9SM

Buildings
Supplementary Material

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9.SM.1 Supplementary Information to Section 9.4

Figure 9.11 shows a summary of the available technologies with climate change mitigation potential in buildings. Here, an extended list of such technologies is presented (Table 9.SM.1 to Table 9.SM.3).

Table 9.SM.1 | Technology strategies contributing to sufficiency aspects.

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Passive strategies for walls				
Insulation materials	– These materials can be used in the different building envelope parts (floor, wall, ceiling and roof). – They have a clear impact on improving the u-value of historic buildings (retrofitting). – Proper installation of insulation using energy-efficient materials reduces the heat loss or heat gain, which leads to the reduction of energy cost as the result.	– Conventional insulation materials are derived from petrochemical substances. – New organic/sustainable materials are more expensive than conventional materials. If the insulation barrier is broken or without a correct design, thermal bridges may appear (Asdrubali et al. 2012; Capozzoli et al. 2013; Jedidi and Benjeddou 2018).	28–37% in winter 45–64% in summer (Cabeza et al. 2010)	Conventional insulation materials (PUR, MW, XPS) Mediterranean continental climate Experimentally tested
			Up to 30% of cooling energy reduction (Kameni Nematchoua et al. 2020)	Conventional insulation materials with phase change materials (PCM) Tropical climate Simulation
			Up to 38.83% reduction in the heating season (Annibaldi et al. 2020)	Calcium silicate in heritage buildings Mediterranean climate Simulation
			Reduced energy losses by 57% and energy gains by 39% (Varela Luján et al. 2019)	External Thermal Insulation Composite Systems (ETICS) in existing buildings Mediterranean continental climate Experimentally tested
Trombe wall	– Capability to be integrated with new technologies such as PV systems. – Reduction of building's energy consumption and decrease of moisture and humidity of interior spaces in humid regions. – The indoor temperatures are more stable than in most other passive systems. Prevention of excessive sunshine penetration into the inhabited space. – Installation is relatively inexpensive, where construction would normally be masonry, or for retrofitting existing buildings with uninsulated massive exterior walls. – The time delay between absorption of the solar energy, and delivery of the thermal energy to the living space can be used for night-time heating. – Trombe wall not only provides thermal comfort in the spaces connected to itself, but also contributes to the enhanced thermal comfort condition of adjacent spaces.	– In regions with mild winters and hot summers, overheating problems may outweigh the winter benefits. – In a climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink. – Trombe walls have low thermal resistance causing to transfer the heat flux from the inside to the outside of a building during the night or prolonged cloudy periods. – The amount of gained heat is unpredictable due to changes occur in solar intensity. – Trombe walls are aesthetically appealing.	20% (Bojić et al. 2014)	Annual heating – Mediterranean climate Simulation
			18.2% and 42.2% (Bevilacqua et al. 2019)	Heating cold climate and cooling cold climate Simulation

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Vertical greenery systems (green walls/ green facades)	– Enhancing building aesthetics. – Improving the acoustic properties. – Reduction of heat gains and losses. – Ability to be integrated with existing buildings.	– Providing a living environment for mosquitoes, moths, and so on. – Requiring significant, and consistent maintenance measures. – Water drainage can be involved in complexities, and difficulties.	58.9% Green wall 33.8% Green facade (Coma et al. 2017)	Cooling season warm climate Experimental study
			37.7% and 50% (Djedjig et al. 2015)	Hot climate Cold climate Cooling savings Simulation
			12% (Chen et al. 2013)	Cooling savings Tropical climate Experimental
			20.5% (Haggag et al. 2014)	Cooling savings Hot climate Experimental
PCM Wall systems	– Availability at different temperatures. – High volumetric energy storage.	– Low thermal conductivity. – Flammability. – Low thermal and chemical stability.	19–26% (Khoshbakht et al. 2017)	Heating savings Mediterranean climate Experimental
			0 up to 29% (Saffari et al. 2017)	Heating savings in different climates Simulation
			9.28% (Seong and Lim 2013)	Annual cooling savings Temperate climate Simulation
Autoclaved aerated concrete (AAC) Walls	– High volumetric energy storage. – AAC walls are light weight concrete, and fire resistance.	– Production cost per unit is higher than other ordinary concretes. – It is not as strong as conventional concrete. – The process of autoclaving concrete requires significant energy consumption.	7% (Radhi 2011)	Annual Dry desert climate Experimental and simulation
Double skin walls	– Provision of sufficient visual connection with the surroundings. – Facilitation of entering a large amount of daylight without glare. – Offering attractive aesthetic values. – Promotion of natural ventilation and thermal comfort without any electricity demand. – Acoustic insulation.	– Higher cost for designing, construction, and maintenance compared to traditional single facades. – Increase weight of building structure. – Risk of overheating during sunny days. – Additional maintenance and operational costs. – Increased airflow velocity inside the cavity. – Potential issues associated to fire propagation.	28–33% (Pomponi et al. 2016)	Heating savings Cooling Average of reviews
			8–9% (Andjelković et al. 2016)	Heating Cooling Moderate climate Simulation
			51% and 16% (Khoshbakht et al. 2017)	Annual savings of temperate and subtropical climate Simulation

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Passive strategies for roofs				
Cool roofs	– Reduction of the solar heat gain in the building increasing the solar reflectance of the roof surface. – Improvement of indoor and outdoor thermal conditions in summer and the decrease of the building energy demand.	– May also cause significant heating penalties during cold seasons. – Not appropriate in cold climates.	0.3–27% (Rosado and Levinson 2019)	Cooling season Warm climate Simulation
			17–25% (Costanzo et al. 2016)	Cooling season Mediterranean climate Simulation
Roof ponds	– Processes indirect evaporative cooing and/or radiant cooling are combined to provide passive cooling. – They can also be used for passive heating in winter. – Knowledge available on design and operation of the systems. – Useful in arid and temperate climates, can be used in humid climates. – Performance is not affected by building orientation. – They do not increase indoor humidity.	– Increased weight of building. – Only to be used in flat roofs. – Affection of accessibility of roof for other uses. – Potential leakage and contamination of water. – Only useful for one- or two-storey buildings.	30% (Spanaki et al. 2014)	Annual savings Mediterranean climate Simulation
Green roofs	– Enhancing building aesthetics. – Improving the acoustic properties. – Reduction of heat gains and losses. – Ability to be integrated with existing buildings. – Reducing greenhouse gas emissions, air pollution and urban heat island effects in highly populated areas.	– Increase weight of building. – Maintenance.	7–16% (Coma et al. 2016)	Cooling season Mediterranean climate Experimental
			15.2% (Yang et al. 2015)	Cooling season Sub-tropical climate Experimental

Sources: Cabeza et al. (2010); Radhi (2011); Asdrubali et al. (2012); Capozzoli et al. (2013); Chen et al. (2013); Seong and Lim (2013); Bojić et al. (2014); Haggag et al. (2014); Spanaki et al. (2014); Djedjig et al. (2015); Yang et al. (2015); Andjelković et al. 2016; Coma et al. 2016; Costanzo et al. 2016; Pomponi et al. 2016; Coma et al. 2017; Khoshbakht et al. 2017; Saffari et al. 2017; Jedidi and Benjeddou 2018; Bevilacqua et al. 2019; Rosado and Levinson 2019; Varela Luján et al. 2019; Annibaldi et al. (2020); Cabeza and Chàfer (2020); Kameni Nematchoua et al. (2020).

Table 9.SM.2 | Technology strategies contributing to efficiency aspects.

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Thermally activated building systems (TABS)	– Reduce energy and cost operation.	– TABS with high thermal mass, as hollow core slabs or active concrete core, have significant slow response time. – The performance evaluations of real building systems using active slabs for ventilation are still rough limited.	17–24% (Prívara et al. 2011)	Ceiling radiant heating panels Monitoring
			15% (Sourbron et al. 2013)	Ceiling radiant heating panels Simulation
Heat pumps	– Low maintenance system. – Low cost (ASHP). – Three technologies available: (Air-source heat pump (ASHP), ground source heat pumps (GSHP), water source heat pumps (WSHP).	– High space requirements. – Complex control optimisation algorithm to achieve maximum energy savings. – Outdoor air-source evaporators demand defrosting.	17–25% (ASHP) (Ling et al. 2020)	Case study
			10% cooling (Peng et al. 2020)	–
			–18.43% to 14.78% (Zhang et al. 2020b)	–
			60% (Mi et al. 2020)	Last case coupled with PVT
Organic Rankine Cycles	– Significant energy recovery. – Reduction of peak demand. – Efficient as heat recovery system.	– High space requirements. – High capital cost.	41% in the cooling season, 63% in the heating season, 9% in the intermediate season (Dong et al. 2020)	High-rise apartment building

