# SUPPORTING THE DEVELOPMENT OF A ROADMAP FOR THE REDUCTION OF WHOLE LIFE CARBON OF BUILDINGS

Final report

11.04.2023

www.ramboll.com // www.bpie.eu // www.kuleuven.be

# SUPPORTING THE DEVELOPMENT OF A ROADMAP FOR THE REDUCTION OF WHOLE LIFE CARBON OF BUILDINGS FINAL REPORT

| | |
|---|---|
| Project name | **Supporting a Roadmap for the Reduction of Whole Life Carbon in Buildings** |
| Recipient | **European Commissions – DG ENV** |
| Document type | **Final Report** |
| Date | **11/04/2023** |
| Authors | **Xavier Le Den, Jacob Steinmann, Attila Kovacs (Ramboll)**<br>**Judit Kockat, Zsolt Toth (BPIE)**<br>**Martin Röck, Karen Allacker (KU Leuven)** |


Ramboll
Square de Meeus 35
1000 Brussels
Belgium

T +32 (0) 2 737 96 80

www.ramboll.com



Ramboll Management
Consulting SA/NV
BE reg.no. 0867596506

# CONTENTS

# EXECUTIVE SUMMARY

## Background and approach

**This report provides the whole-life carbon (WLC) emission baseline and projections of EU buildings according to three different scenarios.** It is the final report of the study *Supporting the development of a roadmap for the reduction of WLC in buildings*, commissioned by DG Environment of the European Commission.

**These results summarise the work of the study team in scaling up building-level emissions to the entire EU building stock through the modelling of building archetypes and stock-level activities** such as new construction, energy efficiency renovation and demolition. This is done by assessing the potential of a list of solutions that can help reducing the operational and embodied carbon footprint of buildings, ranging from sufficiency measures avoiding new constructions to improvements in material production and efficiency in material use, as well as increasing the market share of alternative building materials.

The findings presented in this report are based on an approach that brings together three key workstreams to gain a better understanding of the building stock's WLC emissions and to outline future pathways for decarbonisation:

1. **representative building archetypes** are used to reflect the lifecycle impacts of new and existing buildings across the EU;
2. **embodied carbon reduction solutions** quantify the decarbonisation potential and implementation curve for measures to avoid new construction, improve building design, and shift to low-carbon materials. These solutions have been primarily assessed and applied to new constructions, though a limited set of these reduction options have also been included in modelling low carbon renovations. The low carbon solutions are modelled to their respective maximum capacity by 2040;
3. **building stock modelling** integrates the above two analyses as well as wider macro-economic, demographic and decarbonisation trends to quantify the emissions and pathway scenarios between 2020 and 2050.

This methodological approach is used to calculate the annual baseline emissions from EU buildings as well as three scenarios. As the study commenced in 2021, it considers the policy landscape at that point in time and, therefore, not all policies of the Fit-for-55 package are reflected[1]:

1. **The business-as-usual (BAU) scenario** which answers the question: How will WLC emissions of EU buildings develop between 2020 and 2050 when relying on current policies and expected market developments?

[1] As the study kicked off in 2021, the scenarios do not take into account the latest policy developments, such as the recast EPBD, nor the ETS Revision for phase 4 (2021-2030) and full decarbonisation of the energy sector. This means, for example, that key construction materials, such as mineral insulation, steel, glass, cement and aluminium, are not modelled at the foreseen decarbonisation rates triggered by these policies. Nonetheless, the study remains valuable and relevant as it effectively highlights the key areas of concern and presents a clear pathway for building stock decarbonisation.

2. **The TECH-Build scenario** which provides answers to the question: How much can we reduce lifecycle emissions in buildings by implementing material efficiencies and technological solutions at the level of individual buildings and that of the building stock?
3. **The LIFE-Build scenario** which answers the question: what changes to lifestyle and social norms are necessary in addition to technological solutions to reduce WLC as closely to the goal of net-zero as possible?

The distinction between the decarbonisation scenarios TECH-Build and LIFE-Build is illustrated in Figure 1.

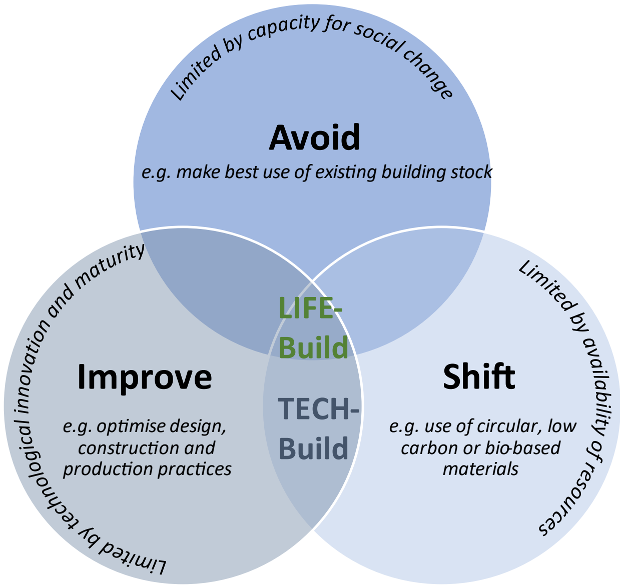



**Figure 1 Design of the two decarbonisation scenarios**

**The approach and the results provide novel insights in the WLC footprint of the EU's building stock.** Each result segment – from baseline emission levels to the decarbonisation scenarios – provides a better understanding of the drivers of WLC emissions as well as corresponding mitigation measures.

## Key findings

The section below presents the key findings of the study based on the assumption made.

### In the baseline year 2020, annual WLC emissions of the EU's building stock amount to 1,360 Mt$CO_2$e.

**This means that WLC emissions of buildings account for 41% of total EU emissions[2] in the baseline year,** a share that is slightly higher than previous studies indicate. The difference is due to the implementation of a bottom-up approach, including the modelling of both building level and building stock emission sources, as well as the comprehensive scope of lifecycle assessment which provides unprecedented level of details and insights about current carbon hotspots. Across the entire EU building stock, 21% of WLC emissions in the baseline year occur as embodied carbon emissions (related to construction, maintenance, renovation and demolition works) while the remaining ratio of 79% is associated with the operation of the building stock. New construction projects are the major drivers for the embodied emissions (71% of embodied carbon). However, these activities only affect 1.5% of the building stock floor area annually, which makes construction an important carbon hotspot. This is supported by the finding that embodied emissions account for up to 74% of WLC emissions in case of advanced energy performance newly constructed buildings. Therefore, embodied emissions represent an important reduction potential both for individual projects and for the building stock in total.

[2] Compared with 2019 EU GHG emission inventory. EEA (2022). National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism. Available at: https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18

**In the business-as-usual scenario, annual EU building stock emissions decrease by 32% in 2050.**

**This represents a reduction to 919 $MtCO_2e$ in 2050** (see Figure 2)**.** Such levels would put the building stock far out of the needed trajectory for a net-zero economy[3], which makes it clear that policy and market actions to reduce WLC emissions of buildings much further are indispensable.

**Overall, the decline in emissions is primarily attributed to operational emission reductions**. The total reduction of 442 $MtCO_2e$ in WLC compared to the baseline year is significant as it is being projected against a 40% increase of the building stock floor area. Renovations and space heating decarbonisation contribute to a reduction of 44% of use-phase operational carbon. On the other hand, embodied emissions are expected to increase slightly over time, linked to an increase in new construction and renovations.

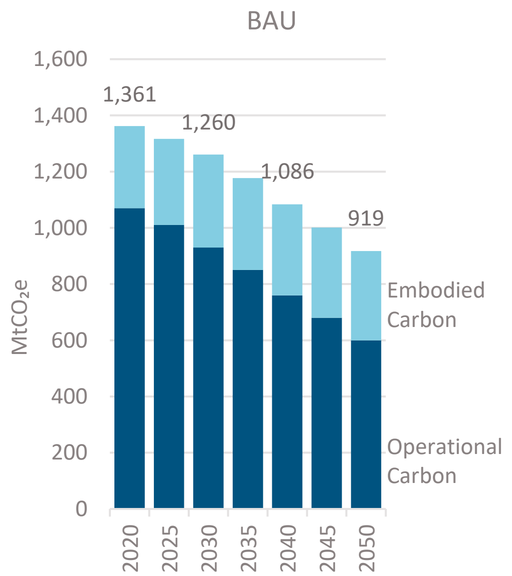



**Figure 2 Development of WLC emissions in a business-as-usual scenario**

Overall, the increase of embodied carbon emissions is outweighed by the improvements in energy efficiency and savings in operational carbon, resulting in a steady decline of whole life cycle (WLC) emissions over the coming decades. However, the reductions are too limited to be compatible with the EU's net-zero target for 2050.

**Comprehensive efforts to avoid and reduce operational and embodied emissions can achieve 75% reduction in annual WLC emissions by 2050 compared to the levels observed in 2020.**

**TECH-Build** represents a transformational scenario for the implementation of technical solutions across Europe, including embodied carbon reduction solutions, a renovation rate of over 3% per year from 2030 onwards, and the decarbonisation of space heating according to the MIX scenario underlying the Fit-for-55 package.

**According to this scenario, it is possible to reduce WLC levels in 2050 by 68% in comparison to the baseline year, to a level of 438 $MtCO_2e$ per year** (see Figure 3). This reduction is driven by a sharp decrease in operational emissions of 90% when comparing 2050 values to the baseline. A high rate of energy renovations increases energy efficiency of the building stock, while decarbonisation of space heating


**Figure 3 Development of WLC emissions in the TECH-Build scenario**

[3] Compared to the middle of the range indicated by the 1.5C scenarios (1.5TECH, 1.5LIFE,1.5LIFE-NB) modelled in the Clean Planet for All. In-depth assessment in support of the Commission Communication COM(2018) 773 (Clean Planet For All). 2018. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

reduces the carbon intensity of the remaining energy demand. The gains in operational efficiency come at the cost of an increase of embodied carbon. The deployment of low carbon measures in both new constructions and renovations helps preventing a larger increase of embodied emissions that would have happened otherwise.

**The amount of embodied carbon in the building stock initially decreases until 2025, but it is projected to remain stable from 2020 to 2050.** While the modelled embodied carbon reduction solutions reduce the upfront impact of new buildings by 51%, the increased volume of renovations leads to a growing share of embodied carbon for these kinds of projects. However, this study does not fully explore the potential for carbon reduction associated with renovations and it can be expected that significant embodied carbon reduction solutions can be applied for this activity as well. Nonetheless, even without having considered the latter in detail, the results from the study still highlight the value of energy renovations to reduce both operational emissions and, thereby, total WLC emissions of the EU building stock.

**The reduction projected by the TECH-Build scenario still results in a slower decarbonisation rate than needed for the EU's net-zero emission levels in 2050**[4].

The additional measures introduced in the **LIFE-Build** scenario to avoid new construction (beyond what can be achieved with in the measures considered in the TECH-Build scenario) further reduce the operational and embodied carbon of new buildings.

**This scenario of combining technological and lifestyle measures could deliver a reduction of 75% in WLC emissions of the building stock in 2050 compared to the baseline 2020 emission levels**, **realising annual WLC levels of 344 MtCO₂e** (see Figure 4)**.** The impact of the avoid solutions take place in the context of an already comprehensive technological transformation captured in the TECH-Build scenario, which limits the sufficiency levers for further decarbonisation. Sufficiency measures are, however, relevant because these reduce the reliance of climate mitigation on technological solutions. Their reduction potentials are especially important in achieving deep decarbonisation goals. By focusing on sufficiency measures, it becomes possible to rely less on technological solutions and subsequently decrease associated costs. Also, should there be delays in implementing technical solutions to reduce WLC, the sufficiency measures will become even more necessary and stringent to compensate carbon lock-ins.

