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Perspectives on decarbonisation of existing buildings in Europe

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ABSTRACT

Decarbonisation of existing buildings is necessary to meet European Union commitments to achieve net zero GHG emissions by 2050. There is no single decarbonisation solution because European buildings are diverse, have different uses and are in different climatic regions. This paper discusses choosing the depth of building renovation, selecting sustainable technologies to cost-effectively decarbonise buildings, and the potential benefits for occupants' health and comfort, energy security and increased building value. The potential for re-using and recycling building materials and components is highlighted, together with the need to reduce embodied as well as operating emissions when renovating buildings. Key actors needed to decarbonise Europe's existing buildings include policy makers, investors, banks, financing institutions, the construction industry and the research community. In 2021, the European Academies' Science Advisory Council (EASAC) published a report on decarbonising buildings and this paper aims to bring the findings to the scientific community. Since the EASAC report was published, more research has been published on decarbonising buildings through renovation, and a revised Energy Performance of Buildings Directive has been adopted (in 2024). This paper recognises these recent developments and offers a broad science-based perspective on the potential benefits and challenges of decarbonising existing buildings in Europe.

1. Introduction

Energy policies generally seek to reconcile three inter-related and sometimes conflicting imperatives, namely reducing energy-related greenhouse gas (GHG) emissions, ensuring security of energy supplies, and making energy affordable to consumers (see Fig. 1).

In 2021, an extensive report containing advice for policy makers on how to reduce GHG emissions from buildings was published by the European Academies' Science Advisory Council (EASAC)[1] [1]. Whilst recent crises have caused Europeans and their policy makers to focus on immediate solutions to very urgent affordability and supply security problems, reducing a large proportion of GHG emissions from buildings must still be tackled as soon as possible to limit global warming and the increased frequency of extreme weather events.

This paper uses the observations and advice published by EASAC in 2021, together with more recent publications by researchers independent of EASAC, to provide broad science-based perspectives on the potential benefits and challenges of decarbonising the existing building stock in Europe.

2. The importance of reducing both operating and embodied GHG emissions

In 2021, GHG emissions from the operation of residential and commercial (non-residential) buildings in the EU accounted for approximately 36 % of energy related GHG emissions or about 25 % of the total GHG emissions from the EU [7]. Of the 36 %, approximately 12 % are produced directly by burning fossil fuels for heating and the rest are

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[1] The European Academies Science Advisory Council brings together experts nominated by the national science academies of Europe to produce reports based on scientific evidence for policy makers https://easac.eu/about-easac/how-we-work.

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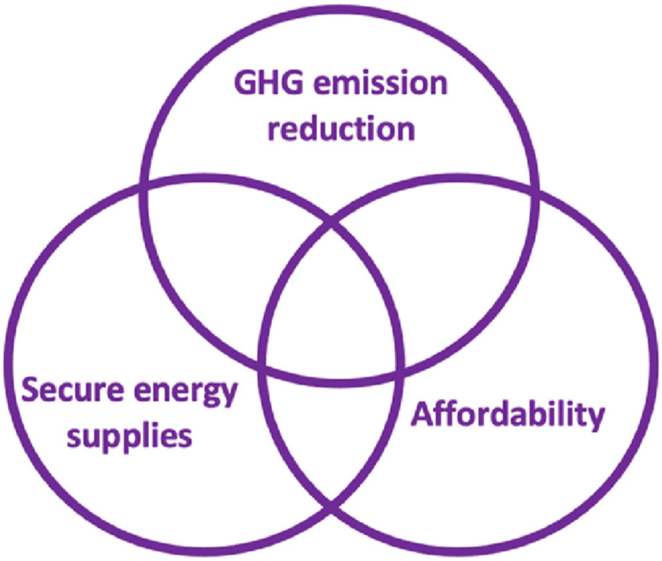


Fig. 1. Energy policy priorities.

