WG III contribution to the Sixth Assessment Report
List of corrigenda to be implemented
The corrigenda listed below will be implemented in the SM during copy-editing.

CHAPTER 9 – Supplementary Material

<table>
<thead>
<tr>
<th>Document (Chapter, Annex, Supp. Material)</th>
<th>Page (Based on the final pdf FGD version)</th>
<th>Line</th>
<th>Detailed information on correction to make</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 9 Supplementary Material</td>
<td>13</td>
<td>5-6</td>
<td>Table SM9.5 header row, replace &quot;Country&quot; with &quot;Country/region&quot;</td>
</tr>
</tbody>
</table>
Chapter 9: Buildings – Supplementary material

SM9.1 Supplementary information to Section 9.4

Figure 9.11 shows a summary of the available technologies with climate change mitigation potential in buildings. Here, an extended list of such technologies is presented (Table SM9.1 to Table SM9.3).
### Table SM9.1 Technology strategies contributing to sufficiency aspects. Adapted from

<table>
<thead>
<tr>
<th>Typology – technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive strategies for walls</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 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 (Jedidi and Benjeddou 2018; Capozzoli et al. 2013; Asdrubali et al. 2012) | Up to 30% of cooling energy reduction (Kameni Nematchoua et al. 2020)  
Conventional insulation materials + PCM  
Tropical 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 | - In regions with mild winters and hot summers, over heating problems may outweigh the winter benefits.  
- In a climate with extended cloudy periods, without employing the adequate operable insulation, the wall may become heat sink.  
- Trombe walls have low thermal resistance causing to transfer the heat flux from the inside to the outside of a building during the night or prolonged cloudy periods.  
- The amount of gained heat is unpredictable due to changes occur in solar intensity.  
- Trombe walls are aesthetically appealing | 20% (Bojić et al. 2014)  
Annual heating – Mediterranean climate  
Simulation  
18.2% and 42.2% (Bevilacqua et al. 2019b)  
Heating cold climate and cooling cold climate  
Simulation |
<table>
<thead>
<tr>
<th>Vertical Greenery Systems (Green walls / Green facades)</th>
<th>- Enhancing building aesthetics.</th>
<th>- Providing a living environment for mosquitoes, moths, etc.</th>
<th>58.9 % Green wall 33.8 % Green facade (Coma et al. 2017)</th>
<th>Cooling season warm climate Experimental study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Improving the acoustic properties.</td>
<td>- Requiring significant, and consistent maintenance measures.</td>
<td></td>
<td>37.7% and 50% (Djejjig et al. 2015b) Hot climate Cold climate Cooling Savings Simulation</td>
</tr>
<tr>
<td></td>
<td>- Reduction of heat gains and losses.</td>
<td>- Water drainage can be involved in complexities, and difficulties.</td>
<td></td>
<td>12% (Chen et al. 2013b) Cooling savings Tropical climate Experimental</td>
</tr>
<tr>
<td></td>
<td>- Ability to be integrated with existing buildings.</td>
<td></td>
<td></td>
<td>20.5 % (Haggag et al. 2014b) Cooling savings Hot climate Experimental</td>
</tr>
<tr>
<td>Vertical Greenery Systems (Green walls / Green facades)</td>
<td>- Availability at different temperatures</td>
<td>- Low thermal conductivity</td>
<td>19 – 26% (Khoshbakht et al. 2016) Heating savings Mediterranean climate Experimental</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- High volumetric energy storage</td>
<td>- Flammability</td>
<td>0 up to 29% (Saffari et al. 2017b) Heating savings in different climates Simulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Low thermal and chemical stability</td>
<td>9.28% (Seong and Lim 2013b) Annual cooling savings Temperate climate Simulation</td>
<td></td>
</tr>
<tr>
<td>PCM Wall systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- High volumetric energy storage</td>
<td>- Production cost per unit is higher than other ordinary concretes</td>
<td>7% (Radhi 2011) Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- AAC walls are light weight concrete, and fire resistance.</td>
<td>- It is not as strong as conventional concrete</td>
<td></td>
<td>Dry desert climate Experimental and simulation</td>
</tr>
<tr>
<td>AAC Walls (Autoclaved aerated concrete)</td>
<td></td>
<td>- The process of autoclaving concrete requires significant energy consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Skin Walls</td>
<td>- Provision of sufficient visual connection with the surroundings.</td>
<td>- Higher cost for designing, construction, and maintenance compared to traditional single facades</td>
<td>28-33% (Pomponi et al. 2016b) Heating savings Cooling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Facilitation of entering a large amount of daylight without glare.</td>
<td>- Increase weight of building structure</td>
<td>-- Average of reviews</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Offering attractive aesthetic values</td>
<td>- Risk of overheating during sunny days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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.
<table>
<thead>
<tr>
<th>Passive strategies for roofs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cool Roofs</strong></td>
<td><strong>Roof ponds</strong></td>
</tr>
<tr>
<td>- Promotion of natural ventilation and thermal comfort without any electricity demand - Acoustic insulation</td>
<td>- Processes indirect evaporative cooling 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</td>
</tr>
<tr>
<td>- Additional maintenance and operational costs - Increased airflow velocity inside the cavity - Potential issues associated to fire propagation</td>
<td>- Enhancing building aesthetics. - Improving the acoustic properties. - Reduction of heat gains and losses.</td>
</tr>
<tr>
<td>8 – 9% (Andjelković et al. 2016)</td>
<td>30% (Spanaki et al. 2014b)</td>
</tr>
<tr>
<td>Heating Cooling</td>
<td>Cooling season</td>
</tr>
<tr>
<td>-- Moderate climate</td>
<td>Simulation</td>
</tr>
<tr>
<td>51 % and 16% (Khoshbakht et al./2016)</td>
<td>Annual savings of temperate and subtropical climate</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
</tr>
<tr>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>Green roofs</td>
<td>Ability to be integrated with existing buildings.</td>
</tr>
</tbody>
</table>

