building because it is often incorrect installation and commissioning or malfunctioning of the control system that causes poor energy performance and a poor indoor environment.

4.7 Barriers to deep renovations

A classic barrier, often called the tenant/owner dilemma, occurs because an investment in the renovation of a rented building is made by the building owner while the benefits (e.g. reduced energy costs and an improved internal environment) accrue to the tenant. This dilemma makes it very important to control the performance of rented buildings through regulations that oblige landlords to meet energy and GHG emission performance levels, rather than through benefits and incentives that might be sufficient to motivate renovation investments by owner-occupiers.

Practical barriers to deep renovations, when using conventional building techniques, can be the need to vacate the building and the disruptions caused while building works are in progress. These barriers can be addressed by the local provision of temporary accommodation and through innovations in building components and construction processes to minimise the time needed for internal renovation work and to reduce the mess created.

A lack of access to affordable financing and a lack of confidence in the expected outcomes of a renovation are also important barriers to the implementation of deep renovations. Such barriers can be addressed by supporting renovations with public funding that is conditional on the provision of performance guarantees covering not only energy and GHG emission performance improvements, but also improvements to internal air quality, winter comfort, summer overheating, moisture tolerance and acoustic insulation. Such guarantees are attractive because they focus attention on improving the health and quality of life of the building occupants. Nevertheless, an additional potential barrier arises when the owner of a residential building compares the time needed to repay the costs of a deep renovation with the time that they expect to remain living in the building. This can be a particularly significant barrier for elderly homeowners that needs to be addressed in financing packages and schemes to ensure that the added value of a renovation is fully reflected in the total value of the building when it is sold.

4.8 Using existing buildings more efficiently

Future GHG emissions from the whole EU building stock could be reduced by using the existing buildings and the space inside them more efficiently. This would reduce both the area of occupied buildings and the need to construct new ones, thereby reducing the energy and GHG emissions from building operation and the embodied GHG emissions that are created by the construction of new buildings (Francart *et al.* 2018; Serrenho *et al.* 2019). A policy discussion has been initiated on this with a proposed four-step hierarchy (Höjer & Mjörnell 2018):

- reduce demand for space (online banking, digital books/music, buy experiences not products);
- intensify the use of existing space (rented rooms, flexible reconfigurable rooms);
- reconstruct existing buildings to suit current needs rather than demolish them;
- only then construct new buildings.

However, with three-quarters of the EU building floor area consisting of residential buildings, and almost three-quarters of that being in urban areas, the scope for intensifying the use of space in existing buildings could be limited for the following reasons:

- wealthy people living in large dwellings may resist downsizing their accommodation because of the impact on their perceived social status;
- growing numbers of working families with second homes for use at weekends or during holiday periods may resist policies that would stop them from doing that;
- growing numbers of people working from home in small residences, which were not designed for such activities, may wish to enlarge their homes or move to larger ones to relieve stress on family members, notably children.

It follows that any policy aimed at intensifying the use of existing residential buildings would probably be avoided by the wealthy and be likely instead to affect the poorest and least advantaged members of society. Nevertheless, there are opportunities for policy-makers to put in place incentives for housing developers to adapt the space inside and outside existing buildings so that it can be used more efficiently, particularly in apartment blocks and other multi-residential buildings. For example, this could be to meet the needs of growing numbers of single-parent families and people living on their own, who would like to enjoy a small but complete residential package with their own kitchen, bathroom and bedroom together with their own indoor and outdoor living spaces.

In contrast, for non-residential buildings, of which offices represent around 75%, options for more intensive use have been adopted for many years, including hot desking and open-plan layouts with reduced floor area per person. Workplace acceptability and productivity varies across open-plan and enclosed office environments depending on physical layouts and occupant control over their interaction with others. The influence of these factors seems to vary with gender and age (Haynes *et al.* 2017).

Nevertheless, there are many underutilised buildings across the EU, including lots that could be renovated for a different use to that for which they were originally built, and with lower resulting embodied GHG emissions than would be created by the construction of new buildings. As part of a strategy to reduce GHG emissions from the building sector, further work across the EU on the use of existing buildings (e.g. conversion of offices or factories into residential apartment blocks) would therefore seem to be justified.

5 Energy supply to the built environment

5.1 Overview

Energy supplies to buildings are needed for space heating, space cooling, water heating, ventilation, lighting and for powering a wide range of appliances and equipment.

Energy is currently supplied to buildings in three main forms:

- electricity for appliances and equipment including lighting, and in some cases also for heating or cooling or both;
- gas, oil and solid fuels used mainly for space and water heating;
- district heating or cooling networks.

Renewable energies are increasingly being used to provide low GHG emission heating, cooling and electricity services in European buildings, and there is enormous potential to expand their use. Renewable electricity is supplied through the grid network and through building-integrated or on-site photovoltaic generators. Solar heating and cooling are provided through passive solar design measures, building-integrated solar panels and district heating and cooling systems. Geothermal heating is provided through on-site ground-coupled heat pumps and through district heating systems.

In most urban areas of the EU, buildings are connected to electricity and natural gas grids, and in some urban areas also to district heating and/or cooling networks.

In most rural areas of the EU, buildings are connected to electricity grids. However, they may have their own natural gas or oil storage tanks to supply their heating systems, and are unlikely to be connected to district heating systems because the distances between buildings are typically much greater than in urban areas, which increases the costs of district heating.

The consumption of fossil fuels in boilers to produce heating on site leads to direct GHG emissions from the buildings concerned, while the consumption of grid electricity and district heat or cooling in buildings leads to indirect GHG emissions from electricity generators and from district heating and cooling systems:

operating GHG emissions from buildings
= direct GHG emissions + indirect GHG emissions

An energy transition is expected by 2030, as the EU moves to establish new long-term sustainable energy supplies. During the transition period, significant reductions in GHG emissions from buildings can be achieved quickly by improving the performance of boilers and other building services (HVAC systems), while ensuring that the right size of these systems is installed to suit the building after it has been renovated (Butler 2020).

However, to reduce GHG emissions from the building sector to nearly zero cannot be done in a cost-effective way only by shifting from fossil fuels to very low GHG emission fuels and renewable energy sources. It will also require deep renovations of existing building envelopes to reduce the need for energy. In addition, the embodied GHG emissions of the materials, components and processes used during renovations must be minimised.

Moreover, given that fossil-fuelled boilers and heating systems typically have lifetimes of up to about 25 years, it is becoming increasingly urgent to set deadline dates after which the installation of new fossil fuel (notably coal, oil and gas) combustion systems in buildings will be banned. In particular natural gas, which is currently a major source of heat from fossil fuels for EU buildings, must be phased out completely within the next few years for new buildings and as quickly as possible for all buildings.

A particular challenge in existing buildings during the energy transition will be to plan renovations wisely, so that steps are taken in the most cost-effective order to ensure that investments in new assets will not become stranded in the future. For example, if gas boilers are replaced with heat pumps that are designed to operate at lower temperatures than gas boilers, then the existing radiators should not be replaced with larger radiators or fan coil units to deliver the heating required. Instead, the building envelope should be renovated as soon as possible with new windows, higher levels of insulation and improved air tightness, so that the existing radiators and fan coil units can deliver sufficient heat when operating at lower temperatures.

5.2 Electrification of buildings

Electrification is expected to play a major role in the decarbonisation of buildings in the EU. Large numbers of buildings have been successfully running on electricity for many years in countries with high fractions of hydropower in their electricity generation mix, such as Norway, and in countries with high fractions of nuclear power, such as France. Consequently, as electricity generation is increasingly decarbonised in the EU, building owners in other countries can have confidence in the sustainable long-term option of decarbonising the building sector by using renewable (green) electricity from wind, photovoltaic and hydropower generation, but this will create three important challenges.

1. To deliver electrified building services at competitive costs, although this should be assisted by the already falling costs of variable renewable power generation, and by the mass introduction of heat pumps, which should lead to cost reductions through economies of scale.

2. To balance the electricity demand from buildings with the variable supplies of electricity coming from variable renewable power generators (wind and solar). This will be helped by

   - installing electricity storage (batteries) in buildings;
   - coupling buildings to batteries in electric vehicles ;
   - storing excess electricity as heat for future use in buildings;
   - adopting a coordinated, holistic and aggregated approach to flexibility management of the grid;
   - on-site generation of renewable electricity (prosumers); and
   - interconnectors, demand response and some large-scale flexible electricity generators.

   Greater use of variable electricity supplies in buildings will provide business opportunities for the emerging role of aggregators, but will also require updated electricity market rules, with time-dependent tariffs and smart metering for self-generation and self-consumption (EASAC 2017).

3. To minimise the total and peak demands for electricity from the building sector so that adequate supplies of green electricity can be secured in the context of competing and growing demands for electricity from the transport and industry sectors. This will require locally optimised combinations of the following:

   - maximising the number of low-energy renovated existing buildings;
   - expanding the use of district heating/cooling systems in urban areas;
   - expanding the storage and use of waste heat;
   - adopting more efficient and well-controlled electrical equipment and appliances, such as heat pumps in place of electrical resistance heaters (which should be phased out as soon as possible); and
   - expanding the use of stored heat from solar collectors and excess renewable electricity generation.

The addition of embodied GHG emissions must be considered in relation to the electrification of buildings, because embodied GHG emissions can currently be substantial if large batteries are used, especially if these are made in countries with electricity supplies that have large carbon footprints. However, the Batteries Initiative in the EU circular economy action plan (EC 2020i), which is being supported as part of the EU Green Deal, is designed to stimulate the production of batteries in the EU using sustainable energy sources, which will minimise their carbon footprints. Batteries manufactured in the EU should therefore not be significant sources of embodied GHG emissions in the future, although attention must continue to be paid to the sourcing of rare metals for use in batteries (EASAC 2017). In contrast, the storage of renewable electricity as heat in tanks of hot water typically involves very low embodied GHG emissions.

Peer-to-peer trading of electricity between generators on different buildings (i.e. using ‘positive energy buildings’) should be permitted provided that this reflects time-dependent price signals for electricity on the grid. This can help with flexibility management and balancing of the grid (EASAC 2017). Nevertheless, to produce secure and decarbonised electricity supplies when the wind is not blowing and the sun is not shining will remain a big challenge. This will require, in addition to the systems in buildings discussed above, some large-scale flexible power generators, which are both dispatchable and decarbonised but will supply electricity to the grid for only limited periods of the year. When they are not needed by the grid, these generators are likely to be used for other purposes, such as to produce hydrogen and synthetic fuels, or to feed electricity into other medium- or long-term energy storage systems. Such generators are likely to be fuelled by a combination of energy sources, including the burning of municipal, agricultural and forest wastes with short carbon payback periods (EASAC 2019b), biomethane from sewage and food waste digestors, the burning of natural gas combined with carbon capture and storage (CCS), and possibly nuclear power if it can be integrated into a sufficiently flexible system in those countries where it is politically accepted and nuclear waste disposal issues have been resolved.

When buildings are renovated, many can be fitted with solar photovoltaic electricity generators on their roofs and/or façades (where these receive adequate insolation and do not need to be shaded to prevent overheating).

Depending on the local context, some buildings may instead be linked to photovoltaic generators mounted on nearby land or structures (e.g. pergolas, barns or outbuildings) within the same site. This allows their occupants to operate as 'prosumers' using the solar electricity themselves (self-consumption) and feeding excess power into the grid (positive energy buildings (PEBs)). Some may store electricity produced during the middle of the day in batteries in the building or in electric vehicles that are connected to the building, so that it can be used later when the sun sets.

However, it is important, when considering 'positive energy buildings' to note that generators that may be large enough to produce excess photovoltaic electricity in the summer will typically contribute little or nothing to the heating energy needs of the building in the winter in much of Central and Northern Europe, when insolation and air temperatures are both low. More work is needed to streamline the legislation, standards and practical tools (e.g. secure apps) to make photovoltaic electricity generation on buildings as economically attractive as possible to building owners and as valuable as possible for other electricity suppliers and users.

In addition, heat storage tanks (e.g. large water tanks in the ground) can be used with district heating and with individual building heating systems (e.g. hot water tanks in buildings) to store energy from excess renewable electricity as heat via heat pumps. This can be used to avoid curtailing wind or solar generators when supplies exceed demand, and thereby help to provide flexibility for electricity grids. Alternatively, where cooling is the priority, cold storage tanks can be used to store excess renewable electricity via heat pumps.

5.3 Replacement of natural gas for heating

Natural gas is the dominant source of heat for most buildings in the EU today, but this will have to change to deliver carbon neutrality by 2050. One way to reduce the creation of stranded assets in the gas supply infrastructure and in the many millions of gas boiler systems in existing buildings would be to replace natural gas with biogas and/or green hydrogen. However, unfortunately, neither could be produced competitively in sufficient volumes, even if the energy needs of existing buildings were to be substantially reduced through deep renovations (see section 5.5.5).

During the transition to a low carbon future, heat pumps installed to replace gas boilers may have to operate on grid electricity with a significant carbon footprint until renewable or other low GHG emission electricity is available in sufficiently large quantities. As discussed in its recent commentary (EASAC 2019b), EASAC regrets the slow progress being made with the development and implementation of CCS[1], and recognises that it is unlikely to achieve decarbonisation levels of more than 90% (EC 2018), but welcomes the first steps that are beginning to emerge. However, if progress can be made more quickly with the deployment of CCS, for example by supporting the establishment of transport and storage hubs near locations where high-emitting industries are located close together, then natural gas may be used as a flexible source of power generation together with CCS, for maintaining supplies when the wind is not blowing and the sun is not shining. Natural gas might also be used with CCS in urban areas for combined heat and power (CHP) plants to supply power to the electricity grid and heat to district heating systems.

5.4 Coupling (integration) of the building sector with the overall EU energy system

Buildings are responsible for approximately 41% of final energy consumption and 60% of electricity consumption in the 27 Member States of the EU plus the UK, with two-thirds of this consumption in residential buildings (Thomas and Rosenow 2020). Their decarbonisation will therefore have important impacts at the EU energy system level (Brown *et al.* 2018; Fridgen *et al.* 2020). In addition, buildings will be in competition with transport and industry for low GHG emission energy supplies, as illustrated by the interconnections between these sectors in Figure 6, which shows that excess renewable electricity will not only be used to produce hydrogen and synthetic fuels, but will also be stored in them, as well as being stored as heat.

5.5 On-site production of renewable electricity, heating and cooling

Renewable energy systems offer opportunities for householders and other building owners to produce electricity, heating and cooling locally. Economies of scale arise when groups of buildings such as whole streets or districts are built or renovated together. For example, renewable electricity can be generated on, or adjacent to, buildings by using solar photovoltaic, wind or hydropower generators. The use of renewable energies can be made more efficient by the provision of distributed heat and electricity storage, either in individual buildings or for groups of buildings, for example in association with district heating and cooling systems.

[1] The current status of carbon capture and storage (CCS) is closely followed by the IEA (IEA GHG 2020), and summarised from an industry perspective by the Global CCS Institute (2019).

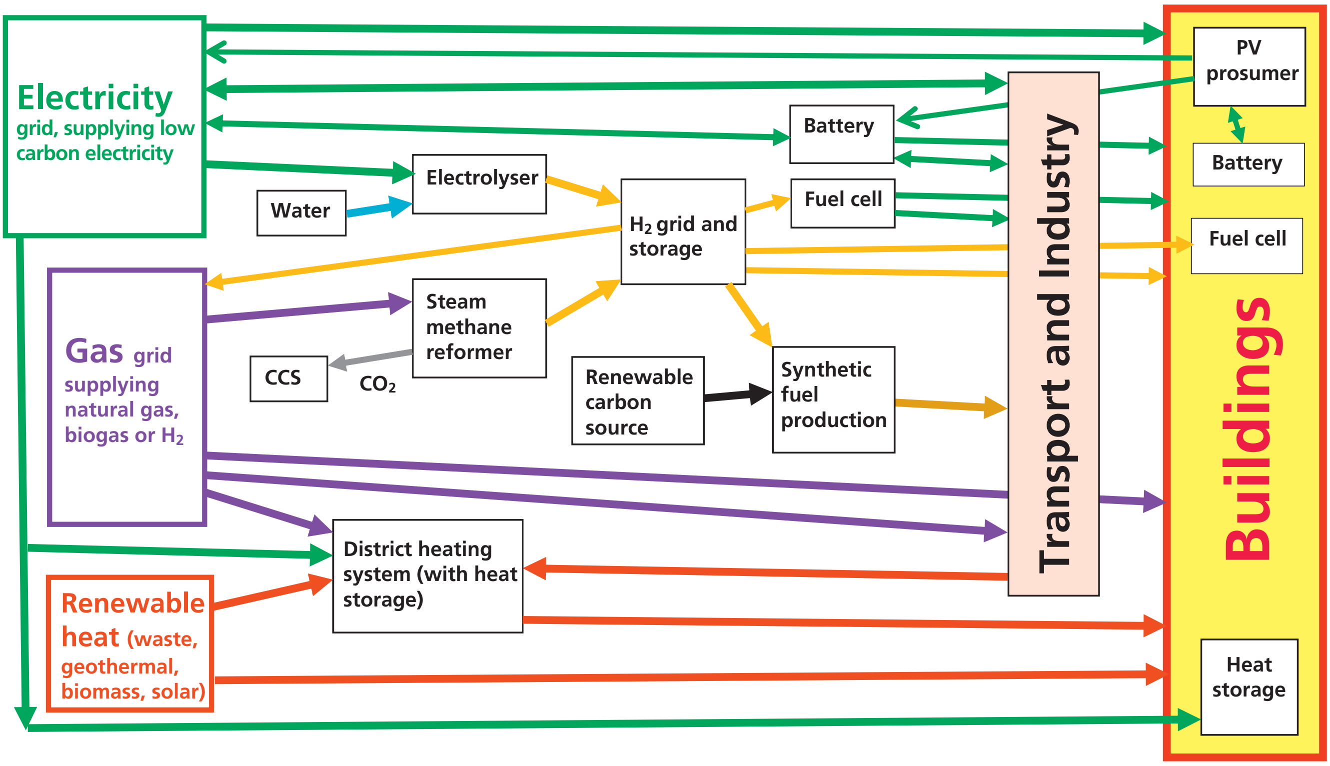


Figure 6 Overview of coupling between energy, buildings, transport and industry sectors.