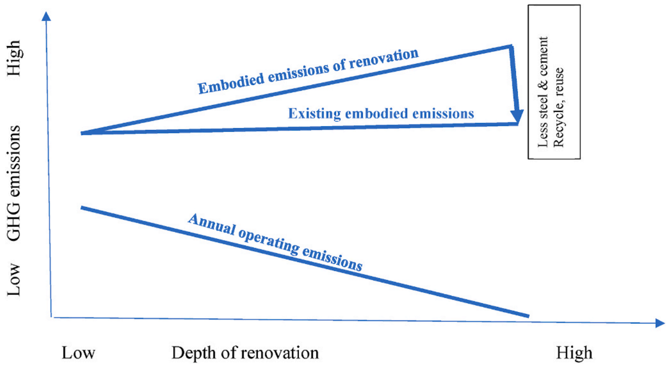


Fig. 2. Variations in operating and embodied emissions with renovation depth.

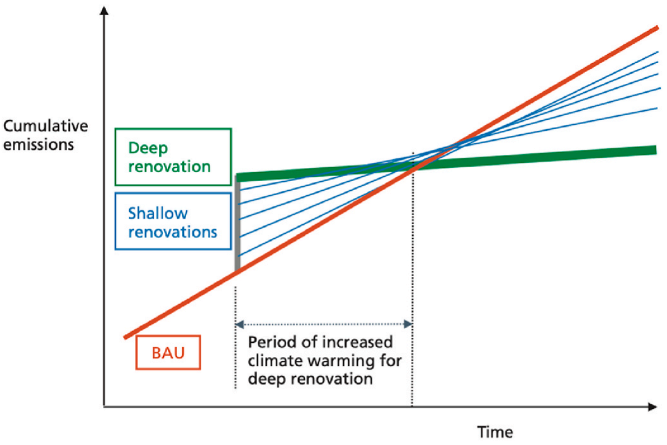


Fig. 3. Renovation reduces operational emissions but adds embodied emissions (BAU = business as usual) (Source: EASAC 2021 [1]).

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 [8]. The contributions of these direct and indirect GHG emissions vary between EU Member States, depending mainly on local climatic conditions and on the mix of 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.

In addition to GHG emissions caused by the operation of buildings, embodied GHG emissions are produced when building materials and components are made and transported to site, and from the use of machinery when buildings are constructed and/or renovated. These embodied GHG emissions must be considered together with operational emissions when investing in renovations to decarbonise existing buildings.

Depending on the depth of renovation, the embodied GHG emissions from renovating today's typical buildings corresponds to about 2–5 years of operational energy emissions (Mohammadpourkarbasi et al. [9]), though this depends also on the status of the unrenovated building and in particular on the heating systems being used before (and after) renovation.

Renewable energy is being more widely used to meet the falling operational energy needs of an increasingly refurbished building stock, and this decarbonises the operation of buildings without deep renovations of the building fabric. Nevertheless, the materials used in renovations must be selected to minimise embodied emissions, for example wood, repurposed building components, and recycled materials can be used to replace new steel, concrete and bricks (see Fig. 2).

Hence, if the shift to materials with low levels of embodied carbon emissions lags behind the introduction of renewable energies, then the equivalent number of years of operational GHG emissions represented by embodied emissions will increase accordingly, and the potential benefits of renovations in terms of reduced impacts on global warming will be delayed, thereby increasing the challenge of limiting global temperature rises to less than 1.5 °C. (see Fig. 3).

It is therefore recommended that strong policies and regulations be implemented to regulate the levels of embodied GHG emissions in building materials and components. These would also encourage the use of recycled materials, re-used building components, and renovation instead of demolition. To assist with this, the EU's long-standing goal of delivering nearly zero energy buildings should be replaced with a goal of delivering zero-GHG emissions buildings.

The updating of EU building performance goals has been discussed recently by Tirelli and Besana [10], who broadly agreed with the conclusions of the EASAC report [1] that:

1. A stronger focus on zero GHG emission buildings must be introduced into building regulations, certification schemes and incentives to deliver new and renovated buildings (see also, D'Agostino et al. [11]).
2. Suppliers must be obliged to openly publish certified data on the embodied GHG emissions of building materials and components. Such data would reflect that the embodied carbon content of building materials and components varies with locations, sources, production process and their energy use (see Alaux et al. [12]). This would make these data more readily available to building owners and professionals, along with better data on the energy and GHG emission performance of new and renovated buildings.

Cost-effective decarbonisation of existing buildings would be more readily achieved in a circular economy (Charef [13]) designed to reduce resource consumption and thereby lessen carbon footprints [10] because many building materials can be recovered, reused, and recycled.

