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Decarbonising buildings in Europe: a briefing paper

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Energy used to provide heating, cooling and ventilation in buildings supplied using fossil fuels produces about 25% of total European (EU) greenhouse gas (GHG) emissions. To reduce this requires lower energy use in both existing and future buildings with the remaining energy supplied from very-low-carbon sources. This briefing paper discusses how to reduce the GHG emissions from buildings in Europe to nearly zero. Coordinated updating of existing policies together with well-targeted and innovative EU, national and local initiatives are required to deliver the required reductions. It will be important to (*a*) ensure that measures to reduce energy and GHG reductions also enhance the health and well-being of building occupants, (*b*) integrate decarbonisation of electricity and heat supplies for buildings with decarbonisation of industry and transport, (*c*) reuse and recycle to reduce embodied GHG emissions in building materials, components and processes used in both the construction of new buildings and in building renovations. Decarbonising buildings is an opportunity to develop and produce new products and services that create new high-quality jobs.

1. Introduction

An expert group nominated by National Science Academies was organised by and worked under the auspices of the European Academies Science Advisory Council to review available options for reducing greenhouse gas (GHG) emissions from buildings. This briefing paper summarises this group's analyses, conclusions and advice for policy makers (EASAC, 2021). The full report extensively cites relevant literature, that for brevity is not included in this briefing paper; it is freely available for download (EASAC, 2021).

2. Designing buildings for low GHG emissions

Buildings incur about 25% of total EU operational GHG emissions with further GHG emissions embodied in their materials, components and systems. Table 1 summarises the origins of those operational and embodied energy and emissions.

Direct GHG emissions produced by burning fuels for energy use in buildings vary daily and annually with weather conditions, number of occupants and their activities, internal temperatures, equipment and appliances used, and heating and cooling control settings. Residential energy consumption, which varies across Europe as shown in Figure 1, overall totals ~245 Mtoe/year, with gas dominating the mix of fuels used as shown in Figure 2.

The key attributes of technologies for decarbonising energy in buildings are summarised in Table 2.

3. Reducing GHG emissions by renovating existing buildings

The opportunities for, and barriers to more energy-efficient use of existing buildings are summarised in Table 3.

As 85–95% of Europe's *c*. 250 million existing buildings will still be in use in 2050 and the rate of constructing new buildings is low, the largest potential for reducing GHG emissions lies in increasing the depth and rate of energy-efficient building renovation. For the residential sector, this requires 146 million renovations in 30 years; equivalent to renovating over 90 000 homes each week across the EU. Energy renovations usually improve indoor air quality, access to daylight, comfort, sound insulation, disabled access and/or access to outdoor space. Wider social benefits also accrue through new renovation businesses creating jobs. Economic cases for investments in energy renovations should therefore aggregate both direct and indirect benefits. Energy use can be reduced by low-cost interventions with short-term financial returns. In contrast, the much 'deeper' energy renovations required to reduce GHG emissions to nearly zero have significantly higher investment costs that typically take up to about 30 years to recover through savings in energy costs, so providing affordable initial finance by way of the approaches summarised in Table 4 becomes essential.

Table 1. Processes leading to GHG emissions from buildings

Operational	Direct	Combustion of fossil fuels in buildings to provide heating and hot water
	Indirect	Use of district heat from fossil fuels
		Use of fossil-fuel-generated electricity
Embodied	Extraction and processing of construction materials	
	Manufacturing building components	
	Transportation to site	
	Construction processes	
	Demolition processes	

Approaches to financing deep renovations need to be sensitive to the challenges of energy poverty, which interconnects with multiple policies including energy use, family welfare, social housing, social care, housing tenure, income support and economic development. Underprivileged vulnerable groups need others to invest to raise them out of energy poverty. Investing in the deep renovation of buildings whose occupants are in energy poverty could be a better use of public funds than social welfare interventions paying high energy bills for energy-inefficient homes over extended periods.