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Adiabatic/ evaporative condensers	– Used in hot climates to enhance the heat rejection process by using the cooling effect of evaporation. – Pre-coolers that draw ambient air through spray mist or porous humidification pads. Adiabatic evaporation of water in the entering airstream boosts the cooling capacity of direct expansion vapour-compression refrigeration, or reduces workload of the compressor. – Spray mist adiabatic cooling nominally air-cooled condensers can work as retrofit of existing plant and equipment.	– Frost formation is the most detrimental and significant problem that happens on the finned-tube evaporator in air conditioning and refrigerating systems.	15–58% (Harby et al. 2016)	Hot dry climate Simulation
Smart ventilation	– Reduces energy consumption and costs. – Improve internal air quality.	– Sometimes energy overconsumption appear.	Up to 60% (Liu et al. 2019)	---
Heat recovery system	– No cross contamination depending of the type of heat recovery system. – High efficiency, especially in temperate climates.	– Difficult to integrate depending on the type of heat recovery system. – Larger than conventional air-handling units. – Expensive both in capital and operation costs.	8% (Vakiloroaya et al. 2014a)	Annual Humid climate Experimental
			60.6% (Mahmoud et al. 2020)	4.8 coefficient of performance (COP) of the proposed district heating
Fuel cells	– Can use hydrogen as energy fuel. – Allows micro-CHP. – Can be used in all climates. – Reduced CO_2 emissions. – No noise during operation.	– High capital cost. – High space requirements.	35% (Romdhane and Louahlia-Gualous 2018)	Single-family house in France Proton-exchange membrane fuel cells (PEMFC)
			15% (Gong et al. 2019)	PEMFC and solid oxide fuel cells (SOFC)
Thermal energy storage	– Significant reduction of electricity costs. – Required smaller ducts. – Increase in flexibility. – Three technologies available (sensible, latent and thermochemical energy storage).	– COP lower than conventional vapour compression systems. – Expensive both in capital and operation costs. – More complex systems.	12–37% (Alam et al. 2019; Omara and Abuelnour 2019)	Latent heat storage system
			19–26% (de Gracia et al. 2013) 30–50% (Navarro et al. 2016a)	Active façade with PCM Cooling and heating Arid climates Activated concrete slab with PCM Cooling and heating Arid climates
			21% to 26% in summer and from 41% to 59% during winter (Fallahi et al. 2010)	Sensible thermal energy storage (TES) with concrete thermal mass with mechanical or natural ventilation
			40–70% (Fallahi et al. 2010)	Aquifer TES (ATES) Large-scale TES
Strategies for cooling				
Direct evaporative cooling	– Reduction of pollution emissions. – Lifecycle cost effectiveness. – Reduction of peak demand. – Cheap.	– Not good when ambient humidity >40%. – Humidity increase.	70% (Mujahid Rafique et al. 2015)	Hot and dry climate
Indirect evaporative cooling	– Higher air quality than direct evaporative cooling. – No humidity increase. – More efficient than vapour compression systems.	– Installation and operation more complex than direct evaporative systems.	50% (Mujahid Rafique et al. 2015)	Hot climate
Liquid pressure amplification	– Significant energy savings.	– Energy savings potential limited to low ambient temperatures. – More expensive than conventional vapour compression systems.	25.3% (Vakiloroaya et al. 2014b)	Simulation

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Ground-coupled	– Less noise and GHG emissions than conventional vapour compression systems.	– Requirements of earth surface. – Very high upfront costs. – Expensive both in capital and operation costs.	50% (Soltani et al. 2019)	Ground-coupled heat pump system
Chilled-ceiling	– Less refrigeration use due to use of cooled water instead of chilled water.	– Unable to moderate indoor humidity. – Risk of condensation at cold surface.	10% (Imanari et al. 1999)	70% of the ceiling surface covered by radiant ceiling panels
Desiccant cooling	– Humidity control is improved when coupled with conventional systems.	– Corrosive materials. – Large response time. – Crystallisation of materials maybe a problem. – Expensive both in capital and operation costs.	77% (Mujahid Rafique et al. 2015)	Dunkle cycle
Ejector cooling	– More simple installation, maintenance and construction than conventional compression systems.	– Need of a heat source >80°C. – Lower COP than conventional compression systems.	14.52% (Yu et al. 2020)	Simulation R236ea Refrigerant
Variable refrigerant flow	– Efficient in part load conditions.	– Requirement of extra control systems. – Cannot provide full control of humidity.	17% (Lee et al. 2018)	Simulation Building temp. set-point 24°C

Sources: adapted from Imanari et al. (1999); Yu and Chan (2009); Cansevdi et al. (2010); Fallahi et al. (2010); Prívara et al. (2011); de Gracia et al. (2013); Sourbron et al. (2013); Sarbu and Sebarchievici (2014); Vakiloroaya et al. (2014a); Mujahid Rafique et al. (2015); Zhu et al. (2015); Harby et al. (2016); Navarro et al. (2016b); Jassim (2017); Luo et al. (2017); Lee et al. (2018); Romdhane and Louahlia-Gualous (2018); Alam et al. (2019); Gong et al. (2019); Hohne et al. (2019); Irshad et al. (2019); Liu et al. (2019); Omara and Abuelnour (2019); Soltani et al. (2019); Zhang et al. (2019); Cabeza and Chàfer (2020); Dong et al. (2020); Ling et al. (2020); Mahmoud et al. (2020); Peng et al. (2020); Yu et al. (2020); Zhang et al. (2020b).

Table 9.SM.3 | Technology strategies contributing to renewables.

Typology – technology	Advantages	Disadvantages	Energy savings	
			Value [%]	Conditions/comments
Geothermal energy or ground source heat pumps	– Abundant and clean. – Provides year around low-cost heating and cooling using district energy technology. – Not affected by climate.	– Expensive start-up and maintenance due to corrosion. – Risk of toxic emissions. – Subsidence, landscape change, and polluting waterways. – Long construction time. – Hard to assess resource. – High cost.	Cooling 30–50% Heating 20–40% (Sarbu and Sebarchievici 2014)	Warm-climate region, Atlanta (cooling- dominated climate) Simulation
Solar energy PV	– Abundant supply. – Less environmental damage compared to other renewable options. – Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers. – Medium – high cost depending of the system used.	– Storage and backup issues. – Not constant supply.	22% (Irshad et al. 2019)	Energy saving potential PV integrated with the TE (thermoelectric technologies)
			12–25% (Luo et al. 2017)	Double skin façade using photovoltaic blinds (PV-DSF) Changsha, Hunan province, China Summer conditions
Solar thermal	– Abundant and clean supply. – Less environmental damage compared to other renewable options. – Significant energy savings.	– Storage and backup issues. – Not constant supply.	30% (Ahmadi et al. 2021)	Simulation HEAT4COOL
			Winter 75.8%, summer 51.5% (Hohne et al. 2019)	Hybrid solar Electric water heater
Biomass energy	– Abundant with a wide variety of feedstock and conversion technologies. – Indigenous fuel production and conversion technology in developing countries. – Low cost.	– May release GHGs during biofuel production. – Landscape change and deterioration of soil productivity.	94.98% (Zhang et al. 2019)	Hybrid solar-biomass
			16–94% (Pardo et al. 2020)	

Source: adapted from Luo et al. (2017); Irshad et al. (2019); Cabeza and Chàfer (2020).

9.SM.2 Supplementary Information to Section 9.5

Table 9.SM.4 presents the details to develop Figure 9.14.

Table 9.SM.4 | GHG mitigation potentials for categories of NT interventions for Residential (R) and Non-Residential (NR) buildings. n.f. = not found.

Region	Non-technological climate mitigation solution	Residential buildings	Commercial buildings	References
AF Africa	Active management and operation	n.f.	10%	McGibbon et al. (2014)
DEV Developed Countries	Active management and operation	53%	n.f.	Faber et al. (2012); Volochovic et al. (2012b); Thomas et al. (2017); European Climate Foundation (2018); Sköld et al. (2018b); Dugast and Soyeux (2019); Cantzler et al. (2020); Ellsworth-Krebs (2020); Ivanova and Büchs (2020b); Mata et al. (2020d); Niamir et al. (2020); Harris et al. (2021a)
	Circular and sharing economy	n.f.	15–75%	
	Flexible comfort	2–20%	n.f.	
	Limited/sufficient comfort levels	1–50%	n.f.	
	Multiple or unspecified behavioural changes	2–27%	8%	
	Passive management and operation	5–6%	n.f.	
	Social and organisational innovations	3%	3%	
Worldwide	Active management and operation	5%	n.f.	van Sluisveld et al. (2016); Ivanova and Büchs (2020); Cantzler et al. (2020); Harris et al. (2021)
	Circular and sharing economy	40–81%	n.f.	
	Limited/sufficient comfort levels	3–25%	n.f.	
	Multiple or unspecified behavioural changes	1–30%	n.f.	
	Passive management and operation	20%	n.f.	

9.SM.3 Supplementary information to Section 9.8

Table 9.SM.5 summarises the results of 17 studies from 12 different countries showing the price premium of energy efficient dwellings.

Table 9.SM.5 | Premium price for rent and sale in residential buildings with high energy performance and/or green features.

Ref	Study	Country/Region	From energy rating X to Y (Y/X)	Impact of energy performance		Comments
				Sale	*Rent*	
1	Tajani et al. (2018)	Italy (Bari)	A/[B,C,D,E,F]	27.9%		Evaluation based on energy performance certificates.
			G/[B,C,D,E,F]	–26.4%		
2	Ayala et al. (2016)	Spain	[A,B,C]/[D,E,F,G]	9.8%		Evaluation based on energy performance certificates.
3	Marmolejo-Duarte and Chen (2019)	Spain (Barcelona)	A/G	7.8%		Evaluation based on energy performance certificates.
			D/G	3.3%		
4	Kahn and Kok (2014)	US (California)	[Green label]/[non-labelled homes]	5.0%		Green labels considered comprise LEED, GreenPoint or Energy Star.
5	Fuerst et al. (2015)	UK (England)	[A,B]/D	5.0%		Evaluation based on energy performance certificates.
			C/D	1.8%		
			E/D	–0.7%		
			F/D	–0.9%		
6	Cajias et al. (2019)	Germany	A+/D		0.9%	Evaluation based on energy performance certificates.
			A/D		1.4%	
			B/D		0.1%	
			C/D		0.2%	
			F/D		–0.1%	
			G/D		–0.3%	
			H/D		–0.5%	

Ref	Study	Country/Region	From energy rating X to Y (Y/X)	Impact of energy performance		Comments
				Sale	*Rent*	
7	Hyland et al. (2013)	Ireland	A/D	9.3%	1.8%	Evaluation based on energy performance certificates.
			B/D	5.2%	3.9%	
			[F,G]/D	–10.6%	–3.2%	
8	Högberg (2013)	Sweden	10% improvement in energy performance.	4.0%		
9	Davis et al. (2015)	UK (Belfast)	B/D	28.0%		Evaluation based on energy performance certificates.
			C/D	4.9%		
			G/D	–2.0%		
10	Jensen et al. (2016)	Denmark	[A,B]/D	6.2%		Evaluation based on energy performance certificates after the advertising requirement implemented by 1 July 2010.
			C/D	5.1%		
			E/D	–5.4%		
			F/D	–12.9%		
			G/D	–24.3%		
11	Fuerst et al. (2016)	Finland (Helsinki)	[A,B,C]/D	1.5 –3.3%		Evaluation based on energy performance certificates. The lower value in estimated when a set of detailed neighbourhood characteristics are included. Results of models 2 and 3 are presented here.
12	Cadena and Thomson (2015)	US (Texas)	Green designation/No	0.7%		The models B, D, and F presented here incorporating as independent variable at least one green designation or green/energy efficient feature.
			Green features/No	1.7%		
			Energy efficient features/No	5.8%		
13	Jayantha and Man (2013)	Hong Kong SAR of China	Green certification/No certification	3.4–6.4%		BEAM certification and GBC Award are used as the measurement of green residential buildings.
14	Brounen and Kok (2011)	Netherlands	A/D	10.2%		Evaluation based on energy performance certificates.
			B/D	5.6%		
			C/D	2.2%		
			F/D	–2.5%		
			G/D	–5.1%		
15	Deng et al. (2012)	Singapore	Platinum/No certification	21.0%		Evaluation of dwellings awarded with a Green Mark.
			[Gold plus, Gold]/No certification	15.0%		
			Green mark/No certification	10.0%		
16	Zheng et al. (2012)	China (Beijing)	Green features/No	17.7%	–8.5%	Dwellings with green characteristics in relation to conventional ones.
17	Koirala et al. (2014)	US	Existence of energy efficiency building energy codes/No		23.3%	The existence of the codes IECC2003 through IECC2006 for American households is evaluated in this study.