Whilst it is easier to design new buildings and their components so that they can be disassembled at the end of the first phase of their working lives, building renovations should also be implemented in ways that will make it easier to reuse and recycle the materials involved in the future [14]. Renovations should therefore be made using secure, but easily demountable fixtures, and standardised components as far as possible. Storage and logistics facilities should also be more widely established to facilitate the salvage, re-use and recycling of building components.

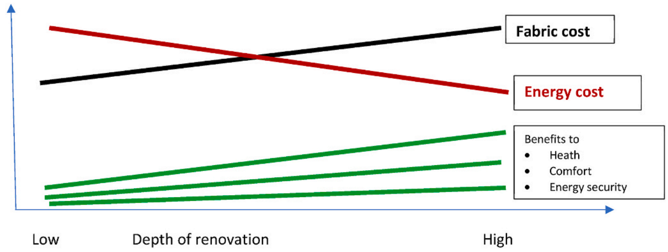


Fig. 4. Variations in costs and benefits with depth of renovation.

3. Consequences of renovation depth

3.1. Relationship between renovation depth and GHG emission reduction

Building renovations are needed to deliver GHG emission reductions in the short term because this will reduce the rate of global warming and help to achieve the 1.5 °C limit set in the Paris agreement. However, this does not answer the question of how deep renovations should be.

The costs of renovations typically increase with renovation depth, whilst the GHG emissions and the annual costs of energy for building operation decrease with renovation depth, so investors must select a depth of renovation on a case-by-case basis.

Whilst it is interesting to compare the costs of renovation with the energy cost savings that a given depth of renovation delivers, it is also important from an investor's perspective to consider the other benefits that different depths of renovation offer, including increases in the value of the building, improved comfort and health of the occupants, and improvements in energy security (see Fig. 4).

3.2. Depth of renovation affects energy consumption

Regarding energy savings from renovations in Europe, Hummel et al. [15] calculated that renovation activities with few technical restrictions and low capital recovery (i.e., long payback periods), together with short refurbishment cycles would lead to cost-efficient savings of up to 47 % of final EU building energy demand between 2019 and 2050. With less favourable conditions for thermal renovation, they calculated that the cost-optimal level of heat savings in buildings for the EU-27 could be expected to be about 30 % of final energy demand. Even with combined simultaneous unfavourable conditions, cost-optimal saving levels could still be expected at around 25 % of current final energy demand. Importantly, these calculations assumed that fossil energy carriers would be either banned or associated with high carbon prices to dis-incentivise their use. Thus, policies for phasing-out and discouraging the use of fossil fuels are key. In addition, long term financing schemes and subsidies for investments in thermal renovation can help to tackle the high upfront investment costs of building renovations.

Building renovations typically contribute to several sustainable development goals. They contribute to environmental goals by reducing GHG emissions, but they also address (i) affordability by reducing building running costs, (ii) health and quality of life by improving thermal comfort, reducing damp risk, overheating risk, and draughts, (iii) heating system performance by reducing peak demands for heating and cooling, and (iv) security of energy supply by reducing the overall demand for energy supplies.

For individual renovation projects, robust analyses for optimising the return on investments are complex, so practical tools, such as those developed in research, e.g. Niemela et al. [16], should be made more widely available for informing decisions on specific renovation measures.

Rosenow and Hamels [17] suggest that the use of simple and pragmatic heuristic rules-of-thumb for decision making may assist policy-makers to develop effective regulatory and market intervention policies for the decarbonisation of building stocks. For existing buildings with very poor energy performance, full heat decarbonisation at a reasonable cost cannot be achieved solely by either energy demand reduction or replacing fossil fuel supplies with renewables. In most contexts, a combination of energy demand reduction and switching to decarbonised energy supplies will be required.

For example, Galvin [18] examined energy-inefficient German apartment buildings, from the 1950s–1970s era, using fine-grained data on national electricity generation and household energy consumption. To renovate an apartment to net-zero-energy levels required the building envelope to be retrofitted with thermal insulation, draughtproofing, double-glazing and an air-source heat pump. In the case that was examined, it was found to be more economically viable to invest in remote wind power than in local photovoltaic power generation, and that the investments in remote wind power would also help to accelerate decarbonisation of the regional energy system.