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

2.  

3.  

4.  

5.  

6.  

SM9-5 Total pages: 69
<table>
<thead>
<tr>
<th>Typology – technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Energy savings</th>
<th>Conditions/comments</th>
</tr>
</thead>
</table>
| Thermally activated building systems     | - 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% (Privara et al. 2011)  
15% (Sourbron et al. 2013) | Ceiling radiant heating panels  
Monitoring                                                                              |
| (TABS)                                   |                                                                                                                                                                                                            |                                                                                                                                                                                                            |                                                                                        |                                      |
| 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 optimization algorithm to achieve maximum energy savings.  
- outdoor air-source evaporators demand defrosting                                      | 17 – 25 % (ASHP) (Ling et al. 2020) | Ceiling radiant heating panels  
Simulation                                                                 |
|                                          |                                                                                                                                                                                                            |                                                                                                                                                                                                            |                                                                                        |                                      |
| 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            |
|                                          |                                                                                                                                                                                                            |                                                                                                                                                                                                            |                                                                                        |                                      |
| 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 mast or porous humidification pads. Adiabatic evaporation of water in the entering airstream boosts the cooling capacity of direct expansion vapour-compression refrigeration, or reduces work load of the compressor | - 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                                                                 |

Table SM9.2 Technology strategies contributing to efficiency aspects.
<table>
<thead>
<tr>
<th>Smart ventilation</th>
<th>- Reduces energy consumption and costs</th>
<th>- Sometimes energy overconsumption appear</th>
<th>Up to 60% (Liu et al. 2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat recovery system</td>
<td>- No cross contamination depending of the type of heat recovery system</td>
<td>- Difficult to integrate depending of the type of heat recovery system</td>
<td>8% (Vakiloroaya et al. 2014a)</td>
</tr>
<tr>
<td></td>
<td>- High efficiency, especially in temperate climates</td>
<td>- Larger than conventional air-handling units</td>
<td>- Annual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Expensive both in capital and operation costs</td>
<td>- Humid climate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Experimental</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.8 COP of the proposed district heating</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>- Can use hydrogen as energy fuel</td>
<td>- High capital cost</td>
<td>35% (Romdhane and Louahlia-Gualous 2018)</td>
</tr>
<tr>
<td></td>
<td>- Allows micro-CHP</td>
<td>- High space requirements</td>
<td>- Single-family house in France</td>
</tr>
<tr>
<td></td>
<td>- Can be used in all climates</td>
<td></td>
<td>- PEMFC</td>
</tr>
<tr>
<td></td>
<td>- Reduced CO₂ emissions</td>
<td></td>
<td>15% (Gong et al. 2019)</td>
</tr>
<tr>
<td></td>
<td>- No noise during operation</td>
<td></td>
<td>PEMFC and SOFC</td>
</tr>
<tr>
<td>Thermal energy storage</td>
<td>- Significant reduction of electricity costs</td>
<td>- COP lower than conventional vapour compression systems</td>
<td>12-37% (Alam et al. 2019) (Omara and Abuelnour 2019)</td>
</tr>
<tr>
<td></td>
<td>- Required smaller ducts</td>
<td>- Expensive both in capital and operation costs</td>
<td>- Latent heat storage system</td>
</tr>
<tr>
<td></td>
<td>- Increase in flexibility</td>
<td>- More complex systems</td>
<td>- Active façade with PCM</td>
</tr>
<tr>
<td></td>
<td>- Three technologies available (sensible, latent and thermochemical energy storage)</td>
<td></td>
<td>- Cooling and heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Arid climates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Activated concrete slab with PCM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Cooling and heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Arid climates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Sensible TES with concrete thermal mass with mechanical or natural ventilation</td>
</tr>
</tbody>
</table>