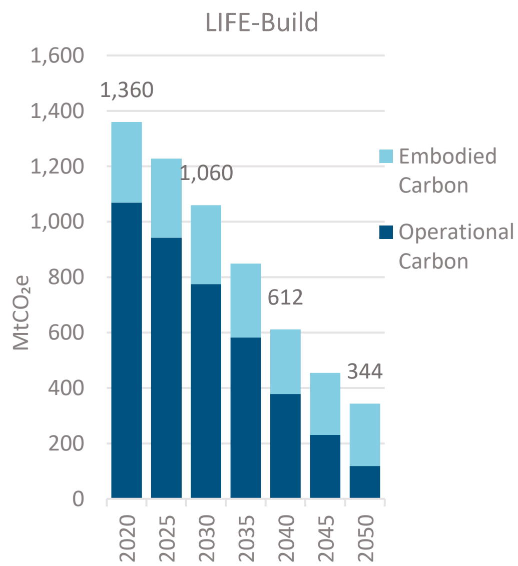



**Figure 4 Development of WLC emissions in the LIFE-Build scenario**

**In addition to reducing WLC emissions even further, avoiding new construction enables and supports the implementation of solutions to reduce embodied emissions through design improvements and material shifts.** A lower material demand from new construction ensures that low-carbon materials are available for the essential construction and renovations works. Therefore, sufficiency can prevent rebound effects and mitigate performance gaps in relation to technical measures.

[4] Compared with the middle of the range indicated by the 1.5C scenarios (1.5TECH, 1.5LIFE,1.5LIFE-NB) modelled in the Clean Planet for All. In-depth assessment in support of the Commission Communication COM(2018) 773 (Clean Planet For All). 2018. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

**The emissions levels projected by the LIFE-Build scenario, combining technical and sufficiency measures, reduces buildings' WLC emissions further and more closely aligned with the sectoral values represented in the economy-wide net-zero target[5].** Additional reductions from renovation projects can be expected, as several design solutions and material alternatives could not be quantified due to data limitations. Yet, these results call for a comprehensive transformation of the building stock and its related value chains. This constitutes the only way WLC emissions can fall below the levels modelled in the LIFE scenario and avoid costly carbon removal efforts in the EU economy.

[5] Compared with the middle of the range indicated by the 1.5C scenarios (1.5TECH, 1.5LIFE,1.5LIFE-NB) modelled in the Clean Planet for All. In-depth assessment in support of the Commission Communication COM(2018) 773 (Clean Planet For All). 2018. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

# GLOSSARY

The table below provides a list and definition of key terms used throughout the study.

| | |
|---|---|
| **Whole life carbon** | Whole life carbon encompasses all greenhouse gas emissions resulting from the materials, construction and the use of a building over its entire life, including its demolition and disposal. It is thus the total amount of embodied and operational emissions (see below).<br>The purpose of using the concept of whole life carbon is to move towards buildings that generates the lowest greenhouse gas emissions over their whole life.<br>In relation to the international standard for life cycle assessments of buildings (EN 15978), providing harmonised calculation rules for the environmental performance of new and existing buildings, *whole life carbon* includes the emissions from the life cycle stages (or "modules") A to C (see Figure 5). |
| **Operational carbon** | Operational Carbon are all greenhouse gases emissions associated with the energy consumed during the building's use phase (operational energy use). This comprises heating and cooling and other uses, such as domestic hot water, appliances, lighting and cooking.<br>In relation to EN 15978: module B6. |
| **Embodied carbon** | Embodied carbon refers to all the greenhouse gas emissions associated with materials and construction processes throughout the whole lifecycle of a building. It thus refers to the upfront emissions attributed to construction, including the extraction, and processing and transport of materials and the energy and water consumption in the production, assembly, and construction of the building. It also includes the 'in-use' stage (the maintenance, replacement, and emissions associated with refrigerant leakage) and the 'end of life' stage (demolition, disassembly, and disposal of any parts of product or building) and any transportation relating to the above[6].<br>In relation to EN 15978: modules A1-3, A4-5, B1-5 and C1-4 |
| **Upfront (embodied) carbon** | The emissions released during the materials production and construction stages before the building begins to be used. In contrast to other categories of emissions, these emissions have already been released into the atmosphere before the building is occupied and operated.<br>In relation to EN 15978: modules A1-3, A4-5 |
| **Annual building stock emissions** | Annual greenhouse gas emissions from the building stock refer to the emissions profile of operational and embodied carbon in an indicated year. These are the sum of operational carbon from all buildings in use in a given year, upfront embodied carbon of new buildings constructed in that year, renovation projects taking place in that year, as well as other use-stage embodied emissions and demolitions in that year. |

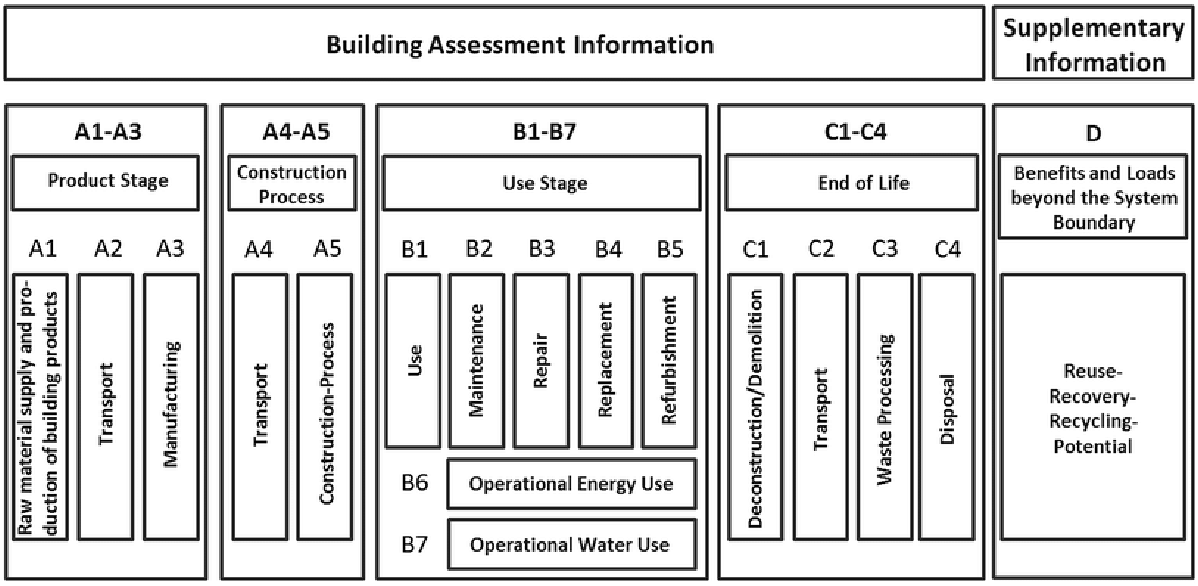
[6] LETI (2020) Embodied Carbon Primer

| | |
|---|---|
| **Building life cycle assessment** | A life cycle assessment (LCA) is typically used to calculate the whole-life carbon of a building. It is a well-established methodology to assess environmental impacts and resource consumption at each stage of the building's lifecycle. The LCA can also include an assessment of the potential benefits from the reuse or recycling of components after the end of a building's useful life. The LCA enables the comparison, prioritisation and optimal allocation of resources. LCA is the approach embraced by the Construction Products Regulation (CPR), Level(s) and the majority of voluntary certification schemes for sustainable buildings.<br><br>EN 15978 is the European standard that provides a framework for assessing the environmental performance of buildings throughout their life cycle. The standard specifies the principles, requirements, and guidelines for carrying out a life cycle assessment (LCA) of buildings, from the extraction of raw materials to the end of the building's life. |

Figure 5 below illustrates the building life cycle stages (A-D) and sub-modules that are included in the assessment of environmental performance of buildings in accordance with the European standard EN 15978 for the assessment of the environmental performance of buildings.

For consistency with the terminology used in EU documents, the term *renovation* is used in this report to refer to the *refurbishment* module of a building life cycle, i.e. the improvements of the building envelope or the technical building systems. The term used by the life cycle assessment and building professional community in reference to the same activity is "refurbishment".

**Figure 5 Life cycle modules of a building according to EN 15978**



# 1. INTRODUCTION

This report presents the findings of the technical study aimed at "Supporting the development of a roadmap for the reduction of whole life carbon of buildings". The objective of this work is to outline how all building-related emissions (both operational and embodied) can be mitigated by 2050. It also provides the evidence base to persuade policymakers and the overall buildings and construction community to take action beyond the policies already in place.

The European Union aims to be climate-neutral by 2050, requiring a fundamental transformation of the building and real-estate sector. This decade is critical as direct building CO2 emissions need to more than halve by 2030 to get on track for a net-zero carbon building stock by 2050. Emissions must be drastically cut throughout the whole lifecycle of buildings, encompassing both operational and embodied emissions.

The scope and scale of this study is unprecedented. For the first time, a bottom-up approach relying on building archetypes and building stock modelling provides projections on future emissions in three scenarios: a business-as-usual (BAU) as well as two transformative decarbonisation pathways.

The business-as-usual scenario is based on current policies and expected market developments. It outlines what levels of embodied carbon emissions can be expected from the EU building stock looking ahead to 2050 under a business-as-usual scenario, taking into account the third trading period EU Emission Trading System (ETS) from January 2013 to December 2020, but neither its fourth trading period 2021-2030, nor the full decarbonisation of the power sector. This means, for example, that key construction materials, such as mineral insulation, steel, glass, cement and aluminium, are not modelled at the foreseen decarbonisation rates triggered by these policies. Nonetheless, the study remains valuable and relevant as it effectively highlights the key areas of concern and presents a clear pathway for building stock decarbonisation.

In comparison to this, the two ambitious decarbonisation scenarios project future emission levels as we progress towards 2050. They answer the questions:

- TECH-Build: how much can we reduce WLC emissions in buildings by implementing material efficiencies and technological solutions at the level of individual buildings and that of the building stock?
- LIFE-Build: what further reductions of WLC emissions can be achieved through changes to lifestyle and social norms?

The scenarios are based on the comprehensive implementation of measures which are expected to reduce future carbon emissions. These transformations include European and national building policies, building design improvements, low-carbon material selection, industry transitions, circular economy, as well as other framework conditions related to carbon intensity and energy mixes, economic growth, demographics, urbanisation and built space utilisation. These solutions have been primarily assessed and applied to new constructions, though a limited set of these reduction options have also been included in modelling low carbon renovations. The low carbon scenarios assume a combined, all-at-once implementation of solutions by 2040 as a reasonable compromise to balance solutions which have a more forthright implementation and solutions which have lower technology and market readiness level.

The outcome of the study will inform the stakeholder discussion and support the design of a roadmap to be developed by the European Commission. The report helps defining the scale and urgency of action, as well as illustrating the WLC reduction potential and the role of various carbon reduction solutions/strategies at both building and stock level. This in turn will enable the setting of milestones with target values against which policy ambitions can be assessed against. Once the emission pathways are established, policies can be identified to support and drive the required interventions, via regulation, economic or fiscal incentives or other market tools.

Chapter 2 describes the approach used to calculate building stock impacts and define the scenarios. The report summarises the baseline results (Chapter 3) before presenting the results of the business-as-usual (Chapter 4) and the two decarbonisation scenarios (Chapter 5). Chapter 6 concludes with some key takeaways from the analysis.