9.SM.4 Supplementary Information to Section 9.9

Box 9.SM.1 presents an example of a policy package, to complement, Section 9.9.

Box 9.SM.1 | EU Policy Package for Energy Efficiency of Buildings

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

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

In 1992, a first EU law (Save Directive) encouraged EU Member States (MSs) to adopt energy performance standards in building energy codes, this resulted in mix action by MSs, with only a few adopting stringent energy performances requirements. To reinforce the action by MSs and align it, in 2002 the EU adopted the Energy Performance Buildings Directive (EPBD 2002), requiring MSs to adopt minimum efficiency performance standards for buildings according to a common methodology both for new and existing buildings, when undergoing major renovation (Bertoldi 2019). The EPBD is a regulatory measure, with its implementation left to individual MSs. This has resulted in very different levels of stringency among MSs. In addition, the enforcement of control on the application of the energy performance requirements is left to national authorities and finally delegated to local authorities, who may lack the technical knowledge or manpower to check compliance with legal requirements. This has resulted in low compliance with normative requirements in many MSs. The 2002 EPBD has also introduce the obligation to show an energy performance certificate when a building is sold or rented (information policy) (Li et al. 2019a). In 2010, the EPBD was amended by introducing the requirements for MSs to set the national energy requirement for new and existing buildings at the cost-optimal level and providing a common methodology for calculating it (Zangheri et al. 2018; Corgnati et al. 2013). The 2010 EPBD introduced the requirement for all new buildings to be nearly zero energy (nZEBs) by 2021, however definitions of nZEBs are again left to EU Member States, which have different requirements for energy consumption limits and contribution of renewables (Attia et al. 2017; Grove-Smith et al. 2018; D'Agostino and Mazzarella 2019; Economidou et al. 2020). In 2018 the latest amendment of the EPBD introduced the requirements for MSs to prepare Long-Term Renovation Strategies (LTRSs) with an overarching decarbonisation target of the national building stock by 2050. In late 2021 the Commission will propose a new amendment to align it with the new –55% GHG target for 2030 and the decarbonisation goal of 2050.

The 2012 Energy Efficiency Directive (EED) requested MSs: to adopt smart meters and smart billing and to charge consumers on their real heating energy consumption, to remove the split-incentive barriers, to foster energy efficient procurement by public authorities, to renovate each year at least 3% of the building stock of central governments. Article 7 of the EED established the obligation for MSs to set up mandatory obligation for energy companies to save at least 1.5% of their energy sales by implementing energy efficiency actions in end-users, including measure on buildings (Fawcett et al. 2019 or alternative policy measures delivering the same amount of energy savings (Rosenow and Bayer 2017). The EED encourages the setting up of financing programmes for the renovation of buildings. MSs have implemented a number of financial mechanisms such as low interest loans, grants, guarantees funds, revolving funds and so on (Bertoldi 2020). Moreover, the EU Regional and Cohesion Funds are also used by MSs for the renovation of existing buildings. Some of the instruments used at national level to finance the renovation of dwellings occupied by low-income families result from the auctioning of allowances under the EU Emissions Trading Scheme, which is used in some MSs.

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

Box 9.SM.1 (continued)

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

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

In the EU over 10,000 cities taking part in the Covenant of Mayors initiative (Palermo et al. 2020) have adopted measures to improve the energy efficiency of public and private as part of the city planning or city building permits.

Despite the comprehensiveness of the EU policy package, the monitoring of the progress made in reducing GHG from the EU building stock shows that the EU would miss its buildings' decarbonisation target for 2050. The following issues were identified as major obstacles to Europe's decarbonisation strategy of the building stock. The inconsistencies between the overarching target of a decarbonised building stock by 2050 and the energy requirement in case of major renovation of existing buildings. Both requirements are included in the EPBD. As of today, there is enough evidence about the lock-in effect of the renovation requirements included in the EPBD. The complexity, and sometimes the impossibility, of bundling public finance targeting GHG mitigation of buildings, with private finance. The Smart Finance for Smart Building (SFSB) initiative addresses this issue only partially. The lack of rigorous monitoring, verification and enforcement (MV&E) for both buildings (including the Energy Performance Gap) and appliances performances, which reduce the level of expected savings. There is no concrete measure to avoid the direct rebound effect and the current energy prices are relatively low. In addition, there are no specific policies and measures at EU level to address energy sufficiency. Regulations and technical standards do not include the lifecycle CO_2 emissions in the performance of the buildings. The complexity of the governance structure at different levels (EU, National, Regional and Local), with many options left to individual MSs, for example the definition of 'near zero energy buildings' (nZEBs). The complexity of managing several instruments, often dealt by different national ministries and departments (industry, environment, construction, urbanisation, etc.) and, finally, the disconnect between high-level EU targets and the lack of ambition of individual policies, which makes the decarbonisation of the EU building stock more challenging. The 2020 Renovation Wave Communication addresses the above issues, in particular on financing renovation of buildings. As indicated the planned revision of the EPBD and EED in 2021 will partly address the above shortcoming, by addressing the new 2030 target and climate neutrality at 2050. Moreover, the EU financing instrument for the post-Covid recovery, the 'EU Next Generation', has earmarked funding for the climate transition, including building renovations. EU MSs have to prepare national Resilience and Recovery Plans. In addition, the EU launched the New Bauhaus Initiative, which aims to change and improve EU citizens daily life in buildings by creating a new lifestyle that matches sustainability, low carbon and affordability with good design. Finally, the EU Commission has proposed to extend the EU Emission Trading Systems to buildings.

9.SM.5 Supplementary Information to Section 9.9

Table 9.SM.6 details the feasibility assessment presented in Figure 9.20.

Table 9.SM.6 | Context and line of sight for the feasibility assessment of mitigation options in the buildings sector.

	Geophysical dimension		
Mitigation options[a]	**Physical potential**	**Geophysical recourses**	**Land use**
Building design and performance [S]	Not applicable	Not applicable	Not applicable
Change in construction methods and circular economy [S]	It is expected that in advanced construction methods (e.g., Building Information Modelling – BIM, industrialisation and rationalisation, design for deconstruction/disassembly, digital fabrication and design for performance) there is a reduction in the consumption of raw materials and natural resources. Design for deconstruction/disassembly allows increasing the reuse potential of building materials and elements. Materials reuse avoid impacts related to the consumption of virgin resources and end-of-life wastes. This decreases pressure for geophysical resources and land use.		
	Ortiz et al. 2009; Cabeza et al. (2014); Ingrao et al. (2014); Diyamandoglu and Fortuna (2015); Hong et al. (2015); Geyer et al. 2016; Agustí-Juan et al. (2017a); Chau et al. (2017); Soust-Verdaguer et al. (2017); Vadenbo et al. (2017); Ahmed and Tsavdaridis (2018); Eckelman et al. (2018); Junnila et al. (2018); Röck et al. (2018); Brambilla et al. (2019); Cavalliere et al. (2019); Navarro-rubio; Pineda and García-martínez 2019); Alhumayani et al. (2020); Ghayeb et al. (2020); González Mahecha et al. (2020); Habert et al. (2020); Kakkos et al. (2020); Kuzmenko et al. (2020); Li and Zheng (2020); Mata et al. (2020[a]); Saade et al. (2020); Santos et al. (2020); Soust-Verdaguer, Llatas, and Moya (2020); Huang et al. (2021); Yu et al. (2021).		
Envelope improvement [E]	Not applicable in historical and heritage buildings where modifications to facade are difficult. Transparent insulation materials (TIM) have the advantage of allowing the use of daylight. Green Roofs enhance building aesthetics and reduce heat gains and losses. Thermal mass is not always beneficial in relation to thermal comfort and energy consumption. Phase change materials (PCM) reduce internal temperature fluctuations in buildings, providing better thermal comfort to occupants. Trombe walls are aesthetically appealing, but in regions with mild winters and hot summers, overheating problems may outweigh the winter benefits.	Conventional insulation materials are derived from petrochemical substances but new sustainable insulation materials have been developed. To consider green roofs as an environmentally friendly technology, the selection of efficient and sustainable components is extremely important. Green walls are still controversial. Improvements in thermal inertia can be achieved with the use of materials with high density, such as concrete or rammed earth or phase change materials (PCM). The process of autoclaving concrete requires significant energy consumption.	Not applicable
	Tatsidjodoung et al. (2013); Pérez et al. (2014); Kalnæs Simen Edsjøand Jelle (2015); Charoenkit and Yiemwattana (2016); Laborel-Préneron et al. (2016); Navarro et al. (2016a); Omrany et al. (2016); Aditya et al. (2017); Olsthoorn et al. (2017); Cabeza et al. (2018); Cascone et al. (2018); Shafigh et al. (2018); Sun et al. (2018a); Belussi et al. (2019); Bhamare et al. (2019); Irshad et al. (2019); Lidelöw et al. (2019); Cabeza et al. (2020); Cabeza and Chàfer (2020).		
Heating, ventilation and air conditioning (HVAC) [E]	High space requirements in buildings.	NA, with the exception of CO_2 storage, through CO_2-based refrigerants.	Not applicable
	Prívara et al. (2011); Abas et al. (2014); Bamisile et al. (2019); Gong et al. (2019); Dilshad et al. (2020); Dong et al. (2020); Ling et al. (2020); Mi et al. (2020); Peng et al. (2020); Zhang et al. (2020a).		
Efficient Appliances [E]	There are technical limitations to energy efficiency, but there is much room for improvement, especially in developing countries.	Not applicable	Not applicable
	Saheb et al. (2018); González-Mahecha et al. 2019; Singh et al. (2019); González Mahecha et al. (2020).		
Change in construction materials [E]	Some low carbon construction materials are already used in civil construction. The physical availability of materials (e.g., wood, bamboo, bio-concretes, earth, concrete with limestone and supplementary cementitious materials and limestone calcined clay cement) is abundant, although there may be some regional scarcity depending on the scale of adoption.		For bio-based materials, feedstock can be developed in degraded areas. However, land competition with agriculture, food and other industrial uses (e.g., cellulose) can happen.
	Van Den Heede and De Belie (2012); Zea Escamilla and Habert (2014); Celik et al. (2015); Fouquet et al. (2015); Berriel et al. (2016); Peñaloza et al. (2016); Teixeira et al. (2016); Zea Escamilla et al. (2016); Cancio Díaz et al. (2017); ; Ruggieri et al. (2017); Arrigoni et al. (2018); Chang et al. (2018); Escamilla et al. (2018); Nakic (2018); Pittau et al. (2018); Ben-Alon et al. (2019); Pillai et al. (2019); Alhumayani et al. (2020); Churkina et al. (2020); Pomponi et al. (2020); Rosse Caldas et al. (2020); Soust-Verdaguer et al. (2020).		
Demand-side management (active management operation, digitalisation and flexible comfort requirements) [E]	Not applicable	Not applicable	Not applicable
Renewable energy production [R]	Large untapped potential for most technologies. Rural areas have a great potential for renewable energy sources.	Most technologies not limited by materials.	Not applicable
	Calvert and Mabee (2015), Capellán-Pérez et al. (2017), Poggi et al. (2018).		