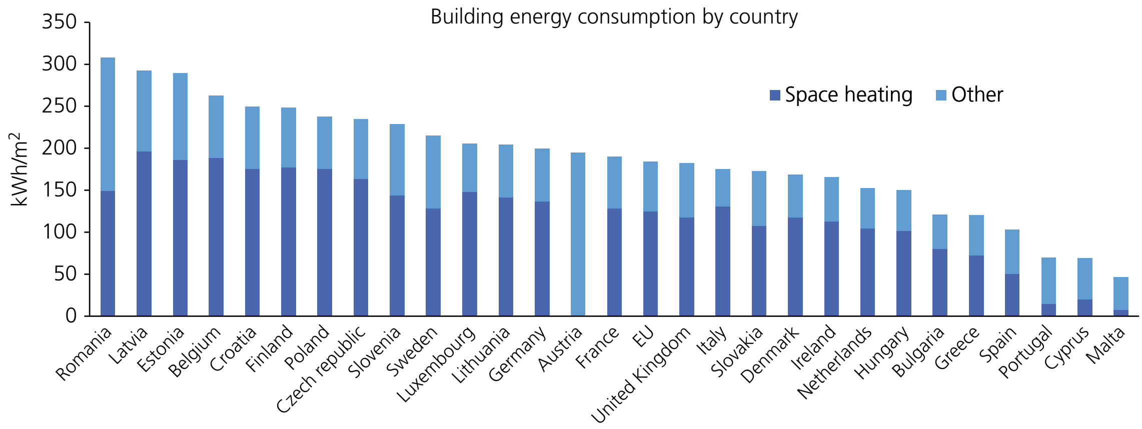

Figure 1. Residential energy consumption across Europe in 2014

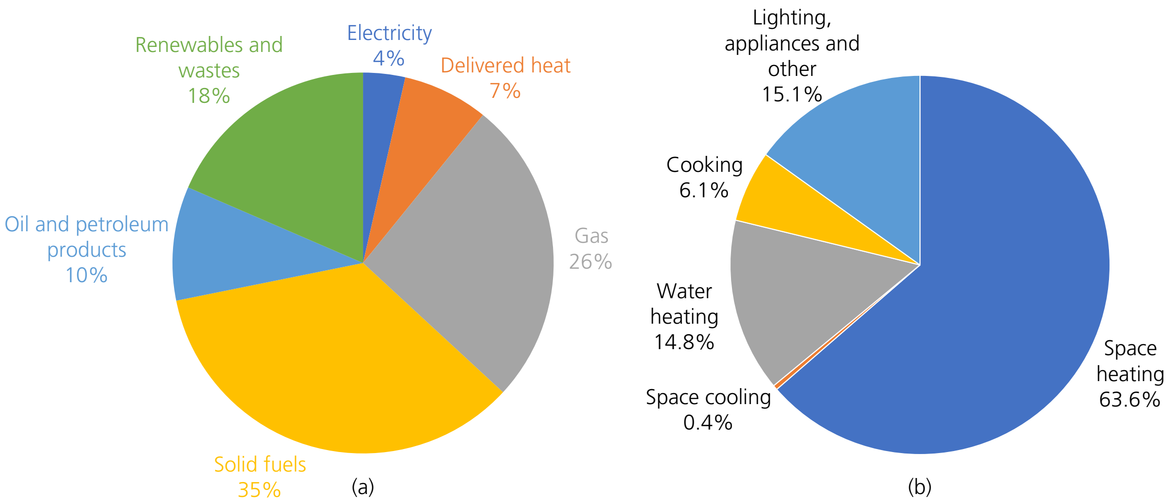

Figure 2. Final energy consumption in EU homes in 2018: (a) space heating fuel type; (b) application