**Whole Life Carbon (WLC): individual building vs. building stock perspectives**

The term "whole life carbon" refers to greenhouse gas (GHG) emissions resulting from the materials, construction, and the use of a building over its entire life, including its demolition and disposal[7]. It is commonly used in the context of individual buildings to provide a true picture of a building's GHG impact on the environment, comprising both embodied and operational emissions. In relation to the international standard for life cycle assessments of buildings (EN 15978), providing harmonised calculation rules for the environmental performance of new and existing buildings, whole life carbon includes the emissions from the life cycle stages (or "modules") A to C, according to the international standard.

**Figure 6 Lifecycle GHG emission profile of individual buildings**

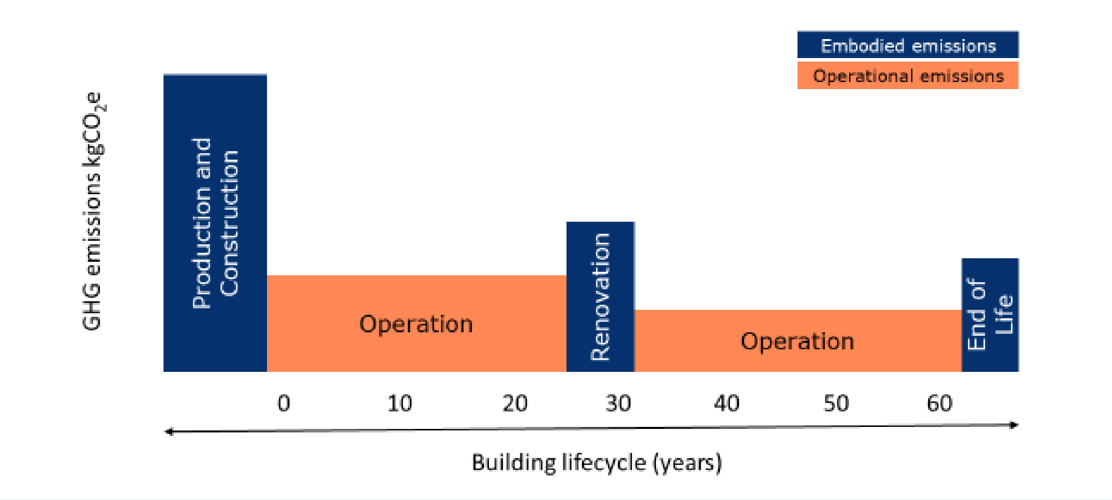
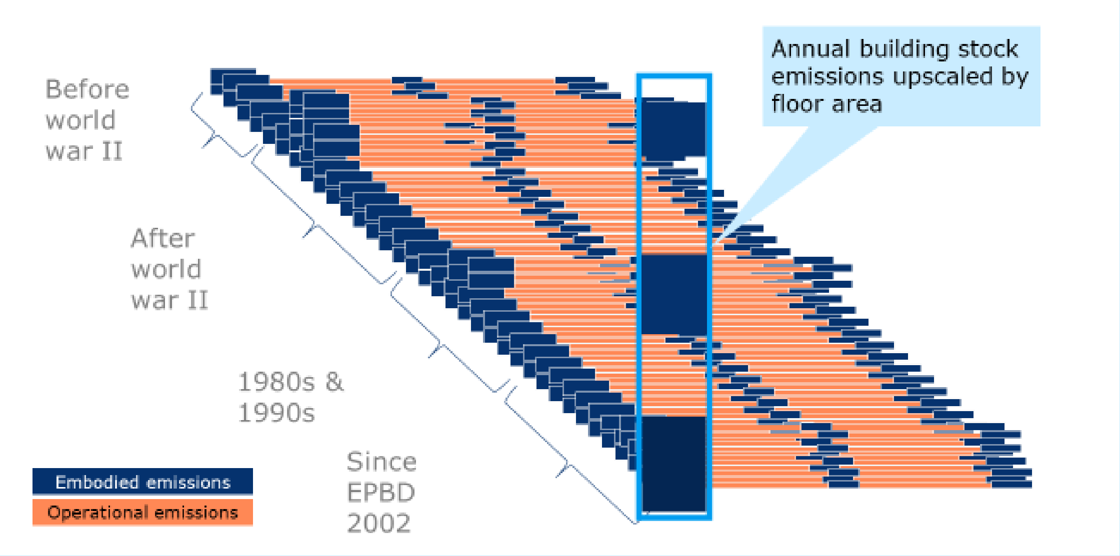



**Figure 7 Annual building stock GHG emissions comprising buildings at various stages of lifecycle**




[7] The terms 'embodied carbon', 'operational carbon' and 'whole life carbon' are being used as synonymous with 'embodied/operational/whole life GHG emissions'. The data and values presented below are based on the Global Warming Potential (GWP) indicators and include both CO2 and non-CO2 GHG emissions. The reference unit applied is kilogram CO2e (equivalent) expressed per m² useful floor area (UFA), per capita, or m² and year, respectively.

It is important to note that building stock WLC emissions are connected to the following **building stock activities**: construction, renovation[8], operation, and demolition. WLC, when applied at the building stock level with a reference period of one year, may indicate a significantly different embodied/operational carbon balance compared to the embodied/operational carbon profile of individual buildings. This is due to the fact that the building stock level analysis shows the complete carbon emissions profile of the entire EU building stock in one year made up of buildings at various stages of lifecycle and not for one building across all the stages of its lifetime.

[8] For consistency with the terminology used in EU documents, the term renovation is used in this report to refer to the refurbishment module of a building life cycle, i.e. the improvements of the building envelope or the technical building systems. The term used by the LCA and building professional community in reference to the same activity is “refurbishment”.

# 2. APPROACH

## 2.1 Overall approach

The objective of this study is to quantify the annual WLC emissions associated with the EU's building stock and identify pathways for decarbonisation in different scenarios. The analysis therefore has to capture annual emissions from existing buildings, renovations and the construction of new buildings across the EU, and captures both the emissions related to construction products produced in the EU as well as those imported. Such quantifications are unprecedented and data availability covering the multitude of building types, traditions and specifications is patchy[9] – particularly for the embodied emissions resulting from materials, construction and demolition processes.

To overcome these challenges, the study employs a representative model of different building features combined with a quantitative model of the building stock developments. The use of representative building archetypes and building stock upscaling gives an overview of the WLC footprint of the EU's building stock according to current design and construction and practices as well as operation and use of buildings. These insights are summarised in a baseline of annual WLC emissions from the EU building stock and a business-as-usual scenario.

Given that annual WLC emissions at the building stock level are far from being on track to meet Paris Agreement goals, it is essential to understand how the buildings sector can reduce its WLC impact in line with the EU's ambition of climate neutrality. For this reason, different transformational decarbonisation options are modelled. Operational emission reductions are realised through energy efficiency renovations and fossil fuel transition[10]. Embodied carbon reduction solutions are identified and quantified and are built into sector-specific decarbonisation scenarios. These solutions relate to design improvements, material shifts and demand reduction strategies. Together with projections for renovations and fuel switch in space heating and cooling, these measures allow the development of two decarbonisation scenarios to drive the building sector towards net-zero whole life carbon by mid-century:

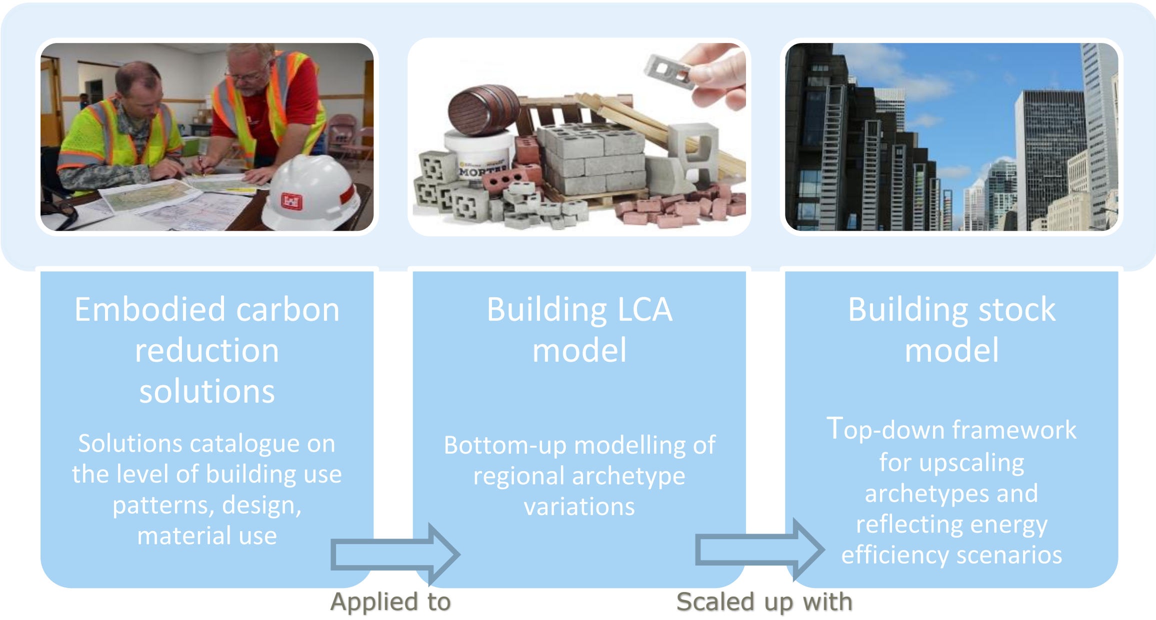
- **TECH-Build**, which employs state-of-the-art technical measures to improve building design and shift to low-carbon materials
- **LIFE-Build**, which completes the first scenario with lifestyle and sufficiency measures to avoid or reduce demand for new construction and materials.

Figure 87 illustrates the methodological approach of the study. The following sections explain the three building blocks in more detail, starting with the building archetypes, followed by the description of embodied carbon reduction solutions and stock-level modelling.

[9] Röck M, Sørensen A, Steinmann J, Le Den X, Lynge K, Horup L H,, Tozan B, Birgisdottir H. Towards Embodied Carbon Benchmarks for Buildings in Europe – Facing the data challenge, 2022, https://doi.org/10.5281/zenodo.6120522

[10] The EU Emissions Trading System (EU ETS) has been taken into account in its phase 3, however the latest revision for phase 4 (2021-2030) is not reflected in this study.

**Figure 8 Overview of the methodological approach**




## 2.2 Building archetypes

Building archetypes are virtual representations of various buildings in the stock that share similar characteristics. The study employs three representative archetypes: single-family homes (SFH), multi-family houses (MFH), and offices (OFF). These representative buildings are tailored according to four different climatic regions as defined in the recast of the EU's Energy Performance of Buildings Directive (EPBD): Oceanic[11], Mediterranean[12], Continental[13] and Nordic[14].

The bottom-up, archetype-based approach is commonly applied for modelling building stocks at the macro scale in order to enable both the detailed modelling and analysis of representative buildings as well as the investigation of macro-level dynamics[15]. Archetypes are defined based on statistical analysis of the building stock to represent as best as possible, the vast diversity in the age, size, construction practices, installed equipment, appliances, behavioural patterns, and emission profile of buildings across Europe. In this study, a total of 60 archetypes were developed to represent existing buildings, different energy renovation options, as well different new building variants specific to each of the four regions, respectively (Figure 8).

Appendix I presents the detailed methodology and data sources used for the characterisation of the current building stock and describes the selection of building archetypes.