In some buildings, no additional fabric improvement will be needed to decarbonise the heating because a heat pump or other low-carbon heating solution will be sufficient, provided adequate supplies of sustainable electricity or heat are available. However, in most countries, the urgent need to decarbonise buildings (to deliver net zero by 2050) can pose logistical challenges for those who plan to renovate the fabric first, because the building industry does not have the workforce needed to renovate the fabric of the whole residential building stock within the timescales needed. Hence, prioritising deep renovations with a fabric-first approach could slow the overall rate of building decarbonisation [19]. Nevertheless, the energy use in buildings will always be higher if their insulation is inadequate, so well insulated building envelopes should continue to be prioritised in new buildings and wherever insulation measures are economically feasible, in order to limit the future demand for sustainable energy supplies.

As suggested in the EASAC report [1], it follows that policies should support the full range of solutions available to decarbonise heating in buildings, taking into account the local conditions and including both energy demand reduction and decarbonisation of heat supplies.

3.3. Depth of renovation affects costs – it must be affordable (reduce energy poverty)

To motivate millions of homeowners to invest in the renovation of their buildings is a big challenge. Grants and incentives can be used to trigger, leverage and de-risk private financing for energy related building renovations. However, public funding is limited and must therefore be prioritised for use by vulnerable groups who risk falling into energy poverty, rather than for subsidising wealthy building owners who can afford to pay for their renovations (especially if the investment is amortised).

Energy poverty is commonly understood to mean the inability of households to secure their energy needs. Factors influencing energy poverty include income inequality, GDP per capita, and heating degree days, but there is no EU wide agreement on a common definition of energy poverty (EASAC 2023 [20]).

Energy poverty is most prevalent in Central, Eastern, and Mediterranean EU countries. Income inequality is often the primary reason for energy poverty, so addressing macroeconomic policies alongside energy efficiency in buildings is crucial to reducing the numbers of cold homes in European winters. For this, investing in deep building renovations for energy-poor households can be a cost-effective solution compared to providing long-term social welfare support for high energy bills in inefficient homes [21]. For example, social housing organizations can recover renovation costs over time without increasing the monthly charges on their residents by balancing rent increases against reduced energy bills.

To deliver fair solutions, energy poverty policies should address both energy consumption per square meter and per head, especially for buildings that are densely occupied by low-income groups.

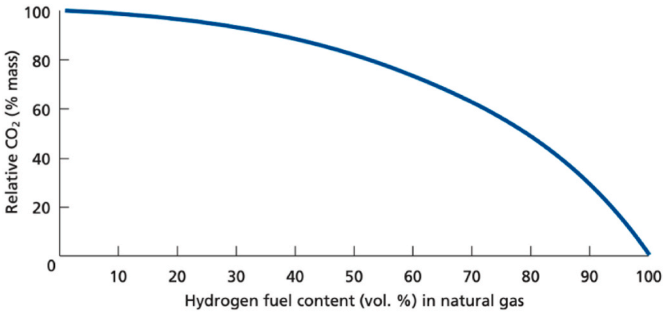


Fig. 5. Blends with about 10 % by volume of hydrogen in natural gas produce negligible (ca. 1 %) reduction in carbon dioxide (CO_2) emissions from combustion [28].

3.4. Depth of renovation affects health benefits for building occupants

Renovating the envelope of a building can not only reduce its GHG emissions but also improve its internal air quality, increase access to daylight, and avoid draughts and overheating. The resulting health and wellbeing benefits can therefore help to convince policymakers, social housing providers and investors to decarbonise buildings through renovation.

Health and wellbeing provision is a prerequisite that must be coordinated with building energy-efficiency. For building facades, daylight and view must be reconciled with solar gain and glare control; though, in dense urban settings, access to daylight and views may be unavoidably curtailed. Surprisingly, the complex causal mechanisms behind the impacts of window views on human wellbeing and health remain poorly understood [22], and this has unfortunately impeded the development of energy-efficient windows and adaptive facade technologies [23]. As a result, there is a lack of deployment of these technologies in integrated building design, which should be addressed to improve the delivery of health, wellbeing, and net zero energy goals.