Table 2. Opportunities and challenges for the adoption of key technologies

Technology	Opportunity	Challenges
Thermal insulation	Low heat losses through building envelope	Can be disruptive to retrofit
Mechanical ventilation with heat recovery	Lower heat losses by controlled ventilation and air-tightness	Regulations required to ensure regular cleaning and thereby avoid airborne virus transmission
Heat pumps	Replace boilers or electric heaters. Can be combined with PV and battery storage	Vapour-compression heat pump efficiencies are relatively high in large-scale applications but lower in small-scale application
District heating	Can use heat pumps, biogas, solar, geothermal and/or waste heat. Large heat stores can balance supply and demand	Without carbon capture and storage, district heating can no longer use fossil fuels
Building-integrated PV	Provides local electricity generation	Shading from trees and adjacent buildings
Solar heating	Country-dependent, offers 3% to 12% of heat supply. District systems in Denmark	Uncompetitive costs compared with other renewable energies in Northern Europe
Biogas	When replacing natural gas, it avoids assets becoming stranded in supply infrastructure and existing gas boilers	Role limited by sustainable biogas resources
Green hydrogen		Green hydrogen more expensive than green electricity used for its production, so not viable in electrifiable applications
Geothermal heat	Use directly or by way of heat pumps.	Geothermal heating largely unexploited
Energy-efficient lights	Lower electricity use and cooling demands.	Control for optimised use of artificial lighting
Solar cooling	Reduces electricity cooling demand as high solar radiation coincides with peak cooling	Niche market. In Northern Europe direct solar radiation too low for type of solar collector used

Table 3. Opportunities for, and barriers to more energy-efficient existing buildings

Action	Impact	Barriers
Deep energy renovation	Reduces energy use and GHG emissions	Need for; access to affordable finance, confidence in renovation outcomes and occupants to vacate and/or accept disruption
Energy renovation of rented housing	Reduces energy use and GHG emissions	Disincentive of benefits accruing to tenant. Needs regulations obliging landlords to renovate.
Renovate for new needs, do not demolish	Reduces energy use and GHG emissions	May not be feasible
Use prefabricated renovation components	High quality control; lower embodied GHG emissions; year-round indoor jobs Economies of scale	Investment in manufacturing facilities requires long-term addressable renovation market
Renovate neighbourhoods	District heating use, positive-energy homes can export energy to neighbours; collective action/support	Enables bundling of renovations to be more easily funded. Easier in areas with similar buildings
Hot desking; open plan flexible office layouts	Lower energy use per unit building area	Acceptability depends on layout, occupant distancing and environmental control
Intensify occupancy of houses	Lower energy use per unit building area	Resistance to downsizing, to solely single-home ownership and from those wishing to enlarge
Leave fewer buildings remaining vacant	Lower energy use per unit building area	Property market conditions; planning constraints

Table 4. Approaches to financing deep renovations

Financing	Established	Debt financing	Soft loans extending an existing mortgage or lease
	Growing use	Equity financing Debt financing Non-repayable rewards	Service agreements and energy performance contracts Commercial loans, revolving funds Through energy-efficiency obligations
	Innovative	Equity financing Debt financing Non-repayable rewards	Crowdfunding On-bill finance, property assessment, energy-efficient mortgages Energy-efficiency feed-in tariffs
Incentives		Grants, subsidies or tax breaks to (*i*) trigger long-term investment and (*ii*) reduce risks	

Table 5. Meeting the challenges of low-carbon building electrification

Challenge	Requires
Electrified building heating at competitive cost	Mass use of heat pumps with cost-reductions and resilient supply chains, through economies of scale
Balancing electricity demand from buildings with variable supplies of electricity coming from renewable generation.	Battery electricity storage in buildings Coupling buildings to batteries in electric vehicles Storing excess electricity as heat for future use Coordinated aggregated approach to grid flexibility management, with updated electricity market rules On-site generation of renewable electricity Reinforcement of electricity transmission and distribution grids Large-scale flexible electricity generation Independent electricity storage in batteries, pumped storage systems or synthetic fuels
Minimising total and peak demands for electricity from buildings	Maximising number of low-energy renovated existing buildings Use of district heating/cooling systems in urban areas Storage and use of waste heat, solar heat and excess renewable electricity generation Load shifting of equipment and appliances Time-dependent tariffs and smart-metering to encourage self-generation and self-consumption
Intersector coupling	Greater interconnection between sectors as low-carbon energy supplies to buildings are optimised at the energy system level with those for transport and industry

4. Energy supply to buildings

Energy can be supplied to buildings from

(*a*) electricity for appliances and equipment, lighting, heating and/or cooling; the challenges and requirements for low-carbon electrification of buildings are summarised in Table 5
(*b*) gas, oil and solid fuels for space and water heating. Given that fossil-fuelled heating systems typically last up to about 25 years, it is urgent to set deadlines for their installation to cease
(*c*) district heating or cooling networks and/or
(*d*) renewable energies providing low GHG emission heating, cooling and electricity through the grid and building-integrated photovoltaics, solar heating and cooling and heat pumps.