The representative archetypes were selected based on statistical analysis of building stock composition and characterisation, using data from EU projects Ambience[16] and Hotmaps[17]. The selected archetypes are defined in detail based on data from TABULA/EPISCOPE[18], which is the main data source for archetype inventory definition and provides national buildings typologies

[11] Belgium, Denmark, Ireland, Germany, France, Luxembourg, and Netherlands

[12] Cyprus, Croatia, Italy, Greece, Malta, Spain, and Portugal

[13] Austria, Bulgaria, Czechia, Hungary, Poland, Romania, Slovenia, and Slovakia

[14] Estonia, Finland, Latvia, Lituania, and Sweden

[15] Röck M, et al. Environmental Modelling of Building Stocks – An Integrated Review of Life Cycle-Based Assessment Models to Support EU Policy Making. Renewable and Sustainable Energy Reviews, 2021. https://doi.org/10.1016/j.rser.2021.111550.

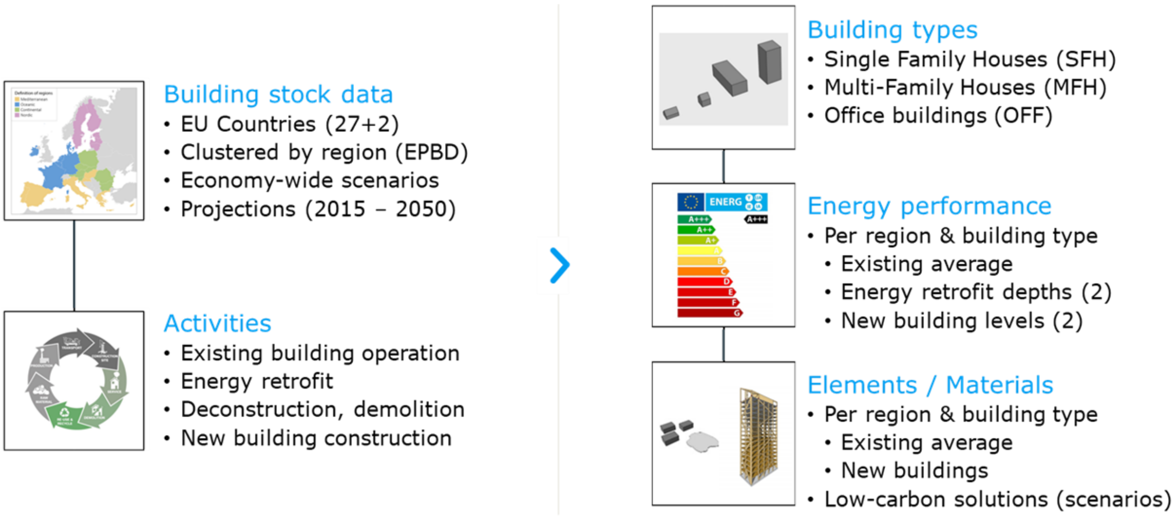
[16] https://www.ambience-project.eu/

[17] https://www.hotmaps-project.eu/

[18] https://webtool.building-typology.eu/

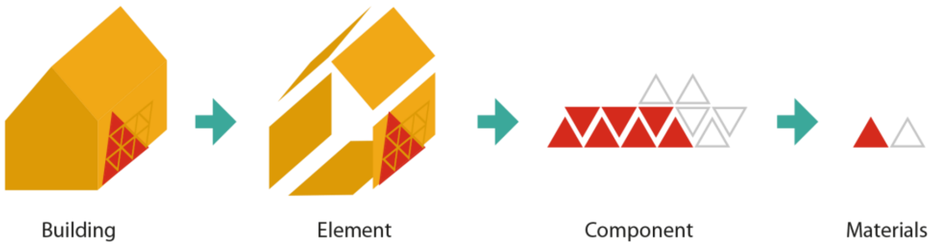
representing the residential building stock. The building archetype inventories were modelled using the SLiCE/MMG building LCA tools of KU Leuven (where SLiCE stands for "Scalable life cycle engineering" and MMG stands for the Dutch version of "Environmental profile of buildings").

**Figure 9 Aspects considered in the characterisation of the building stock baseline.**




The modelling of the building archetypes is structured in a hierarchical way, which is presented in Figure 109. At each level, environmental impacts are calculated for the respective life cycle stages and transferred onto the next level. Firstly, **materials** are modelled by defining their thermal conductivity (λ, W/mK) and density (ρ), their impacts for production (life cycle stages A1-A3), and by selection of suitable scenarios for stages transport to site (A4), and the construction and installation process (A5), as well as transport to end of life (C2) and disposal (C4). Next is the **component** level, in which multiple materials are selected and their quantity per unit of component is defined. In addition, scenarios for maintenance (B2), replacement (B4) and deconstruction/demolition (C1) are selected. Then, a similar approach is used to define building **elements** (e.g walls, floors), by selecting various components, i.e. by defining the quantity of component per unit of building element. At this level, the U-values of the building elements are calculated based on the λ and thickness of the components and the thermal resistances of the surfaces. Lastly, **buildings** as a whole are defined as a compilation of building elements and technical systems. This level includes, on one hand, specifying the building geometries (e.g. m² of building element areas, number of doors etc.), and on the other hand, creating combinations of specific building element compositions (e.g. wall type 1, floor type 3 etc.). Hence, a building is defined by combining one building geometry with one building element combination, and by filling in parameters related to technical systems and energy use (B6).

**Figure 10 Hierarchical structure of the MMG method[19]**




[19] Lam W.C., Trigaux D. Environmental profile of building elements [update 2021]. 2021.

Deconstruction and demolition activities, as well as end-of-life treatment of the building elements, are modelled as part of the respective life cycle of the buildings. These are included for both existing and new buildings and represent current common practices. The end-of-life scenarios for the various materials in the building elements and technical systems are following the MMG method[20].

Operational energy use modelled includes energy use for space heating, domestic hot water (DHW), and ventilation, where applicable. Cooling is modelled for the office archetypes but not for single-family house (SFH) and multi-family house (MFH) archetypes, as cooling-related energy use is unregulated and not captured in the statistical data at the building stock level, which is used for upscaling later. A detailed description of the calculation of the energy use of these different aspects can be found in Trigaux (2017)[21].

## 2.3 Embodied carbon reduction solutions

This study defines embodied carbon reduction solutions as practical measures implemented by market actors with direct GHG emission reduction impacts achieved by reduced material demand, carbon intensity or waste generation. The scope of embodied carbon reduction solutions is focused on solutions on a building project level. These solutions relate to sufficiency in building demand (avoid), material efficiency through improved design or improved means of production (improve), and shifting to the use of alternative, low-carbon material solutions (shift). Table 1 presents the solutions across the three categories in the columns left to right.

The identification, categorisation, and quantification of the GHG reduction impacts are supported by a comprehensive literature review that includes academic publications, reports of international organisations, government publications, as well as industry roadmaps. This evidence was compared across sources and validated through interviews with experts. Still, in some cases, limited data availability meant that a quantification of potential future diffusion had to be assumed relying on comparable sectors or technologies.

**Table 1 Embodied carbon reduction solutions to avoid, improve and shift**

| Avoid new construction | Improve building design | Shift to low-carbon materials |
|---|---|---|
| • Optimise the use of space in offices and residential buildings<br>• Use existing assets that are currently unused instead of new buildings.<br>• Renovate instead of building new | • Design based on light construction method instead of massive construction<br>• Design for adaptability, resilience and extended lifespan which could also lead to reduced demand for new construction<br>• Design for disassembly<br>• Reduce concrete demand by use of void formers in concrete slabs<br>• Use carbon cured concrete<br>• Carbon capture in cement production<br>• Carbon capture in steel production | • Re-use existing building components and materials<br>• Full timber construction<br>• Hybrid structures in new construction<br>• Use other bio-based materials<br>• Use industry by-products instead of clinker in cement<br>• Use alternative cementitious materials instead of cement in concrete<br>• Use recycled concrete and other by-products for new concrete<br>• Use recycled steel in steel production<br>• Use recycled glass in glass production<br>• Use renewable energy in cement production<br>• Use renewable energy in steel production and other metals<br>• Use renewable energy in glass production |

[20] Lam W.C., Trigaux D. Environmental profile of building elements [update 2021]. 2021.

[21] Trigaux, D. "Elaboration of a sustainability assessment method for neighbourhoods." (2017).

Each solution has a specific scope of building typologies, materials, building elements and lifecycle stages for which emissions reductions can be realised. Additionally, the impact occurs on different levels of modelling in the archetypes or stock upscaling.

The list of solutions is applied to the business-as-usual scenario together with projections for energy efficiency renovations and the decarbonisation of space heating and cooling to provide decarbonisation scenarios for the EU's building stock. Depending on the scope of the solution, they are applied either to the respective building archetype or to the overall building stock projections. As a result, a new set of archetypes is created, which reflect the decarbonisation potential at a project level. These solution archetypes are then gradually replacing the baseline archetypes to reflect the transition from current practices and technologies to a projected full implementation of these solutions by 2040.

Table 2 summarises the integration of embodied emission reduction solutions in the modelling. A detailed overview as well as a description of how each of the solutions is modelled is included in Appendix II.

**Table 2 Integration of embodied carbon solutions in the archetype and building stock modelling**

| | | Applied to | | | | |
|---|---|---|---|---|---|---|
| **Category** | **Embodied carbon reduction solution** | **Stock-level activities** | **Construction material** | **Building element** | **Building project** | **Not modelled** |
| **Avoid** | Optimize/reduce the use of space in offices and residential buildings | X | | | | |
| **Avoid** | Use existing assets that are currently unused instead of new buildings. | X | | | | |
| **Avoid** | Renovate instead of build new | X | | | | |
| **Improve** | Design for adaptability, resilience and extended lifespan | | | | | X[22] |
| **Improve** | Design for disassembly | | | | | X[23] |
| **Improve** | Design based on light construction methods instead of massive construction | | | | X | |
| **Improve** | Reduce concrete demand by use of void formers in concrete slabs | | | X | | |
| **Improve** | Use carbon cured concrete | | | X | | |
| **Improve** | Implement carbon capture in cement production | | X | | | |
| **Improve** | Implement carbon capture in steel production | | X | | | |
| **Shift** | Re-use existing building components and materials | | X | | | |
| **Shift** | Use industry by-products instead of clinker in cement | | X | | | |
| **Shift** | Use alternative cementitious materials instead of cement in concrete | | X | | | |
| **Shift** | Use recycled concrete and other by-products for new concrete | | X | | | |
| **Shift** | Full timber construction | | | | X | |
| **Shift** | Hybrid (concrete + timber) structures in new construction | | | | X | |
| **Shift** | Use other bio-based materials | | | X | | |
| **Shift** | Use recycled steel in steel production | | X | | | |
| **Shift** | Use recycled glass in glass production | | X | | | |
| **Shift** | Use renewable energy in cement production | | X | | | |
| **Shift** | Use renewable energy in steel production and other metals | | X | | | |
| **Shift** | Use renewable energy in glass production | | X | | | |

## 2.4 Building stock modelling

The different archetypes defined in Section 2.2 are extrapolated to represent the entire EU building stock. This step is called "upscaling" and is carried out by multiplying archetypes to account for the complete floor area of the EU building stock. In addition, the building stock modelling applies current and future construction, renovation, and demolition rates to calculate the embodied emissions resulting from these activities.

The upscaling is done in four steps:[24]

1. The building stock composition is reflected by distributing the archetypes to represent typical building types, construction periods, energy performance levels and construction materials.
2. Relevant projections for the stock level activities such as new construction, renovation and demolition rates are applied, as well as resulting future energy performance levels.
3. Macroeconomic framework developments are integrated to factor in indirect actions such as floor area demand, the decarbonisation of space heating and cooling, as well as general industry trends that enable the reduction of WLC emissions.
4. Building stock emissions are calculated by combining the parameters of the first three steps.

Assumptions used in the building stock modelling are described below. Some of these input points, specifically the projected building stock activities and resulting floor area developments, are scenario dependent. These are described in detail in context of these scenarios in Chapters 4 and 5.