- Sensible TES with concrete thermal mass with mechanical or natural ventilation
| Strategies for cooling | Direct evaporative cooling | - Reduction of pollution emissions  
- Life cycle cost effectiveness  
- Reduction of peak demand  
- Cheap | - Not good when ambient humidity >40%  
- Humidity Increase | 40-70% (Fallahi et al. 2010)  
- Aquifer TES (ATES)  
- Large scale TES | - 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 | 70% (Mujahid Rafique et al. 2015) | - Hot and dry climate |
| Liquid pressure amplification | - Significant energy savings | - Energy savings potential limited to low ambient temperatures  
- More expensive than conventional vapour compression systems | 25.3% (Vakiloroaya et al. 2014b) | - Simulation |
| Ground-coupled | - Less noise and GHG emissions than conventional vapour compression systems  
- Requirements of earth surface  
- Very high upfront costs  
- Expensive both in capital and operation costs | - 70% of the ceiling surface covered by radiant ceiling panels | 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 | - 70% of the ceiling surface covered by radiant ceiling panels | 10% (Imanari et al. 1999) | - Simulation |
| Desiccant cooling | - Humidity control is improved when coupled with conventional systems  
- Corrosive materials  
- Large response time  
- Crystallization of materials maybe a problem  
- Expensive both in capital and operation costs | - Dunkle cycle | 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 | - Simulation  
- R236ea Refrigerant | 14.52% (Yu et al. 2020) | - Simulation |
| Variable refrigerant flow | - Efficient in part load conditions  
- Requirement of extra control systems  
- Cannot provide full control of humidity | - Building temp set-point 24°C | 17% (Lee et al. 2018) | - Simulation |
### Table SM9.3 Technology strategies contributing to renewables.

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

Adapted from Irshad et al. 2019; Luo et al. 2017; Cabeza and Chàfer 2020
Table SM9.4 Supplementary information to Section 9.5

Table SM9.4 GHG mitigation potentials for categories of NT interventions for Residential (R) and Non-Residential (NR) buildings. N.f., not found.

<table>
<thead>
<tr>
<th>Region</th>
<th>Non-technological climate mitigation solution</th>
<th>Residential buildings</th>
<th>Commercial buildings</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF Africa</td>
<td>Active management and operation</td>
<td>n.f.</td>
<td>10%</td>
<td>(McGibbon et al. 2014)</td>
</tr>
<tr>
<td>Developed Countries</td>
<td>Active management and operation</td>
<td>53%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Circular and sharing economy</td>
<td>n.f.</td>
<td>15-75%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible comfort</td>
<td>2-20%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limited/sufficient comfort levels</td>
<td>1-50%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiple or unspecified behavioural changes</td>
<td>2-27%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Passive management and operation</td>
<td>5-6%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Social and organizational innovations</td>
<td>3%</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Worldwide</td>
<td>Active management and operation</td>
<td>5%</td>
<td>n.f.</td>
<td>(van Sluisveld et al. 2016; Ivanova and Büchs 2020; Cantzler et al. 2020; Harris et al. 2021)</td>
</tr>
<tr>
<td></td>
<td>Circular and sharing economy</td>
<td>40-81%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limited/sufficient comfort levels</td>
<td>3-25%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiple or unspecified behavioural changes</td>
<td>1-30%</td>
<td>n.f.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Passive management and operation</td>
<td>20%</td>
<td>n.f.</td>
<td></td>
</tr>
</tbody>
</table>
Supplementary information to Section 9.8

Table SM9.5 summarizes the results of 17 studies from 12 different countries showing the price premium of energy efficient dwellings.