[a] [S] Sufficiency, [E] Efficiency, [R] Renewable energy.

	Environmental-ecological dimension			
Mitigation options[a]	**Air pollution**	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**
Building design and performance [S]	As a result of the reduced consumption of natural resources and reduced air pollution levels.			Green roofs and walls, particularly if connected to other green spaces, enhance urban biodiversity.
	Hui and Chan (2011); Sunikka-Blank et al. (2012); Joimel et al. (2018); Mayrand and Clergeau (2018).			
Change in construction methods and circular economy [S]	The use of Building Information Modelling (BIM) together with the lifecycle assessment (LCA) methodology allows a faster, holistic and more assertive assessment of the potential environmental impacts of a building project, reducing impacts throughout the project's lifecycle. Advanced construction methods are expected to reduce the consumption of raw materials and natural resources and associated environmental impacts during the production of these materials. In addition, it is expected a decrease in waste generation. However, some trade-offs between environmental impacts can occur, depending on products/processes. Reduced environmental impact depends on solutions and materials. Potential rebound for reduced ownership.			
	Ortiz et al. 2009; Osmani (2012); André and Jorge (2013); Lu and Yuan (2013); Cabeza et al. (2014); Ajayi et al. (2015); Cossu and Williams (2015); Diyamandoglu and Fortuna (2015); Ingrao et al. 2014; Geyer et al. (2016); Agustí-Juan et al. (2017a); Agustí-Juan et al. (2017); Amal et al. (2017); Soust-Verdaguer et al. (2017); Vadenbo et al. 2017; Zink and Geyer (2017); Ahmed and Tsavdaridis (2018); Eckelman et al. (2018); Junnila et al. (2018); Schiller et al. (2018); Brambilla et al. (2019); Volk et al. (2019); Alhumayani et al. (2020); Habert et al. (2020); González Mahecha et al. (2020); Kuzmenko et al. (2020); Mata et al. 2020a; Mohit et al. (2020); Saade et al. (2020); Santos et al. (2020); Huang et al. (2021).			
Envelope improvement [E]	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor).	As a result of the reduced consumption of natural resources and reduced air pollution levels.	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.	Reduced air pollution levels achieved by mitigation actions improves biodiversity.
	Hui and Chan (2011); Holland et al. (2015); Fricko et al. (2016); Levy et al. (2016); Balaban and Puppim de Oliveira (2017); Joimel et al. (2018); Thema et al. (2017); MacNaughton et al. (2018); McCollum et al. (2018); Mayrand and Clergeau (2018); Mzavanadze (2018).			
Heating, ventilation and air conditioning (HVAC) [E]	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor).	As a result of the reduced consumption of natural resources and reduced air pollution levels.	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.	Reduced air pollution levels achieved by mitigation actions improves biodiversity.
	Holland et al. (2015); Fricko et al. (2016); Levy et al. (2016); Balaban and Puppim de Oliveira (2017); Ferreira et al. (2017); Thema et al. (2017); MacNaughton et al. (2018); McCollum et al. (2018); Mzavanadze (2018).			
Efficient appliances [E]	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor). The promotion of improved cook-stoves and other modern energy-efficient cooking appliances, are of paramount importance to improve indoor air quality in several developing countries.	Positive impacts as a result of the reduced consumption of natural resources and reduced air pollution levels. On the other hand, a switch to more efficient appliances could result in negative impacts from increased resource use, which can be mitigated by avoiding premature replacement and maximising the recycling of old appliances.	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.	Reduced air pollution levels due to mitigation actions improves biodiversity.
	Holland et al. (2015); Fricko et al. (2016); Levy et al. (2016); Smith et al. (2016); Thema et al. (2017); Thema et al. (2017); Balaban and Puppim de Oliveira (2017); Goldemberg et al. (2018); MacNaughton et al. (2018); McCollum et al. (2018); Mzavanadze (2018); Rosenthal et al. (2018); Steenland et al. (2018).			
Change in construction materials [E]	Engineered wood/bamboo products normally use petroleum-based adhesives, which can release toxic gases (e.g., formaldehyde and volatile organic compounds – VOCs). Lifecycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with supplementary cementitious materials (SCM) replacing cement or clinker is less polluting.	Some biomass treatment processes use toxic materials and substances. The use of fertilisers in forestry activities can increase eutrophication. Lifecycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with supplementary cementitious materials (SCM) replacing cement or clinker is less polluting.	An increase in water demand can be observed during the forest activities.	Normally monoculture production is encouraged and can put pressure on native forest areas.
	Van Den Heede and De Belie (2012); Zea Escamilla and Habert (2014); Celik et al. (2015); Heeren et al. (2015); Peñaloza et al. (2016); Teixeira et al. (2016); Zea Escamilla et al. (2016); Cancio Díaz et al. (2017); Ruggieri et al. (2017), Widder (2017), Arrigoni et al. (2018); Chang et al. (2018); Escamilla et al. (2018); Harb et al. (2018); Nakic (2018); Pittau et al. (2018); Ben-Alon et al. (2019); Pillai et al. (2019); Xiong et al. 2019; Alhumayani et al. (2020); Churkina et al. (2020); Pomponi et al. (2020); Rosse Caldas et al. (2020); Sotayo et al. (2020); Soust-Verdaguer et al. (2020); Pauliuk et al. (2021).			

	Environmental-ecological dimension			
Mitigation options[a]	**Air pollution**	**Toxic waste, ecotoxicity eutrophication**	**Water quantity and quality**	**Biodiversity**
Demand-side management (active management operation, digitalisation and flexible comfort requirements) [E]	Support interventions can eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor). However, it should be taken into account that smart controls and connected devices result in increased electricity consumption.	As a result of reduced consumption of natural resources and air pollution levels.	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities. Smart meters give the opportunity to monitor and reduce water consumption in households.	Reduced air pollution levels achieved by mitigation actions improves biodiversity.
	Miara et al. (2014); Holland et al. (2015); Beucker et al. 2016; Creutzig et al. (2016); Fricko et al. (2016); Levy et al. 2016; Balaban and Puppim de Oliveira (2017); International Energy Agency (2017); Jabir et al. (2018); Thema et al. (2017); MacNaughton et al. (2018); McCollum et al. (2018); Mzavanadze (2018); B. Yang et al. 2019; Sovacool et al. (2020).			
Renewable energy production [R]	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor).	Not applicable	An upscaling of renewable energy systems can reduce water demand for thermal cooling at energy production facilities. Improved access to electricity is necessary to treat water at homes. In some situations switching to bioenergy could increase water use compared to existing conditions.	Reduced air pollution levels achieved by mitigation actions improves biodiversity. Bioenergy production may have both positive and negative impacts on biodiversity.
	Immerzeel et al. (2014); Hejazi et al. (2015); Holland et al. (2015); Fricko et al. (2016); Song et al. 2016; Ürge-Vorsatz et al. (2016); Correa et al. (2017); Thema et al. (2017); Balaban and Puppim de Oliveira (2017); Rao and Pachauri (2017); Goldemberg et al. (2018); Rosenthal et al. (2018); Steenland et al. (2018); McCollum et al. (2018); Mzavanadze (2018c); Wu et al. (2018).			

[S] Sufficiency, [E] Efficiency, [R] Renewable energy.