5. Reducing embodied GHG emissions in buildings

Buildings have embodied GHG emissions from the energy used to produce, transport and install materials, components and systems when they are built, maintained, renovated and eventually demolished. The largest embodied emissions of a building are in foundations, floor slabs and structural components that contain steel and cement.

Embodied GHG emissions will become an increasingly significant part of the total GHG emissions from buildings as operating emissions reduce in future. An immediate increase in cumulative emissions occurs at the time of renovation due to the embodied emissions in the additional materials and components used. Reducing embodied GHG emissions requires (*a*) improved availability and quality of embodied GHG emissions data for building materials and components, (*b*) improved documentation on embodied GHG emission from new buildings and renovations, (*c*) setting limits for embodied GHG emissions per m^2 floor area of both new and renovated buildings, (*d*) more use of recycled building materials and components and (*e*) designing components for re-use and recycling if they have high embodied GHG emissions.

With solutions that limit fire risks, timber can be engineered to replace concrete and steel and is well-suited for prefabrication. By using timber, carbon absorbed by trees can be locked into a building, delaying the negative impacts on forest carbon sinks caused by cutting down trees. However, as less than half the carbon in harvested trees can end-up in wood products with a long lifetime, the carbon footprints of all timber sources need to be closely monitored.

6. Projected carbon impacts of a European renovation wave

Depending on the approach adopted, the materials and components used, the complexity and the depth of renovation, embodied emissions from renovations can be up to 50% of those from new buildings. Therefore, while it is usually preferable from a life-cycle GHG emission perspective to renovate existing buildings instead of demolishing them and re-building using new materials, embodied emissions from renovation must not be overlooked. Renovations can be expected to reduce operational GHG emissions from buildings, but will increase emissions in the short term due to the embodied carbon emissions associated with the renovation works.

Cumulative GHG emissions from both residential and non-residential buildings in the EU (i.e. the sum of those from the combustion of fuels in buildings and those produced by the suppliers of electricity and heat) were calculated for the two scenarios in Table 6 using (*i*) European Environment Agency data for GHG emissions from gas-fired heating and domestic hot water systems and from public electricity and heat production (*ii*) Eurostat data for the proportion of public electricity and heat production consumed and (*iii*) an embodied carbon benchmark study (Carbon Leadership Forum, 2021).

Cumulative emissions from both scenarios as shown in Figure 3, are broadly similar until around 2030, when they start to diverge. The carbon budgets for the EU buildings sector to deliver its share (i.e. about 25% of EU's carbon budget) of the GHG emissions reductions needed to limit climate warming to 1.5 and 2°C are also shown in Figure 3.

Figure 3 indicates that if building renovation rates are increased to deliver an average of 3.3% per year with a bell curve distribution between 2021 and 2050, and each renovation reduces the operational emissions of the building to zero, while producing a modest level of embodied GHG emissions (e.g. 125 $kgCO_2e/m^2$ in 2021 declining to zero by 2050), then the EU buildings sector could deliver its share of the GHG emission reductions needed to limit climate warming to 2°C.

The trade-off, between renovations reducing operational emissions but adding embodied emissions, is sensitive to the level of embodied GHG emissions produced by renovation. This is shown in Figure 4 where cumulative emission curves are presented for renovation waves with different levels of embodied GHG emissions ($kgCO_2e/m^2$ of floor area) but all other parameters remain unchanged.

7. Conclusions

There is no unique optimal solution 'silver bullet' for prioritising between investments in building renovations and in the

Table 6. Scenarios examined for projecting cumulative emissions from EU buildings to 2050