<p>| Table SM9.5 Premium price for rent and sale in residential buildings with high energy performance and/or green features |
|---|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Ref</th>
<th>Study</th>
<th>Country</th>
<th>From energy rating X to Y (Y/X)</th>
<th>Impact of energy performance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tajani et al., 2018</td>
<td>Italy (Bari)</td>
<td>A / [B,C,D,E,F]</td>
<td>27.9%</td>
<td>Evaluation based on energy performance certificates</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>G / [B,C,D,E,F]</td>
<td>-26.4%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Marmolejo-Duarte and Chen, 2019</td>
<td>Spain (Barcelona)</td>
<td>A / G</td>
<td>7.8%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>D / G</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Kahn and Kok, 2014</td>
<td>US (California)</td>
<td>[Green label] / [non-labelled homes]</td>
<td>5.0%</td>
<td>Green labels considered comprise LEED, GreenPoint or Energy Star</td>
</tr>
<tr>
<td>7</td>
<td>Fuerst et al., 2015</td>
<td>UK (England)</td>
<td>[A,B] / D</td>
<td>5.0%</td>
<td>Evaluation based on energy performance certificates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C / D</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Cajias et al., 2019</td>
<td>Germany</td>
<td>A+ / D</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>A / D</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>B / D</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>C / D</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>F / D</td>
<td>-0.1%</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>G / D</td>
<td>-0.3%</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>H / D</td>
<td>-0.5%</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Hyland et al., 2013</td>
<td>Ireland</td>
<td>A / D</td>
<td>9.3%</td>
<td>Evaluation based on energy performance certificates</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>B / D</td>
<td>5.2%</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>[F,G] / D</td>
<td>-10.6%</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Davis et al., 2015</td>
<td>UK (Belfast)</td>
<td>B / D</td>
<td>28.0%</td>
<td>Evaluation based on energy performance certificates</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>C / D</td>
<td>4.9%</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>G / D</td>
<td>-2.0%</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Jensen et al. 2016</td>
<td>Denmark</td>
<td>[A,B] / D</td>
<td>6.2%</td>
<td>Evaluation based on energy performance certificates after the advertising requirement implemented by 1 July 2010</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>C / D</td>
<td>5.1%</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td>E / D</td>
<td>-5.4%</td>
<td></td>
</tr>
</tbody>
</table>

SM9-13 Total pages: 69
<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Green Features</th>
<th>Energy Efficient Features</th>
<th>[A,B,C] / D</th>
<th>1.5-3.3%</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuerst et al. 2016</td>
<td>Finland (Helsinki)</td>
<td>[A,B,C]</td>
<td></td>
<td>[A,B,C] / D</td>
<td>1.5-3.3%</td>
<td>Evaluation based on energy performance certificates. The lower value is estimated when a set of detailed neighbourhood characteristics are included. Results of models 2 and 3 are presented here.</td>
</tr>
<tr>
<td>Cadena and Thomson, 2015</td>
<td>US (Texas)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>0.7%</td>
<td>The models B, D, and F presented here incorporating as independent variable at least one green designation or green/energy efficient feature</td>
</tr>
<tr>
<td>Jayantha and Man, 2013</td>
<td>Hong Kong</td>
<td>No certification</td>
<td>No</td>
<td>No</td>
<td>5.8%</td>
<td>BEAM certification and GBC Award are used as the measurement of green residential buildings.</td>
</tr>
<tr>
<td>Brounen and Kok, 2011</td>
<td>Netherlands</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>-2.5%</td>
<td>Evaluation based on energy performance certificates</td>
</tr>
<tr>
<td>Deng et al., 2012</td>
<td>Singapore</td>
<td>Platinum</td>
<td>No</td>
<td>No</td>
<td>21.0%</td>
<td>Evaluation of dwellings awarded with a Green Mark.</td>
</tr>
<tr>
<td>Zheng et al., 2012</td>
<td>China (Beijing)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>17.7%</td>
<td>Dwellings with green characteristics in relation to conventional ones.</td>
</tr>
<tr>
<td>Koirala et al. 2014</td>
<td>US</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>23.3%</td>
<td>The existence of the codes IECC2003 through IECC2006 for American households is evaluated in this study</td>
</tr>
</tbody>
</table>
Box SM9.1 presents an example of a policy package, to complement, Section 9.9.

**START BOX SM9.1 HERE**

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

Buildings consume 40% of final energy in the EU and are responsible for 36% of the EU CO₂ emissions (Renovation Wave, 2020). In the EU the majority of buildings are already built, with several buildings between 50 and 20 years old, i.e., 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 P. 2019). The EPBD is a regulatory measure, with its implementation left to individual MSs. This has resulted in very different levels of stringency among MSs. In addition, the enforcement of control on the application of the energy performance requirements is left to national authorities and finally delegated to local authorities, who may lack the technical knowledge or manpower to check compliance with legal requirements. This has resulted in low compliance with normative requirements in many MSs. The 2002 EPBD has also introduce the obligation to show an energy performance certificate when a building is sold or rented (information policy) (Li et al. 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 nZEB are again left to EU Member States, which have different requirements for energy consumption limits and contribution of renewables (D’Agostino and Mazzarella 2019; Attia et al. 2017; Grove-Smith et al. 2018; Economidou et al. 2020). In 2018 the latest amendment of the EPBD introduced the requirements for MSs to prepare a Long Term Renovation Strategies (LTRSs) with an overarching decarbonisation target of the national building stock by 2050. 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 etc. (Bertoldi 2020). Moreover, the EU Regional and Cohesion Funds are also used by MSs for the renovation of existing buildings. Some of the instruments used at national level to finance the renovation of dwellings occupied by low-income families result from the auctioning of allowances under the EU Emissions Trading Scheme, which is used in some MSs.