Good indoor air quality is critical for the health of building occupants, and it is particularly important in healthcare and school buildings because, compared to healthy adults, children and people who are unwell are typically more sensitive to heat, cold and moisture. In schools, a well-maintained indoor environment has been found to reduce absence rates and enhance learning [24]. However, further studies with large sample sizes would be useful to better quantify relationships between indoor environmental metrics and occupant health, wellbeing, and performance [25].

4. Sustainable fuels and technologies for decarbonising buildings

4.1. Sustainable gaseous fuels

Bans on the sales of new gas boilers are being introduced in a growing number of EU countries, though this important step towards the decarbonisation of buildings appears to be resisted by incumbent oil and gas industries [26]. There is also a risk that it will be resisted by households unless it is adequately supported by well targeted subsidies together with national, regional, and local information campaigns.

Neither biomethane nor hydrogen are likely to be widely used to replace natural gas for heating because these gaseous fuels will be more highly valued for applications in industry or transport that are ‘hard to electrify’ [27]. Moreover, to supply these gases for heating would risk locking users into inefficient solutions that will become more economically unattractive in the future.

Limited GHG emission reductions can be achieved by blending hydrogen and natural gas [29] for example, as shown in Fig. 5, a blend of 10 % hydrogen (by volume) in natural gas would produce negligible (*ca.* 1 %) CO_2 emission savings, and more than 80 % hydrogen (by volume) would reduce CO_2 emissions by only 50 %. Green hydrogen blends are therefore unlikely to be used in gas boilers for space heating because unacceptably high blends of hydrogen would be needed to achieve significant reductions in GHG emissions from combustion.

4.2. Heat pumps

Some European countries are already providing subsidies to promote the use of heat pumps in place of gas boilers and in recent years there has been a rapid increase in installations of heat pumps in existing buildings [30]. As modern heat pumps can provide both heating and cooling, they can meet both winter needs for space heating and in summer provide cooling to counter the growing problem of overheating.

In a whole-energy system optimisation study in two geographical areas with very different climatic conditions, Aunedi et al. [31] found that up to 97 % of building heat demand could be met using electrical heat pumps. They studied whole-energy systems, both with 400 TWh overall annual electricity demand, in two geographic areas:

1. A cold climate with abundant wind resource, 10.7 °C average temperature with 1884 heating degree days and residential heating and cooling electricity demands of 185 TWh and 6 TWh respectively
2. A mild climate with high incident solar energy, 18.3 °C average temperature with 554 heating degree days and residential heating and cooling electricity demands of 36 TWh and 40 TWh respectively.

For both geographical areas, they found that the best mix of heating and heat storage varied significantly depending on the patterns of heat demand and the availability of renewable generation. They used thermodynamic and component-costing models of heating technologies (integrated models) to determine the most cost-efficient mix of low-carbon heat technologies needed to minimise the overall costs of the system for its end-users.

Analyses by Gibb et al. [32] of data from field testing of 550 heat pumps showed that, for standard air-source heat pumps, coefficients of performance (COP) remained around 2 even on the coldest winter days. In most European countries, heat pumps thus do not require back-up heating. However, heat pumps specifically designed to achieve COPs above 1.5 are required in regions where winter temperatures can approach −30 °C [32].

Heat pump studies by Lamb and Elmes [33] have shown that the requirements for additional insulation, mechanical ventilation, and fan coils to replace existing radiators, vary with local climate conditions and building characteristics. Bertoldi et al. [34] have shown that independent advisory services (one-stop-shops or local energy agencies) can help potential investors to make informed decisions on these issues.

4.3. Storage of electricity and heat

Energy storage together with digital controls, artificial intelligence (AI), and management systems permit a wider use of demand response and participation in electricity markets, for example using stationary batteries in buildings and/or mobile batteries in electric vehicles, as discussed by Petrucci et al. [35] and Chatzigeorgiou et al. [36]. In buildings, electricity can be used to heat tanks of water, which can be stored for future use as low temperature heat.

Electricity and heat storage become increasingly valuable as the fraction of variable renewable electricity generation from wind and solar generators on the grid increases. Energy storage also enables use of otherwise curtailed renewable electricity generation, and could be a possible route to alleviating energy poverty [37]. However, independent decentralised electricity storage in battery systems currently poses a financial risk for private investors due to low numbers of full charge/discharge cycles [38].