	Technological dimension		
Mitigation options[a]	**Simplicity**	**Technological scalability**	**Maturity and technology readiness**
Building design and performance [S]	Wide range of measures with different levels of simplicity. A straightforward approach to reducing emissions from materials and energy demand in new buildings is by building smaller, especially in developed regions.	Limited by buildings' stock lock in, in which case retrofitting may be necessary.	Wide range of measures with different levels of maturity.
	Bomberg, Furtak, and Yarbrough (2017); Grubler et al. (2018); Singaravel, Suykens, and Geyer (2018); Li et al. (2019); Si et al. (2019); Deng et al. (2020); Ge et al. (2020); Rice (2020); Roca-Puigròs et al. (2020); Vilar et al. (2020); Aimar and Foti (2021); Berrill and Hertwich (2021); Dalla Valle (2021); Danny and Soo (2021); Du (2021); Feng et al. (2021); Getuli and Bruttini (2021); Gholami; Røstvik and Steemers (2021); Hosseini et al. (2021); Kunwar, Cetin, and Passe (2021); Pauliuk et al. (2021); Čurpek and Čekon (2022).		
Change in construction methods and circular economy [S]	Many advanced construction methods are common and widespread, mainly in developed countries. There is a need for a change of thinking during the project design, especially for complex building design and shapes. Prescriptive standards need to be modified so that products and processes achieve the final performance required for a given situation/need. Circular solutions (reduced waste, materials reuse and recycling) have varying technological complexity.	Construction methods can be applied for a building component, façade or to a whole building. However, it tends to be more difficult to apply to larger scale projects. Circular solutions are not yet implemented at scale. Requires improved design for flexibility and deconstruction, improved procurement and prefabrication and off-site construction, improved standardisation and dimensional coordination, with differences among solutions.	Some technologies are well known, but their market applicability varies from country to county. There are few projects using highly advanced construction methods (e.g., Building Information Modelling, design for deconstruction/disassembly, digital fabrication and design for performance). Technological improvements in circular economy are expected (waste reduction and management, recycling and materials and products upgrade), together with improved compatibility with existing design, tools and technologies.
	Osmani (2012); André and Jorge (2013); Lu and Yuan (2013); Ajayi et al. (2015); Cossu and Williams (2015); Diyamandoglu and Fortuna (2015); Hong et al. (2015); Agustí-Juan et al. (2017a); Amal et al. (2017); Amal et al. (2017); Chau et al. (2017); Soust-Verdaguer et al. (2017); Niamir et al. (2017); Soust-Verdaguer et al. (2017); Ahmed and Tsavdaridis (2018); Eckelman et al. (2018); Röck et al. (2018); Schiller et al. (2018); Schmidt, Alexander, and John (2018); Cavalliere et al. (2019); Brambilla et al. (2019); Pineda and García-martínez (2019); Volk et al. 2019; Alhumayani et al. (2020); Habert et al. (2020); Ghayeb et al.(2020); González Mahecha et al. (2020); Brambilla et al. (2019); Huang et al. (2021); Diyamandoglu and Fortuna (2015); Eckelman et al. (2018); Habert et al. (2020); Kakkos et al. (2020); Kuzmenko et al. (2020); Li and Zheng (2020); Llatas, and Moya (2020); Mohit et al. (2020); Saade et al. (2020); Navarro-rubio, Huang et al. (2021); Yu et al. (2021).		

	Technological dimension		
Mitigation options[a]	Simplicity	Technological scalability	Maturity and technology readiness
Envelope improvement [E]	There are different envelope measures with different levels of simplicity. Building integrated concepts (such as insulation or phase change materials) are very simple. Reducing infiltration is achieved by replacing windows and doors, and sealing cracks, the simplicity of this varies by building. Other concepts such as greenery systems can be more complicated.	From a façade to a building to a multifamily house.	Insulation is very well-known technology, however sustainable materials need future research. A step forward is the use of transparent insulation materials (TIM) for building energy savings and daylight comfort. Vertical greenery systems are still controversial depending on the climate and materials. Phase change materials can be organic or inorganic, each type with their advantages and disadvantages.
	Soares et al. (2013); Tatsidjodoung et al. (2013); Noro et al. (2014); Pérez et al. (2014); Raji et al. (2015); Khadiran et al. (2016); Laborel-Préneron et al. (2016); Mavrigiannaki and Ampatzi (2016); Omrany et al. (2016); Silva et al. (2016); Aditya et al. (2017); Riley (2017); Riley (2017); Reddy et al. (2018); Shafigh et al. (2018); Sun et al. (2018b); Wang et al. (2018); Belussi et al. (2019); Drissi et al. (2019), Irshad et al. (2019).		
Heating, ventilation and air conditioning (HVAC) [E]	Different levels of simplicity depending on the technology. Evaporative cooling systems have higher simplicity than heat pumps and ground-coupled systems.	It is widely implemented at all scales. For example, vehicles, houses, buildings, warehouses, and so on.	It is a widely implemented technology. Efforts continue to be allocated to research and development to improve energy efficiency.
	Choe (1973); Mujahid Rafique et al. (2015); Harby et al. (2016); Soltani et al. 2019; Cvok et al. (2020); Hadjadj et al. (2020); Husin et al. (2020); Peng et al. (2020); Ling et al. (2020); Pahinkar et al. (2020); Sha and Qi (2020); Talkar et al. (2020); Teja S. and Yemula (2020); Zhang et al. (2020a); Chen et al. (2021); Lo Basso et al. (2021).		
Efficient appliances [E]	Simple efficiency improvements are available in many regions. However, increasing appliance efficiency can be complex in countries with already high efficient standards.	Can be easily scaled up.	Many efficient appliances are technologically mature. Moreover, efforts continue to be allocated to research and development to improve energy efficiency.
	Ma et al. (2016); Zhang et al. (2016); Cabeza et al. (2018); Kaur and Bala (2019); Rajagopal et al. (2019); Singh et al. (2019); Himeur et al. (2020); Hopkins et al. (2020); Joshi et al. (2020); Mariano-Hernández et al. (2021); Wang et al. (2021).		
Change in construction materials [E]	Bio-concretes use available materials and similar infrastructure of conventional concrete production. However, more research is needed. Biomaterials are widely used and have a variety of applications in residential, commercial and industrial buildings. However, attention is needed for fire protection and biological durability. Other materials such as earth, concrete with limestone and supplementary cementitious materials and limestone calcined clay cement use available materials with adequate performance and similar infrastructure of Portland cement production.	Biomaterials can be applied to furniture, façade and to the whole building in general. Bio-concrete can be used to produce construction elements that do not require high mechanical performance. Emissions from cement can be reduced by using alternative binders, electrifying kilns, using substitute cementitious materials, and reducing over specification of building elements.	Some bio-based materials (e.g., wood and bamboo) are well known and widespread used. However, their applicability in varies from country to county. Some bio-concretes (e.g., hempcrete) are already available in the market. However, they are still not widespread in the construction industry. Other bio-concretes are still at the research phase. The use of limestone in large quantities still needs to be further researched. Earth materials and some supplementary cementitious materials are already used commercially, such as soil-cement bricks and fly ash, respectively. However, others are still at the research stage.
	Van Den Heede and De Belie (2012); Zea Escamilla and Habert (2014); Berriel et al. (2016); Gursel, Maryman, and Ostertag (2016); Peñaloza et al. (2016); Teixeira et al. (2016); Zea Escamilla et al. (2016); Cancio Díaz et al. (2017); Ruggieri et al. (2017); Widder (2017); Arrigoni et al. (2018); Chang et al. (2018); Escamilla et al. (2018); Nakic (2018); Pittau et al. (2018); Ben-Alon et al. (2019); Pillai et al. (2019); Alhumayani et al. (2020); Churkina et al. (2020); Pamenter and Myers (2021); Pomponi et al. (2020); Rosse Caldas et al. (2020); Soust-Verdaguer et al. (2020).		
Demand-side management (active management operation, digitalisation and flexible comfort requirements) [E]	Ranges from very simple monitoring sensors, or simple concepts to smart cities.	High potential for scalability. Simple measures can be easily upscaled via information campaigns and a high willingness to adopt in some regions. Nevertheless, cultural values and local physical conditions can affect the scalability of measures that affect comfort and well-being directly. Information and communication technologies, peer effects and rewards could help foster scalability, keeping in mind potential barriers such as perception of control, concerns over information sharing and privacy and expectations in terms of effort and benefits.	The simple measures require no technology development, while more complex measures are already widely available, still with potential for improvement.
	Christidou et al. (2014); (Jensen et al. (2015); Miezis et al. (2016b); Sadeghi et al. (2016); Khan (2019); Dane; Kim and Yang (2020); Osunmuyiwa et al. (2020); Spandagos et al. (2020); Al-Shareefi et al. (2021); Ardito et al. (2021); Del Río Castro et al. (2021); Del Río Castro et al. (2021); Dornberger and Schwaferts (2021); Gavrila Gavrila and de Lucas Ancillo (2021); Pigliautile et al. (2021); Sabarish et al. (2021); Serrano (2021); Strenger and Frerich (2021); Wan and Bai (2021).		

	Technological dimension		
Mitigation options[a]	**Simplicity**	**Technological scalability**	**Maturity and technology readiness**
Renewable energy production [R]	Most technologies are simple. However, supply of technical support at the local scale can be a barrier. Hybridisation between several technologies can achieve better results both for energy production and power generation.	Most technologies can be scaled up to most regions.	Most technologies are mature. Moreover, efforts continue to be allocated to research and development to improve.
	Cabeza and Chàfer (2020); Guo et al. (2020); Montoya and Perea-moreno (2020); Reindl and Palm (2020); Shahid (2018); Singh et al. (2020); Ürge-Vorsatz et al. (2020); Usman et al. (2020); Gonçalves et al. (2021).		