The following renewable energy technology options (sections 5.5.1–5.5.5) may be used to provide decarbonised heating and/or cooling to buildings in place of conventional fossil fuels.

5.5.1 Heat pumps

There were more than 11.8 million heat pumps installed across Europe in 2018, and the number has been growing by about 1 million per year in recent years according to the European Heat Pump Industry Association (EHPA 2019). For example, about 85% of new residences in Austria and 45% of new residences in Germany now use heat pumps, most of which are air-to-air heat pumps, although the use of ground-coupled heat pumps is also growing (IRENA 2017).

GHG emissions from buildings can be reduced by replacing conventional boilers or electric heaters with heat pumps, particularly when combined with photovoltaics and battery storage (Litjens *et al.* 2018). Heat pumps usually use vapour-compression technology, with relatively high efficiencies in large-scale applications but lower efficiencies in small-scale applications. Efficiency requirements for different heat pump sizes for water heating and for space heating are specified in the EU's ecodesign regulations (ENS 2014).

When supplied with green electricity, heat pumps offer the possibility of providing conventional or underfloor heating in winter with much higher overall efficiencies than the resistance heaters (which should be phased out as soon as possible) or boilers that have been widely used in the past. They can also provide cooling in summer, when they have the potential to work together with photovoltaic generators (Rinaldi *et al.* 2021). Heat pumps should be used together with heat storage in domestic hot water and in the building fabric, so that they can be programmed to benefit from demand response incentives (Steinmann *et al.* 2019).

Early vapour-compression heat pumps used CFCs (chlorofluorocarbons) as refrigerant fluids, which damaged the Earth's ozone layer, so their use was phased out under the Montreal Protocol of 1987. Since then, the fluids used have been largely HFCs (hydrofluorocarbons), but these have a high global warming potential and are therefore also being phased out following the 2016 Kigali Amendment to the Montreal Protocol (UNEP 2019). Air conditioner and chiller manufacturers across the world are now bringing new machines onto the market with refrigerant fluids that do not damage the ozone layer and that have lower global warming potentials, for example HFOs (hydrofluoroolefins) or HCFOs (hydrochlorofluoroolefins) (EFCTC 2020), CO_2, hydrocarbons or ammonia. This change is providing opportunities for manufacturers to develop new systems with improved efficiencies for the rapidly growing air conditioning and heat pump markets.

Heat pumps typically have potential drawbacks which must be addressed by system designers and regulators, notably the following.

- The relatively high start-up currents of heat pumps can cause demand spikes on the electricity grid each time they start operating. These spikes must be controlled and regulated.
- In very cold weather, air-to-air (or air-to-water) heat pump performance can fall because of icing on their outdoor (evaporator) heat exchangers, especially in humid areas. This is increasingly being managed by automatic defrost cycling, but is also managed by adding electric resistance heaters to the evaporator. The latter option should be avoided because it adds to an already high peak demand for electricity, which may be difficult for the grid network to deliver.
- Traditional air-to-air and air-to-water heat pump evaporators were fitted with fans that produced noise, which became a nuisance when many homes in a neighbourhood had heat pumps installed. Since 2015, the noise produced by heat pumps has been restricted by the EU's ecodesign and labelling regulations (ENS 2014), and by a growing number of local authorities. Modern heat pumps can therefore be expected to operate with low noise levels.
- Heat pumps typically supply hot water for space heating to radiators and/or underfloor heat exchangers at temperatures that are lower than those supplied by gas boilers. Heat pumps should therefore be installed after the heating needs of a building have been reduced by renovations so that, where possible, the existing radiators can continue to be used to deliver sufficient space heating despite operating at lower temperatures.

Ground-coupled heat pumps are more costly, but do not create noise and offer better yields than air-to-air (or air-to-water) heat pumps because they collect heat by pumping a brine/water solution through pipes that are buried in the ground and therefore do not suffer from icing problems. They can also be used to cool buildings in the summer while storing heat in the ground (seasonal storage).

In individual household applications, it is important to install heat pumps that are large enough to meet the peak heating demand. Small (cheap) heat pumps should not be combined with electric resistance heating to minimise the initial capital costs, because this can lead to potentially excessive electricity demands, which may be difficult for the electricity grid to deliver during periods when the weather is very cold.

Note: absorption heat pumps are already being used to a limited extent and adsorption heat pumps are being developed for use with solar thermal cooling systems (see section 5.5.3).

5.5.2 Solar heating systems

Across Europe, active solar heating can potentially meet from 3% to 12% of national heat supply, depending on the country[2]. However, where there are high penetrations of other forms of renewable energy, particularly in Northern Europe, active solar heating can face challenges to deliver competitive energy costs and energy system flexibility (Hansen and Mathiesen 2018).

Solar water heaters have, nevertheless, been installed on buildings in urban and rural areas in Southern Europe for many years, where they have proved to be both cost effective and reliable. Small-scale solar water heating systems together with a small number of solar combi-systems (for combined hot water and space heating) in single-family houses, apartment buildings, multi-family houses, hotels and public buildings represent about 60% of annual solar heating installations worldwide. A growing market trend is to install solar water heaters as building-integrated systems, which are more aesthetically pleasing.

Active solar space heating systems, which use solar heating collectors with air- or water-based heat transfer fluids have proved to work reliably in some climates, notably in mountain areas with high levels of insolation and low air temperatures. However, they have not proved to be a competitive option for use in all areas of Europe.

Megawatt-scale solar heating systems for district heating and industrial applications have shown consistent market growth. For example, in Denmark, which leads the world in this field, the market grew by about 170% in 2019 because of the installation of two large-scale plants in that year. By the end of 2019, about 400 large-scale solar thermal systems (greater than 350 thermal kilowatts) connected to district heating networks and residential buildings were in operation worldwide. The total installed capacity of these systems equalled 1,615 thermal megawatts (2.3 million square metres), excluding concentrating systems that added 162,784 square metres (IEA 2020b). The combination of a solar thermal system with short-term heat storage of 0.1–0.3 cubic metres of water storage per square metre of solar collector

[2] Global solar thermal capacity in operation (2019) was 479 thermal gigawatts, i.e. 684 million square metres of collector (IEA 2020b). This has an annual thermal yield of 389 terawatt-hours, saving 41.9 million tonnes of oil and 135.1 million tonnes of CO_2.

area has been shown to enable solar heat to contribute approximately 20–25% of the heat in a district heating system in Denmark (Tian *et al.* 2019).

Photovoltaic thermal (PVT) collectors and systems, mainly using air as the heat transfer medium, are another emerging solar application, notably in France (IEA 2020b). The global market for photovoltaic thermal collectors and systems developed well during 2019 and saw significant global growth of 9%. This trend was also seen in the European market, with a growth rate of 14%, which corresponds to an increase of the newly installed capacity per year of 40.8 thermal megawatts and 13.3 megawatts-peak. By the end of 2019, the global total installed collector area of photovoltaic thermal collectors and systems was 1,166,888 square metres (606 thermal megawatts, 208 megawatts-peak), of which 58% was in Europe.

Passive solar space heating systems, which use elements of the building envelope (e.g. walls and windows) together with controllable shading devices to manage the heat gains from solar radiation and provide useful space heating, can be found in many different building types across the EU. In contrast, indirect passive solar space heating systems, such as Trombe walls (Cao 2020) and sunspaces, have not been so widely exploited, apart from in some mountainous regions, and have therefore not benefited from the economies of scale that have been achieved with mass-produced active solar heating panels.

5.5.3 Solar cooling systems

In residential buildings in continental Europe, the first step should be to avoid or reduce overheating by passive measures, notably solar shading and the use of heat storage in the building fabric together with night ventilation. Unfortunately, there is often insufficient thermal mass to use for cooling in timber-framed buildings, so these have typically to be fitted with active cooling systems. Similarly, in office buildings, passive measures are often insufficient because of internal heat gains from electrical equipment.

The global market for cooling and refrigeration is expected to keep growing. It is foreseen that, by 2050, 37% of total electricity demand growth will be due to air conditioning, which suggests that there could be a huge potential for solar cooling systems (IEA 2020a).

Solar cooling and air conditioning can be provided by either thermal or photovoltaic systems. Advantages of using solar thermal systems are that they consume less conventional energy (up to a factor of 5) and use natural refrigerants, such as water and ammonia, which do not harm the environment. However, they typically require the use of relatively high temperature solar collectors (greater than 80 °C), which operate largely using direct solar radiation and so are not well suited for use in most areas of Central and Northern Europe.

Both solar thermal and photovoltaic-powered cooling have the potential to reduce peak electricity demand, because the supply of solar radiation is typically available when the cooling demand is at its peak. Solar cooling therefore saves money by avoiding the need to purchase electricity when it is at its highest price. Solar thermal cooling has the advantage that solar heat can be stored more cheaply than electricity to meet demands for cooling in the evenings, nights and early in the morning.

Solar thermal cooling using absorption chillers with a cooling capacity larger than 350 kW has improved significantly in performance over recent years and, at the same time, decreased in costs. There have also been significant improvements in the performance of large flat plate solar collectors at temperatures up to 120 °C. These performance improvements, combined with economies of scale, have started to make solar cooling applications for large office buildings, hotels, hospitals and commercial/industrial applications more cost competitive in some parts of Southern Europe. However, small solar absorption cooling systems cannot compete with electric heat pumps powered by solar photovoltaic electricity for domestic applications, and solar adsorption cooling technologies are still under development (Zeosol 2020). Overall, solar thermal cooling continues to have a small niche market, with fewer than 2000 systems deployed worldwide as of 2019 (IEA 2020a).

5.5.4 Geothermal heating

Geothermal heating is already being used in many EU countries, notably in Italy, Hungary, Germany, France and The Netherlands, where there are readily available resources (JRC 2019b). Where the temperatures are too low to allow direct use of geothermal heating, then geothermal resources are being exploited using ground-coupled or aquifer-coupled heat pumps, and the markets for these are growing. Installed capacity (megawatts per population) of geothermal heat pumps is greatest in Iceland, followed by Sweden, Finland, Switzerland and Norway (EGEC 2019; Lund and Toth 2020).

Geothermal heating resources could be developed much more widely in the EU, since only a tiny fraction of their potential is currently exploited (Limberger *et al.* 2018). The technologies for geothermal heating applications are mature, notably those for ground-coupled heat pumps, so they represent a ‘low-hanging fruit’ for heating in the EU.

5.5.5 Firewood, biogas and hydrogen for heating

Wood burners and wood-fired boilers are used for heating in many rural areas, but they are not widely used in urban areas other than for district heating systems because of the challenge of limiting smoke, particulate emissions, carbon monoxide and other gases that cause air pollution.

For biogas, its long-term role will be limited by the lack of sustainable biogas resources. As an increasing number of EU countries have moved to capacity market mechanisms to support the deployment of biogas in the electricity sector, there has been limited growth of biogas in the EU electricity markets (Banja *et al.* 2019). Biogas-fuelled CHP production is only viable when low-cost feedstocks are available to enable efficient plants to produce competitively priced biomethane (Bedoić *et al.* 2020). Because of the limited resources, biogas may also have a limited role to play as a replacement for, or blended with, natural gas during the energy transition.

Green hydrogen can be fed into gas grids as is being demonstrated in several EU Member States, with a view to supplying energy demands for which it is difficult to find alternative low GHG emission sources, such as for heavy-duty road transport vehicles. To replace the 'grey' hydrogen, which is currently produced in the EU largely by steam methane reforming of natural gas (approximately 10 Mt per year), with green hydrogen produced using electrolysis of water would be technically feasible but require about 15% of the annual total electricity production in the EU (Kakoulaki *et al.* 2021). Moreover, green hydrogen will always be more expensive than the green electricity that is used to produce it. Consequently, while it may become feasible in the future to import hydrogen at competitive costs and to store it for use during periods of peak energy demand, it is most unlikely to become economically attractive to use green hydrogen produced in the EU on a large scale for applications that can be readily electrified, such as space and water heating in buildings (EASAC 2020). Similarly, low-carbon hydrogen (sometimes called blue hydrogen), which is produced by combining steam methane reforming of natural gas with CCS, is unlikely to become cost competitive with electrification for space and water heating in buildings, and the carbon footprint of blue hydrogen will limit its ability to contribute to the EU target of carbon neutrality by 2050 (EC 2020j).

5.6 District heating and cooling

District heating offers an attractive solution for providing decarbonised heating in densely populated urban areas and in city centres with heritage buildings, where the potential for energy efficiency measures and on-site renewable production is limited (HRE 2019a).

District heating systems across the EU currently use boilers and cogeneration plants with a mix of fossil fuels (including coal, oil and natural gas) and renewable energy systems (including biomass, biogas, solar and geothermal heat). District heating allows the use of large centralised boilers with heat storage instead of individual boilers in each building. When solid fuels are used in large boilers, combustion can be controlled and pollutant emissions can be filtered out and removed because large boiler plants are professionally managed.

However, unless they can be coupled to CCS networks, which currently seems unlikely in the foreseeable future in most urban areas, district heating systems will soon have to stop using fossil fuels. When this happens, the use of fossil fuels should not be replaced with the burning of wood pellets made from whole trees. This is because burning whole trees does not reduce GHG emissions within a short enough time period to meet the Paris Agreement target of limiting the increase in global average temperature to less than 1.5 °C above pre-industrial levels (EASAC 2019b).

Instead, depending on the local availability of resources, district heating systems should use renewable heat from sources such as sustainable biomass (e.g. from agricultural or forest wastes, wood industry or food industry wastes), solar, geothermal, biogas and/or waste heat from sustainable sources that would otherwise be dumped into the atmosphere. Waste heat can be obtained from many different sources including power generation, industry, data centres (Huang P. *et al.* 2019), supermarkets (Mateu-Royo *et al.* 2020) and numerous others such as underground (metro) stations, sewage systems and service sector buildings (Sandvall *et al.* 2021). Waste heat from municipal incinerators may also be used, but for this to be classified as a low GHG emission heat source, all fossil-fuel-based plastics must be removed and recycled before the municipal wastes are burned (Burnley *et al.* 2018).

Some district heating systems are linked to large heat stores, which help to balance heat supply and demand. Large heat stores can be used to absorb and store excess energy from variable renewable electricity generators (wind and solar), thereby avoiding their curtailment during periods of low electricity demand. To maximise its value (energy efficiency first principle), all excess renewable electricity should be supplied to district heating systems through electric heat pumps.

Wherever possible, low-temperature district heating systems should be used because of their higher energy efficiency, owing to lower heat losses from the heat distribution pipework. Where large buildings in an area covered by a district heating network may produce excess heat at some times of year, then the system should be designed so that this is shared with other buildings in the network that need it.

The development of district heating systems is often described in terms of different generations, with each subsequent generation having lower supply temperatures, higher efficiencies and more possibilities for heat production technologies. The latest, termed 'fourth generation district heating' enables the following.

- Integration of low-temperature renewable energy and waste heat sources.
- Coupling with the power sector through power-to-heat technologies, such as heat pumps.
- Smart energy concepts that allow interconnection of multiple energy sectors through smart metering and demand response (Lund *et al.* 2016). These could also have future roles in 100% renewable energy systems (Sorknæs *et al.* 2020).

By using power-to-heat technologies, fourth generation district heating systems can utilise low prices in power markets during periods with high renewable electricity (e.g. wind) production (Dorotić *et al.* 2020a, 2020b), thus supporting grid balancing and serving as low-cost thermal storage.

Recent work by a group of university and research institutions, industry representative organisations and an association of local authorities has shown that the use of district heating to supply heat demands across the EU could be increased from today's level of approximately 12% to around half of the heat demand in 2050, with contributions ranging from 20% to 70% depending on the country (HRE 2019b). The group estimates that this would require more than 20,000 new district heating systems to be built, which would clearly involve massive investments and strong political commitments at EU, national and local levels. Although the details, including building renovations to reduce heat demands, the provision of low GHG emission energy supplies and financing, need to be worked out for each locality, this study provides a valuable basis for stakeholder discussions, and gives confidence that there is substantial scope for increasing the future contribution of district heating in the EU's urban areas.