4.4. PV electricity generation on buildings

PV can be installed on or near to buildings to reduce their annual GHG emissions and can be particularly valuable if it is used for cooling in summer (self-consumption), even in central and northern Europe, where it typically contributes little to the major energy demand represented by the winter heating load. However, the current building stock presents a significant opportunity for the installation of PV systems that has yet to be fully realised. A recent modelling study estimated the global potential for PV on buildings and found that the current global rooftop potential is around 1.5 times the residential electricity demand [39].

Many definitions of positive energy buildings (PEB) have been proposed. According to Magrini et al. [40], a PEB is a building for which the annual building energy demand is calculated by deducting PV electricity exported to the grid in summer from the total annual energy imported from the grid or other sources. Ala-Juusela et al. [41] defines PEB as "an energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year". A typical PEB is able to integrate technologies, such as electric vehicles, with the motivation to maximize the utilization of local renewable energy sources.

Such definitions, however, can be misleading because they hide the fact that heating energy used in winter, which is often supplied using fossil fuels, typically generates substantial GHG emissions.

4.5. Sustainable district heating

District heating systems can offer valuable reductions in GHG emissions compared with individual gas fired heating, and they are therefore expected to play a larger role in the future. If operated at lower temperatures than are widely used today, they can take inputs from many different energy sources, including renewable heating (solar and geothermal) as well as waste heat from industry or from other local sources such as data centres, sports centres, or shopping malls. District heating is particularly attractive in urban areas with high building densities. Integrated, highly efficient, multi-sector, multi-energy district heating systems have been studied, developed and implemented in showcase projects over many years [42].

Typical space heating systems in existing buildings operate with supply temperatures in the range of 30–70 °C and return temperatures as low as 25–35 °C. However, supply temperatures of no more than 55 °C are adequate to ensure end-user comfort for most of the year [42]. In district heating, lower temperature bi-directional heat networks are being deployed and used to supply heat from renewable and other low temperature sources to buildings [43,44]. In renovated buildings, depending on the extent of various adverse behavioural effects (see Lange et al. [45]), smaller space heating loads are likely in future, so domestic hot water (DHW) will become an increasing fraction of the total building heat demand in many parts of Europe.

To avoid legionella growth, DHW should be stored at 60 °C or higher and distributed at 50 °C or higher [46]. Hence, if DHW is to be provided using a low temperature district heating network, heat pumps must be used to raise the temperature sufficiently to ensure that legionella bacteria cannot grow and potentially infect the building occupants [47].

5. Expansion and modernisation of the building industry to deliver decarbonisation

The building industry in the EU must expand and modernise to decarbonise Europe's existing buildings. This will require more training programme frameworks for energy renovation, such as those developed by Ekambaram and Olsson [54], and must include training in the skills needed for effective project delivery with high productivity.

Modern methods of low embodied emissions construction from project initiation and design through to building operation should be promoted, despite potential tacit resistance to change [55]. Future training programmes must reflect the expected evolution of construction methods to include greater use of sustainable off-site manufactured, re-used, and recycled components to displace traditional construction [56]. Strong collaborative skills, underpinned by investments in systems for data sharing via Building Information Modelling [57,58] are essential for effective working across teams, both for planning and for physical construction.

Contractual agreements between providers of different, but increasingly interconnected, construction skills and capabilities must be simplified to facilitate cost-effective delivery of large-scale, complex and sustainable refurbishments.

6. Public and civic authorities play key roles in the decarbonisation of buildings

Holistic renovation strategies are needed by cities and communities because, in practice, building renovations typically serve multiple goals at the same time. For example, a well-renovated building can offer not only lower GHG emissions, but also reduced energy bills, improved thermal comfort, improved internal air quality and other health benefits resulting from better access to daylight and to outside space.