[a] [S] Sufficiency, [E] Efficiency, [R] Renewable energy

	Economic dimension	
Mitigation Options[a]	**Costs in 2030 and long term**	**Employment effects and economic growth**
Building design and performance [S]	There is evidence of new buildings with very high performance relying on advanced design, such as net-zero energy buildings (NZEB), with lower investment costs than standard practices. These buildings are not yet universally cost-effective and often 0–10% more expensive than buildings built according to minimum energy performance standards. The incremental costs of these buildings are however expected to decline further.	Limited Evidence.
	Energetics (2016); Canes (2018); D'Agostino and Parker (2018); Köhler et al. (2018); Erhorn-Kluttig et al. (2019); Morck et al. (2019); Nocera et al. (2019); Onyenokporo and Ochedi (2019); Zinzi and Mattoni 2019; Ürge-Vorsatz et al. (2020).	
Change in construction methods and circular economy [S]	Potential cost-competitiveness (lower lifecycle costs, green/quality premium) for circular economy, but still uncertain to large-scale investors due to perceived higher investment costs.	Construction is a labour-intensive activity, which means there are potential positive effect along the value chain (job creation, business value, networking), including synergies with digitalisation.
	Mokhlesian and Holmén (2012); Vatalis et al. (2013); Ferreira et al. (2015); Schenkel et al. (2015); Debacker and Manshoven (2016); Energetics (2016); Witjes and Lozano (2016); Azcárate-Aguerre et al. (2018); Canes (2018); D'Agostino and Parker (2018); Ghisellini et al. (2018); Köhler et al. (2018); Hart et al. (2019b); Morck et al. (2019); Nocera et al. (2019); Erhorn-Kluttig et al. (2019); Onyenokporo and Ochedi (2019); Zinzi and Mattoni (2019); L.K. et al. (2020b); L.K. et al. (2020a); Ürge-Vorsatz et al. (2020), Patwa et al. (2021).	
Envelope improvement [E]	There are many individual examples of cost-effective deep retrofits involving envelope improvement. However, few studies calculate the costs of deep retrofits at a large scale. Literature tends to agree that cost-effective deep retrofits are not universally applicable for all cases and at a large scale, being one of the most expensive measures. Due to high upfront costs, the key factor determining feasibility is coupling the retrofit with business-as-usual improvement and applying an industrialised one-stop-shop approach. Given the long payback time, energy price dynamics and a discount rate play an especially large role.	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy expenditures and fostering innovation. Improvements in labour productivity.
	Mirasgedis et al. (2014); Markewitz et al. (2015); Mata et al. (2015, 2019); European Commission (2016); Holopainen et al. (2016); Ürge-Vorsatz et al. (2016); Akander et al. (2017); Ismailos and Touchie (2017); Mofidi and Akbari (2017); Niemelä et al. (2017); Paduos and Corrado (2017); Semprini et al. (2017); Streicher et al. (2017); Subramanyam et al. (2017b,a); Thema et al. (2017); D'Oca et al. (2018); McCollum et al. (2018); Novikova et al. (2018); Saheb et al. (2018); Alawneh et al. (2019); BAL KOÇYİĞİT et al. (2019); Bleyl et al. (2019); Cabrera Serrenho et al. (2019); Nocera et al. (2019); Österbring et al. (2019); Reiter et al. (2019); Zuhaib and Goggins (2019); Grande-Acosta and Islas-Samperio (2020); Stancioff et al. (2021); Streicher et al. (2020); Zhang et al. (2021).	
Heating, ventilation and air conditioning (HVAC) [E]	Cost-effectiveness depends on the HVAC technology and its maturity. It could range from very cost-effective to not cost-effective. Incremental costs of advanced HVAC such as heat pumps and those based on integrated renewables are expected to decline due to learning and market development. HVAC-related measures come with high upfront capital costs, which act as a barrier for stakeholders even if the investment is cost-effective in the long term. Given the long payback time, energy price dynamics and a discount rate play an especially large role.	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy expenditures and fostering innovation. Improvements in labour productivity.
	Afshari et al. (2014); Mirasgedis et al. (2014); Energetics (2016); European Commission (2016); Ürge-Vorsatz et al. (2016); Akander et al. (2017); Ismailos and Touchie (2017); Mofidi and Akbari (2017); Niemelä et al. (2017); Subramanyam et al. (2017a,b); Thema et al. (2017); Vijay and Hawkes (2017); Köhler et al. (2018); McCollum et al. (2018); Saheb et al. (2018); Alawneh et al. (2019); Bleyl et al. (2019); González-Mahecha et al. (2019); Alajmi et al. (2020); Cruz et al. (2020); Grande-Acosta and Islas-Samperio (2020); William et al. (2020); Calise et al. (2021); Deetjen et al. (2021); Rafique and Williams (2021), Seeley and Dhakal (2021).	

	Economic dimension	
Mitigation Options[a]	**Costs in 2030 and long term**	**Employment effects and economic growth**
Efficient appliances [E]	Efficient appliances are typically among the most cost-effective technologies. This is a key mitigation option. The risk is however that more efficient appliances may have larger sizes and other advanced features that to some extent offsets the positive economic effects.	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy expenditures and fostering innovation. Improvements in labour productivity. Expanding clean cooking in developing countries would increase the productive time for women and children that can be used for income generation or rest.
	Department of Environmental Affairs (2014); Mirasgedis et al. (2014); Galán-Marín et al. (2015); Prada-hernández et al. (2015); Energetics (2016); European Commission (2016); Mills (2016); Ürge-Vorsatz et al. (2016); Bonan et al. (2017); Mofidi and Akbari (2017); Niemelä et al. (2017); Makumbe et al. (2017) ; Mehetre et al. (2017); Thema et al. (2017); Subramanyam et al. (2017a,b); D'Agostino and Parker (2018); Saheb et al. (2018); McCollum et al. (2018); Alawneh et al. (2019); Bleyl et al. (2019); González-Mahecha et al. (2019); Alajmi et al. (2020); Churkina et al. (2020); Grande-Acosta and Islas-Samperio (2020); Ren et al. (2021).	
Change in construction materials [E]	There are only a few fragmented studies on the cost implications of the change in construction materials.	Potential positive effect along the value chain (job creation and value added).
	Zea Escamilla et al. (2016); Cabrera Serrenho et al. (2019); Nambiar (2019); Churkina et al. (2020); Pomponi et al. (2020); Winchester and Reilly (2020); Zhang et al. (2021).	
Demand-side management (active management operation, digitalisation and flexible comfort requirements) [E]	Demand-side management measures have proved to be among the most cost-effective measures. Many of them (e.g., various sensors, controls, energy consumption feedback measures) are already mature and are typically very cost-effective. Many more are appearing such as advanced smart management systems or thermal and electric storages linked to fluctuating renewables. These are not yet al.ays cost-effective, but literature tends to expect these solutions to become cost-effective due to learning and scale.	Implementing digitalisation to enhance energy efficiency of buildings creates new jobs, which are mainly upfront by nature. At the same time, the increased use of data, sensors, smart devices, and HighD printing could provide new businesses job opportunities in advanced manufacturing. Furthermore, the implementation of digitalisation interventions to consumers and enterprises could create long-term jobs due to innovations and new technologies and increase the competitiveness and productivity of local enterprises. Flexible comfort requirements enhance economic dispatching of electric systems, resulting in lower energy prices and contributing to economic development. All interventions, create positive and negative direct and indirect effects associated with lower energy demand, possible reductions in energy prices and lower energy expenditures.
	Afshari et al. (2014); Deepak and Hussain (2015); Nguyen et al. (2015); Prada-hernández et al. (2015); Stötzer et al. (2015); Energetics (2016); Aryandoust and Lilliestam (2017); Balaban and Puppim de Oliveira (2017a); International Energy Agency (2017); Subramanyam et al. (2017a); Thema et al. (2017); Jabir et al. (2018); McCollum et al. (2018); Saheb et al. (2018); Huang et al. (2019); Sovacool et al. (2020); Costa and Soares (2020); Uchman (2021); Köhler et al. (2018); Alajmi et al. (2020); Janhunen, Leskinen, and Junnila (2020); Mata et al. (2020); Schäuble, Marian, and Cremonese (2020); Duman et al. (2021); Seeley and Dhakal (2021); Sharda et al. (2021); Stancioff et al. (2021); Rashid et al. (2021).	
Renewable energy production [R]	The cost-effectiveness of buildings-integrated renewable energy technologies varies. Such measures as roof-top PVs have become cost-effective in several regions worldwide. Still in many locations, they remain expensive technologies. Learning curves are expected to bring them further down by 2030 and beyond.	Positive and negative direct and indirect effects associated with lower demand for fuels and possible reductions in energy prices, renewable energy systems (RES) investments, improved energy access and fostering innovation. Improvements in labour productivity. In addition, electrification of remote rural areas and other regions that do not have access to electricity, through RES and microgrids, enables people living in poor developing countries to read, socialise, and be more productive during the evening, and it is also associated with greater school attendance by children.
	Torero (2015); Rao et al. (2016); Ürge-Vorsatz et al. (2016); Mofidi and Akbari (2017); European Commission (2016); Akander et al. (2017); Makumbe et al. (2017); Niemelä et al. (2017); Thema et al. (2017); Barnes and Samad (2018); Köhler et al. (2018);McCollum et al. (2018); Saheb et al. (2018); Alawneh et al. (2019); Bleyl et al. (2019); Vimpari and Junnila (2019); Alajmi et al. (2020); Fina et al. (2020); Grande-Acosta and Islas-Samperio (2020); Parupudi et al. (2020); Sharda et al. (2021); Calise et al. (2021); Lindholm et al. (2021).	

[a] [S] Sufficiency, [E] Efficiency, [R] Renewable Energy.