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

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

In the EU over 10000 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 MV&E for both buildings (including the Energy Performance Gap) and appliances performances, which reduce the level of expected savings. There is no concrete measure to avoid the direct rebound effect and the current energy prices are relatively low. In addition, there are no specific policies and measures at EU level to address energy sufficiency. Regulations and technical standards do not include the life cycle CO2 emissions in the performance of the buildings. The complexity of the governance structure at different levels (EU, National, Regional and Local), with many options left to individual MSs, for example the definition of Near Zero Energy Buildings. The complexity of managing several instruments, often dealt by different national ministries and departments (industry, environment, construction, urbanisation, etc.) and, finally, the disconnect between high-level EU targets and the lack of ambition of individual policies, which makes the decarbonisation of the EU building stock more challenging. The 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.

END BOX SM9.1 HERE
SM9.5 Supplementary information to Section 9.9

Table SM9.6 details the feasibility assessment presented in Figure 9.20.
### Table SM9.6. Context and line of sight for the feasibility assessment of mitigation options in the buildings sector

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Physical potential</th>
<th>Geophysical resources</th>
<th>Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building design and performance [S]</strong></td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Change in construction methods and circular economy [S]</strong></td>
<td>It is expected that in advanced construction methods (e.g. BIM – Building Information Modelling, industrialization and rationalization, 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 decrease avoid impacts related to the consumption of virgin resources and end-of-life wastes. This reduces pressure for geophysical resources and land use.</td>
<td>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, although their physical potential of building materials and elements. Materials decrease avoid impacts related to the consumption of virgin resources and end-of-life wastes. This reduces pressure for geophysical resources and land use.</td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Envelope improvement [E]</strong></td>
<td>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.</td>
<td>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, although their physical potential of building materials and elements. Materials decrease avoid impacts related to the consumption of virgin resources and end-of-life wastes. This reduces pressure for geophysical resources and land use.</td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Heating, ventilation and air conditioning (HVAC) [E]</strong></td>
<td>High space requirements in buildings.</td>
<td>NA, with the exception of CO₂ storage, through CO₂ based refrigerators.</td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Efficient Appliances [E]</strong></td>
<td>There are technical limitations to energy efficiency, but there is much room for improvement, especially in developing countries.</td>
<td>Not applicable.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td><strong>Change in construction materials [E]</strong></td>
<td>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 lime and supplementary cementitious materials and limecrete, calcium clay cement) is abundant, although there may be some regional scarcity depending on the scale of adoption.</td>
<td>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.</td>
<td>Not applicable.</td>
</tr>
</tbody>
</table>

*The table lists mitigation options that are either not applicable or are not considered in the context of the buildings sector.
### Geophysical Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Physical potential</th>
<th>Geophysical resources</th>
<th>Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements) [E]</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Renewable energy production [R]</td>
<td>Large untapped potential for most technologies / Rural areas have a great potential for renewable energy sources.</td>
<td>Most technologies not limited by materials.</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

(Capellán-Pérez et al. 2017; Calvert and Mabee 2015; Poggi et al. 2018)

* [S] Sufficiency; [E] Efficiency; [R] Renewable Energy

### Environmental-ecological Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Air pollution</th>
<th>Toxic waste, ecotoxicity eutrophication</th>
<th>Water quantity and quality</th>
<th>Biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building design and performance [S]</td>
<td>As a result of the reduced consumption of natural resources and reduced air pollution levels.</td>
<td></td>
<td></td>
<td>Green roofs and walls, particularly if connected to other green spaces, enhance urban biodiversity.</td>
</tr>
</tbody>
</table>

(Joimel et al. 2018; Mayrand and Clergeau 2018a; Sunikka-Blank et al. 2012; Hui and Chan 2011)

| Change in construction methods and circular economy [S] | The use of Building Information Modelling (BIM) together with the Life Cycle Assessment (LCA) methodology allows a faster, holistic and more assertive assessment of the potential environmental impacts of a building project, reducing impacts throughout the project's life cycle. Advanced mitigation 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. | | | |