### Activity levels for new construction, renovation, and demolition

The development of the building stock – in terms of floor area growth and energy/carbon intensity – is modelled using assumptions such as construction, demolition and renovation activity.

[22] The impacts of a reduced need for new construction due to today's new buildings applying 'design for flexibility' are effective only after 2050, i.e., they lie in future beyond the timeline of this study. Therefore, the solution is not modelled.

[23] The impacts of a reduced need for new materials due to today's new buildings applying 'design for disassembly' are effective only after 2050, i.e., they lie in future beyond the timeline of this study. Therefore, the solution is not modelled.

[24] The baseline captures a single year of emissions from the building stock (2020) and, in this case, only the first step is applied

10 and  Figure 11 Overview of annual construction rates assumed in different scenarios 11 below provide a comparative overview of the construction and renovation rates assumed in different scenarios.

The renovation rate in the business-as-usual scenario is increased gradually to reach 2% by 2030 in line with the target set out by the EU Commission in the Renovation Wave.[25] The other scenarios aim at full stock renovation. The scenario assumptions are discussed in detail in section 5.1.1 Building stock developments in the business-as-usual scenario (BAU) and 5.1 Activity levels for new construction, renovation and demolition for the TECH-Build and the LIFE-Build scenarios. These renovation rates are higher than what is assessed in other studies[26], and as such represent scenarios of an ambitious transformation.

[25] COM(2020) 662 final

[26] See for instance Figure 41, In-depth analysis in support of the Commission Communication COM(2018) 773, A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

**Figure 11 Overview of annual construction rates assumed in different scenarios**

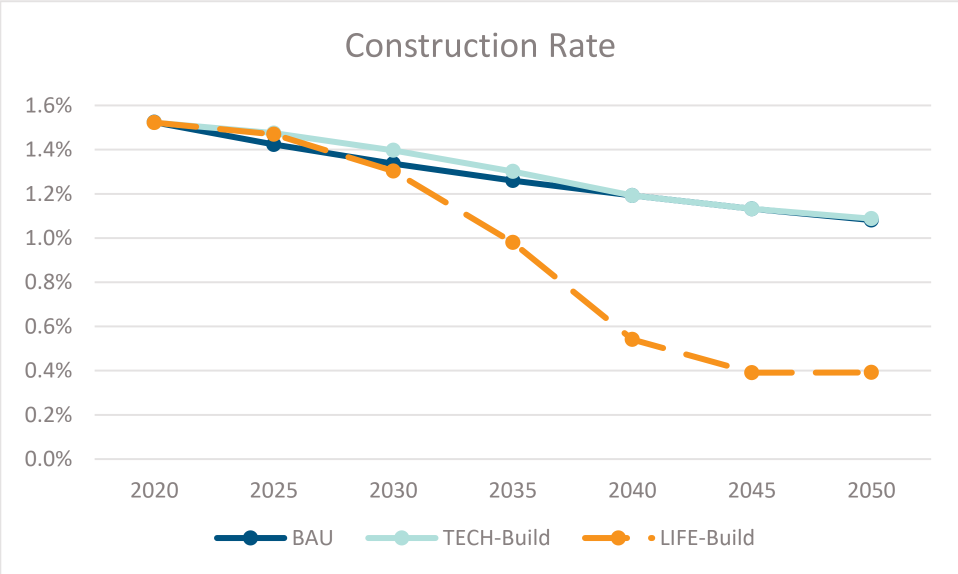
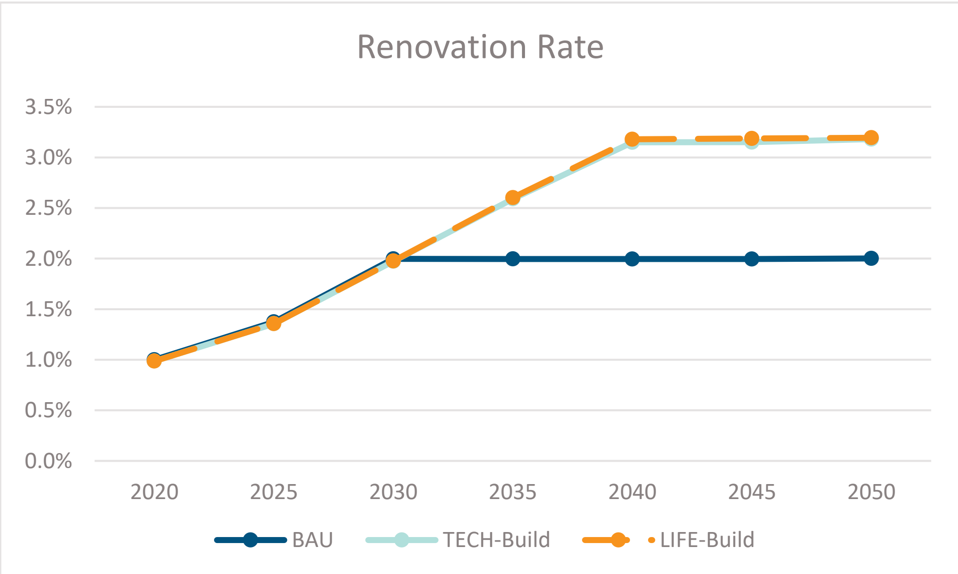



**Figure 12 Overview of annual renovation rates assumed in different scenarios**




## Decarbonisation of space heating

Decarbonisation of space heating in addition to improvements in energy efficiency of buildings contributes significantly to reducing building related operational emissions. The decarbonisation of space heating is accounted for in all three scenarios (BAU, TECH-Build, LIFE-Build). Decarbonisation rates are different according to different scenarios: space heating is decarbonised at the current rate in the business-as-usual scenario (BAU); the rate is faster in the TECH-Build and LIFE-Build scenarios that aim at carbon-neutrality in 2050. The EUCalc Reference Scenario provides the projections for carbon intensity factors of space heating representing advances in technology and fuel mix[27] for the business-as-usual scenario. This business-as-usual scenario is based on the reference scenario before the update of key policies in the Fit for 55 package. Table 3 below provides the comparison of scenarios regarding the rate of heating decarbonisation. This decarbonisation includes the decarbonisation of the energy supply for space heating in the form of electricity and district heating. .

**Table 3 Space heating carbon intensity factor without unit of measurement indicating the advance or development of the fuel mix starting in 2020 (100 or 1.00).**

| Year | BAU | TECH-Build and LIFE-Build |
|---|---|---|
| **2020** | 1.00 | 1.00 |
| **2025** | 0.94 | 0.86 |
| **2030** | 0.89 | 0.74 |
| **2035** | 0.84 | 0.62 |
| **2040** | 0.79 | 0.50 |
| **2045** | 0.75 | 0.38 |
| **2050** | 0.70 | 0.27 |

### Carbon intensity of construction materials supply chains and industrial decarbonisation

The decarbonisation of the energy system is also relevant for the carbon intensity of energy delivered to industry processes that produce/manufacture construction and renovation relevant products (construction products, technical systems) and construction machinery. To reflect these reductions in the carbon intensity of processes, the business-as-usual scenario applies the EUCalc Reference Scenario projections which reproduces, as far as possible, the main sectoral assumptions and outputs of the EU Reference Scenario 2016.[28] The EU Reference Scenario models the impact of EU Emission Trading System (ETS) in the scope of its third trading period from January 2013 to December 2020, but neither, its fourth trading period 2021-2030, nor the full decarbonisation of the power sector.

The business-as-usual scenario accounts for reductions in the carbon intensity of processes using an overall decarbonisation rate for selected construction related industries. In contrast, the TECH-Build and LIFE-Build scenarios assume specific decarbonisation solutions for construction materials such as light building design or using recycled concrete, industry by-products in cement, or using bio-based materials as described above in section 2.3 (full list is available in the Appendix II). By using these specific carbon reduction solutions, the TECH-Build and LIFE-Build scenarios are more ambitious in the assessment of carbon emissions.

### Application of embodied carbon reduction solutions

The application of embodied carbon reduction solutions constitutes the main difference between the two decarbonisation scenarios TECH-Build and LIFE-Build.

The **TECH-Build scenario** represents a measure-driven decarbonisation pathway implementing planned policy pathways to reduce operational emissions as well as a series of technical solutions to reduce embodied carbon. Specifically for reducing embodied carbon, this scenario analyses the impact of solutions which replace conventional materials used (*shift*) and construction techniques

[27] The levers corresponding to TECH-Build and LIFE-Build scenarios can be accessed here: http://tool.european-calculator.eu/app/buildings/energy-carriers/?levers=33333333333333333333333333333333333333333333333311l21n221

[28] P. Capros et al (2016) EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050

(*improve*) with less carbon-intensive ones. For these measures, diffusion boundaries[29] have been identified in literature, expert interviews, and practitioner feedback. These boundaries represent absolute limits for the implementation at project level (e.g., structural safety) or at building stock level (e.g., availability of timber for construction). Therefore, this scenario strongly builds on technology and material solutions to reduce WLC emissions– which also suggests the title *TECH-Build*. These measures are reflected in a new set of building archetypes that take into account the implementation of the carbon reduction solutions at building level.

The implementation of the TECH-Build solutions at building stock level is limited by boundaries arising from technical requirements (e.g. structural safety) and material availability (e.g. sustainably sourced timber). Each solution is phased-in replacing the baseline archetypes for new construction and renovations according to the diffusion curve up to 2040[30]. The baseline archetypes are phased out respectively until only the archetypes reflecting the embodied carbon reduction solutions remain for new construction and renovations.

The **LIFE-Build** scenario adds the so-called "*Avoid*" solutions. These measures define changes in cultural norms and user behaviour, reducing the floor area per person needed, using existing buildings prior to building new[31] and, thus, reducing the need for new construction. These measures are also referred to as "sufficiency" or "lifestyle" solutions. Thus, the title LIFE-Build is chosen for this scenario. The additional solutions in this scenario are applied to the building stock model, affecting the demand and supply for new construction, renovation rates and ambition. These solutions do not have technical limitations but are connected to social boundaries such as public acceptance. Their level of diffusion is based on ambitious but realistic assumptions found in academic literature.

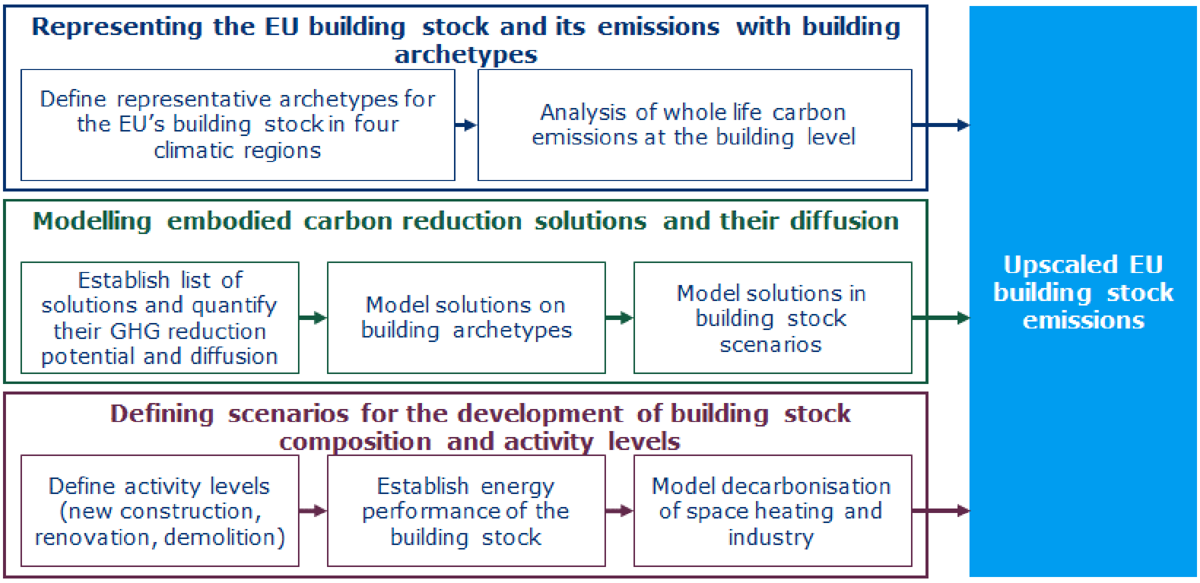
In conclusion, the building stock modelling brings together the insights from the various embodied carbon reduction solutions, archetype modelling, and modelled building stock developments under one common framework. Figure 132 summarises the approach to arrive at upscaled EU building stock emissions.