Local authorities and urban planners can facilitate decarbonisation of buildings by making recurrent operational energy costs more affordable and, in this way, they can also reduce energy poverty. By implementing a Climate Action Plan (Barrett et al. [48]), they can:

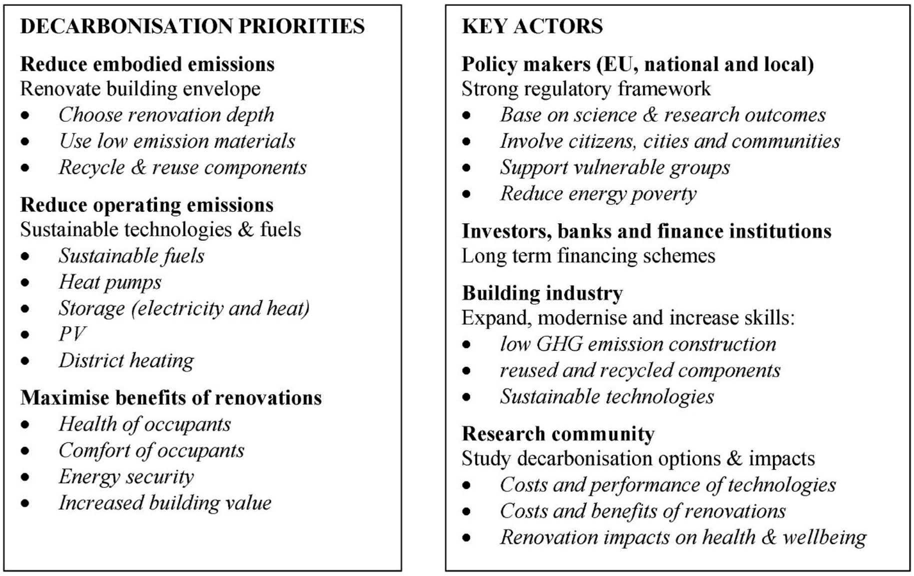
a. Have a strong influence on procurement specifications [49,50].
b. Stimulate the renovation and construction of nearly zero GHG emission neighbourhoods with integrated energy and transport systems and adequate green spaces. For example, by renovating clusters of buildings using a coherent approach, they can ultimately create a "positive energy district" [51].
c. Upgrade existing district heating and cooling systems [52] and build new ones with optimised use of renewable energy, including PV, heat pumps, solar and geothermal heating, waste heat and natural cooling.
d. Oversee renovations of social housing and subsidise the renovation of privately rented housing where necessary to reduce energy poverty [53].

7. The role of science in guiding policies and strategies for decarbonising buildings

The European Union (EU) is committed to reducing its GHG emissions to net zero by 2050 and has put in place policies and strategies for the decarbonisation of buildings. However, research on the successes and challenges of the different decarbonisation options is continuing and more needs to be done, so policy makers and market actors should work closely with the research community and feed the outcomes of research back into the policy making process.

In 2020, the European Commission (EC) proposed a 'Renovation Wave' strategy to reduce energy demand and GHG emissions by renovating buildings in the EU [59]. This strategy was predicated on an estimate that almost 75 % of EU residential buildings had a poor energy performance, and that to renovate them would require 146 million renovations to be completed in 30 years, i.e., renovation of more than 90,000 homes per week across the EU. EASAC [1] highlighted that this would be an enormous challenge, requiring renovation rates to be tripled from around 1 % per year today to around 3 % per year.

Since publication of the EASAC report in 2021, the EU has invested heavily in its recovery from the COVID pandemic and there has been a growing cost-of-living crisis, driven partly by high energy prices. After Russia invaded Ukraine in 2022, the EU adopted the REPowerEU plan [2] to phase out Russian gas before 2030 by accelerating more efficient use of energy, fuel supply diversification, and greater renewable energy use. These policies aimed to reduce gas demand by at least 155 billion



DECARBONISATION PRIORITIES

Reduce embodied emissions
Renovate building envelope
- *Choose renovation depth*
- *Use low emission materials*
- *Recycle & reuse components*

Reduce operating emissions
Sustainable technologies & fuels
- *Sustainable fuels*
- *Heat pumps*
- *Storage (electricity and heat)*
- *PV*
- *District heating*

Maximise benefits of renovations
- *Health of occupants*
- *Comfort of occupants*
- *Energy security*
- *Increased building value*

KEY ACTORS

Policy makers (EU, national and local)
Strong regulatory framework
- *Base on science & research outcomes*
- *Involve citizens, cities and communities*
- *Support vulnerable groups*
- *Reduce energy poverty*