| 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. | | | |

### Environmental-ecological Dimension

<table>
<thead>
<tr>
<th>Mitigation Options</th>
<th>Air pollution</th>
<th>Toxic waste, ecotoxicity</th>
<th>Water quantity and quality</th>
<th>Biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating, ventilation and air conditioning (HVAC) [E]</td>
<td>Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor).</td>
<td>As a result of the reduced consumption of natural resources and reduced air pollution levels.</td>
<td>Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.</td>
<td>Reduced air pollution levels achieved by mitigation actions improves biodiversity.</td>
</tr>
<tr>
<td>Effcient Appliances [E]</td>
<td>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.</td>
<td>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 maximizing the recycling of old appliances.</td>
<td>Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities.</td>
<td>Reduced air pollution levels due to mitigation actions improves biodiversity.</td>
</tr>
<tr>
<td>Change in construction materials [E]</td>
<td>Engineered wood/bamboo products normally use petroleum-based adhesives, which can release toxic gases (e.g. formaldehyde and Volatile Organic Compounds - VOCs). Life cycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with supplementary cementitious materials (SCM) replacing cement or clinker is less polluting.</td>
<td>Some biomass treatment processes uses toxic materials and substances. The use of fertilizers in forestry activities can increase eutrophication. Life cycle assessment studies show that the production of raw earth materials is less polluting than conventionally used materials such as concrete, ceramics and steel, and production of concrete with supplementary cementitious materials (SCM) replacing cement or clinker is less polluting.</td>
<td>An increase in water demand can be observed during the forest activities.</td>
<td>Normally monoculture production is encouraged and can put pressure on native forest areas.</td>
</tr>
<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements) [E]</td>
<td>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.</td>
<td>As a result of the reduced consumption of natural resources and air pollution levels.</td>
<td>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.</td>
<td>Reduced air pollution levels achieved by mitigation actions improves biodiversity.</td>
</tr>
<tr>
<td>Renewable energy production [R]</td>
<td>Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor).</td>
<td>Not Applicable</td>
<td>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.</td>
<td>Reduced air pollution levels achieved by mitigation actions improves biodiversity. Bioenergy production may have both positive and negative impacts on biodiversity.</td>
</tr>
</tbody>
</table>

* [S] Sufficiency; [E] Efficiency; [R] Renewable Energy
Mitigation Options<br>

Building design and performance [S]<br>

- 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.

Change in construction methods and circular economy [S]<br>

- 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.
- 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.
- Some technologies are well known, but their market applicability varies from country to country. There are few projects using highly advanced construction methods (e.g. Building Information Modelling, design for deconstruction/dismantling, digital fabrication and design for performance).

Envelope improvement [E]<br>

- 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.

Heating, ventilation and air conditioning (HVAC) [E]<br>

- 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, etc.
- It is a widely implemented technology. Efforts continue to be allocated to research and development to improve energy efficiency.

Efficient Appliances [E]<br>

- 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.
### Technological Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Simplicity</th>
<th>Technological scalability</th>
<th>Maturity and technology readiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in construction materials [E]</td>
<td>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.</td>
<td>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.</td>
<td>Some bio-based materials (e.g. wood and bamboo) are well known and widespread used. However, their applicability in series from country to country. 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 at 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.</td>
</tr>
<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements) [E]</td>
<td>Ranges from very simple monitoring sensors, or simple concepts to smart cities.</td>
<td>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.</td>
<td>The simple measures require no technology development, while more complex measures are already widely available, still with potential for improvement.</td>
</tr>
<tr>
<td>Renewable energy production [R]</td>
<td>Most technologies are simple. However, supply of technical support at the local scale can be a barrier / Hybridization between several technologies can achieve better results both for energy production and power generation.</td>
<td>Most technologies can be scaled up to most regions.</td>
<td>Most technologies are mature. Moreover, efforts continue to be allocated to research and development to improve.</td>
</tr>
</tbody>
</table>

### Economic Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Costs in 2030 and long term</th>
<th>Employment effects and economic growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building design and performance [S]</td>
<td>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 other 0-30% more expensive than buildings built according to minimum energy performance standards. The incremental costs of these buildings are however expected to decline further.</td>
<td>Limited Evidence.</td>
</tr>
</tbody>
</table>

* [S] Sufficiency; [E] Efficiency; [R] Renewable Energy

1

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SM9-23  Total pages: 69
## Economic Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Costs in 2030 and long term</th>
<th>Employment effects and economic growth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Change in construction methods and circular economy [S]</strong></td>
<td>Potential cost-competitiveness (lower life cycle costs, green/quality premium for circular economy, but still uncertain to large-scale investors due to perceived higher investment costs.)</td>
<td>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 digitalization.</td>
</tr>
<tr>
<td><strong>Envelope improvement [E]</strong></td>
<td>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 industrialized one-stop-shop approach. Given the long payback time, energy price dynamics and a discount rate play an especially large role.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Heating, ventilation and air conditioning (HVAC) [E]</strong></td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Efficient Appliances [E]</strong></td>
<td>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 large size and other advanced features that to some extent offsets the positive economic effects.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Change in construction materials [E]</strong></td>
<td>There are only a few fragmented studies on the cost implications of the change in construction materials.</td>
<td>Potential positive effect along the value chain (job creation and value added).</td>
</tr>
</tbody>
</table>
### Economic Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Costs in 2030 and long term</th>
<th>Employment effects and economic growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements) [E]</td>
<td></td>
<td>Implementing digitalization 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 business opportunities in advanced manufacturing. Furthermore, the implementation of digitalization 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.</td>
</tr>
<tr>
<td>Renewable energy production [R]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