	Socio-cultural dimension		
Mitigation options[a]	Public acceptance	Effects on health and well-being	Distributional effects
Building design and performance [S]	May require retrofits of existing buildings. May require change in users' preferences. Enhanced asset values of energy efficient buildings. Split incentives between tenants and landlords.	As a result of the reduced consumption of natural resources and reduced air pollution levels. May improve buildings' users' quality of life.	Limited evidence.
	Fournier et al. (2019); Lorek and Spangenberg (2019); Thomas et al. (2019); Ellsworth-Krebs (2020); Cohen (2021).		
Change in construction methods and circular economy [S]	Although many stakeholders see advantages in new construction methods, especially in terms of sustainable construction, there are social barriers, such as information interaction between software, insufficient technical training for employees, cultural resistance, and so on.	Biomass-based materials, such as wood and bamboo, has aesthetic advantages and brings the concept of biophilia. However, the preservatives and glues used in the production can bring health problems related to the presence of volatile organic compounds.	Biomass based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities.
	Park et al. (2010); Celik and Attaran (2011); Vatalis et al. (2013); Bueren and Broekhans (2014); Zea Escamilla and Habert (2014); Ferreira et al. (2015); Schenkel et al. (2015); Moreno et al. (2016); Witjes and Lozano (2016); Zaeri et al. (2016); Chang et al. (2018b); Escamilla et al. (2018); Ghisellini et al. (2018); Harb et al. (2018); Olawumi et al. (2018); Hart et al. (2019); Oesterreich and Teuteberg (2019); Xiong et al. (2019); L.K et al. (2020a); L.K et al. (2020b); Mata et al. (2020a); Sotayo et al. (2020); Winchester and Reilly (2020); Huang et al. (2021); Patwa et al. (2021).		
Envelope improvement [E]	Perceived as increased comfort and status; with limited concerns for heritage or aesthetic values in regions with higher living standards. Split incentives between tenants and landlords.	Health benefits through better indoor air quality; energy/fuel poverty alleviation; better ambient air quality and alleviation of the heat island effect. Envelope improvement with inadequate ventilation may lead to sick building syndrome symptoms.	Result in lower energy bills; avoiding the 'heat or eat' dilemma, alleviating energy/fuel poverty and improving energy security. Furthermore, these interventions have positive impacts to the energy systems, by improving the primary energy intensity of the economy and reducing dependence on fossil fuels, which for many countries are imported.
	Allcott and Greenstone (2012); Boermans et al. (2015); Curl et al. (2015); García-López and Heard (2015); Lacroix and Chaton (2015); Liddell and Guiney (2015); Payne et al. (2015); Thomson and Thomas (2015); Willand et al. (2015); Friege (2016); Levy et al. (2016); Markovska et al. (2016); Miezis et al. (2016); Mortensen et al. (2016); Smith et al. (2016); Tam et al. (2016); Ürge-Vorsatz et al. (2016); Balaban and Puppim de Oliveira (2017); Curtis et al. (2017); Ferreira et al. (2017); Lilley et al. (2017); Ozarisoy and Altan (2017); Swan et al. (2017); Thema et al. (2017); Thomson et al. (2017); Zuhaib et al. (2017); Cedeño-Laurent et al. (2018); Howarth and Roberts (2018); Ketchman et al. (2018); Poortinga et al. (2018); Saheb et al. (2018); Si and Marjanovic-Halburd (2018); Tonn et al. (2018); Tsoka et al. (2018); Wierzbicka et al. (2018); Abreu et al. (2019); Alawneh et al. (2019); Azizi S Nair T (2019); Bright et al. (2019); Kim et al. (2019); Mastrucci et al. (2019); Ortiz et al. (2019); Karlsson et al. (2020); Reindl and Palm (2020).		
Heating, ventilation and air conditioning (HVAC) [E]	Perceived as increased comfort and status, with limited concerns for lack of space for installation in regions with higher living standards. Split incentives between tenants and landlords.	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and mitigation of the heat island effect. Many studies have highlighted the crucial role of ventilation in creating healthy indoor environmental conditions, which result in (mainly respiratory) health benefits.	Result in lower energy bills, avoiding the 'heat or eat' dilemma, alleviating energy/fuel poverty and improving energy security. Electrification of thermal energy uses is expected to increase the demand for electricity in buildings, which in most cases can be reversed (at national or regional level) by promoting nearly zero energy new buildings and a deep renovation of the existing building stock.
	Christidou et al. (2014); Qiu et al. (2014); Boermans et al. (2015); Hamilton et al. (2015); Liddell and Guiney (2015); Willand et al. (2015); Markovska et al. (2016); Mortensen et al. (2016); Ürge-Vorsatz et al. (2016); Balaban and Puppim de Oliveira (2017); Clancy et al. (2017); Couder and Verbruggen (2017); Heiskanen and Matschoss (2017); Silva et al. (2017); Thema et al. (2017); Cedeño-Laurent et al. (2018); Curtis et al. (2018); Fisk (2018); Ketchman et al. (2018); Månberger (2018); Militello-Hourigan and Miller (2018); Morris et al. (2018); Mzavanadze (2018); Si and Marjanovic-Halburd (2018); Tonn et al. (2018); Tumbaz and Moğulkoç (2018); Tumbaz and Moğulkoç (2018); Underhill et al. (2018); Alawneh et al. (2019); Azizi and Nair (2019); Bright et al. (2019); Mastrucci et al. (2019); Trencher and van der Heijden (2019); Cunha et al. (2020); TL (2020); Bevan et al. (2020); Spandagos et al. (2020); Mata et al. (2021).		
Efficient appliances [E]	Perceived as increased comfort and status, with limited concerns for technical issues and durability in regions with lower living standards. Split incentives between tenants and landlords.	The promotion of efficient appliances and particularly clean cook stoves results in significant health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and mitigation of the heat island effect.	Result in lower energy bills, avoiding the 'heat or eat' dilemma, alleviating energy/fuel poverty and improving energy security. Improved cook stoves provide better food security and reduce the danger of fuel shortages in developing countries (under real world conditions these impacts may be limited).
	García-Frapolli et al. (2010); Heffner and Campbell (2011); Malla et al. (2011); Zografakis et al. (2012); Aunan et al. (2013); Christidou et al. (2014); Johansson et al. (2015); Willand et al. (2015); Figueroa (2016); Hanna et al. (2016); Ürge-Vorsatz et al. (2016); Balaban and Puppim de Oliveira (2017); Berrueta et al. (2017b); Bonan et al. (2017); Hernandez-Roman et al. (2017); Thema et al. (2017); Jeuland et al. (2018); Ketchman et al. (2018); McCollum et al. (2018); Mzavanadze (2018); Rosenthal et al. (2018); Tonn et al. (2018); Alawneh et al. (2019b); Wang et al. (2019); Reindl and Palm (2020); Rey-Moreno and Medina-Molina (2020); Mata et al. (2021).		

	Socio-cultural dimension		
Mitigation options[a]	Public acceptance	Effects on health and well-being	Distributional effects
Change in construction materials [E]	Bio-based materials, such as wood, can be well accepted for being a natural and aesthetically pleasing material. However, in some cases (mainly in developing countries) it is associated with low quality buildings. There is limited information about other materials.	Biomass-based materials, such as wood and bamboo, has aesthetic advantages and brings the concept of biophilia. However, the preservatives and glues used in the production can bring health problems related to the presence of volatile organic compounds.	Bio-based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities.
	Wang et al. (2014); Zea Escamilla and Habert (2014); Escamilla et al. (2018); Harb et al. (2018); Chang et al. (2018); INBAR (2019); Xiong et al. (2019); Nfornkah et al. (2020); Obiri et al. (2020); Obiri et al. (2020); Pomponi et al. (2020); Sotayo et al. (2020); Winchester and Reilly (2020).		
Demand-side management (active management operation; digitalisation and flexible comfort requirements) [E]	Willingness to accept due to the potential to reduce energy and water bills. Nevertheless, cultural values and local physical conditions can affect the scalability of measures that affect comfort and well-being directly. Perceived as environmental and technological friendly, with concerns for costs and lack of control in regions with higher living standards. Limited literature in regions with lower living standards.	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and mitigation of the heat island effect. Furthermore, smart controllers and wireless communications capabilities that are used for controlling lighting, windows, HVAC equipment, water heaters and other building equipment provide many other non-energy benefits such as improved security, access control, fire and other emergency detection and management, and early identification of maintenance issues.	Smart meters support the introduction of new and dynamic tariff schemes that allow price benefits for the end-users. Active management and digitalisation practices can effectively enhance energy access and security by reducing peak demand, improving the primary energy intensity of the economy, mitigating the dependence on fossil fuels, postponing the installation of new facilities, reducing electricity prices volatility, and so on.
	Allcott and Greenstone (2012); Liang et al. (2012); Poortinga et al. (2012); Shih (2013); Balta-Ozkan et al. (2014);Christidou et al. (2014); Jaramillo et al. (2014); Dixon et al. (2015); Kendel and Lazaric (2015); Lee and Tanverakul (2015); Sarasti (2015); Ala-Mantila et al. (2016); Creutzig et al. (2016); European Commission (2016b); Sadeghi et al. (2016); Taniguchi et al. (2016); Ürge-Vorsatz et al. (2016); Vassileva and Campillo (2016); Vallés et al. (2016); Aryandoust and Lilliestam (2017); Balaban and Puppim de Oliveira (2017); Hwang et al. (2017); International Energy Agency (2017); Moser (2017); Tan et al. (2017); Thema et al. (2017); Christensen et al. (2018); Ferreira et al. (2018); Ponce de Leon Barido et al. (2018); MacNaughton et al. (2018); McCollum et al. (2018); Mir-Artigues et al. (2018); Mzavanadze (2018); Park et al. (2018); Saheb et al. (2018); Si and Marjanovic-Halburd (2018); Soland et al. (2018); Ruokamo et al. 2019; Tonn et al. (2018); Jabir et al. (2018); Xu et al. (2018); Alawneh et al. (2019b); Mastrucci et al. (2019); Nikou (2019); Pal et al. (2019); Safdar et al. (2019); Seidl et al. (2019); Vimpari and Junnila (2019); Yang et al. (2019); Zhuang and Wu (2019); Batalla-Bejerano and Trujillo-Baute (2020); Cunha et al. (2020); Mata et al. (2020c); Reindl and Palm (2020); Rey-Moreno and Medina-Molina (2020); Sovacool et al. (2020); Spandagos et al. (2020); Sundt et al. (2020); Yoo et al. (2020); Wohlfarth et al. (2020); Mata et al. (2021).		
Renewable energy production [R]	Perceived as environmental and technological friendly. Split incentives between tenants and landlords.	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and elimination of the heat island effect.	Improving energy access enhances agricultural productivity and improves food security. Result in energy/fuel poverty alleviation and in improving energy security. On the other hand, increased bioenergy production may restrict the available land for food production.
	Ahmad and Byrd (2013); Lay et al. (2013); Radmehr et al. (2014); Sagebiel and Rommel (2014); Hasegawa et al. (2015); Liddell and Guiney (2015); Overholm (2015); Payne et al. (2015); Torero De Boeck Supérieur (2015); Willand et al. (2015); Jimenez et al. (2016); Jung et al. (2016); Levy et al. (2016); Sola et al. (2016); Torani et al. (2016); Ürge-Vorsatz et al. (2016); Vorsatz et al. (2016); Balaban and Puppim de Oliveira (2017); Burney et al. (2017); Hai et al. (2017); Heiskanen and Matschoss (2017); Shukla et al. (2017); Thema et al. (2017); Qureshi et al. (2017); Frey and Mojtahedi (2018); Grubler et al. (2018); Rosenthal et al. (2018); Roth et al. (2018); Saheb et al. (2018); Tonn et al. (2018); MacNaughton et al. (2018); McCollum et al. (2018); Mzavanadze (2018); Wolske et al. (2018); Abreu et al. (2019); Alawneh et al. (2019b); De Groote and Verboven (2019); Dong and Sigrin (2019); Kirchhoff and Strunz (2019); Kosorić et al. 2019; Leibrand et al. (2019); Stauch and Vuichard (2019); Van de Ven et al. (2019); Vimpari and Junnila (2019); SunHorizon (2020); Peñaloza et al. (2021).		