The spatial distribution of thermal demand and supply is a crucial input for optimising district heating and cooling systems, and various geographical information systems can be used to determine this. Researchers have mapped over 90% of the heat demand in 27 EU Member States plus the UK, thus establishing a framework for analysing district heating potentials (Möller *et al.* 2018). This has shown that 78% of the total heat demand is in densely populated urban areas, and that district heating could reach approximately 50% of the heating market at competitive costs (Persson *et al.* 2019). The Heat Roadmap Europe project has shown great potential for district heating expansion. In 14 EU Member States, up to 71% of building heat demand in urban areas can be met with district heating (Möller *et al.* 2019). Of this, up to 78% can be covered with excess heat, while the remainder can be covered with low-enthalpy renewable energy sources (Möller *et al.* 2018).

District cooling systems are not only important for urban areas in Southern Europe. Examples of district cooling systems can already be found across Europe, for example in Helsinki, Paris, London and Barcelona. Like district heating, an important advantage of district cooling is that it can use a mix of energy sources and systems, including natural cooling from nearby rivers, lakes or seawater as well as electric and absorption chillers. As is the case for district heating, there is good potential for expanding the use of district cooling in the EU, and valuable work has already been done on ways to achieve that (Rescue 2015).

5.7 Combined heat and power

Cogeneration (combined heat and power, CHP) plants offer an efficient means of transforming energy because they generate electricity and supply the otherwise wasted heat to meet nearby heat demands, for example in industry or in densely populated areas that are connected to district heating (Dorotić *et al.* 2021). CHP enables efficient coupling of heating and power sectors, especially when integrated with thermal storage, which improves the overall system efficiency and reduces total system costs (Jimenez Navarro *et al.* 2018, 2020).

Most CHP plants currently use fossil fuels (coal, natural gas or oil), but these will need to be phased out to meet the EU's decarbonisation commitments, unless the CHP plant can be connected to a nearby CCS network. In future, most CHP plants must therefore burn sustainable fuels as discussed for district heating systems (see section 5.6).

The outputs of CHP systems can be well matched to the energy needs of buildings during the heating season, when buildings need both electricity and heat, but this matching is typically more difficult in the summer months, unless the buildings are fitted with absorption chillers that use heat to produce cooling and air conditioning.

6 Embodied and operating greenhouse gas emissions in buildings

6.1 Overview

Buildings cause not only GHG emissions from the energy that they consume during operation, but also embodied[3] GHG emissions from the energy that is used to produce, transport and install materials, components and systems when they are built, maintained, renovated and eventually demolished (Cuellear-Franca and Azapagic 2012; Lavagna *et al.* 2018; Orsini and Marrone 2019). The importance of addressing both embodied and operational GHG emissions from the building sector has been highlighted by many stakeholder groups in recent years, including the World Green Building Council (WGBC 2020).

The largest contribution to the embodied emissions of a building is caused by its initial construction, of which the biggest elements are typically the foundations, floor slabs and structural components that contain steel and cement (Box 1) (Cuellear-Franca and Azapagic 2012; Hrabovszky-Horvath and Szalay 2014; Anderson and Moncaster 2020). However, substantial amounts of embodied emissions can also be caused by renovations.

6.2 GHG emissions produced by buildings over the next 10 years and over their lifetimes

Life cycle assessment (LCA) is a tool that can be used to illustrate the importance of both embodied and operational GHG emissions, and to highlight the need to take embodied GHG emissions into account when designing new buildings and renovations. It can also be used for drawing up national long-term renovation and building operation strategies.

In view of the EU commitment in the Paris Agreement to limit the increase in global average temperature to less than 1.5 °C above pre-industrial levels, it is particularly important to minimise both the operating and the embodied GHG emissions from the construction and renovation of buildings by 2030. This critical period for limiting global warming which, for renovations and new buildings, will include initial and some recurrent embodied GHG emissions (from maintenance and use), is illustrated by the dashed blue line at the bottom of Figure 7 (Röck et al 2020).

Embodied GHG emissions in buildings will become an increasingly significant contributor to the total GHG emissions from buildings as the operating emissions are reduced to near zero in the future. The significance of embodied GHG emissions varies with the mix of energy and materials used, and with the design and construction of the buildings or, in the case of renovations, with the depth and measures implemented to reduce both the embodied and operating emissions.

6.3 Embodied emissions created by renovations

Figure 8 shows the effects of different levels of renovation on the cumulative emissions from a

Box 1 Embodied GHG emissions in cement and concrete

Concrete has lower embodied GHG emissions per kilogram than some other materials (e.g. steel), but the world consumes very high volumes of concrete compared with other materials (Sivakrishna 2020). It is therefore important to note that the criterion for minimising the embodied GHG emissions in a building is not simply the embodied emissions per kilogram or cubic metre of the materials used in its construction, but the total amount used must also be taken into account. Different materials have different strengths (e.g. high-strength concrete), so it may be necessary to use more of one material than another to deliver the required strength in a building structure. It is therefore the total embodied emissions in the whole building structure which must be minimised.

A major contributor to global GHG emissions is ordinary Portland cement, which accounts for about 8% of global CO_2 emissions (Chatham House 2018). If cement production were a country, it would be the world's third-largest emitter after China and the USA (Olivier *et al.* 2016).

About half of the embodied GHG emissions in cement come from the chemical reaction (calcination) when making clinker, one of the major components of cement. Embodied emissions from concrete can be reduced by using alternative clinker-free cements or by substituting a proportion of clinker with other materials, such as waste materials or industrial by-products such as fly ash and blast furnace slag (IEA 2018; de Brito and Kurda 2021). Low-clinker cement has an environmental benefit, but the use of alternative constituents can impact the performance of concrete, and their availability depends on the location.

Clinker-free cements are a promising alternative but have not yet reached large-scale commercial deployment. Research continues on how to optimise the use of carbon-cured cements that absorb CO_2 and could potentially offer significant reductions in the future global warming potential of concrete (Jian Zhan 2016; Huang H. *et al.* 2019).

[3] The use of the terms 'embodied carbon' and 'embodied GHG emissions' in this EASAC report is broadly consistent with the recommendations of IEA EBC Annex 57 (Mistretta and Guarino 2016).

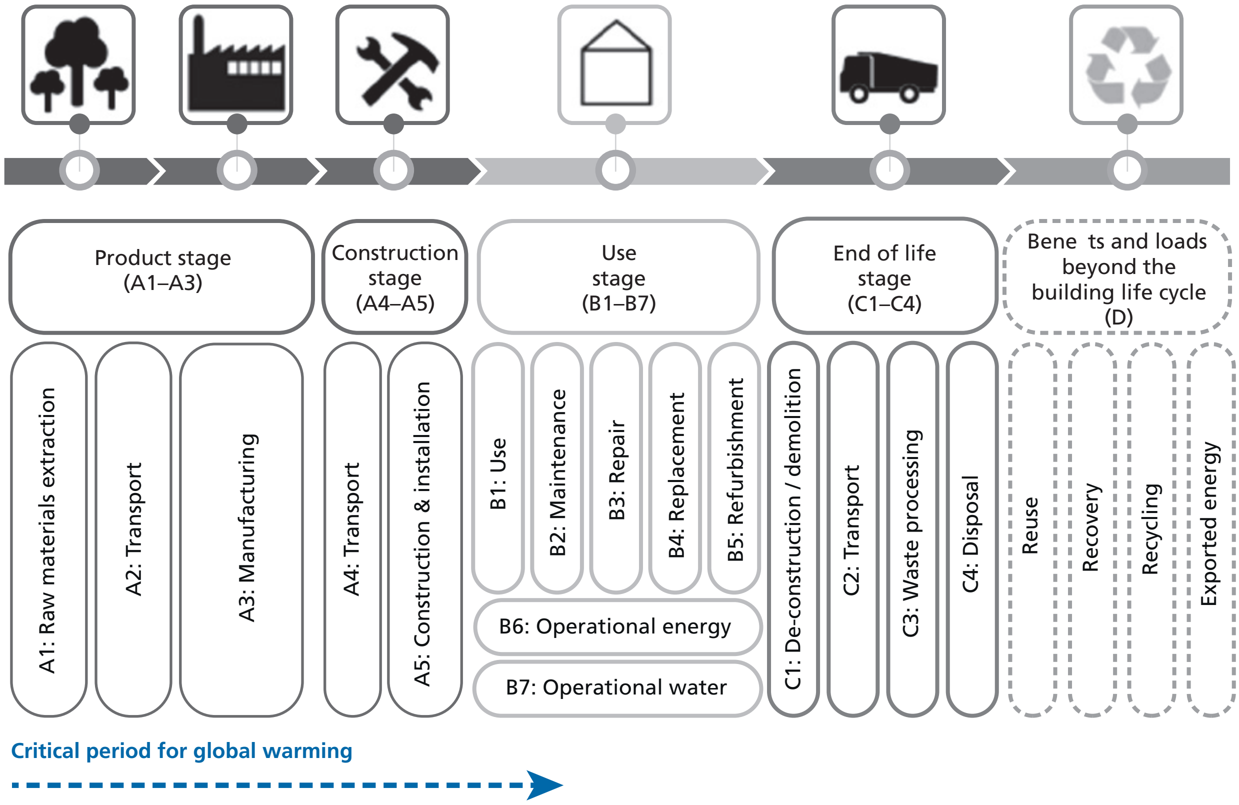


Figure 7 Building life cycle stages (adapted from Mistretta and Guarino 2016).

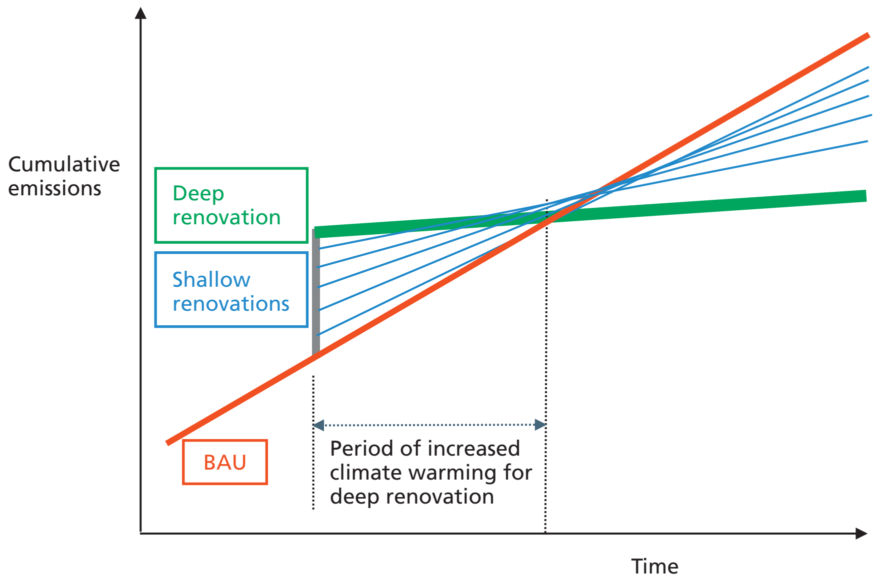


Figure 8 Renovation reduces operational emissions but adds embodied emissions (BAU = business as usual).

single building if there is no change to the level of decarbonisation of the energy supply. It shows an immediate increase in cumulative emissions at the time of renovation, which is caused by the addition of embodied emissions in the materials and components used. After the renovation, the rate of growth in cumulative emissions (the slope of the blue and green lines) depends on the depth of the renovation, which also determines the length of time before the cumulative emissions become less than would have occurred if the renovation had not taken place, i.e. the red line for business as usual. To contribute positively to keeping global warming below 1.5 or 2 °C, this period must end by 2030 (Röck *et al.* 2020).

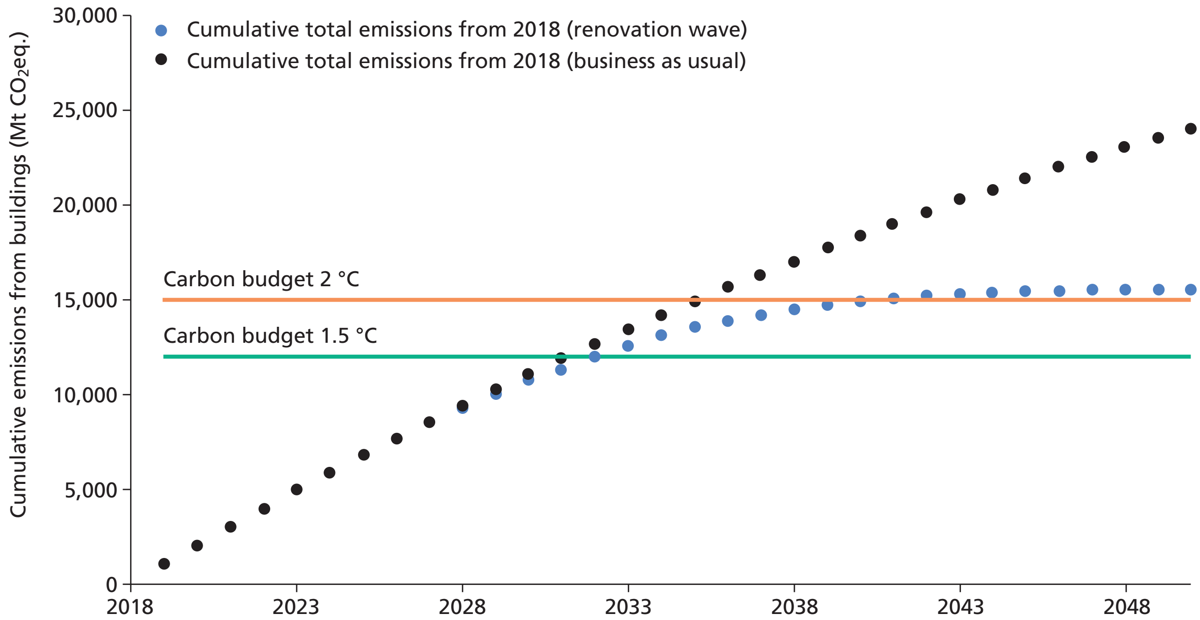


Figure 9 Cumulative GHG emissions: comparison of Renovation Wave with business as usual. The data assume added embodied GHG emissions of 125 kg CO_2eq./m^2 for the EU Renovation Wave (adapted from Koninx 2020).

6.4 Quantification of GHG emissions from buildings

Studies of embodied GHG emissions in buildings (Rasmussen *et al.* 2018; Moncaster *et al.* 2019; Ylmén *et al.* 2019; Lausselet *et al.* 2021) have shown that typical values of embodied GHG emissions per square metre of floor area for new buildings lie between 250 and 400 kilograms of carbon dioxide equivalent per square metre (kg CO_2eq./m^2), whereas the operating GHG emissions from existing buildings typically lie between 30 and 50 kg CO_2eq./m^2 per year (Odyssee-Mure 2018). The studies also show that the addition of embodied emissions caused by the renovation of an existing building, depending on the nature and depth of the renovation works and the materials used, is typically less than 50% of the embodied emissions for a new building (i.e. less than 125–200 kg CO_2eq./m^2). It can be much lower if the renovation focuses, for example, on insulation and heating or cooling system improvements without major structural changes (Brown *et al.* 2014). Hence, if a renovation using materials with modest levels of embodied emissions, together with decarbonised energy supplies (e.g. renewable electricity), is able to successfully reduce the operating emissions from an existing building to near zero, then the period during which the cumulative emissions are greater than they would have been without the renovation can typically be less than about 3 years[4].

6.5 Cumulative GHG emissions from the proposed Renovation Wave

While an average renovation rate of about 3.3% over the next 30 years, reducing as many buildings as possible to nearly zero GHG emission performance, would be necessary to deliver zero operating emissions from the building sector by 2050, it is also important to consider the impact of total building sector emissions (operating plus embodied) on the remaining carbon budget over this period.

Recent work for the European Parliament suggested a remaining carbon budget for the EU of between 47.7 and 61.5 gigatonnes of carbon dioxide (Gt CO_2) to be compatible with the 1.5 and 2 °C pathways (Matthes 2018), which is broadly consistent with the results of PRIMES modelling prepared for the Clean Planet for All strategy (EC 2018) that showed values for similar scenarios of between 48 and 60 Gt CO_2 (between 2018 and 2050). This corresponds to between 12 and 15 Gt CO_2 for the building sector if the carbon budget is shared in proportion to its share of total EU GHG emissions, namely about 25% (see section 1.3).

[4] Assumes current operating energy use of between 165 and 220 kW h/m^2 per year, based on gas boilers emitting 0.2 kg CO_2eq./kW h, a gas mix with 11 kW h/m^3, and buildings rated between 15 and 20 m^3 of gas/m^2 per year (see Figure 11).

Recent simplified modelling results for the proposed EU Renovation Wave[5] suggest, as shown in Figure 9, that the building sector would approach its fair share of the remaining carbon budget for limiting the increase in global average temperature to 2 °C by around 2040, provided that the embodied emissions created by the renovations do not exceed about 125 kg CO_2eq./m^2.