### Socio-cultural Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Public acceptance</th>
<th>Effects on health &amp; wellbeing</th>
<th>Distributional effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building design and performance [S]</td>
<td>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.</td>
<td>As a result of the reduced consumption of natural resources and reduced air pollution levels. May improve buildings’ users’ quality of life.</td>
<td>Limited Evidence</td>
</tr>
<tr>
<td>(Lorek and Spangenberg 2019; Thomas et al. 2019; Fournier et al. 2019; Cohon 2011; Ellsworth-Ribis 2020b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in construction methods and circular economy [S]</td>
<td>Although many stakeholders see advantages in new construction methods, especially in terms of sustainable construction, there are social barriers, such as information interaction between software, insufficient technical training for employees, cultural resistance, etc.</td>
<td>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.</td>
<td>Biomass based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities.</td>
</tr>
<tr>
<td>(Olawumi et al. 2018; Osterirriich and Toctiburg 2019; Huang et al. 2023; Mata et al. 2020a; Patwa et al. 2021) (Harb et al. 2018; Xiong et al. 2019; Sataya et al. 2020; Zea Escamilla and Habert 2014; Escamilla et al. 2018; Chang et al. 2018b); (Ferreira et al. 2015; Hart et al. 2018; Schenkel et al. 2015; Tapajó et al. 2013; Wijes and Lozano 2016; L.K et al. 2020b; Ghivizzini et al. 2018) (Winchester and Reilly 2020; Pomponi et al. 2020) (L.K et al. 2020a) (Moreno et al. 2016; Park et al. 2010; Celik and Attaran 2013; Bueno and Bressani 2014; Zaei et al. 2016)</td>
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**Socio-cultural Dimension**

<table>
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</tr>
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<tbody>
<tr>
<td><strong>Envelope improvement</strong> [E]</td>
<td>Perceived as increased comfort and status, with limited concerns for the material, 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.</td>
<td>Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and mitigation of the heat island effect.</td>
<td>Result in lower energy bills, avoiding the “heat or eat” dilemma, alleviating energy/fuel poverty and improving energy security. Electricity of thermal energy use 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.</td>
</tr>
<tr>
<td><strong>Heating, ventilation and air conditioning (HVAC)</strong> [E]</td>
<td>Perceived as increased comfort and status, with limited concerns for the material, 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.</td>
<td>Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality and mitigation of the heat island effect.</td>
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</tr>
<tr>
<td><strong>Efficient Appliances</strong> [E]</td>
<td>Perceived as increased comfort and status, with limited concerns for the material, 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.</td>
<td>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.</td>
<td>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).</td>
</tr>
<tr>
<td><strong>Change in construction materials</strong> [E]</td>
<td>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.</td>
<td>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.</td>
<td>Bio-based materials, such as wood and bamboo, can be developed in degraded areas and by socially vulnerable communities.</td>
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Socio-cultural Dimension

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<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements) [E]</td>
<td>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. (Christodoulou et al. 2014; Sadeghi et al. 2016; Rey-Moreno and Medina-Molina 2020; Ti 2020; Mata et al. 2021; (Balta-Özkan et al. 2014; Batalla-Bayarri et al. 2020; Ibarzabal et al. 2014; Kendel and Lazac 2015; Moser 2017; Nkou 2019; Pal et al. 2019; Poortinga et al. 2012; Saffar et al. 2019; Shin 2013; K 2019; Sundt et al. 2020; Tan et al. 2017; Vassileva and Campillo 2014; Vippari and Junnila 2019b; Zhuang and Wu 2019; Mata et al. 2020c; Park et al. 2018; Reindl and Palm 2020; Si and Marianovics-Halburd 2016; Mata et al. 2021; (Aréz Bio and Greenstone 2012; Carha et al. 2020; (Jiang et al. 2017; Mil-Antunes et al. 2018; (Huckel et al. 2019; Xu et al. 2018; Yos et al. 2020; Ferreira et al. 2018; Seidl et al. 2019; Soland et al. 2018) (Thema et al. 2017; Sahel et al. 2018; Balaban and Puppin de Oliveira 2017; Tonn et al. 2018; Urge-Vorsatz et al. 2016; Mtsamurade 2018; MacNaughton et al. 2018; Macrindl et al.)</td>
<td>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. (Fournier et al. 2020; Vadovics and Živčič 2019; Pellegrini-Malpezi 2019; Thomas et al. 2019; Fournier et al. 2019)</td>
<td>Smart meters support the introduction of new and dynamic tariff schemes that allow price benefits for the end-users. Active management and digitalization 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, etc.</td>
</tr>
</tbody>
</table>