[a] [S] Sufficiency, [E] Efficiency, [R] Renewable energy.

	Institutional dimension		
Mitigation options[a]	Political acceptance	Institutional capacity and governance, cross-sectoral coordination	Legal and administrative feasibility
There is not yet much evidence in literature on the political acceptance of policies for the support for options in building design and performance. If the concept is linked to well-being of energy-poor households the political acceptance can increase.	Institutional capacity can enable building design and performance to support sufficiency, in particular in managing building space in order to contribute to energy justice, reduction of energy poverty.	Administrative and legal process have to be introduced in such a way to increase the feasibility of building design and performances in order to promote energy sufficiency. Renewed interest in passive strategies has led to passive design being introduced into the latest versions of many green building rating tools owing to its proved effectiveness in saving energy.	
	Chen et al. (2015); Fournier et al. (2019); Pellegrini-Masini (2019); Thomas et al. (2019); Vadovics and Živčič (2019); Fournier et al. (2020).		
Change in construction methods and circular economy [S]	Politicians support circular economy since it has a positive impact on the environment and the economy and may create local jobs. At the same time politicians are neutral on new construction methods as this could have a negative impact on employment, substituting low-skilled workers with robots (e.g., High D printing) or robotised manufacturing in plants. In some (a few developed) countries there are public policies that encourage industrialisation and rationalisation of construction.	There should be a change in institutional capacity to follow up technology development in new construction methods, as testing, for example, could be done in factories and sample buildings rather than in each building. The same is valid for circular economy, where controls have to be done at the production stage, institutional capacity can be an enabler for circular economy.	The legal and administrative practices have to change to follow the new technology and methods for construction and circular economy, which could be a barrier.
	Edirisinghe (2015); González Mahecha et al. (2020); Succar and Kassem (2015); Kassem and Succar (2017); de Abreu and Ceglia (2018); Li et al. (2018); Yang and Chou (2018); Whalen and Whalen (2018); Li et al. (2020), L.K. et al. (2020b); Hamam et al. (2021).		
Envelope improvement [E]	Not perceived as a priority policy for energy efficiency in buildings by many policy makers in particular in warm climate and in developing countries. Policy makers are neutral to the technology implemented to improve the building energy performances. Incentives are often used to promote insulation in residential buildings.	Very often building performance and envelopment improvements require very specific technical capabilities. In some countries building codes are established at local level, with gaps in governance and coordination between different levels of government.	Building codes are difficult to enforce, often compliance is based on design and verification is not carried out when in use. Actual energy used may be much higher than projected. In particular, envelope improvement for existing buildings are difficult to verify – this is also the case with public subsidies.
	Chandel et al. (2016); Khosla (2016); Khosla et al. (2017); Sun et al. (2016); Pérez-Bella et al. (2017); Yan et al. (2017); Enker and Morrison (2020); Kwag et al. (2020); Liu et al. (2020), Schwarz et al. (2020).		
Heating, ventilation and air conditioning (HVAC) [E]	HVAC energy system retrofits reduce buildings' carbon footprint substantially but are often hindered by financial, regulatory or design constraints. Local market constraints and building ownership types might also affect the retrofit decision for HVAC systems. For example, newly constructed buildings must typically fulfil specific energy codes and further retrofitting can become cost-ineffective from an investment point of view. Technical HVAC retrofits often require modifications to existing buildings' design, which can be challenging especially in old and historic buildings.	In developing countries in particular there is lack of institutional capacity to adopt and enforce efficiency requirement for air conditioners.	HVAC sections of non-residential building codes need strengthening, as evidenced in 30 countries which show a variety in regulatory approaches. Regulatory agencies should adopt more stringent and homogenous requirements and develop new documentation and software specifications to improve code knowledge, compliance, and enforcement. Further, there is scarcity of studies quantifying energy savings from optimal HVAC temperature set points comprehensively, either as part of individual building retrofit planning or as part of energy policy regulations.
	Pérez-Lombard et al. (2011); Pisello and Asdrubali (2014); Kelpsaite et al. (2019); Kontokosta et al. (2020); Papadopoulos et al. (2019).		
Efficient appliances [E]	There is strong support for appliances labelling and standards by policy makers both in developing and developed countries.	In developing countries in particular there is lack of institutional capacity to adopt and enforce efficiency requirements for appliances and lighting.	
	Mahlia and Saidur (2010); McNeil et al. (2013); Rahman et al. (2015); Gerke et al. (2017); Russo et al. (2018); Singh et al. (2019).		

	Institutional dimension		
Mitigation options[a]	**Political acceptance**	**Institutional capacity and governance, cross-sectoral coordination**	**Legal and administrative feasibility**
Change in construction materials [E]	Bio-based materials, such as wood and bamboo, have been pointed as important alternatives for the construction sector in low-carbon policies in some countries. But a host of factors limit contemporary use of solid wood: such as the changes to the material based on humidity and water absorption, in spite of being fire-resistant, the charring properties of large structural timbers are recognised in most international building codes, the popular association of timber construction with catastrophic urban conflagration.	The economic, technical, practical and cultural barriers to the uptake of alternatives materials include perceptions of high cost, ineffective allocation of responsibility, industry culture, lack of skills of technicians and companies, and the poor availability of product and building-level carbon data and benchmarks. Opportunities to overcome barriers include earlier engagement of professionals along the supply chain, effective use of whole-life costing, and changes to contract and tender documents. A mounting business case exists for addressing embodied carbon but has yet to be effectively disseminated. There is a need for new regulatory drivers to complement changing attitudes.	Engineered timber products lack capacities and market demand to be more than just a niche market. Instruments are necessary to unlock potential for net carbon storage and increase the market share for engineered wood products, such as the gradual introduction of stricter rules for carbon emissions trading or more incentives for the voluntary use of innovative wood construction materials. In addition to the availability of forest resources, transition to timber-based building structures will require changes in building codes, training construction workforce, expansion of manufacturing capacities for bio-based products, and downscaling production of mineral-based materials. Increased demand for timber in construction would have to be supported by a strong legal and political commitment to sustainable forest management, robust forest certification schemes, empowerment of people living in forests, efforts to curb illegal logging and exploring bamboo and other plant fibres as a replacement for timber in tropical and subtropical regions.
	Laguarda Mallo and Espinoza (2015); Giesekam et al. (2016); Hildebrandt et al. (2017); Kremer and Symmons (2018); Orsini and Marrone (2019); Churkina et al. (2020); Himes and Busby (2020); Nfornkah et al. (2020).		
Demand-side management (active management operation, digitalisation and flexible comfort requirements) [E]	There is still some scepticism by politicians for demand-side management (active management operation, digitalisation, and flexible comfort requirements).	There is the need to change the governance of the electricity systems to allow demand option to participate in electricity market and get rewarded for their flexibility. Institutional capacity can be a strong enabler of demand side options.	There are still legal and administrative barriers to demand-side management (active management operation, digitalisation and flexible comfort requirements) which hinder the feasibility of this option.
	Izsak and Edler (2011); Mengolini et al. (2016); Warren (2017); Forouli et al. (2021).		
Renewable energy production [R]	While in central governments there is a very high political acceptance and promotion of renewable energy systems as a key mitigation strategy, there can be opposition at the local political level, where local politicians defend views of citizens opposing renewable for aesthetic reasons or to attract tourists.	Institutional capacity is a key enabler of renewable energies. In particular, the permitting of new installations, clear rules for connection to the grid, costs and incentives are essential elements. Other important institutional factors, for example, the legal system and property rights, technical and market regulations and freedom to trade internationally, are other important enablers. However, at the moment, the institutional capacity to support the deployment of renewable is not present in all countries, with some developing countries still lacking it.	Renewable energies investment still faces several constraints from a legal and administrative point of view. In particular there are in some countries cumbersome administrative procedures to be granted the authorisation to install renewable both on and off-site, as well as legal issues on the system charges that renewable producers may face.
	Cohen et al. (2016); Jung et al. (2016); Koecklin et al. (2021).		

[a] [S] Sufficiency, [E] Efficiency, [R] Renewable energy.

9.SM.6 Supplementary information to Section 9.9

Table 9.SM.7 presents several studies examined in the context of Section 9.9.2.

Table 9.SM.7 | Estimates of the direct and indirect rebound effects for households

Rebound effects		Range	Mean	Median	References
Direct	Including thermal uses	–9–127%	43%	36%	Hens et al. (2010); Cayla and Osso (2013); Chitnis et al. (2013); Thomas and Azevedo (2013); Wang et al. (2014b); Galvin (2015); Lin and Liu (2015); Cali et al. (2016); Galvin and Sunikka-Blank (2016); Teli et al. (2016); Terés-Zubiaga et al. (2016); Aydin et al. (2017); Copiello and Gabrielli (2017); Madonna et al. (2017); Sandberg et al. (2017); Brøgger et al. (2018); Holzmann and Schmid (2018); Bardsley et al. (2019).
	Electric uses	3–14%	7%	5%	Chitnis et al. (2013); Schleich et al. (2014); Chen et al. (2018).
Indirect		–1.8–23.5%	10%	11%	Cellura et al. (2013); Chitnis et al. (2013); Santos et al. (2018); Thomas and Azevedo (2013); Walzberg et al. (2020).
Direct and indirect		4.5–80%	32%	27%	Murray (2013); Scheer et al. (2013); Orea et al. (2015); Qiu et al. (2019).

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