[29] Diffusion describes the potential for implementation across the EU building stock based on technical feasibility, material availability and other relevant considerations.

[30] 2040 was chosen as a reasonable approach to balance solutions having a more forthright implementation, such as design based on light construction methods, and solutions that have lower technology and market readiness level, such as carbon capture and storage in material production.

[31] These are modelled as renovations aimed at reuse and repurposing of existing assets and are different from energy efficiency renovations. Renovations aimed at reuse and repurpose of existing buildings have only been applied in the LIFE-Build scenario. See Appendix II for further details.

**Figure 13 Detailed approach to quantify WLC emissions at the EU building stock level**




The underlying assumptions of the different scenarios are compared in Table 4 below.

**Table 4 Comparison of assumptions used in the various scenarios**

| Assumption/ Parameter | Business-as-usual | TECH-Build | LIFE-Build |
|---|---|---|---|
| **Annual new construction rate**[32] | 2020 1.5%<br>2030 1.3% - 1.4%<br>2040 1.2%<br>2050 1.1% | 2020 1.5%<br>2030 1.3% - 1.4%<br>2040 1.2%<br>2050 1.1% | 2020 1.5%<br>2030 1.3%<br>2040 0.5%<br>2050 0.4% |
| **Annual renovation rate** | 2020 1.0%<br>2030 2.0%<br>2040 2.0%<br>2050 2.0%<br>Reaching 2% by 2030 as per renovation wave | 2020 1.0%<br>2030 2.0%<br>2040 3.1%<br>2050 3.2% | Beyond 2% to fully renovate the building stock |
| **Energy performance levels in new buildings and renovation** | 87.5 % standard energy performance<br>12.5 % advanced energy performance | Increasing from BAU level to<br>30 % standard energy performance<br>70 % advanced energy performance<br>until 2030 | |
| **Annual demolition rate** | about 0.1 % in all scenarios and all years | | |
| **Decarbonisation of space heating/cooling** | 2020 1<br>2030 0.89<br>2040 0.79<br>2050 0.7 | 2020 1<br>2030 0.74<br>2040 0.5<br>2050 0.27 | |
| **Embodied carbon reduction** | Decarbonisation of construction material supply chains and their energy supply:<br>2020 1<br>2030 0.90<br>2040 0.85<br>2050 0.80 | Excluding "avoid" solutions described on the next slide | Including "avoid" solutions described on the next slide |

[32] BAU and TECH-Build scenarios: assuming a constant amount of new floor area being added by constructions, the rate is slowly decreasing due to a growing stock. LIFE-Build scenario: the construction rate is decreasing assuming sufficiency measures that reduce demand for new constructions.

## 2.5 Limitations

As of yet, there is very little prior research on whole life carbon emissions stemming from the European buildings stock. This study fills an important gap providing a first comprehensive overview of the current and expected future levels of emissions. However, the methodology is not without limitations. These constraints are also an opportunity to identify gaps and guide further research in the area.

### Integration of the embodied emissions reduction solutions in the building archetypes

A first limitation relates to the practical integration of embodied carbon reduction solutions in the modelling of building archetypes and the building stock. A combined, all-at-once implementation of solutions in the decarbonisation scenarios was the only feasible method within this study. This implies that the mitigation impact of specific solutions could not be quantified individually and, therefore, the ranking of most promising solutions was not possible. A more granular and stepwise approach will be needed to understand the potential of each embodied carbon reduction solution.

A similar simplification was used in relation to the market uptake of the solutions. Solutions modelled in the TECH-Build scenario have a diffusion curve that reaches the assumed full potential in 2040. Different assumptions can lead to different full potentials[33]. The low carbon solutions are modelled to their respective maximum capacity by 2040 which was chosen as a compromise to balance solutions which have a more forthright implementation, such as lightweight construction, and solutions which have lower technology and market readiness level, such as carbon capture and storage. A future solution-specific approach would enable the quantification of the differences in technology and market diffusion.

The material-related solutions to reduce embodied carbon are focused on key upfront emission drivers of material considered most relevant, such as concrete, steel or glass. The necessary selection of strategies meant that, for some materials or sectors, the specific decarbonisation potentials will not be fully captured in this study. For example, materials such as aluminium, paints and adhesives, or plastics, are not covered, even though their contribution to the baseline building stock embodied carbon emissions is found to be relevant, largely through use phase emissions. Future research will need to explore specific embodied carbon reduction solutions for these materials.

### Quantification of the reduction potential for embodied emissions in renovation projects

The focus of the embodied carbon reduction solutions in this study is on new constructions. Opportunities to reduce embodied emissions from constructions are well researched and offer a range of design and material options. This is also well aligned with the urgency to reduce embodied carbon attributed to the construction and production of buildings because it is a current carbon hotspot. However, this doesn't mean that renovation embodied emissions should be ignored.

[33] See appendix II for a description of the solutions as well as the discussion in chapter 2.5 on the limitations on notably the modelling of mitigation options for embodied carbon in renovations. Moreover, the outcomes of the modelling regarding embodied emissions from new built, obviously depend on the assumptions made and should not be understood as facts. Examples for modified assumptions are the potential for higher uptake of alternative cementitious materials instead of cement in concrete (solution 7b), increased use of CCU with permanent storage (for instance solution 7e, but this can also apply in other sectors such as certain plastics), higher shares of recycled steel (solution 11a), higher shares of renewable energy for cement or glass production, including for the latter higher use of electrification (solutions 12a and 12c), higher use of carbon capture storage in cement and the impact of biomass use in this context on generating removals which was not modelled (solutions 13a), a set of building materials for which no reduction assumptions have been assumed (e.g. paints, glues, insulation, copper, etc) but which represent as significant amount of the remaining embodied emissions in new built as well as in renovation.

Regrettably, data on reducing embodied carbon in renovations is much sparser. For this reason, the reduction potential of embodied emissions from renovation will be larger than what is covered by this study, which models a limited set of low carbon solutions for renovations. Solutions which do not require any design adjustments (e.g. materials produced with renewable energy) were applied to renovation projects. Yet, these projects by nature require fewer quantities of these materials. On the other hand, solutions that consider building design beyond the choice of materials could not be accurately assessed due to the limited availability of comprehensive data across various projects. This includes for instance, timber as construction material or other bio-based materials, even if their application is expected to be relevant. Additional research and data collection will be required to analyse the whole life carbon mitigation potential in renovations.

### Quantification of the decarbonisation effect of sufficiency solutions

Likewise, the deployment of sufficiency and avoid solutions is limited by data constraints. In effect, a limited number and scope of solutions is modelled in this category and therefore likely to leave carbon reduction potential untapped. For example, vacant or under-occupied buildings represent assets that can be repurposed and reused with very little additional embodied emissions. Yet, data on unused buildings is not systematically collected across the EU and existing data sources vary substantially in scope. Targeted data collection on sufficiency solutions and a more dynamic building stock model reflecting population development and standards of living will be needed to reflect more accurately the carbon reduction potential of avoid and demand reduction measures.

Furthermore, the sequencing of the scenarios and policy interventions has an important influence on the relative impacts of each set of decarbonisation solutions. The first set of technical measures applied will realise the highest emission reductions as it applies directly to the baseline of relatively high carbon intensity. Sufficiency measures modelled in the following set are applied to an already reduced base of emissions and are therefore bound to have a lower relative carbon saving impact. Given that the technical measures are applied first, the results may suggest an overly optimistic outlook in terms of the impact and effectiveness of technology. Starting applying sufficiency solutions to reduce demand and avoid new construction in parallel with technological solutions would have produced more substantial carbon savings from the sufficiency measures than the study currently suggests. Future work should assess different sequencing and combinations of decarbonisation measures to arrive at an optimal mix of interventions.

### Methodological choices on biogenic carbon content and time horizon

While not necessarily a limitation, it is also worth noting that this study applies a 0/0 approach to account for the biogenic carbon content of bio-based construction materials. This means that there is no consideration of biogenic GHG uptake, storage and later release in those materials, or storage that is considered permanent and would represent removals. Other methods exist but are either not robust enough or would create distorted results over the 2050 timeline due to later GHG releases (or benefits) are not being considered. With the maturing of dynamic LCA approaches, a comparison of results in the context of temporary carbon storage could be considered.

Finally, the 2050 milestone leaves less than 30 years to realise the impact of decarbonisation solutions and bring the sector on track to carbon neutrality. However, some embodied carbon reduction solutions, such as circularity or design for deconstruction and reuse, would provide emission savings only beyond this timeline. These solutions are not accounted for but should be pursued nonetheless to achieve long-term decarbonisation of the building stock.

# 3. BASELINE EMISSIONS OF THE EU BUILDING STOCK

The current level of whole life cycle GHG emissions associated with the EU building stock forms the baseline for any further analysis. This baseline corresponds to the whole life cycle GHG emissions released in the baseline year 2020.[34] The baseline assessment is realised through the definition of representative building archetypes for each climatic zone, building typology, energy performance and project type and the subsequent modelling of their emissions for the different life cycle stages. This yields insights into the shares of embodied and operational emissions for the different building types, components and materials. Combining the results from the archetype assessment with a model of annual building stock activities, such as new construction, renovation and demolition, quantifies the baseline building stock emissions.

## 3.1 Building-level baseline

The archetypes were developed for newly constructed buildings as well as existing buildings which undergo energy renovation processes. This section first presents the results obtained for new buildings before focusing on existing buildings further below.

### 3.1.1 New buildings in the baseline

Figure 14 below illustrates the analysis of embodied carbon (EC) and operational carbon (OC) for standard (STD) and advanced (ADV) energy performance levels across different individual building archetypes.[35]

**The embodied carbon share averages 34% of whole life carbon (WLC) for standard (STD) energy performance levels,** ranging from 23% to 59%.

**The embodied carbon share averages 74% of whole life carbon (WLC) for advanced (ADV) energy performance levels,** ranging from 39% to 96%.

**However, in absolute terms, advanced energy performance levels clearly result in lower whole life carbon emissions across all regions and building types modelled.** Relative embodied carbon contribution to WLC increases, as expected, for energy efficient ADV variants with reduced operational carbon values. Only minor increases of absolute embodied carbon are observed for advanced energy performance (ADV) cases compared to their standard energy performance counterparts (STD).

The analysis of the embodied carbon for new building archetypes is shown in Figure 155 further below.

[34] The baseline analysis is built using generic LCA background data and building stock model that does not take into account the impact of COVID-19 pandemic. The COVID-related slowdown in overall construction activity caused delays in the project pipelines and for the purpose of this study, it is assumed that its impact on embodied carbon emissions is only temporary given the subsequent rebound that followed as restrictions eased and construction projects resumed.