6.6 Policies to reduce embodied GHG emissions

The potential impacts of the Renovation Wave on the remaining carbon budget confirm the urgent need to accelerate the reduction of embodied GHG emissions in building renovations, and in new buildings. Policies that could help to accelerate the reduction of embodied GHG emissions include the following:

- improving the availability of high-quality data on the embodied GHG emissions of building materials and components, for example through a dedicated Web portal;
- streamlining the use of Environmental Performance Declarations (EPDs), and improving the consistency of information given in EPDs with that in the new Product Environmental Footprints (EC 2019d; Durão *et al.* 2020);
- improving documentation on the embodied GHG emission performance of new buildings and renovations, for example by including embodied GHG emissions in Energy Performance Certificates and/or building passports (labelling).

In addition, on the basis of work that is already underway in some Member States, the EU could put in place legally binding limits for embodied GHG emissions per square metre of floor area for new buildings and for refurbishments. A first step in the process of developing such embodied GHG emission limits could be to require Member States to set targets for such limits in their national long-term renovation strategies and to include these within the criteria for environmentally sustainable building activities in the EU Taxonomy. Legally binding limits for embodied GHG emissions per square metre of floor area could also become a key component of future specifications for green public procurement.

6.7 EU Level(s) initiative

In 2015, the European Commission Directorate-General for Environment, working with the Joint Research Centre, started to develop a voluntary reporting framework for sustainable buildings, called 'Level(s)', which aims to unite the whole building sector value chain around a common European language for better building performance. The Level(s) initiative covers a wide range of sustainability aspects for buildings, and is therefore similar to many voluntary sustainability certification tools for buildings that are used in national contexts. Apart from addressing the life cycle GHG emissions of buildings, it also addresses efficient and circular resource flows, and how to support the safety, health and well-being of building occupants. Level(s) was designed to serve as a galvanising force for actors across Europe's building sector, to encourage collaboration and to create a sustainable built environment for all Europeans. After approximately 5 years of development and testing, it was officially launched on 15 October 2020, and can be expected to make important contributions to the decarbonisation of buildings in the years to come.

6.8 National policies and benchmarking for GHG emissions from buildings in the EU

There are growing demands across the world for national environmental LCA benchmarks to be set, including targets for embodied as well as for operating GHG emissions from buildings (Lavagna *et al.* 2018; Frischknecht *et al.* 2019; Wiik *et al.* 2020). Several European countries have begun to address whole LCA in their building sector policy, and some have developed or adopted specific LCA tools for doing this, such as the following examples.

- Denmark has the 'LCAbyg' context-specific LCA tool for buildings (Kanafani *et al.* 2021) that continues to be developed to enable building designs to demonstrate compliance with the 'Voluntary Sustainability Class' by designers submitting LCAbyg files as part of their project approval documentation.
- Finland, which aims for carbon neutrality by 2035, will introduce normative GHG emission limits for different building types before 2025, and criteria for green public procurement have been developed to reduce the climate impacts of buildings, incorporating global warming potential and climate benefits (Kuittinen and Hakkinen 2020). The Finnish LCA software One Click LCA is used with major building certification schemes worldwide (Binova Ltd 2020).
- France is developing an E+C scheme to introduce energy + environmental/GHG emission targets for buildings (Ademe 2019).
- Germany is supporting research on benchmarking, and addressing the challenge of developing

[5] Analysis for EASAC, based on a normal distribution curve for ramping up the average renovation rate across the EU from 1.5% in 2020 to achieve an overall average of 3.3% between 2020 and 2050 (Koninx 2020).

schemes that could work with any of the many available LCA software tools (Schlegl *et al.* 2019).

- The Netherlands has since 2013 required an environmental calculation to be attached to building permissions, in accordance with the SBK Environmental Assessment Method (Stichting Bouwkwaliteit 2019).

- Sweden has regulations in preparation, with an act requiring a mandatory climate declaration (covering embodied GHG emissions) for new buildings, to be in effect from 2022. The national authority Boverket has proposed to connect limit values to this legislation in 2027 (Boverket 2020; EC 2020g).

6.9 Selection of building materials with low embodied GHG emissions

Many criteria need to be considered when choosing materials for a specific building, including their abilities to resist exposure to the expected changes in the local climate during the building lifetime. Traditional as well as new and emerging structural materials, prefabricated building components, advanced thermal insulation and building services technologies all offer the potential to reduce the operating and the embodied GHG emissions in buildings. However, the production of some materials and components will require major investments in new manufacturing plants and supply chains, and/or the use of processes fitted with CCS before they can deliver significant reductions in the overall GHG emissions from the EU building sector (Favier *et al.* 2019; Alig *et al.* 2020).

The Carbon Border Adjustment Mechanism, which is being developed as part of the European Green Deal, could help to discourage the use of imported building materials and components with high levels of embodied GHG emissions (EC 2020c). Working in combination with the EU Emissions Trading System (ETS) (EU 2020d), the mechanism could also encourage the future manufacture of some materials and components with lower embodied GHG emissions in the EU.

To make generalised recommendations on using or not using particular materials in buildings is risky because it is possible to use low embodied GHG emission materials badly and high embodied GHG emission materials well. However, from a policy perspective, it is clearly important to put in place regulations and market signals, such as carbon prices and embodied GHG emissions targets, which will encourage building designers and the producers of building materials and components to focus on low embodied GHG emission solutions, such as less material use, more recycled materials, greater re-use of materials and components (after re-testing and re-certification if appropriate) and circular supply chains (Boverket 2018; Erlandsson & Malmqvist 2018; Malmqvist *et al.* 2018; Francart *et al.* 2019).

6.9.1 Timber

Timber from sustainably managed sources is one potentially useful material that inherently has low embodied GHG emissions. It can be engineered to form structural timber and engineered wood products, which can be used in place of concrete and steel. Solutions are available to limit the likelihood that it will introduce fire risks and it has the advantage that it is well suited for use in prefabricated building components. However, timber brings other design challenges because of its low thermal capacity (important for heat storage), sound insulation characteristics (important for multi-occupancy buildings) and its limited resistance to environmental exposure (moisture and sunlight). It therefore requires expertise in design and installation to guarantee durability over its service life. In some applications, timber floors may not be the optimal solutions to replace traditional concrete floors (possible reasons are acoustic or fire regulations, or the dynamic response of the floor or even the entire structure). In such cases, hybrid structures such as timber–concrete composites are a valuable alternative, which can replace most concrete with a more sustainable material. However, recycling of treated timber and timber composites can be difficult owing to contamination and the need to separate multiple materials.

By using structural timber and engineered wood products in buildings, carbon that has been absorbed from the atmosphere by trees can be locked into a building for decades or perhaps even for centuries (Hurmekoski 2017; Leskinen *et al.* 2018). Such buildings therefore have the potential to act as a carbon sink (Churkina 2020), thereby delaying the negative impacts on forest carbon sinks caused by cutting down trees. However, it is important to note that less than half of the carbon in a harvested tree typically ends up in wood products with a long lifetime. The rest is burned or left to decompose naturally, releasing GHG emissions including methane. Moreover, forest management, harvesting, transportation of logs and the industrial production of construction timber also produce some, although typically limited, GHG emissions. Consequently, construction timber does have a carbon footprint and discussions continue between experts on this topic (Hart and Pomponi 2020; Moomaw *et al.* 2020).

6.9.2 Recycling and re-use of materials and components

The use of recycled building materials and components can help to reduce the embodied GHG emissions created during building renovations. This is because the global warming potentials of recycled materials and

Box 2 Building designers' checklist for minimising embodied GHG emissions

- Consider the re-use of existing buildings rather than building new ones.
- Prioritise the option of renovation over that of demolition and the construction of a new building.
- Perform a full LCA for the whole building to be sure that design decisions are well founded.
- Optimise/reduce the building size and thus the overall need for materials, if the client can be convinced to accept this.
- Consider the re-use of materials, components and systems rather than using new ones.
- Choose materials with low embodied GHG emissions, such as wood products, natural materials, recycled plaster, low carbon concrete and recycled (or re-used) steel or aluminium.
- Use materials and components with embodied GHG emissions that are certified in environmental performance declarations (product environmental footprints where appropriate).
- Wherever feasible, build light structures, lightweight instead of compact roofs, and strip foundations instead of massive concrete ground floors. (Note: such designs typically have low thermal mass and may therefore need active cooling systems to prevent overheating.)
- Use building-integrated systems such as building-integrated photovoltaic generators.
- Choose local materials (where available with appropriate quality) to reduce GHG emissions produced by transporting materials to site. (Note: transportation emission savings may be small.)
- Choose durable, long-life materials to reduce the need for replacement/renovation.
- Design for ease of disassembly and re-use or recycling of materials and components when the building has to be demolished at the end of its life.
- Select waste-free, fossil-free and emission-free construction sites, and use electric construction machinery.

components are lower than those of virgin materials or new components. To reduce the life cycle emissions of the next generation of buildings, it is also important to design for the future when a building will be demolished, for example by designing for the re-use and recycling of components made of materials with high embodied GHG emissions, such as aluminium, steel, concrete blocks and bricks (where possible). (Note: some materials and components, notably structural components, may need to be re-tested and re-certified before being re-used.) Structural timber and engineered wood products should be re-used as far as possible, and only burned as fuels when they can no longer be used as building components (the cascade principle for the use of biomass).

6.9.3 Insulation materials

Conventional thermal insulation materials including rock mineral wool, glass mineral wool and expanded or extruded polystyrene have very different levels of embodied GHG emissions per kilogram. However, their embodied emissions per square metre of floor area of the building in which they are used will depend on where and how they are to be installed, which should be taken into account when they are selected.

Bio-based insulation materials such as cellulosic fibres (e.g. straw), sheep's wool or cork typically have much lower levels of embodied GHG emissions than conventional insulation, and offer the added advantage that they can contribute to the temporary storage of carbon (Pittau *et al.* 2018, 2019). However, it is important to ensure that they have been treated to give adequate moisture and fire resistance.

6.9.4 Data on embodied emissions of materials

Simple advice on the embodied GHG emissions from new and recycled materials and from re-used components is needed by building designers and owners. This should be made more readily available across the EU, for example through an open-access Web portal that includes generic data as well as specific data for commercially available materials and products through Environmental Product Declarations (and Product Environmental Footprints where appropriate).

The portal should be accompanied by simple guides such as the Danish construction material pyramid (Cinark 2020) which is available online as an interactive tool but is shown as a static image in Annex 1. This guide has been selected for inclusion here because of its memorable style and ease of use. However, such data vary of course with the source of each material, the location of its use and the date of its production. Embodied emissions are expected to fall as the means of producing each material are decarbonised. All data on embodied GHG emissions must therefore be regularly updated.

In addition, checklists of measures for reducing embodied GHG emissions in buildings, such as that shown in Box 2, can be useful to building designers.

7 Financing building renovations

7.1 Overview

The decarbonisation of new buildings across the EU will require not only more demanding building regulations and codes, but also public sector support to reduce investment risks, and help from financiers in the form of long-term affordable financing that is conditional on demanding GHG emission performance requirements. The costs of imposing such requirements on new buildings can be expected to fall as a result of economies of scale because advanced building components will become more widely used. Costs will also fall because of improved efficiencies in the construction process as builders gain experience with the installation and commissioning of new technologies.

Such a massive challenge must be largely implemented at national and local levels, but could be greatly helped by obligations at EU level, together with funding from the EU and financial support from the European Investment Bank to leverage private investments.

The total costs of the proposed Renovation Wave are difficult to estimate because of the big differences between Member States, uncertainties about the current energy performance of much of the EU building stock, and the many other variables involved. However, in most cases, investors can expect the costs of renovations to increase with depth of energy-related renovations and the corresponding impacts on GHG emission reductions. The costs of different depths of building renovation have been estimated in studies by the Buildings Performance Institute Europe (BPIE 2011) and by the European Commission (EC 2019f), which have found renovation costs lying between less than €50/m^2 and more than €600/m^2, depending not only on the depth of renovation but also on the type and location of the building, its use and its existing energy performance.

On the basis of an average deep renovation cost of (say) €300/m^2, the renovation of about 3% per year of the 25 billion square metres of EU buildings until 2050, which is proposed in the EU's Renovation Wave strategy (EC 2020a), would cost about €225 billion per year. Most of this cost would have to be covered by private financing, but private investments could be usefully de-risked, leveraged and accelerated by publicly funded incentives; for example, the European Parliament has proposed a subsidy of €100/m^2 for deep energy-efficient building renovations, which corresponds to €75 billion per year of public funding (EP 2020b).

7.2 Financing approaches for building renovations

As the EU implements its recovery from the COVID-19 pandemic, the proposed Renovation Wave (EC 2020a) offers new employment and business opportunities as well as major contributions towards EU commitments to GHG emission reductions. A re-focused regulatory framework together with a well-targeted use of public funding to mobilise much larger amounts of private financing will be needed to guide the EU's economic recovery and to mitigate the climate crisis at the same time.

The EU's EPBD not only requires Member States to establish national minimum energy performance requirements for new and renovated buildings, but it also encourages them to put in place financing schemes and incentives to encourage improvements to the energy performance of their existing buildings. Such renovation financing schemes should focus on deep renovations that deliver nearly zero GHG emission buildings, and they should not support shallow renovation options (with short payback times). This is important because it typically becomes more difficult than expected and less cost-effective to perform deep renovations if buildings have recently been subjected to shallow renovation.

For new buildings, it may be possible to achieve nearly zero GHG emission performance with costs that are affordable for potential owners, most of whom will in any case have to take out a mortgage over many years. However, the situation is typically very different for owners of existing buildings, where deep renovations usually require major and unforeseen investments, which can typically take up to about 30 years to recover through savings in energy costs.

Financing schemes for deep renovations therefore need to be like those used for house purchasing mortgages, based on long-term loans with low interest rates. Incentives, such as grants, may also be needed to trigger such long-term investments and to reduce the risks that are likely to be perceived by investors.

There are three main approaches that can be used for financing energy renovations of residential buildings: equity financing, debt financing and non-repayable rewards (Bertoldi *et al.* 2020). The extent of their adoption reflects the diversity of contexts for building renovations across the EU and the maturity of the different approaches shown in Figure 10.

The most well-established approaches are the traditional options of

- debt financing with soft loans (e.g. by extending an existing mortgage) or leasing; and
- non-repayable rewards from governments such as grants, subsidies or tax incentives.

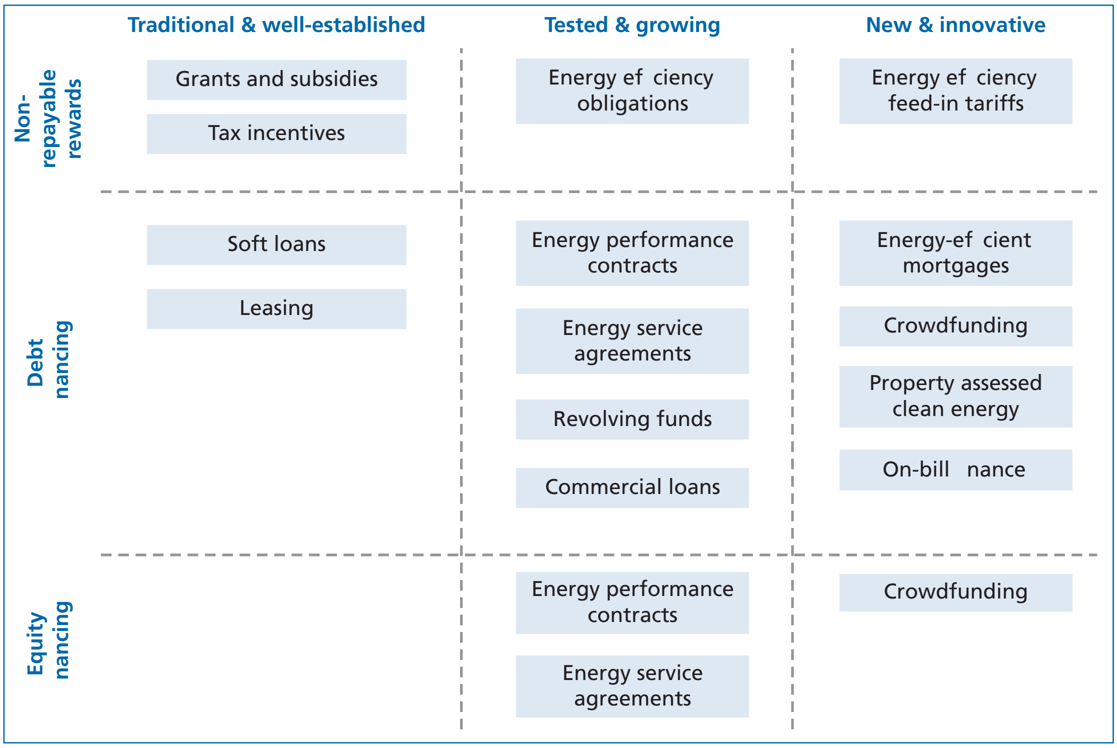


Figure 10 Approaches to financing energy renovation of dwellings (adapted from Bertoldi et al. 2020).

Approaches that have been tested in recent years, and whose use is growing include the following:

- equity financing through service agreements and energy performance contracts;
- debt financing through commercial loans, revolving funds, service agreements and energy performance contracts; and
- non-repayable rewards through energy efficiency obligations.