Institutional Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Political acceptance</th>
<th>Institutional capacity &amp; governance, cross-sectoral coordination</th>
<th>Legal and administrative feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building design and performance [S]</td>
<td>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 wellbeing of energy poor households the political acceptance can increase. (Fournier et al. 2020; Vadovics and Živčič 2019; Pellegrini-Malpezi 2019; Thomas et al. 2019; Fournier et al. 2019)</td>
<td>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. (Fournier et al. 2020; Vadovics and Živčič 2019; Pellegrini-Malpezi 2019; Thomas et al. 2019; Fournier et al. 2019)</td>
<td>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)</td>
</tr>
</tbody>
</table>
### Institutional Dimension

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<tr>
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<tbody>
<tr>
<td><strong>Change in construction methods and circular economy [S]</strong></td>
<td>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 robotized manufacturing in plants. In some (a few) developed countries there are public policies that encourage industrialization and rationalization of construction.</td>
<td>There should be a change in institutional capacity to follow up technology development in new construction methods, as for example testing 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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Envelope improvement [E]</strong></td>
<td>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.</td>
<td>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.</td>
<td>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. Retrofit improvement in particular for existing building are difficult to verify also in the case on public subsidies.</td>
</tr>
<tr>
<td><strong>Heating, ventilation and air conditioning (HVAC) [E]</strong></td>
<td>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 type might also affect the retrofit decision for HVAC systems. For e.g., 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.</td>
<td>In particular in developing countries there is lack of institutional capacity to adopt and enforce efficiency requirement for air conditioners.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>Efficient Appliances [E]</strong></td>
<td>There is strong support for appliances labelling and standards by policy makers both in developing and developed countries.</td>
<td>In particular in developing countries there is lack of institutional capacity to adopt and enforce efficiency requirement for appliances and lighting.</td>
<td>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.</td>
</tr>
</tbody>
</table>

*The mitigation options are grouped into institutional, economic, technical, cultural, and social dimensions.*

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**References:**

## Institutional Dimension

<table>
<thead>
<tr>
<th>Mitigation Options*</th>
<th>Political acceptance</th>
<th>Institutional capacity &amp; governance, cross-sectoral coordination</th>
<th>Legal and administrative feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Side Management (active management operation, digitalization and flexible comfort requirements)</td>
<td>There is still some scepticism by politicians for demand side management (active management operation, digitalization, and flexible comfort requirements).</td>
<td>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.</td>
<td>There are still legal and administrative barriers to demand side management (active management operation, digitalization and flexible comfort requirements) which hinder the feasibility of this option.</td>
</tr>
<tr>
<td>Renewable energy production</td>
<td>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.</td>
<td>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, e.g., 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.</td>
<td>Renewable energies investment still faces several constraints from a legal and administrative point of view. In particular there are in some countries cumbersome administrative procedure to be granted the authorisation to install renewable both on and off-site, as well as legal issue on the system charges that renewable producers may face.</td>
</tr>
</tbody>
</table>


(Mengolini et al. 2016; Warren 2017; Forouli et al. 2021; Izsak and Edler 2011)

(Jung et al. 2016; Cohen et al. 2016; Koecklin et al. 2021)
SM9.6 Supplementary information to Section 9.9

Table SM9.7 presents several studies examined in the context of Section 9.9.2.

Table SM9.7 Estimates of the direct and indirect rebound effects for households

<table>
<thead>
<tr>
<th>Rebound effects</th>
<th>Range</th>
<th>Mean</th>
<th>Median</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>Electric uses</td>
<td>3-14%</td>
<td>7%</td>
<td>5% (Schleich et al. 2014; Chen et al. 2018; Chitnis et al. 2013)</td>
</tr>
<tr>
<td>Indirect</td>
<td>-1.8 - 23.5%</td>
<td>10%</td>
<td>11%</td>
<td>(Cellura et al. 2013; Santos et al. 2018; Walzberg et al. 2020; Thomas and Azevedo 2013; Chitnis et al. 2013)</td>
</tr>
<tr>
<td>Direct and indirect</td>
<td>4.5-80%</td>
<td>32%</td>
<td>27%</td>
<td>(Scheer et al. 2013; Qiu et al. 2019; Murray 2013; Orea et al. 2015)</td>
</tr>
</tbody>
</table>
References


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