[35] Standard energy performance new buildings correspond to new constructions complying with current/recent building regulations in EU Member States. Advanced performance levels correspond to passive houses, low-energy buildings or near/net-zero energy or emission (NZEB) buildings. While the Energy Performance of Buildings Directive requires that EU countries had to ensure that all new buildings were nearly zero-energy by the end of 2020 (all new public buildings had to be nearly zero-energy after 31 December 2018), implementation gaps remain and not all Member States required NZEB standards at the time the data for baseline analysis was gathered. For more information on the STD/ADV distinction, see Annex I and Röck et al. 2020.

**Figure 14 Whole life embodied and operational carbon emissions (annualized) for the different new building archetypes (SFH, MFH, OFF), per region and energy performance level (GWP)**

Whole life embodied and operational carbon vary substantially across building types: embodied carbon per $m^2_{UFA}$ tends to be highest for Single-family house (SFH), lowest for multi-family house (MFH), and in between for office buildings (OFF).

**Single-family house (SFH) archetypes absolute embodied carbon value is the highest of the three building types with, on average, about 915 kg$CO_2$e/m²,** ranging from around 550 to almost 1.380 kgCO2e/m². For SFH archetypes, highest embodied carbon values are observed for Mediterranean region, influenced by local construction culture and requirements related to seismic resilience.

**Multi-family house (MFH) archetypes show the lowest embodied carbon results and these are considerably less varied with a mean value of about 560 kg$CO_2$e/m²** and values ranging from around 435 up to 695 kg$CO_2$e/m².

**Office (OFF) archetypes display embodied carbon values around 685 kg$CO_2$e/m²,** very much between the average values observed for SFH and MFH archetypes, respectively. Embodied carbon of archetypes ranges from around 615 to 750 kg$CO_2$e/m².

Comparison with recent embodied carbon baseline studies shows building level embodied carbon levels which are consistent with literature and absolute values at the upper end and above values of previous studies. This is likely due to the application of a useful floor area (UFA) based reference unit (as opposed to gross floor area (GFA) or other definitions in different studies). This implies that a smaller value (UFA) is used for division of the whole life carbon results, which leads to ~25% higher per-m² values.[36] Another reason for the higher than expected results is the comprehensive scope of life cycle analysis and building parts covered in this study (e.g. the explicit modelling of technical services production and replacement).

### Analysis of embodied carbon contributions at building-level across life cycle stages

This section presents the analysis of embodied carbon contributions from different lifecycle stages, illustrated in Figure 15.

**Upfront embodied carbon emissions – i.e., product stage (A1-3), transport to building site (A4) and the construction and installation process (A5) – account for more than 8/10 of embodied carbon, highlighting the immediate climate impact of new building activity**.

On average, upfront embodied carbon emissions account for 84% of embodied carbon (79% to 87%). The product stage (A1-3) is the most important individual life cycle stage as it accounts for an average of 76% - more than 3/4 - of whole life embodied carbon emissions (71% to 80% for individual new buildings archetypes). An average 4% of embodied carbon is contributed by Transport to site (A4) (3% to 5%), and the construction-installation process (A5) (4% to 5%), respectively.

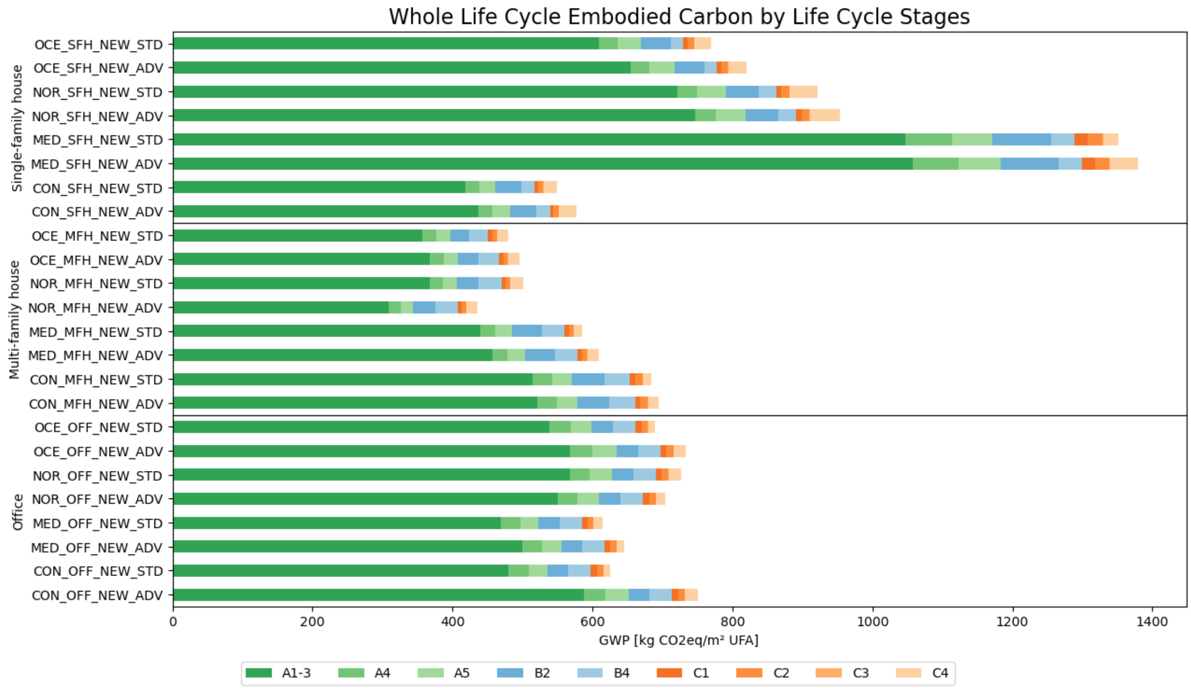
Building use-related embodied carbon occurring from maintenance (B2) and replacement (B4) accounts for 10% (7% to 14%) of embodied carbon, on average. The individual contribution to embodied carbon from maintenance (B2) is 6% (4% to 7%) and 4% (2% to 7%) from replacement (B4), respectively.

Only about 5% (4% to 7%) of embodied carbon occur during end-of-life (C1, C2, C3, C4). Within this stage, an average of 3% of embodied carbon emissions occur during disposal (C4) (1% to 5%),

[36] As a general rule, GFA indicates the total constructed area, while UFA refers to the area inside the building and excludes the area covered by the outer walls as well as circulation spaces of a building. The specific ratio of UFA per GFA depends on the building typology and commonly ranges around 0.8 m2 UFA per m2 GFA. (For further information see, e.g., ISO 6707-1; Commission Directive (EU) 2015/996 of 19 May 2015 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council, 2015.)

while 2% or less of embodied carbon are related to each of deconstruction and demolition (C1) (1%), transportation to end-of-life (C2) (1% to 2%), or waste processing (C3) (<1%), respectively.

**Figure 15 Whole life embodied carbon for new building archetypes by life cycle stage (GWP)**

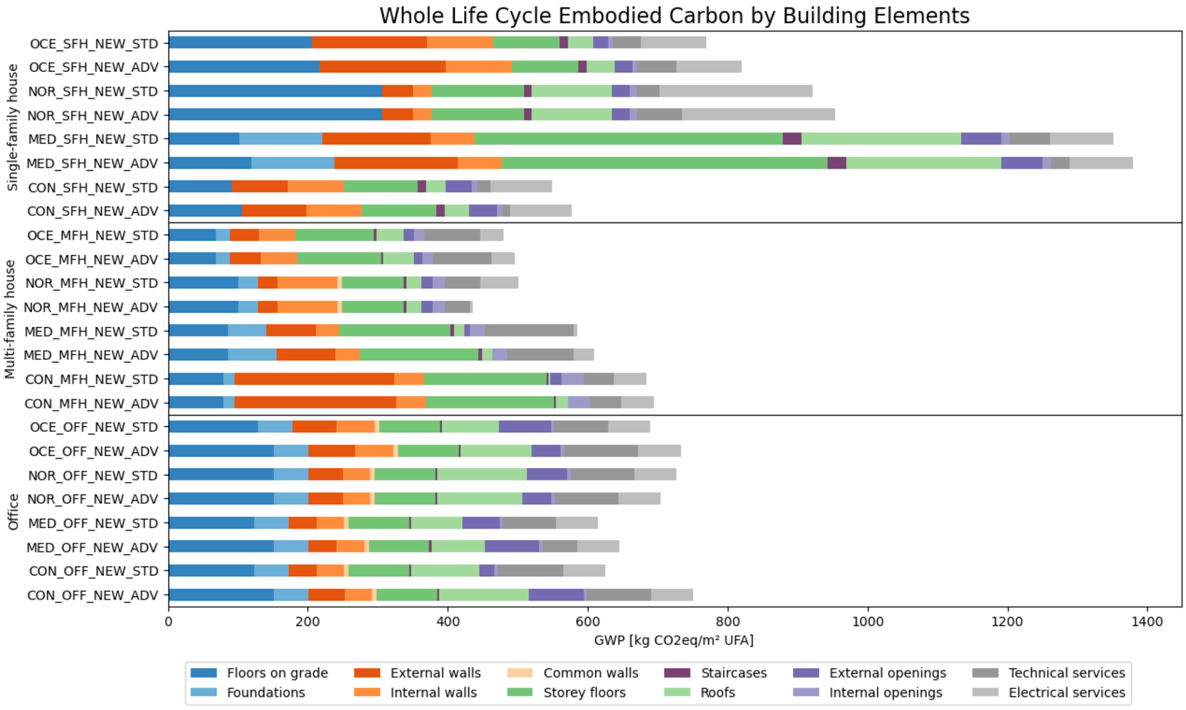



## Analysis of embodied carbon contributions across different building elements

Figure 166 presents the analysis of embodied carbon contributions from different building elements.

**The most important building element sections, on average, are floors on grade (19%) and foundations (5%), storey floors (19%) and roofs (10%), and external walls (12%) and external openings (5%), which together account for more than 2/3 of embodied carbon, on average**. Another 10% are, on average, related to technical and electrical services, respectively. This is followed by internal elements such as internal walls (8%), internal openings (doors) (2%), or staircases (1%). However, the contribution of different building elements varies strongly across different building types and regions, as both building geometry as well as regional construction culture and materials influence the distribution of embodied carbon in buildings regarding both their spatial and temporal distribution.

**Figure 16 Whole life embodied carbon for new building archetypes by building elements.**




### 3.1.2 Existing buildings in the baseline

#### End of Life emissions

Existing buildings archetypes End of Life (EoL) embodied carbon emissions (modules C1-C4) differ to a lower extent across the regions, but the analysis shows a difference in drivers of these emissions. The building type, i.e., form, layout and size of building as well as the build-up of the elements determines the GHG emissions at the end-of-life. In consequence, opportunities to lower EoL GHG emissions depend on the building type and materials used.

**The most important elements leading to EoL GHG emissions appear to be floor on grade, foundations, external walls, storey floors, roofs, windows and technical systems)**, which emphasizes the potential of "saving" embodied carbon through adaptive reuse of existing buildings.