New and innovative approaches include the following:

- equity financing through crowdfunding;
- debt financing through on-bill finance, the 'property assessment clean energy scheme' (in the USA) and energy-efficient mortgages; and
- non-repayable rewards through energy efficiency feed-in tariffs.

With all of these renovation financing approaches, before-renovation and after-renovation assessments should be made to check that foreseen improvements in energy and GHG emission performance have actually been delivered. Such performance assessments should cover typical variations in weather conditions and user behaviour, and be openly reported to help build investor confidence by minimising the risk of disappointment and misunderstanding (see section 8.4.4).

Some examples of renovation financing schemes include the following.

- KfW Bank in Germany offers loans with interest rates that are more attractive for deeper renovations (KfW 2017).
- Property Assessed Clean Energy (PACE) programs in the USA have helped over 200,000 homeowners to invest US$5 billion in energy-related improvements as of 2019 (PACE 2019). PACE programs allow a property owner to finance the upfront cost of energy improvements to a property and then pay the costs back over a set time period (typically 10–20 years) through property assessments, which are secured against the property itself and paid as an addition to the property tax bills. Hence, importantly in PACE, assessment is attached to the property rather than to an individual.
- Utilities and energy service companies can finance building renovations with inherently low risks because they can make long-term commitments of perhaps 20–30 years. They can do the following:
  - bring together clusters of buildings;
  - raise the capital investment needed for a whole cluster in one deal;
  - recover investment from building owners/users via their fuel bills (on-bill payments);

- ○ realise economies of scale from bulk purchasing of similar building products and an experienced workforce performing similar renovations over an extended period.

However, this scheme carries risks for the bill payer because, even in a deeply renovated building that could deliver low energy performance, actual energy consumption can be increased by user behaviour. In addition, while this business model is likely to continue to work well for electricity suppliers, it will stop working for gas and other fossil fuel suppliers as these fuels are phased out.

7.3 Financing infrastructure for energy supplies to buildings

To decarbonise the EU building sector by 2050 will require major investments in the EU's energy supply infrastructure, including substantial increases in offshore electricity generation together with additional electricity transmission and reinforced electricity distribution networks.

Major changes will also be needed to natural gas distribution networks, as the use of individual natural gas boilers is phased out in many areas. To allow the continued use of natural gas in some applications, it is likely that major investments will be needed in new CCS infrastructure. Natural gas applications requiring CCS are likely to include the supply of flexible electricity generation for use in electricity capacity markets, CHP plants for district heating and cooling systems in cities and other urban areas, and possibly also steam methane reforming plants for producing hydrogen from natural gas (EASAC 2020).

Major investments in the construction of new and the renovation of existing district heating and cooling systems will also be needed (see section 5.6).

The financing requirements for infrastructure investments are already being studied by and for the European Commission in the context of the European Green Deal, but are outside the scope of this EASAC report.

7.4 Taxonomy regulation: to focus investments on environmentally sustainable activities

The EU Taxonomy regulation (EU 2020b), which entered into force in July 2020 and is expected to become increasingly important for financing sustainable growth, has three main goals:

- to provide agreed definitions to companies and investors for which economic activities can be considered environmentally sustainable;
- to empower investors, including retail investors, to channel capital towards environmentally sustainable activities, by limiting the risks of 'greenwashing' through its definitions;
- to avoid market fragmentation by providing a single point of reference for investors, companies, and Member States, with definitions of environmentally sustainable activities for investment purposes.

The Taxonomy regulation has been developed with the help of a technical expert group on sustainable finance, which in 2020 published a Taxonomy Report (EU 2020c) with a technical annex that includes detailed criteria for what can be considered an environmentally sustainable activity. At the time of writing this EASAC report, the European Commission is preparing a delegated act, taking into account stakeholder feedback and an inception impact assessment, to ensure full application of the Taxonomy by the end of 2021. For new and renovated buildings, the Taxonomy is largely guided by the existing EPBD and Energy Efficiency Directive (EU 2018a, 2018b, 2018c), so its requirements are based on primary energy demand rather than on energy used. Also, it allows energy inefficiencies in buildings to be counterbalanced by exporting renewable energy that is generated on site, and does not adequately address embodied GHG emissions.

To make the EU Taxonomy criteria, and the EPBD that underpins it, more relevant to the 2050 climate neutrality goal, more understandable and more user friendly, it should do the following:

- focus on the fossil-based energy used by a building instead of primary energy demand (i.e. use an updated concept of NZEB);
- take into account embodied GHG emissions from building materials, components and processes; and
- address renewable energy exports from buildings separately, excluding them from building energy performance assessments (see chapter 8).

7.5 Estimating the energy savings and other benefits resulting from building renovations

There is frequently a gap between the calculated (theoretical) and the actual energy consumption of buildings (Kragh *et al.* 2017). The calculated energy consumption of older buildings with a poor energy performance is typically higher than the actual energy consumption while, in contrast, the calculated energy consumption is typically lower than the actual energy consumption for buildings with a good energy performance. This is illustrated in Figure 11, which compares actual and calculated data from The Netherlands (Majcen 2013).

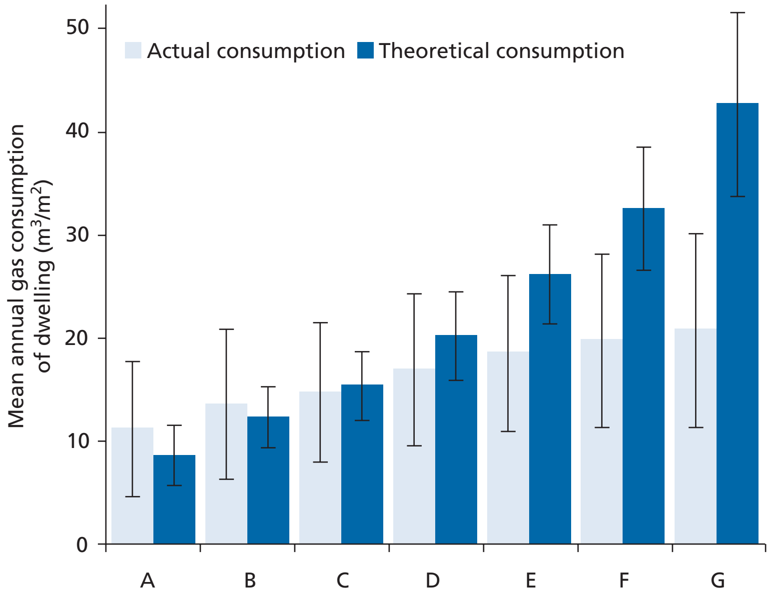


Figure 11 Actual and theoretical gas consumption in Dutch dwellings for each energy label per square metre of dwelling area (adapted from Majcen 2013). (Note: 10 m^3 of natural gas per square metre is equivalent to about 110 kW h/m^2)[6].

This gap has potentially important implications for policy-makers and for investors in building renovations. It results partly from oversimplification of the calculation method: for example, fixed average indoor temperatures are assumed in the calculation while in reality poorly insulated buildings typically have lower indoor temperatures and highly insulated buildings typically have higher indoor temperatures (Koene *et al.* 2015). Other differences between the assumptions used for calculations and reality may occur if heating systems are only installed or working in parts of existing buildings with poor energy performance: for example, bedrooms are seldom heated in many areas of the EU, and because of differences in user behaviour.

User behaviour can have substantial impacts on the energy performance of buildings, especially in residential buildings but also in other buildings where users are free to adjust temperature settings, switch off heating or cooling in some rooms, open windows, pull down blinds, etc. (Gram-Hanssen 2010). Moreover, buildings are changed by renovations and their occupants may therefore react in unexpected ways. For example, bedrooms may become hotter after the addition of roof insulation, or occupants may feel 'suffocated' after buildings have been made more air tight. Occupants may therefore open the windows more than before and sometimes leave them open in winter (Hansen *et al.* 2017; Wolf *et al.* 2017). In some cases 'people behave less efficiently in more energy-efficient buildings because it doesn't matter that much'. Some experts identify this as a rebound effect (Hens *et al.* 2010). As a result, the building may produce not only lower energy savings than expected after renovation, but also offer less comfortable living conditions and a poorer indoor environment than expected (Broderick *et al.* 2017).

Nevertheless, in most cases, deep renovations, which include the building envelope and its ventilation and other building services, will provide a range of co-benefits for building occupants in addition to energy savings and consequent reductions in GHG emissions. These co-benefits typically include improved air quality, better access to daylight (e.g. if window sizes are increased and their quality improved), better comfort, better sound insulation and acoustics (depending on the positioning and types of insulation, window and ventilation system used), better lighting and other services that improve health, well-being and quality of life. In addition, the opportunity can often be taken during renovations to improve disabled access, and access to outdoor space (e.g. by adding or extending balconies).

Valuable benefits to society can also accrue through the construction of new nearly zero GHG emission buildings and the implementation of deep renovations, including new business activities leading to job creation, increases in gross domestic product, and growth in carbon markets (through carbon pricing). The economic case for investments in nearly zero GHG emission buildings and for implementing deep renovations should therefore take into account the total value of the benefits and co-benefits (Birleanu *et al.* 2013).

[6] Assumes gross calorific value for natural gas = 40 MJ/m^3.

7.6 Role of emissions trading systems

As part of the Green Deal, the European Commission has announced its intention to propose the inclusion of buildings and transport in the EU Emission Trading System (ETS) (EU 2020d). The use of electricity in buildings is already covered by the ETS, but the use of other fuels such as gas, oil and coal in buildings is currently managed through the Effort Sharing Regulation (EU 2018d). At the time of writing this report, it is not yet clear how the European Commission will move buildings into the ETS. It could be done by fully integrating buildings into the existing ETS or by establishing a parallel emission trading system for heating fuels, to be applied when these fuels are used for applications that are not already covered by the ETS, and managing this parallel system separately.

An analysis by the European Climate Foundation suggests that full integration would be unlikely to achieve the objective of reducing the GHG emissions from buildings because of the inelastic nature of the building energy market. Instead, the Foundation found that the result of fully integrating buildings into the ETS would be more likely to increase pressure on the other sectors covered by the ETS to accelerate their emission reductions (ECF 2020).

The option of establishing a parallel trading system might be rather like the approach that was adopted in 2019 in Germany. For this, a separate cap and trade system was established in parallel with the ETS, for fuels supplied to GHG emitters that are not covered by the ETS, mainly buildings and transport (CLEW 2020). The German parallel emission trading system is an 'up-stream' approach, in which the participants are not the GHG emitters themselves but rather the fuel suppliers. For the first 5 years, the system will work with carbon prices fixed by the German Government, although this is later expected to work through auctions.

Apart from the continuing debate over the level of the carbon price in such systems, one of the biggest concerns about the introduction of carbon pricing of fuels for heating domestic residences, through the ETS or otherwise, is its potential impact on energy poverty. When any carbon pricing systems are implemented to reduce GHG emissions, adequate provision must therefore be put in place to protect the most vulnerable and low-income groups in society from energy poverty (EC 2020d).

Also important will be to link the revenues from emission trading to investments in deep building renovations, so that the overall objective of reducing GHG emissions from the building sector can be achieved.

7.7 Project development assistance

Modest amounts of funding for project development assistance (e.g. through the European Local ENergy Assistance 'ELENA' funding scheme) have been shown to trigger deep energy-related renovations in groups of buildings by local communities (EIB 2020). Energy-related investments at the neighbourhood scale (in groups of buildings) bring economies of scale and allow many small investments to be bundled together such that they can be more easily funded by the major financing institutions.

The grouping of buildings for the renovation of neighbourhoods also offers several potential benefits, which future incentive schemes should take into account:

- economies of scale in the production of prefabricated building components, and therefore further cost reductions;
- help with the introduction of district heating systems, and positive energy buildings that export heat or cooling to neighbouring buildings;
- help to overcome hesitation by private building owners, who can be encouraged to see such schemes as a 'now or never' opportunity to improve their own building together with those of their neighbours who are doing the same.

Neighbourhood approaches may be easier to introduce in areas with similar buildings, but have also been shown to work in areas with heterogeneous building stocks (Wiik *et al.* 2019).

8 Making it happen (policies, legislation and financing)

8.1 Overview of key challenges

As discussed in the previous chapters, decarbonisation of the EU building sector to meet the objective of zero GHG emissions by 2050 will depend not only on renovating existing buildings, but also on the decarbonisation of energy supplies, and on minimising the fossil-based energy consumption of all new buildings. All three of these actions are costly and are unlikely to be implemented quickly without changes to the relevant market and regulatory frameworks.

The performance of new buildings is the easiest of these three actions for policy-makers to address because the EPBD and national regulations already include energy performance requirements for all new buildings.

In contrast, to improve the performance of existing buildings is a much bigger challenge because it will require policy-makers to revise, update and strengthen the current policy and regulatory framework, so that it will deliver two to three times current renovation rates with a focus on deep energy-related renovations that are designed to minimise both the energy needed to operate existing buildings and the creation of newly embodied GHG emissions caused by their renovation.

Last but not least, to decarbonise energy supplies, the updated policy and regulatory framework must phase out the use of fossil fuels, and replace them with adequate supplies of sustainable energies.

8.2 Investment policy priorities: building renovations or sustainable energy supplies?

Policy-makers who are working on decarbonising the building sector can be expected to ask whether priority for public funding should be given to promoting investments in building renovations (Renovation Wave) or investments in decarbonising the energy supplies to buildings (Generation Wave) because both will lead to GHG emission reductions. Unfortunately, there is no simple answer to this question.

Investment costs of building renovations vary substantially with location and depth, as discussed in chapter 7, and the amounts of public funding (subsidies) needed to trigger renovation investments also vary. In addition, most energy-related building renovations bring additional valuable benefits, notably through improvements to the indoor environment, which may motivate positive investment decisions by building owners and therefore reduce the need for public funding.

Investment costs of renewable electricity generation and district heating systems are also location dependent, but the costs of renewable electricity generation are continuing to fall. Investment decisions in them are typically taken by project developers on the basis of business plans, and their need for public funding is also falling. In contrast, neither the costs of reinforcing the EU's electricity grid infrastructure nor the costs of building or extending district heating systems are falling, and these often include a substantial but unpredictable administrative cost for securing planning and construction authorisations, so these sectors are likely to continue to need public funding.

Investments in building renovations can help to reduce the need for investments in renewable electricity and heat generation capacity because they reduce both peak and average energy demands from the building sector. For example, electricity and heat storage installed during building renovations can be used not only to reduce peak energy demands from buildings but also to balance energy demands with variable renewable energy supplies. However, reductions in the need for renewable electricity generation capacity caused by future building renovations may be smaller than expected because the building sector will share an integrated EU energy system with the industry and transport sectors, which may dominate peak energy demands at certain times of the day and year.

The speed with which decarbonisation investments can be implemented is also important for policy-making and can vary with the local context. Buildings can typically be renovated within a few months and many can be renovated in parallel, but it will nevertheless take decades to renovate the entire EU building stock of approximately 250 million buildings. Similarly, the speed at which new renewable energy generators can be brought online will vary not only with the time taken to build them but also with the time taken to secure authorisations for their construction and for reinforcing the transmission and distribution grids. To obtain such authorisations can take several years, so it may be faster in some parts of the EU to decarbonise energy supplies, whereas in others it may be faster to implement building renovations.

In summary, there is no 'one size fits all' optimal solution for prioritising public investment resources between building renovations and decarbonising energy supplies at EU or national levels. This is not only because of cost variations and location-dependent authorisations, but also because of future interactions between the building, industry and transport sectors in an integrated EU energy system.

8.3 EU legislation to promote building renovation

In line with its Clean Planet for All strategy (2018), the European Commission launched its European

Green Deal in 2019 (EC 2019a), which includes a Renovation Wave initiative and a strategy for energy sector integration (EC 2020e). These EU initiatives build on the earlier EU strategy for heating and cooling (EC 2016a) and confirm the importance of decarbonising the building sector. They also recognise that much of the existing legislation needs to be updated and strengthened to deliver that.

To legislate for the renovation of existing buildings is more difficult than for the construction of new buildings because many private owners of existing buildings have both limited resources and limited motivation to renovate. There is a well-known split incentive between tenants and owners, and the fragmentation of ownership in multi-family apartment buildings also creates challenges for investment decision-making. Some renovations can change the appearance and character of existing buildings, and so may be prohibited to maintain the cultural heritage of a locality. In addition, most existing buildings are occupied and provisions may therefore be needed to accommodate occupants if the building needs to be vacated for renovations to take place.

Deep renovations of existing buildings are therefore unlikely to occur without some form of trigger to kick off the process. This can be a change in ownership or a change of tenant, which can be legally linked to new requirements for energy performance certification; but for many buildings such triggers may not occur for many decades. Alternatively, electronic energy performance monitoring (usually for large buildings and systems) or obligatory periodic inspections (usually for energy systems) may be put in place to trigger renovation investments. However, it seems most unlikely that the massive numbers of renovations needed to meet the EU's decarbonisation objectives can be triggered without either substantial programmes of very attractive financial incentives or a package of legal/regulatory obligations on building owners or their energy suppliers, or both.