Scenario	Features	Assumptions
Renovation wave	Decarbonisation of electricity and heat supplied to buildings, (as in no renovation scenario). Energy renovation decreases the operational GHG emissions from buildings, but increases their embodied GHG emissions.	Operational GHG emissions for each building (or floor area) decrease to zero after renovation. Average 3.3% (630 000 000 m^2/a) of total EU floor area renovated annually from 2021 to 2050. Total floor area unchanged after renovation. Each floor area is renovated only once. Renovations incur embodied GHG emissions when renovated, falling from 125 $kgCO_2e/m^2$ in 2021 to zero in 2050 (due to projected decarbonisation of manufacturing processes).
No renovation (business as usual – BAU)	Annual emissions from buildings decrease year-on-year with decarbonisation of electricity. In 2050 there are still emissions from combustion of fuels in buildings.	Consistent with EU targets, assuming that GHG emissions from electricity and district heat production will fall by 55% (compared to 1990) by 2030, and reach net-zero by 2050. GHG emissions from combustion of fuels in buildings remain at their mean level between 2010 and 2018 as heating systems within buildings are not renovated.

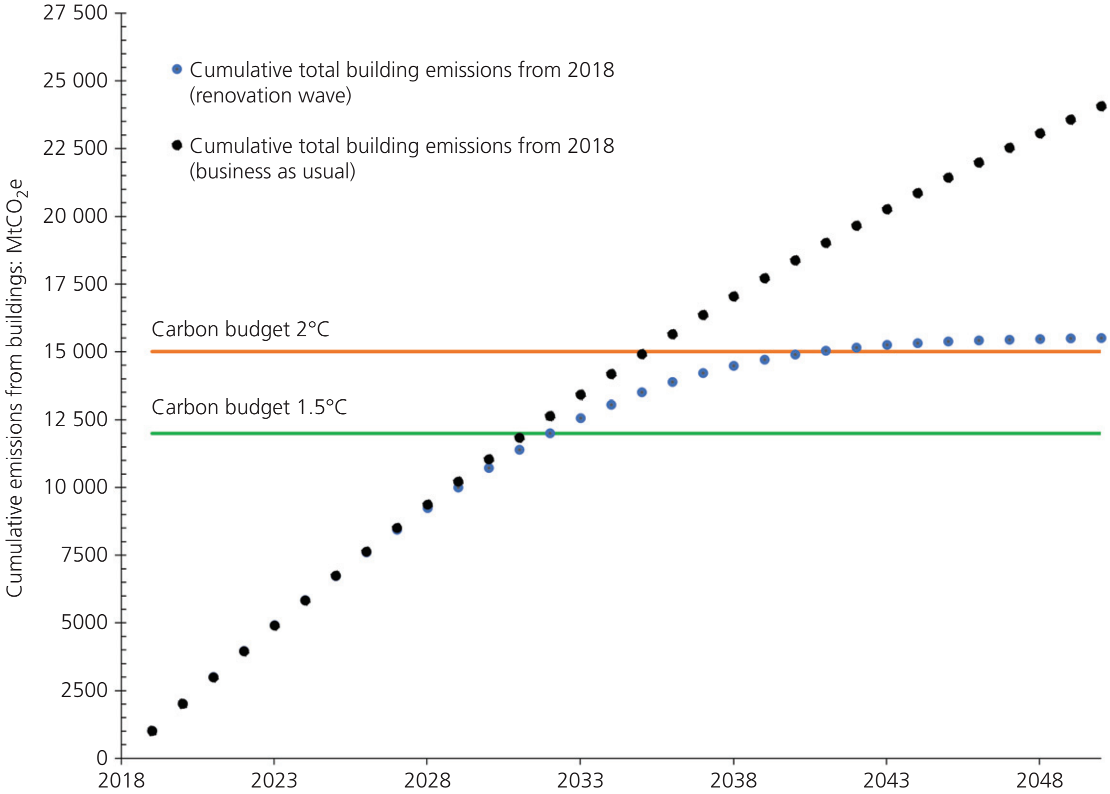

Figure 3. Impact of a European renovation wave on the cumulative emissions from EU buildings

provision of decarbonised energy supplies, so policy and investment decisions aiming to reduce the carbon dioxide emissions of buildings must be taken on a case-by-case basis. The key priorities to reduce the carbon dioxide emissions of new and existing buildings are summarised in Table 7.

Agreed definitions (taxonomy) are increasingly important for channelling capital towards environmentally sustainable economic activities and limiting risks of 'greenwashing'. For buildings, such definitions should (*i*) focus on fossil-based energy used by a building instead of primary energy demand, (*ii*) include embodied GHG emissions from building materials, components and processes and (*iii*) separate renewable energy exports and energy consumption when making building energy performance assessments to avoid perverse incentives that might discourage the reduction of underlying building energy demand.