Investors, banks and finance institutions
Long term financing schemes

Building industry
Expand, modernise and increase skills:
- *low GHG emission construction*
- *reused and recycled components*
- *Sustainable technologies*

Research community
Study decarbonisation options & impacts
- *Costs and performance of technologies*
- *Costs and benefits of renovations*
- *Renovation impacts on health & wellbeing*

Fig. 6. Overview of building decarbonisation priorities and key actors.

cubic meters of fossil gas, equivalent to the volume supplied by Russia in 2021. Overall, these measures have been estimated to cost over €296 bn [3].

When finalising and implementing this work, EU policy makers can be confident that there is flexibility in Europe's energy demand because good progress was achieved in 2022, with a 15 % reduction in EU demand for gas, 80 % of Russian pipeline gas replaced in less than 8 months, and 39 % of electricity coming from renewables [2]. To build on this success, it will be important to decarbonise Europe's energy supplies by phasing out the use of fossil fuels and rapidly increasing supplies of renewable energies. In increasingly interlinked energy systems, future energy markets need to consider electricity, heat and biogas equitably [60]. Energy demands must continue to be reduced by improving energy efficiency, notably in buildings.

In 2023, the United Nations COP 28 agreed to transition away from fossil fuels [4], and in 2024 it was agreed at COP 29 to triple the financing for developing countries to USD 300 bn annually by 2035, to support them in the fight against climate change [5]. However, fulfilling these emission reduction goals, originally set in the Paris Agreement, has become increasingly challenging, especially for the buildings sector, where barriers to delivering net zero emission buildings include a lack of long-term financing and of experience with technical solutions [6].

In March 2024, a revised Energy Performance of Buildings Directive (EPBD) was adopted [61], that takes forward many of the key recommendations of the EASAC report on decarbonisation of buildings [1]. For the first time, the EPBD will require regulation of the carbon embodied in buildings, during their construction, maintenance, and demolition. Under the new EPBD, from 2030 Member States must (i) disclose both embodied and operational carbon for all new buildings and (ii) set whole life carbon targets for buildings that progressively decrease over time. From 2030, all new buildings must not produce any emissions on site, and they must use only a very small amount of renewable energy or district heating wherever feasible.

Member States will be required to (i) provide finance to support the renovation of the existing building stock by 2050, (ii) establish national renovation plans, and (iii) introduce bespoke stage-by-stage plans for enabling building owners to proceed with deep renovations. Importantly, there is a requirement to protect tenants from eviction following renovation. The EPBD also aims to (i) increase the number of buildings that directly harness solar energy and (ii) phase out fossil fuel boilers by 2040. As recommended by EASAC [1], the EPBD has a clear focus on maintaining indoor environmental quality.

8. Discussion and conclusions

The renovation of existing buildings in Europe was shown in the EASAC report [1] to be a "no regrets" option from many different standpoints, notably GHG emission reduction, improved health and wellbeing of residents, increased quality of life and value of neighbourhoods, as well as increased local investment opportunities and jobs. However, as illustrated in Fig. 6, determining the most suitable form of renovation depends on many local and national factors and objectives that must be assessed on a case-by-case basis.

Researchers across the world continue to analyse and determine decarbonisation options that are appropriate for very different local conditions. In addition to scientific and engineering investigations, there are many behavioural, socio-economic and ethical challenges that require further research [62]. Research also continues to be needed on how best to achieve occupant-healthy zero-GHG emission buildings with optimised daylighting and indoor air quality.

In view of the rapidly increasing rate of global warming, the widespread implementation of building renovations, using proven technologies, is likely to deliver GHG reduction goals more quickly and economically than investing in major new technologies that have yet to be proven [63].

Nevertheless, challenges remain on how best to manage the implementation of building renovations on a very large scale, to finance and reduce (spread over time) the capital costs of renovations, and to decarbonise historic buildings without losing their precious attributes.

CRediT authorship contribution statement

W.B. Gillett: Writing – review & editing. **S.A. Kalogirou:** Writing – review & editing. **P.E. Morthorst:** Writing – review & editing. **B. Norton:** Writing – original draft. **M. Ornetzeder:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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