8.4 Potential revisions to the EPBD

EASAC welcomes the requirement of the 2018 version of the EPBD (EU 2018a) for Member States to deliver long-term building renovation strategies as part of their integrated national energy and climate plans (EC 2019b, 2019c). However, several elements of this version of the EPBD have been found confusing or lacking by key stakeholders and, at the time of writing this report, further revisions of the EPBD are being considered by the European Commission. Attention is therefore drawn below to several elements of the EPBD that could be usefully revised and updated.

8.4.1 Targets (and eventually limits) for GHG emissions

The EPBD focuses on reducing the energy that is used to operate a building and the GHG emissions that this energy produces. However, it fails to adequately address the key issue of the embodied energy and corresponding embodied GHG emissions that are caused by the processes and the manufacture of the materials, components and systems with which a building is initially constructed and subsequently renovated (Szalay 2007).

To deliver carbon neutrality by 2050, embodied energy and embodied GHG emissions should be more strongly regulated for new buildings and for renovations. For example, Member States should set limits for embodied GHG emissions per square metre of floor area for new buildings and be required to address them in their long-term building renovation strategies. For renovations, they should set limits for GHG emissions that are low enough to ensure that the cumulative GHG emissions (reduced building operation emissions plus embodied emissions added during renovations) after the first 10 years of a renovation will not exceed the cumulative GHG emissions from building operation that would have occurred without the renovation. In addition, data on the embodied emissions from the initial building construction and subsequent renovations should be documented in EPCs (see section 8.4.4).

The EPBD should therefore be revised to require Member States to set national targets and eventually limits per square metre of floor area for both operating and embodied GHG emissions in new buildings and renovations.

8.4.2 Nearly zero-energy building definitions

The EPBD defines a 'nearly zero-energy building' (NZEB) as a building that has a very high energy performance, as determined in accordance with EPBD Annex I, and states that the nearly zero amount of primary energy required should be covered to a very significant extent by energy from renewable sources, including those produced on site or nearby. This definition and its required calculation scheme are complemented by Commission guidelines (EC 2012) and recommendations (EC 2016b), which are illustrated in Figure 12.

The definition of NZEB in the EPBD was helpful when it was first introduced because it focused attention on the need to improve the energy efficiency of buildings that were consuming large amounts of fossil-based energy. However, it is becoming increasingly outdated as EU energy supplies are decarbonised. The definition and EPBD requirements of NZEB have been discussed by the Concerted Action on the EPBD (CA-EPBD 2016), where

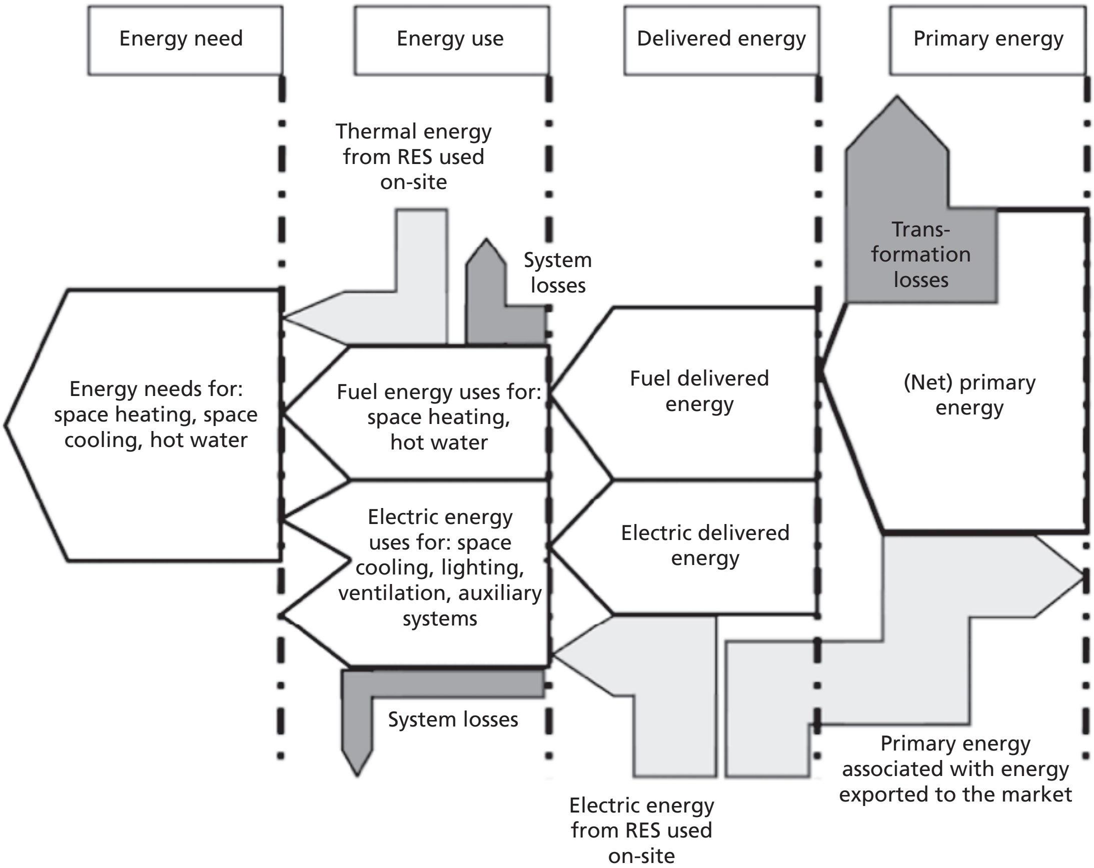


Figure 12 EPBD calculation scheme from EC (2012).

it was concluded that different Member States have adopted different approaches for the renewable energy requirements.

The complexities of using the EU definition of NZEB have also been reviewed by The Federation of European Heating, Ventilation and Air Conditioning Associations, which has highlighted the importance of identifying the relevant system boundaries, as illustrated in Figure 13 (REHVA 2013).

Although it is clearly not the intention of the EPBD, with the current definition of NZEB, a building can be deemed to deliver NZEB performance if it consumes any amount of energy provided that an equal amount of renewable energy (or more) is produced on site and exported to the grid during the same year. In extremis, the current (outdated) NZEB performance requirements of the EPBD could be met by building a large solar photovoltaic generator in the garden, so 'renovating' an existing building without making any changes to the building itself. Such a 'renovation' may have the advantage that the building would be able to export excess solar electricity for use by other buildings and electricity users in the summer (known as the 'positive energy building' concept), but this would not reduce the building's continuing high energy demand for heating in the winter. The current definition of NZEB can therefore weaken the case for investing in renovations of the building envelope and its HVAC systems because it puts them in direct competition with investing in on-site or nearby renewable energy generators, which may be quicker and cheaper to build.

Such potential outcomes are avoided for new buildings in most EU Member States by separate regulations specifying maximum U-values for elements of the building envelope and/or for the whole building or a maximum energy consumption per unit floor area calculated by a standard procedure.

Obligations were put in place through the EPBD 2010 for new NZEB to be delivered in specific market sectors by specified deadlines. However, each EU Member State has its own evolving definition of NZEB (EC 2019e), so there has been a confusing evolution of primary energy requirements for buildings across the EU varying between 0 and 170 kW h/m^2 per year for residential buildings (see Annex 2). The range of definitions has been analysed by several teams over the past few years, and there seems to be broad agreement on the need for the EPBD requirements for NZEB to be revised (BPIE 2015; Erhorn and Erhorn-Kluttig 2015; ZEBRA2020 2020).

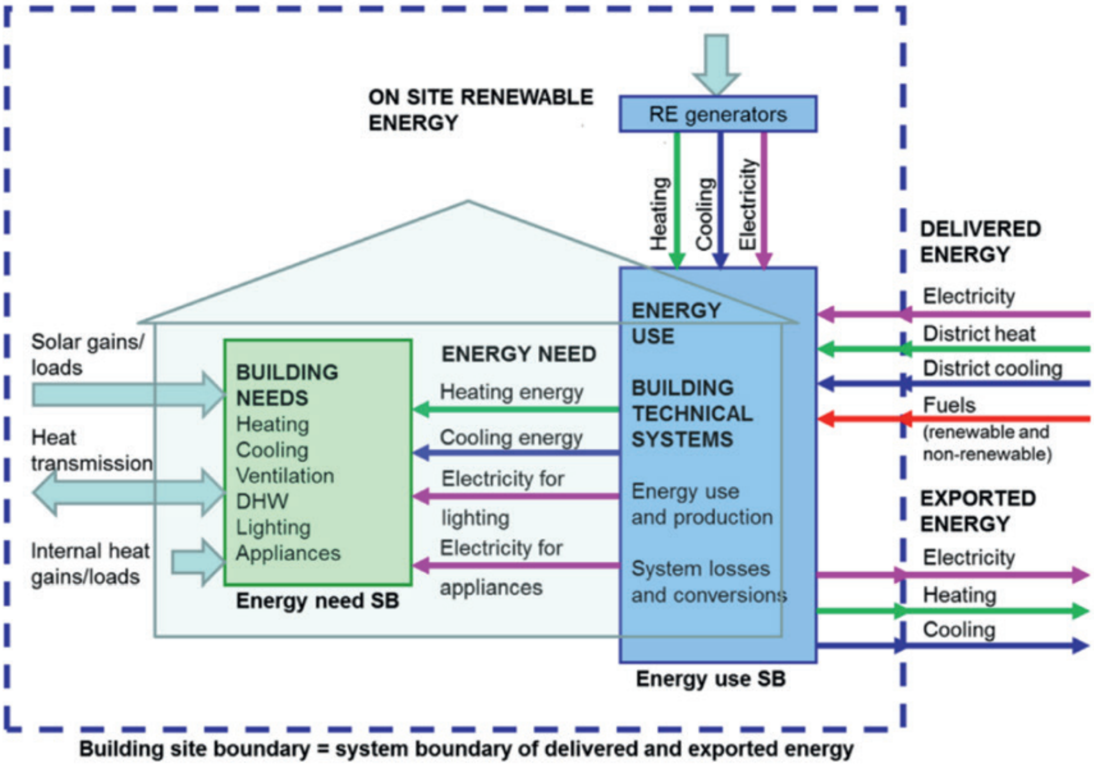


Figure 13 System boundaries (SB) for NZEB (adapted from REHVA 2013).

The definition of NZEB, given in the EPBD, is also used in the proposed Taxonomy criteria (EU 2020c), which refer directly to the EPBD and are intended for use by future investors. Any revision to the EPBD should therefore be reflected also in the final Taxonomy criteria.

The EPBD should therefore be revised to adopt an updated approach to the definition of nearly zero-energy/emission buildings. A more relevant approach for the future would be to shift the focus from energy to GHG emissions. This could be done, for example, by redefining NZEB as a nearly zero emission building, which includes the GHG emissions from the use of fossil-based energy for day-to-day building operation and embodied GHG emissions from the materials, components and processes used for its construction and renovation. The positive energy contribution of a building, which generates and exports electricity (and/or heat) to the integrated EU energy system, could then be counted separately, with targets (eventually obligations) put in place to promote it.

8.4.3 Use of primary energy for minimum building energy performance requirements

The EPBD requires each Member State to calculate cost-optimal levels of minimum energy performance requirements for buildings in their territories, using a comparative methodology framework that is specified in general terms in Annex 1 to the directive. This methodology uses primary energy factors (PEFs), together with agreed national methods to calculate the primary energy consumption of the building. The EPBD then requires that this be used for reporting on the energy performance of buildings and for specifying national cost-optimal minimum energy performance requirements for buildings.

PEFs describe the efficiency of converting energy from primary sources (e.g. coal, oil, gas) to the energy that is finally delivered to end-users, thereby providing potentially useful indications of the GHG emissions that would result from different choices of energy supplies. However, PEFs can be particularly confusing for electricity supplies because their values are affected by the mix of primary energy sources that contributes to the electricity delivered as well as by the efficiency of the grid networks involved; consequently, PEFs are both time and location dependent. The time dependency of PEFs is particularly important, given that major reductions in GHG emissions from EU electricity supplies are planned by 2030 (notably by increasing the contribution from renewable electricity generators), and most new heating systems, which might be selected for installation in buildings on the basis of today's PEFs, will have a longer working life than that.

In addition, the EPBD gives flexibility to Member States to set their own PEF values. This has been widely criticised on the grounds that it is confusing, open to political influence and detrimental to understanding the energy performance of a building (BPIE 2017a;

CA-EPBD 2018[7]). To address this problem, one approach is the development of a new Standard Document EN 17423, 'Reporting of Primary Energy Factors and CO_2 emission coefficients for a correct estimation of the real impact of buildings on energy and climate change'. This document sets out transparency standards that must be adhered to by Member States when calculating their own PEFs and CO_2 emissions potential for different energy carriers (REHVA 2020).

However, as electricity supplies to buildings are decarbonised and the use of fossil fuels in them is phased out, it would make sense to shift the focus of the EPBD away from primary energy calculated using PEFs and onto the final energy that will actually be consumed in buildings and the GHG emissions that this energy will produce in the future. This would allow building designers and those responsible for policing national minimum energy and GHG emission performance requirements to use the values directly. It would also be directly meaningful to those who pay bills for the final energy used in their building.

Most Member States already require the values of annual energy consumed to be included in their EPCs, and some also require it to be broken down into its renewable and non-renewable components. However, the proposed use of Taxonomy criteria for environmentally sustainable investments unfortunately remains based on primary energy consumption because they naturally follow the requirements of the EPBD.

The EPBD should therefore be revised together with the Taxonomy criteria to focus on final energy consumption and GHG emissions instead of primary energy consumption. This will help to ensure potential investors are appropriately guided and informed when they come to estimate the financial returns on environmentally sustainable investments in specific buildings and renovations.

8.4.4 Energy performance certificates

Energy performance certificates (EPCs) are required by the EPBD to be issued when buildings are constructed, sold or rented out in the EU, and can remain valid for up to 10 years. However, unfortunately, they have not been strongly supported or widely accepted across the EU, with only rather small numbers of EPCs being produced in several Member States (BPIE 2020). Consequently, a growing number of organisations, including the European Parliament (EP 2020a) and the Member States Concerted Action on the EPBD (CA-EPBD 2015), have been calling for EPCs to be improved.

As highlighted in section 8.4.3, EPCs are required by the EPBD to be based on primary energy consumption, and have not been standardised across the EU. As a result, each Member State has established its own ways of determining building energy performance, which are based on assessments by accredited experts and computer modelling, or measurements or combinations of these options.

Unfortunately, there can be no single value for the energy performance of a building, for the reasons explained below. So this should be made clearer by updating the EPBD to require the use of ranges of performance in EPCs, together with easily understandable building energy rating schemes.

The annual energy consumption to be used in the EPC of a building can be determined either by measurement or by computer modelling (for specified reference conditions). However, in both cases, the actual energy consumption of the building in any given year will depend on the following:

- how the building is used (for example, changes occur in a residential building when babies are born, elderly relatives join a household or occupants start to work from home);
- internal temperature and ventilation rate settings of the HVAC systems (which typically depend on occupant choices);
- weather conditions (which vary from year to year and are generally becoming warmer because of climate change);
- the building's local surroundings (which may change, for example, as nearby trees grow or are cut down, or neighbouring buildings are changed).

In view of these variations, it is important for regulators to make clear that the energy performance rating (A, B, C, etc.) of a building represents a range of values of annual energy consumption, and to present these ranges on EPCs, as illustrated in Figure 14.

It follows that to compare single calculated 'before and after' values of annual primary energy consumption is not a reliable basis for making investment decisions or for allocating public funding for the renovation of buildings (despite the option included in EPBD Article 10.6c). Instead, investors or public authorities should compare the ranges of building performance that

[7] Concerted Action (CA-EPBD) facilitates regular discussions between responsible experts from EU Member State ministries on the implementation of EPBD. It is an invaluable source of guidance for reviews of the directive.

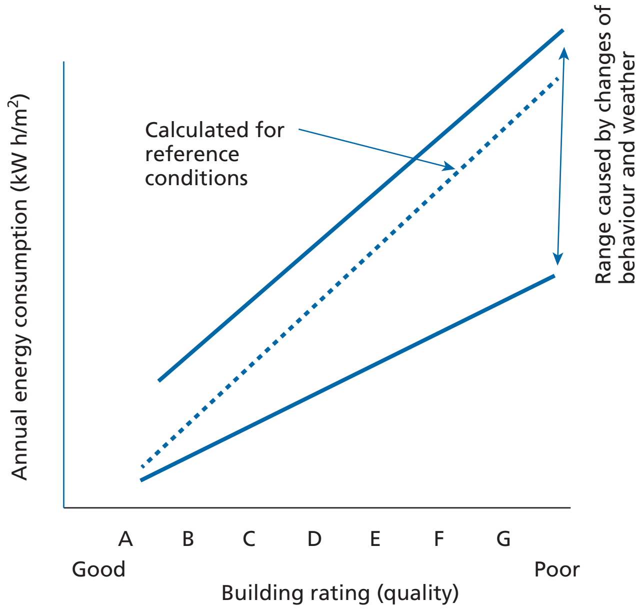


Figure 14 Building energy performance by rating[8].

correspond to the performance ratings 'before' and 'after' a renovation.