Obligatory deep renovations of existing buildings should be triggered by (*i*) change in ownership or a change of tenant legally linked to new energy performance certification requirements, or (*ii*) the results of electronic energy performance monitoring (usually for large buildings and systems) or obligatory periodic inspections.

Substantial programmes of very attractive financial incentives and/or a package of legal/regulatory obligations on building owners or their energy suppliers will be required.

EU legislation should be updated with:

(*a*) national targets, and eventually limits per m^2 of floor area for both operating and embodied GHG emissions in new buildings and renovations
(*b*) separate accounting of (a) embodied plus operating GHG emissions and (b) positive energy contributions of a building by generating and exporting electricity and/or heat
(*c*) a new focus on final energy consumption and GHG emission data (instead of primary energy consumption data) for setting building performance limits and determining financial returns on environmentally sustainable investments in specific buildings and renovations.

Decarbonisation of the EU building sector requires major expansion of workforce numbers together with adoption of innovative technologies, materials, components, systems and

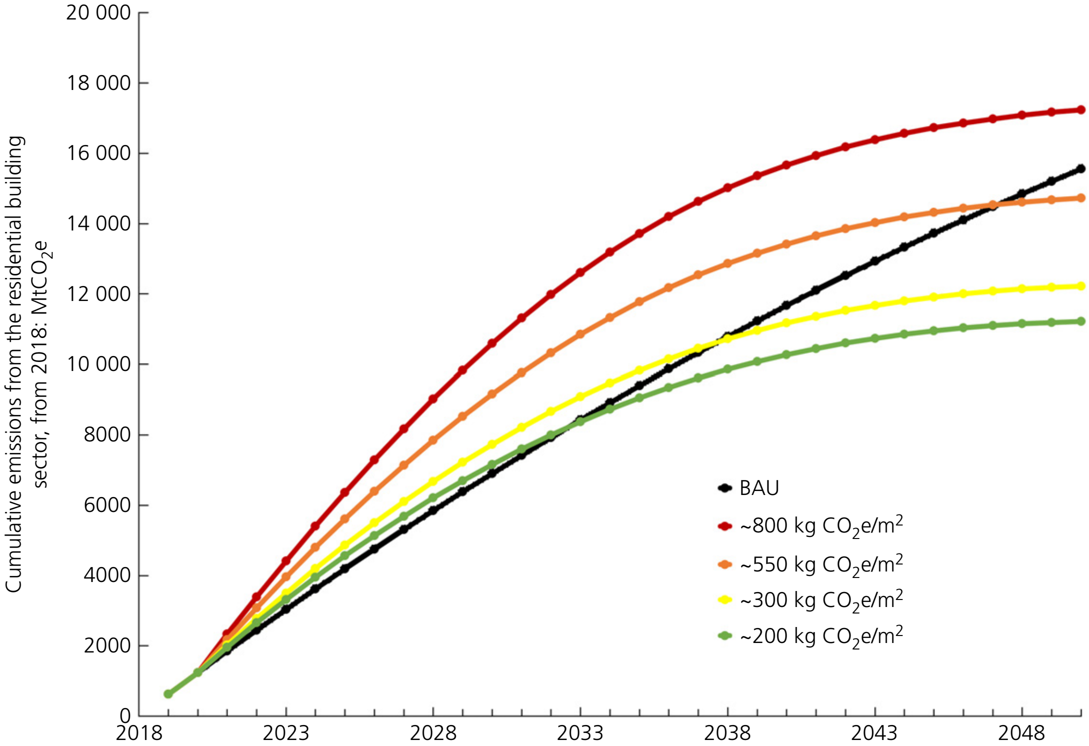

Figure 4. Sensitivity of cumulative GHG emission trajectories to embodied GHG emissions

Table 7. Key priorities to reduce the carbon dioxide emissions of new and existing buildings