The EPBD requires an EPC to be produced by suitably qualified (accredited) experts, which can be costly. The EPBD permits the annual energy performance given in an EPC to be determined by measurements or by calculation using a national calculation methodology, which it requires to be in line with EPBD Annex 1 and the relevant International Standards Organisation (ISO) standard. For this, several Member States currently require specific computer models to be used. Alternatively, the EPBD permits the annual energy performance to be based on that for a similar building that already has an EPC, or calculated using nationally applicable default values for the performance of specific building elements (roof, wall, floor, etc.) based on building codes and regulations applicable at the time of construction.

However, when adopting the approach specified in the EPBD, systematic errors have been found in many national EPC datasets of calculated annual energy performance values because building insulation levels are improved over time. So default U-values are often higher than real U-values, which leads to overestimates of the energy savings that can be achieved by building renovations. For example, Irish EPC data have been shown to overestimate the potential energy savings from renovations by 22% in dwellings built under thermal building regulations, and by 70% in dwellings built before the introduction of thermal building regulations (Ahern and Norton 2019).

As discussed in section 8.4.3, the focus of the EPBD on primary energy consumption is becoming outdated. Annex 1 of the EPBD already requires the final delivered energy (energy used) to be calculated to determine the primary energy consumption, and many Member States already require the energy used to be reported in EPCs. To report expected ranges of final delivered energy in EPCs is more consumer-friendly than to report calculated values of primary energy consumption; it also makes building energy performance more understandable and comparable, because final delivered energy is what the consumer can see on their energy bills.

As explained in section 8.4.1, EPCs should also document the embodied energy in the materials of the building and its construction and renovation processes, and the total GHG emissions from the building, including those from its operation and those embodied in it. These GHG emissions data should be compared in the EPC with the applicable national target for GHG emissions per square metre of floor area.

The EPBD should therefore be revised to require more useful reporting in EPCs of energy consumption and GHG emissions, including the following:

(1) the energy needed by the building;

(2) the energy supplies to the building;

(3) the embodied energy in the materials and components of the building and its construction and renovation processes per square metre of floor area;

(4) the total GHG emissions of the building, including those from its operation and those embodied in it per square metre of floor area (compared with the applicable national target).

8.4.5 Building renovation passport

A building renovation passport is effectively an evolution of the concept of an EPC, but is much more useful for building renovations. It is a document that contains a long-term (up to 15–20 years), step-by-step renovation roadmap for achieving the deep renovation for a specific building. It addresses the context of the building, including the needs of the owner or occupier, and the required renovation works. It is a working document that provides both a roadmap for the future and a record of what has been done in the past. Building

[8] Note: the annual energy consumption rating of a building (in kW h/m^2) under reference conditions is rather like a vehicle's fuel consumption in litres per 100 km under specified driving conditions. Each can vary substantially (higher or lower) depending on how the building or vehicle is used.

renovation passports have been proposed for several years (BPIE 2017b). They have been adopted in various forms in several Member States including Belgium, France, Finland and Germany. Building renovation passports should now become an EU-wide requirement under the EPBD.

The EPBD should therefore be revised to strengthen requirements for the use of building renovation passports.

8.4.6 Digitalisation (BACS) and smart readiness indicators

The EPBD 2018 (Articles 3, 8, 14 and 15) includes several provisions that concern the deployment of building automation and control systems (BACS). A recent industry study has suggested that BACS could save as much as 14% of total primary energy use by 2038, if they are deployed in commercial and residential buildings (Waide 2019). The actual energy savings will depend on the extent to which building operators and users are able to understand and willing to use such BACS, so intuitive design of system controls to avoid their misuse is essential.

The amended EPBD 2018 and its associated delegated act (EU 2020e) also introduced a voluntary scheme for Member States to establish smart readiness indicators for buildings. This was in recognition of the ways in which the controls of HVAC systems are becoming increasingly automated, buildings are being fitted with charging points for electric vehicles, and electricity supplies to buildings are expected to become increasingly subject to time-dependent tariffs and demand response options (BPIE 2019a). It is too early to draw conclusions on the progress of this scheme, but it is expected to help with the development of the emerging aggregator businesses and to become an increasingly important aspect of building operation in the future.

The EPBD may therefore need to be revised in the future to strengthen requirements for digitalisation and the use of smart readiness indicators.

8.5 Policies for decarbonising building energy supplies

As the use of fossil fuels in buildings is phased out, the GHG emissions from buildings that have not yet been renovated will become increasingly dominated by indirect GHG emissions from electricity generation and from district heating and cooling systems, until these too have been fully decarbonised.

It can be anticipated that the majority of energy demands in most buildings will be electrified when they are renovated, so it is clear that the decarbonisation of buildings will rely heavily on the decarbonisation of grid electricity. Decarbonisation of the EU's electricity supplies is a complex task, which lies outside the scope of this EASAC report, but some relevant points can be found in the EASAC report on electricity storage (EASAC 2017). Similarly, the phasing out of natural gas, which is the most widely used fuel in the EU for space heating, is also outside the scope of this report. Valuable information on these issues is provided in the EU strategy for energy sector integration (EC 2020e) and the related EU strategy for offshore energy production (EC 2020f).

8.6 Policies to address health, well-being and comfort in buildings

Good health and well-being are both highlighted among the 17 UN Sustainable Development Goals (UN 2015), and the costs of treating people who develop physical or mental health problems can be very high. It is particularly important to ensure that the development of children is not badly affected by the indoor environment in which they live or spend time at school.

It is therefore good news that the renovation of private and social housing and of tertiary buildings offers great opportunities for making improvements to the indoor conditions in which people have to live and work, and thus to reduce the development of health problems and to improve people's health, well-being and comfort (see chapter 2). However, to ensure that indoor conditions are actually improved, it is very important that renovations are well planned and implemented, particularly in relation to the provision of adequate ventilation, when old buildings are sealed and insulated to reduce the demand for heating and cooling.

In addition to the many health and safety policies and regulations that have already been put in place for the building sector, such as requirements for safety glass in door panels and windows if these could put children at risk, the introduction of new regulations for nearly zero GHG emissions from buildings offers the opportunity to add important health-related requirements for ventilation (air change rates), access to daylight and access to outside space.

If such requirements are adequately promoted at EU, national, city and district levels, then they could not only benefit the occupants of individual buildings but also become important drivers for the renovation of whole streets and neighbourhoods. By improving the character and status of a whole neighbourhood, they would make it more attractive and therefore of higher value to its owners and occupants as well as contributing to the 2050 decarbonisation goal. Cities and other local authorities can help to improve the health and well-being of their inhabitants by adopting in their urban plans the measures discussed in chapter 2, including the provision of green spaces and water to reduce heat island effects, which are likely to increase in the future as a result of climate change.

Avoiding energy poverty is crucial for the health and well-being of building occupants, especially vulnerable occupants, as the costs of heating a poorly designed or poorly maintained domestic dwelling can be more than 10% of the income of low-income families. Energy poverty can occur in private and social housing. For environmental and health reasons, it should therefore be addressed by investments in deep renovation to reduce the energy demand to nearly zero, rather than by subsidising the energy bills of families who are living in poorly performing buildings.

8.7 Refreshing, developing and expanding the EU's building industry

8.7.1 General

Decarbonisation of the EU building sector by 2050 will require increasing the rate of building renovation across the EU by a factor of two to three (see section 7.1). This can only be done by refreshing the EU building industry with a major expansion of the numbers in the workforce, together with adaptations of the technologies, materials, components, systems and processes involved. It will also require a major training and skills (including smart skills) development programme to produce many more accredited experts.

8.7.2 Job creation

The development and manufacture of innovative building components will provide many new opportunities for creating high-quality jobs and new businesses. The European Commission has estimated that 160,000 new jobs will be created from the proposed Renovation Wave by 2030 (EC 2020a), which represents an increase of about 5% in the overall number of 3.4 million persons employed in the construction of buildings in the EU (Eurostat 2016). This estimate of the number new jobs seems to be rather small in view of the planned doubling of the building renovation rate. In contrast, the IEA concludes in its special report on sustainable recovery (IEA 2021) that around 15 jobs will be created by each million dollars spent per year on building efficiency retrofits. This would correspond to more than 3 million jobs (almost doubling the building workforce) if the estimate of €225 billion per year discussed in section 7.1 were to be spent on the Renovation Wave. The validity of these estimates will no doubt become clearer over time as Member States update their long-term building renovation strategies. In the meantime, an important message to the building industry and to skills and training centres is that now is a good time to invest in upskilling and expanding the EU's building workforce.

8.7.3 Prefabricated building components

Prefabricated building components can be manufactured with good quality control in factories, which offer attractive jobs for a skilled workforce. They benefit from economies of scale, can be installed quickly and offer important ways to make deep renovations more attractive to investors, especially those who invest in social and private housing (see chapter 4). The use of prefabricated components typically causes less disruption during the building works and can make renovated buildings more comfortable and more healthy for their occupants (see Box 3).

Prefabricated building components can also be used for new buildings, particularly for clusters or estates of new buildings which allow suppliers and installers to benefit from economies of scale by using mass production lines that bring down costs. Financing schemes that encourage the pioneering of innovative prefabricated building technologies and systems in new buildings may also help to raise investor confidence for their future deployment in deep building renovations.

EU-wide trading of prefabricated building components, together with EU-wide financing, would facilitate larger potential markets and consequently greater potential for economies of scale in the manufacture of building

Box 3 Energiesprong (Energiesprong 2020)

Energiesprong is a multiple-award-winning, integrated package for building renovations, which includes financing. Energiesprong works with independent market development teams, which aim to create mass demand for high-performance retrofits that are cheaper and more desirable than conventional solutions.

The idea of Energiesprong originated in The Netherlands, where it began as a government-funded innovation programme to drive an improved energy-efficient standard in the Dutch market. It involves the local production of prefabricated building components and their deployment as part of an integrated design, installation and financing package. Today in The Netherlands, over 5000 homes have been renovated to desirable, low-energy houses at no extra costs for the residents.

The mission of the Energiesprong Foundation is to scale this approach to more markets, and to create an industry that is able to design, produce and deliver whole house retrofits with excellent energy performance across millions of houses. Currently, Energiesprong teams are active in The Netherlands, France, UK, Germany and northern Italy. In New York state (RetrofitNY) and California, initiatives inspired by Energiesprong are working on a solution for the USA. The approach works particularly well for groups of similar buildings.

components. It could therefore lead to cost reductions in building renovations for those cases where similar designs are acceptable in different countries.

8.7.4 Specialised building renovation services

The building industry will need to adapt to deliver faster and cheaper renovation solutions. For example, specialised companies are already providing and installing thermal insulation solutions. These could be rapidly expanded to deliver economies of scale, and to train and employ more staff, thereby creating valuable new green jobs.

8.7.5 Utilising data for designing site-specific and optimal renovation measures

The design of renovation measures for a specific building requires the collection and use of empirical data on the design and performance of the building and the preferences of its users. This, as discussed in chapter 4, can now be done using low-cost measurement equipment and software. Moreover, after the renovation, the same measurements can be repeated for quality control and calibration.

EU policies for strengthening and developing the building industry should include promoting the wider use of such empirical assessment methodologies and the training of more of the building workforce in their use. This will help renovation designers and the builders themselves to use the available funding to maximise reductions in GHG emissions.

8.7.6 Training of builders and building system technicians

It has long been recognised that it is not sufficient to design buildings with a high energy performance because it is also necessary to build them adequately. This has led to EU-supported public and private initiatives such as Build Up and Build Up Skills (EC 2020b), which disseminate information on a wide range of building energy performance issues including skills and training courses. However, the arrival of new technologies and building systems, and the introduction of robots on building sites to streamline traditional tasks (such as bricklaying), are changing the training needs. Smarter skills are now required.

The introduction of innovative digital energy management systems for the heating and cooling of buildings also requires the training and/or retraining and accreditation of people to design, install, operate and maintain the new systems. This is a continuing process, but will require substantial acceleration to meet the needs of the rapidly growing markets required to deliver carbon neutrality by 2050. Today, there is no real single market for the building sector in the EU, largely because every country has its own traditions, with national, or in some cases local, building designs and products. However, to meet the needs of a two- to threefold increase in the renovation rate, it may become more feasible to introduce greater numbers of standardised products and specialist services, such as installers of insulation. These will be able to offer economies of scale across more EU national borders, especially those of the smaller Member States.

National and international schemes for the accreditation or certification of designers, builders and renovators of buildings to deliver nearly zero GHG emission performance are likely to become increasingly important for promoting and maintaining confidence in the EU Renovation Wave. Similarly, schemes for the accreditation of the buildings themselves should be able to build on the experience that has already been gained with schemes such as BREEAM, HQE, DGNB and LEED (Ecorys 2014).

8.8 Further research

A vast amount of work has been and continues to be funded by the EU with the aim of reducing the energy demands of buildings (Economidou *et al.* 2020). This includes detailed studies of building construction and operation, as well as monitoring the energy performance of clusters of buildings and modelling of building energy performance.

A lot of the research that has been done on energy in buildings has focused on a demand-side perspective; less attention has typically been given to energy supplies for use in buildings, which are equally important for delivering high levels of decarbonisation. Further research on integrated energy supplies to buildings, specifically on the use of renewable electricity and heat storage, is needed. This should address both imported and self-generated renewable energies at the neighbourhood level as well as for individual buildings. It should also explore the potential roles of digitalisation, tariff structures and demand response in facilitating integration and optimisation of energy supplies to the building sector together with supplies to industry and transport in an integrated EU energy system.

Further research on the analysis of building design and performance data is needed to improve the future operation of buildings, the future designs of renovation measures and digitalisation (including BACS), as well as the equipment and software for data collection. Stakeholders should be encouraged to make such data widely available for researchers and interested stakeholders to work on.

Also important, especially following the impacts of the COVID-19 pandemic, will be more studies of the impacts of building design and operation on human health. These studies should include work on how pollutants from outdoor and indoor sources, such as innovative energy-efficient building materials and biological pollutants, may affect human health (Geels *et al.* 2015). In view of the expected future impacts of climate change, more studies of health effects are also needed in low-energy houses that experience overheating and low levels of ventilation.

Integrated approaches to building renovation, such as Energiesprong (see Box 3), offer widespread potential. So further research is justified to better understand their limitations and to study how best to transfer such approaches to different political, social, geographical and legal contexts, as well as to different building structures.

Socio-economic research is important for studying the future expansion of the building industry, which will be needed to deliver the Renovation Wave, including its future impacts on the work force, the future labour market, business models, market prices, financing and training facilities.

Social changes will also impact the future needs of society for buildings, including the ageing of populations, more single-parent families and people living alone. The COVID-19 pandemic has demonstrated the potential for more people to work from home, using the Internet to deliver their work and to interact with colleagues, customers and peers through video-conferencing and webinars. More research is needed to study the long-term impacts of such social changes on the future design requirements of individual buildings and neighbourhoods.

9 Conclusions

The documents, data and analyses that have been reviewed by EASAC during the preparation of this report have highlighted the importance of creating a good indoor environment in new and renovated buildings because of its potential impacts on the health and well-being of building users, and its resulting role in motivating investments in building renovations. They have also shown that, for buildings to make a fair contribution to the Paris Agreement commitments and thereby help to limit the increase in global average temperature to 1.5 or 2 °C above pre-industrial levels, their cumulative GHG emissions must be substantially reduced by 2030, which will be a very big challenge.

Reductions must be made in the energy needs of buildings, so that these can be supplied at affordable costs by energy sources that produce very low GHG emissions, such as renewable energies. Reductions must also be made in the embodied GHG emissions in the materials, components and processes used for the construction of new buildings and the renovation of existing ones. Both types of emission reduction must be accelerated and continue for the long term.

The proposed EU Renovation Wave will have a key role to play in delivering these GHG emission reductions, but will require the building industry to make changes to its ways of working. The energy supply industries will have to replace their existing fuel supply chains with decarbonised alternatives, and the financial institutions will need to offer targeted long-term products with low interest rates for building renovations. In addition, national, regional and local authorities must take more active roles in triggering deep building renovations, working with the energy industries to phase out the use of fossil fuels and accelerate the introduction of new decarbonised energy supplies, informing the many different stakeholders, and supporting the delivery of sustainable decarbonised solutions.

At Member State level, there is a need for more ambitious long-term national building renovation strategies because building codes and regulations remain in the hands of Member States, and they must address the changing climates and traditions of the construction sectors in their countries. These strategies should include making improvements to the spatial efficiency with which buildings are used (for example through multifunctionality), and reducing the numbers of buildings that remain vacant for very long periods.

At EU level, substantial revisions to the current EU legislative and policy framework are needed to strengthen obligations and facilitate the required reductions in GHG emissions. These revisions should be made in cooperation with the key stakeholders, including the building and energy industries, financial institutions, national, regional and local authorities, and civil society, to build confidence and trust among investors and decision-makers at EU, national and local levels.

Policy-makers and decision-makers at all levels who are responsible for or involved in decarbonising the building sector should reinforce policies that recognise building renovations and decarbonised energy supplies are complementary. Both are urgently needed to deliver the EU's 2050 carbon neutrality target, and the building sector must operate with the transport and industry sectors in an integrated energy system. There is no unique optimal 'silver bullet' solution for prioritising between investments in building renovations and in the provision of decarbonised energy supplies. So policy and investment decisions aiming to decarbonise buildings must be taken on a case-by-case basis for the foreseeable future.

10 Messages for policy-makers

Future priorities for policies, legislation and investments aiming to decarbonise new and existing buildings in the EU are summarised below.

1. **Phase out fossil fuels by 2030, increase integrated supplies of decarbonised electricity and heat to buildings, industry and transport, and accelerate the deployment of carbon capture and storage.**
   (a) Establish a single regulatory framework for managing the transition to an integrated and sustainable long-term EU energy system, with cost-optimised coupling of investments in (i) energy efficiency measures to reduce energy demands in the buildings, industry and transport sectors and (ii) low carbon electricity and heat supplies to replace fossil fuels.
   (b) Phase out the use of coal, oil and gas for electricity generation and heat production by 2030. Use the EU Emissions Trading System (ETS), the Effort Sharing Regulation and the proposed new Carbon Border Adjustment Mechanism to create a level playing field during the transition phase and to accelerate the phasing out of all fossil fuels.
   (c) Create investment opportunities (e.g. auction schemes) to accelerate the decarbonisation of electricity supplies so that investors can confidently electrify buildings when renovating them. Focus on the deployment of renewable energy generation, transmission, distribution and storage, carbon capture and storage (CCS) for use with fossil-fuelled electricity generators, low greenhouse gas (GHG) emission district heating and cooling systems, and possibly nuclear generation in countries where it is politically accepted and waste disposal issues have been resolved.
   (d) Implement time-varying tariffs that encourage consumers (and prosumers) to store low-priced electricity during periods of excess renewable generation as heat or in batteries (in their electric vehicles or buildings). Use time-varying tariffs to reduce peak demands and the related needs for additional generating capacity and grid reinforcements.
   (e) Decarbonise district heating and cooling systems by replacing fossil fuels with renewables and waste heat from industry and other sources. Install heat storage to improve flexibility.
   (f) Minimise the embodied GHG emissions created by the construction and reinforcement of electricity and heat supply infrastructures.
   (g) Supply sustainable biogas and biofuels for heating only where there are no economically competitive alternatives, because these are scarce resources that can be better used for back-up power generation and for heavy-duty road and maritime transport.
   (h) Supply green hydrogen only to applications for which there are no economically competitive alternatives. This implies that green hydrogen produced in the EU should be supplied for applications, such as industrial processes or heavy-duty long-haul transport, but not for heating buildings because green hydrogen production is an inefficient use of renewable or low carbon electricity generated in the EU.

2. **Use grants and incentives to trigger, leverage and de-risk private financing for deep energy-related building renovations.**
   (a) Implement well-managed schemes that incentivise deep renovations by providing readily accessible grants and affordable loans, which are subject to energy and cumulative GHG emission guarantees, on the basis of monitored performance. Guarantees should be for ranges of energy consumption and GHG emissions that correspond to typical local variations in weather conditions and user behaviour.
   (b) Promote the use of energy and GHG emission performance guarantees and assurance to mitigate risks and support first movers who are willing to bring innovative building technologies and solutions to the market as well as those who are willing to deploy them.
   (c) Incentivise financing institutions to offer long-term affordable loans with very low interest rates to finance renovations with guaranteed energy consumption and cumulative GHG emissions, on the basis of monitored performance.
   (d) Incentivise economies of scale by giving higher levels of support to schemes that deliver large numbers of deep renovations at competitive costs with low levels of disruption to building occupants, and short renovation times.

3. **Regulate levels of embodied GHG emissions in building materials and components, and promote recycled materials, re-used building components and renovation instead of demolition.**
   (a) Regulate and limit the cumulative GHG emissions from each new and renovated building per square metre of floor area, and monitor them for at least 10 years after construction and renovation. Limits should

include annual emissions from building operation plus embodied emissions from materials, components and processes used for construction or renovation.

(b) Prohibit the demolition of existing buildings unless they are in such bad condition that they cannot be renovated. Require as many as possible of the materials and components from demolished buildings to be recycled or re-used.

(c) Require the embodied GHG emissions of all new and renovated buildings to be independently assessed and reported on energy performance certificates after specified time intervals, or when tenants change, or when they are sold.

4. **Refocus building regulations, certification schemes and incentives to deliver new and renovated buildings that operate with nearly zero GHG emissions.**
   (a) Require all new and renovated buildings to have the following.
      (i) An optimised building envelope with minimised peak energy demands throughout the year (well insulated roof, walls and floors, high-performance windows and doors, controlled ventilation, shading to prevent overheating, etc.).
      (ii) Optimised prosumer use of on-site-generated and imported renewable electricity and heat.
      (iii) High-efficiency HVAC systems of the right size for their (renovated) building envelope, which use sustainable (not fossil) fuels combined with passive measures for heating, cooling, and ventilation.
      (iv) Efficient lighting combined with optimised daylighting measures.
      (v) Advanced/intelligent digital system controls (BACS) with intuitive interfaces that are unlikely to be misused, and will therefore help to deliver low energy consumption.
   (b) Create triggers to make deep renovations happen (e.g. legislate to stop landlords from letting buildings with poor energy performance).
   (c) Incentivise the measurement of building data over limited periods on site, to identify the best renovation options and user preferences for building operation, as well as to calibrate building models for predicting the future performance of building renovation options.
   (d) Incentivise the digitalised use of electricity storage and heat storage in buildings to help the management of flexibility on electricity grids with high levels of wind and solar generation.
   (e) Incentivise the use of district heating and cooling with sustainable fuels and waste heat and cooling, where possible, in densely populated urban areas.
   (f) Incentivise the use of individual heat pumps powered by very low carbon electricity or sustainable biogas or sustainable biofuels for heating in low heat-density areas (outside towns and city centres).

5. **Promote health and well-being to double or triple renovation rates that improve air quality, increase access to daylight, and avoid draughts and overheating, as well as reducing GHG emissions.**
   (a) Engage with architects and building developers, for example through the proposed European Bauhaus initiative, and encourage them to place occupants at the heart of the design process so that building occupants can enjoy a sustainable, comfortable and healthy indoor environment.
   (b) Require all new and renovated buildings to have adequate ventilation to ensure good air quality and comfort (avoid overheating). All new and renovated ventilation systems (natural and mechanical) should be checked, approved and monitored by regular inspections. All occupied buildings should have windows that can be opened if ventilation systems fail.
   (c) Require all new and renovated residential buildings to provide occupants with adequate access to daylight (with shading to avoid overheating), and to provide each household unit (e.g. apartment) with adequate access to outside space (e.g. balcony or garden).
   (d) Require all new and renovated buildings to be resilient to climate change. For example, they should be fitted with passive measures or active cooling systems to prevent overheating, and designed to withstand extreme weather, storms and flooding.
   (e) Reduce energy poverty by obliging landlords of rented residential properties, including private and social housing, to renovate their buildings to low GHG emission performance levels.

6. **Champion public authorities and cities, and facilitate and support their commitments to decarbonise buildings and reduce energy poverty.**
   (a) Lead by example, renovate public buildings as demonstrations of good practice, and produce public procurement specifications containing quality standards and requirements, which can also be used by private sector investors.

(b) Renovate social housing and subsidise the deep renovation of private housing where necessary to reduce energy poverty.
(c) Work with the Climate Pact, Covenant of Mayors and local regulations to stimulate the renovation and construction of nearly zero GHG emission neighbourhoods with integrated energy and transport systems and adequate green space to limit urban heat island effects and facilitate good health and well-being.
(d) Promote and subsidise nearly zero GHG emission neighbourhood renovation schemes, which not only increase local property values and the local quality of life, but also maximise the potential for private investors to benefit from economies of scale and use mass-produced (prefabricated where feasible) components with low embodied GHG emissions.
(e) Upgrade existing district heating and cooling systems or build new ones with nearly zero GHG emissions and optimised use of renewable energy, including renewable electricity, heat pumps, solar and geothermal heating, waste heat and natural cooling.
(f) Establish and fund real and virtual one-stop shops at national, regional and local levels in collaboration with universities, energy service companies, utilities, building industries and financiers to disseminate convincing narratives and inform building professionals, owners and potential investors about the options available for financing and implementing deep renovations to achieve cumulative GHG emissions and energy performance targets.

7. Expand and modernise the building industry to operate using circular business models with 3 million more jobs (including high-quality jobs) to deliver new and renovated buildings with nearly zero GHG emissions.

(a) Expand the number of jobs by more than 3 million and modernise construction methods to deliver two to three times the current renovation activity levels.
(b) Further develop prefabrication options to improve the quality of construction and increase job opportunities for a more highly (smart) skilled and gender-balanced building sector workforce.
(c) Expand, retrain and re-skill the building sector workforce to quickly deliver sustainable deep renovations which, as far as possible, deliver nearly zero GHG emission performance within cumulative GHG emission limits, and with a high-quality indoor environment that meets the health and well-being needs of occupants on a competitive basis.
(d) Move to a circular economy model in which used materials, components and systems are given a second life, and manufacturing, recycling processes and supply chains have much lower embodied GHG emissions. Increase the volumes of materials, components and systems with very low embodied GHG emissions to meet the needs of the Renovation Wave, and ensure that they continue to meet high-quality standards for durability and other properties.
(e) Improve the speed of construction and quality of new buildings and renovations using low GHG emission (including prefabricated) building components and industrialised building practices, which are guaranteed to deliver performance within GHG emission limits.
(f) Promote guaranteed design–build–finance packages that are systemised for clusters of new buildings and for deep renovations of clusters of existing buildings, improve internal comfort and produce an architecturally pleasing appearance at competitive costs.

8. Improve access for building owners and professionals to certified data on the embodied GHG emissions of building materials and components, and on the energy and GHG emission performance of new and renovated buildings.

(a) Strengthen obligations on Member States to gather data on the performance of their building stocks. Improve the quality of data recorded in energy performance certificates (EPCs) and building passports, and require data on final energy and cumulative GHG emissions performance of buildings to be included in the database of the European Building Stock Observatory. Make these data freely available for researchers and interested stakeholders to work on.
(b) Promote energy and cumulative GHG emission labelling of buildings, using measured data and calculated ranges for typical variations in weather conditions and occupant behaviour. Include information related to internal comfort and health on the labels.
(c) Establish Web portals for use by building professionals with independently certified information on the embodied GHG emissions (e.g. Environmental Product Declarations and Product Environmental Footprints) of building materials and components.
(d) Help small and medium-sized enterprises to obtain certification for their innovative low carbon building products and components by supporting and funding the processing

of Environmental Product Declarations and Product Environmental Footprints.

(e) To promote the Renovation Wave and to build investor confidence, publish independently monitored energy and cumulative GHG emission performance results (before and after) and costs for building renovations that have received public funding.

9. Update EU legislation (Energy Performance of Buildings Directive (EPBD), Energy Efficiency Directive (EED), Renewable Energy Directive (RED), Emissions Trading System (ETS), Construction Products Directive (CPD), Taxonomy) using an integrated approach to phase out fossil fuels, increase renewable energy supplies and reduce cumulative GHG emissions from buildings.

(a) Strengthen the links between the Energy Performance of Buildings Directive (EPBD), the Construction Products Directive (CPD), CE marking of new and re-used building components, Environmental Product Declarations and Product Environmental Footprints to reduce embodied GHG emissions in building materials, components and systems.

(b) Require Member States to set targets (eventually limits) for the cumulative GHG emissions (operating and embodied emissions) per square metre of floor area over at least the first 10 years of life of a new building and the first 10 years after a renovation.

(c) Require Member States to set national targets for cumulative GHG emissions (reduced operating emissions plus added embodied emissions), and to submit reports showing that actual emissions do not exceed those that would have occurred without renovations. Member States could begin by including target trajectories in their long-term renovation strategies.

(d) Require Member States to replace their cost-optimal energy performance requirements, on the basis of primary energy consumption (calculated using primary energy factors), with new requirements based on final energy consumption. Primary energy factors will become increasingly irrelevant as energy supplies are decarbonised.

(e) Require Member States, in their long-term renovation strategy, to analyse and explore the potential for using the space in their existing buildings more efficiently, and to reduce the demand for new buildings by developing policies for restricting the demolition of existing buildings, and for utilising existing buildings that remain vacant for very long periods.

(f) Define low GHG emission buildings, for example by redefining NZEB as nearly zero GHG emissions building (including GHG emissions from building operation and embodied GHG emissions). To avoid confusion, the definition should not permit GHG emissions from heating energy that is imported in winter to be offset against renewable energy that is exported in summer.

(g) Promote the role of positive energy buildings (new and renovated) that contribute to the EU energy system through exports of on-site electricity and/or heat generation. Also promote the storage of excess renewable electricity in batteries (in buildings or associated electric vehicles) and as heat to help with managing flexibility on the electricity grid.

(h) Make energy performance certificates, building passports and labels more understandable and comparable for building owners, users and potential investors. Replace primary energy consumption data with annual final energy consumption ranges that correspond to typical variations in weather conditions and user behaviour. Also show how much energy is supplied by electricity, district heating/cooling and other fuels (on the basis of utility bills or measurements).

(i) Require all mechanical ventilation systems to be maintained (e.g. replacement of filters) and inspected to ensure that they deliver safe air quality and adequate ventilation.

(j) Make the Taxonomy criteria consistent with the above revisions to the Directives, notably replacing primary energy consumption requirements with cumulative (operating plus embodied) GHG emission requirements together with final energy consumption requirements for new buildings and building renovations.

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Abbreviations

BACS	Building automation and control systems
BAU	Business as usual
CCS	Carbon capture and storage
CHP	Combined heat and power (cogeneration)
CO_2	Carbon dioxide
CPD	Construction products directive
EASAC	European Academies' Science Advisory Council
EC	European Commission
EEA	European Environment Agency
EED	Energy efficiency directive
EPBD	Energy Performance of Buildings Directive
EPC	Energy performance certificate
ETS	Emissions trading system
EU	European Union
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
JRC	Joint Research Centre of the European Commission
LCA	Life cycle assessment
NZEB	Nearly zero-energy building (or nearly zero GHG emissions building)
PACE	Property Assessed Clean Energy
PEB	Positive energy building
PEN	Positive energy neighbourhood
PEF	Primary energy factor
PVT	Photovoltaic and thermal (solar collector panels)
RED	Renewable energy directive
SDG	Sustainable Development Goal (United Nations)
UN	United Nations

Working Group composition and timetable

The project was approved by EASAC's council in November 2019, and EASAC's member academies nominated experts to form a Working Group in the first quarter of 2020. The work was done from Spring 2020 to Winter 2021, and the report was finalised in Spring 2021.

Co-chairs

Brian Norton, Royal Irish Academy, Ireland
Wim van Saarloos, The Royal Netherlands Academy of Arts and Sciences, The Netherlands

Working Group members

Name	Organisation	Nominated by	Country
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William Gillett	EASAC Energy Programme Director	EASAC secretariat	United Kingdom

All Working Group meetings were held by Zoom because of the COVID-19 pandemic.

A draft working document was produced using e-mail inputs in Spring 2020, and the first Working Group meeting was held as a kick-off workshop in five sessions on the 4, 8 and 9 June 2020, with invited speakers from the European Commission and other leading stakeholders. Most of the work was done by e-mail, with Working Group meetings on 20 July, 3 September, 10/11 November, 7 December 2020 and 8 February 2021.

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Peer reviewers

EASAC thanks the following academy-nominated experts for their peer reviews (in March 2021):

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Annex 1 Construction material pyramid

The figure below is the Danish construction material pyramid (Cinark 2020) which is available online as an interactive tool but is set here as a static image. It shows embodied carbon emissions in units of kilograms of carbon dioxide equivalent per cubic metre (kg CO_2eq./m^3). The values of embodied emissions shown are currently typical for materials in the EU, but may be different in some regions and are expected to evolve over time. Many other performance requirements must also be considered when choosing building materials, including strength, stiffness, moisture tolerance, overall durability, fire safety and visual appearance.

Annex 2 Primary energy requirements for new buildings in the EU (EC 2019e)

Member states	NZEB definition status*	Primary energy requirements (new buildings) (kWh/m^2 per year)
Austria		160–170
Belgium (Brussels)		45–85
Belgium (Flanders)		32–45
Belgium (Wallonia)		95
Bulgaria		30–50
Croatia		30–80
Cyprus		100
Czech Republic		43–51
Denmark		20
Estonia		50–100
Finland		78–150
France		40–105
Germany		36–45.75
Greece		Class A (new), B+ (existing)**
Hungary		65–100**
Ireland		45
Italy		15–20 & Class A1
Latvia		95
Lithuania		A++
Luxembourg		45 & Class A/Class AAA
Malta		55–115
Netherlands		0–25
Poland		65–75
Portugal		33
Romania		93–117
Slovakia		32–54
Slovenia		50–80
Spain		40–70 & Class A
Sweden		30–75
United Kingdom		39–46

	Yes
	Under development

*Status April 2018.
**Updated information for Greece (Bololia and Androutsopoulos 2020), and for Hungary (7/2006 (V. 24.) TNM decree on the determination of the energy performance of buildings).

The primary energy requirements contain indicative information about their ranges for new buildings on the basis of a literature review. However, it should be noted that different calculation approaches might exist at national level; therefore values cannot easily be compared with each other.

EASAC, the European Academies' Science Advisory Council, consists of representatives of the following European national academies and academic bodies who have issued this report:

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