Priority	Action
Improve health and wellbeing by deep-energy renovation	Ensure deep energy renovations provide high indoor air quality, good access to daylight, and avoid draughts and overheating
Deliver new and renovated buildings operating with nearly zero GHG emissions	Refocus regulations, certification schemes and incentives Facilitate and support commitments by public authorities Grants/incentives to trigger, lever and de-risk financing for deep-energy building renovations Increase deep renovation rates 2–3 times
Reduce operating and embodied GHG emissions	Make available certified data on energy and GHG emissions for new and renovated buildings, and in materials and components Promote recycled materials, re-used building components, and renovation instead of demolition
Expand and modernise the building industry	More circular business models Up to 3 million more workers, with relevant skills Innovation in construction processes for new and renovated buildings with lower GHG emissions
Phase-out fossil fuels by 2030	Integrate decarbonised supplies of electricity and heat to buildings, industry and transport. Legislate for an integrated approach to eliminate fossil fuels and increase renewable energy

Table 8. The authors wish to thank the other EASAC working group members, who are listed in this table

Name	Organisation	Nominated by	Country
A. Azapagic	University of Manchester	Royal Society	UK
N. Duic	University of Zagreb	Croatian Academy of Sciences and Arts	Croatia
G. Fink	Aalto University	Council of Finnish Academies	Finland
G. Grün	Universität Stuttgart	German National Academy of Sciences	Germany
A. Gustavsen	Norwegian University of Science & Technology	Norwegian Academy of Science and Letters	Norway
H. Hens	KU Leuven	Royal Academies for Science and the Arts	Belgium
S. Kalogirou	Cyprus University of Technology	Cyprus Academy of Sciences, Letters and Arts	Cyprus
A. Kitanovski	University of Ljubljana	Slovenian Academy of Sciences and Arts	Slovenia
J. Kurnitski	Tallinn University of Technology	Estonian Academy of Sciences	Estonia
T. Malmqvist Stigell	KTH Royal Institute of Technology	Royal Swedish Academy of Sciences	Sweden
M. Nilsson	Umeå University	Royal Swedish Academy of Sciences	Sweden
M. Ornetzeder	Austrian Academy of Sciences	Austrian Academy of Sciences	Austria
A. Schlüter	ETH Zürich	Swiss Academy of Sciences	Switzerland
F. Simančík	Slovak Academy of Sciences	Slovak Academy of Sciences	Slovak Rep.
Z. Szalay	Budapest University of Technology & Economics	Hungarian Academy of Sciences	Hungary
J. Toftum	Technical University of Denmark	Royal Danish Academy of Sciences & Letters	Denmark
M. Spiekman	TNO	Royal Netherlands Academy of Arts and Sciences	Netherlands
W. van Saarloos	University of Leiden	Royal Netherlands Academy of Arts and Sciences	Netherlands

processes. It will also require a major training and skills development programme as perhaps up to 3 million new EU jobs (almost doubling the building workforce) may arise from energy renovation of buildings.

Energy supply industries will have to replace their existing fuel supply chains with decarbonised alternatives, and financial institutions will need to offer long-term low interest rates for building renovations. In addition, national, regional and local authorities must take active roles in triggering deep energy renovations; working with energy industries to phase-out use of fossil fuels and accelerate the introduction of new decarbonised energy supplies.

Further research on integrated energy supplies to buildings and specifically on the use of renewable electricity and heat storage 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 integrated energy systems.

As calculated energy consumption ratings of older buildings with a poor energy performance are typically higher than actual energy consumption while, in contrast, calculated energy consumption ratings are typically lower than actual energy consumption for buildings with a good energy performance, building energy rating calculation methods and their assumptions require up-dating. More building performance data are needed to improve the future (*i*) operation of buildings, (*ii*) designs of renovation measures and (*iii*) equipment and software for data collection. Stakeholders should be encouraged to make such data widely available for researchers. Also important, following the impacts of the Covid-19 pandemic, will be more studies on the impacts of building design and operation on human health, particularly on how pollutants from outdoor and indoor sources affect human health.

In view of the expected future impacts of climate change, more studies of the health effects of overheating and low ventilation are needed. Social changes will impact the future needs of society for buildings. These include more (*i*) aged populations, (*ii*) single-parent families and (*iii*) 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 and customers. More research is needed to study the long-term impacts of social changes on the future design requirements of individual buildings and neighbourhoods.

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