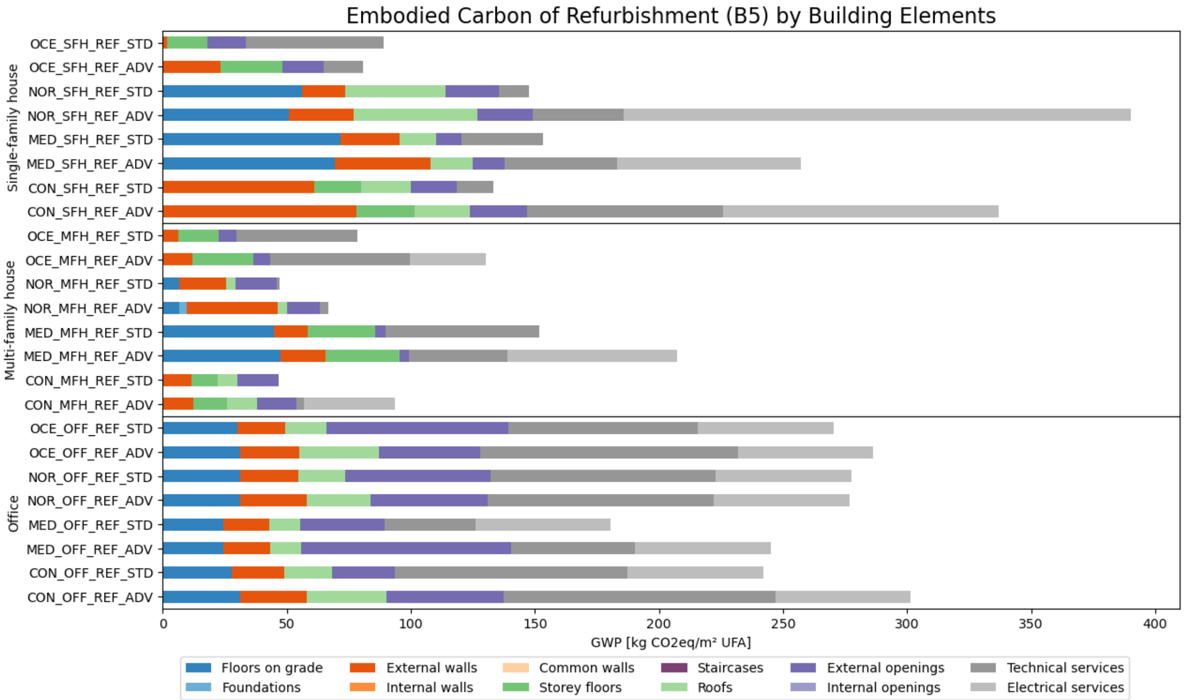
#### Renovations

As shown in Figure 177, embodied carbon from renovations (B5) of existing buildings archetypes reveal large differences between the typologies, with higher embodied carbon per $m^2_{UFA}$ for single family houses and offices than the multi-family houses. The embodied carbon emissions of the energy renovation measures moreover vary depending on the region and the energy performance obtained after renovation, i.e. the resulting operational energy use (B6) and related carbon emissions. For the energy renovation of single-family houses (SFH), the highest GHG emissions are noticed for the advanced (ADV) energy renovations on the Nordic region (NOR), as well as in the Mediterranean (MED) and Continental (CON) region. In the case of multi-family houses (MFH), the highest embodied carbon from energy renovations occurs in the Mediterranean region (MED). The office renovations shows a more equal spread of emissions over the various regions**.**

**Across regions and building types, the most carbon intensive elements related to energy renovations are technical services and electrical services, which can make up 50% and**

**more of the embodied carbon of advanced energy renovations** (see Figure 177). Embodied carbon emissions further stem from energy renovation measures related to the envelope – with floors on grade, roofs, external walls and external openings being the main contributors of envelope-related embodied carbon investment for renovation measures.

**Figure 17 Embodied carbon from energy renovations (B5) by building elements.**

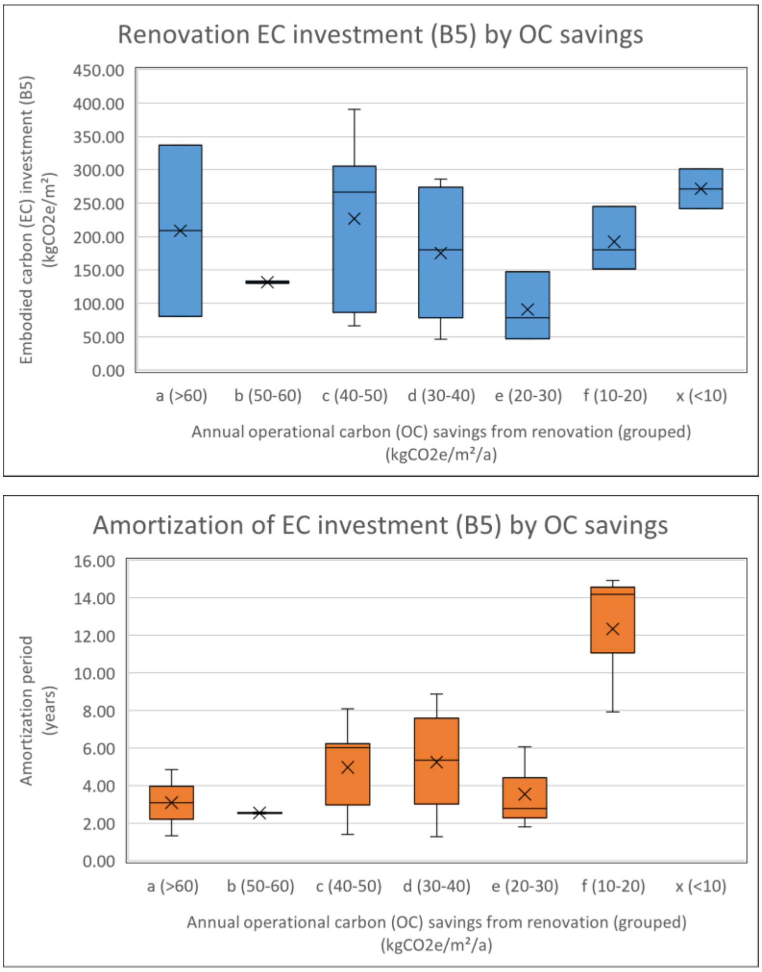



## Break-even points: renovation operational carbon savings and embodied carbon costs

Renovations are currently designed on the principle to optimise energy and cost savings by adding insulation or replacing old systems with more energy-efficient ones. Thus, renovations result in occupants using less energy day-to-day, but it also means more embodied carbon as more material is added to the building and older systems are thrown away. Furthermore, renovations can extend the lifespan of the building and so it helps avoid the embodied carbon needed to replace an old building with a new one. Integrating whole-life carbon considerations, in addition to energy efficiency, would enable deep renovations that also ensure low embodied carbon by striking the optimal balance between operational carbon savings and embodied carbon investments.

Initial analysis shows a strong deviation and no clear trends in terms of embodied carbon investments and operational carbon savings achieved through renovation (Figure 18)**. Carbon payback times however indicate a clear trend that embodied carbon investment for good renovation pays-off within few years and that quicker amortisation is achieved for renovations where higher operational carbon savings are achieved**. Payback occurs within less than 10 years for all building archetypes and renovation projects, bar the least effective renovations (those achieving operational carbon savings <20 $kgCO_2e/m^2/a$). Cosmetic or poor-quality renovations, that only lead to little or no operational carbon reduction (<10 $kgCO_2e/m^2/a$), may not 'pay-off' the embodied carbon invested within the life cycle, thereby causing embodied emissions with no direct WLC reduction effects. Most effective renovation projects, however, pay back initial embodied carbon investment within 5 years or less (i.e., when reducing operational carbon by 50 $kgCO_2e/m^2/a$, or more). As renovations are usually bespoke projects, these should be tailored and optimised for simultaneous operational carbon savings and reduced embodied carbon investment.

**Figure 18. Operational carbon (OC) savings from renovation (B5) versus embodied carbon (EC) investment (top) and amortisation/payback period (bottom)**




## 3.2 Building stock emissions in the baseline year

The results of the building-level modelling are scaled up to the entire EU building stock considering the annual activities. The findings are illustrated in a series of graphs presented in Figure 20.

The building stock analysis estimates that **1,360 Mt$CO_2$e are released by activities connected to the whole life cycle of EU buildings in the baseline year** (Figure 2020, graph e) and suggests that **approximately 79% of the life cycle emissions are associated with the operation of the building stock, while embodied carbon emissions represent the remaining 21%** (graph b).

Embodied emissions are further broken down according to the following life cycle modules, as shown in Figure 20 graphs c and f below:

- 71% emitted during construction and production of the buildings
- 14% associated with the use phase of the building (e.g. maintenance, repair)
- 14% caused by renovations
- Less than 1% emitted due to the demolition of existing buildings.

These figures need to be understood in the context of the building stock perspective. The building stock includes various building types, both new and old buildings, as well as buildings of different sizes, designs, and construction standards. Construction, renovation and demolition activities, which are mainly responsible for the release of embodied emissions, are only undertaken to a small (2.6%) share of the overall building stock. The bulk of the building stock floor area is existing buildings, undergoing – at most – maintenance and repair woks (Figure 19).

This means that only 2.6% of the EU's floor area in a given year give rise to most of the embodied emissions, representing 21% of the annual building stock emissions. In particular, only 1.5% of the total floor area is newly constructed in the baseline year, yet this newly constructed floor area results in embodied carbon levels that account for 15% of the total building stock emissions. In total, energy renovations account for a much smaller share of the total embodied carbon, partly due to less floor space being renovated than newly constructed, and partly due to the fact that renovation typically requires less material than new built per square meter.

This fact highlights new construction as a second emission hotspot in the current building stock, besides operational carbon.

**Figure 19 Building stock floor area distribution in million m² in the baseline year 2020 (standard – buildings complying with current/recent building regulations in EU Member States; advanced – (nearly) zero energy buildings)**

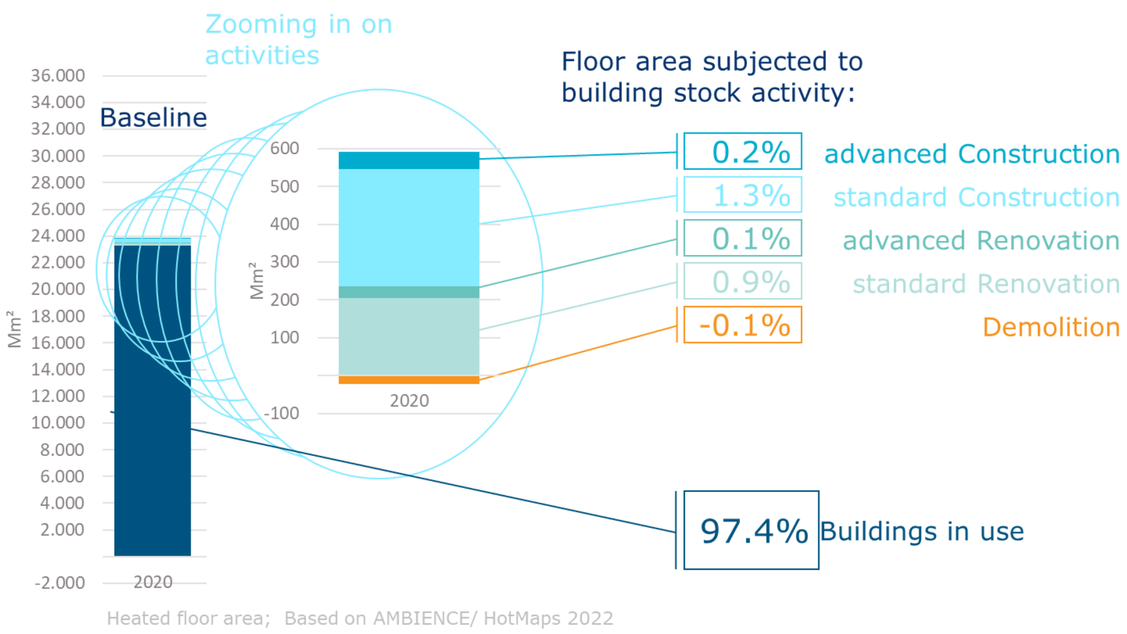
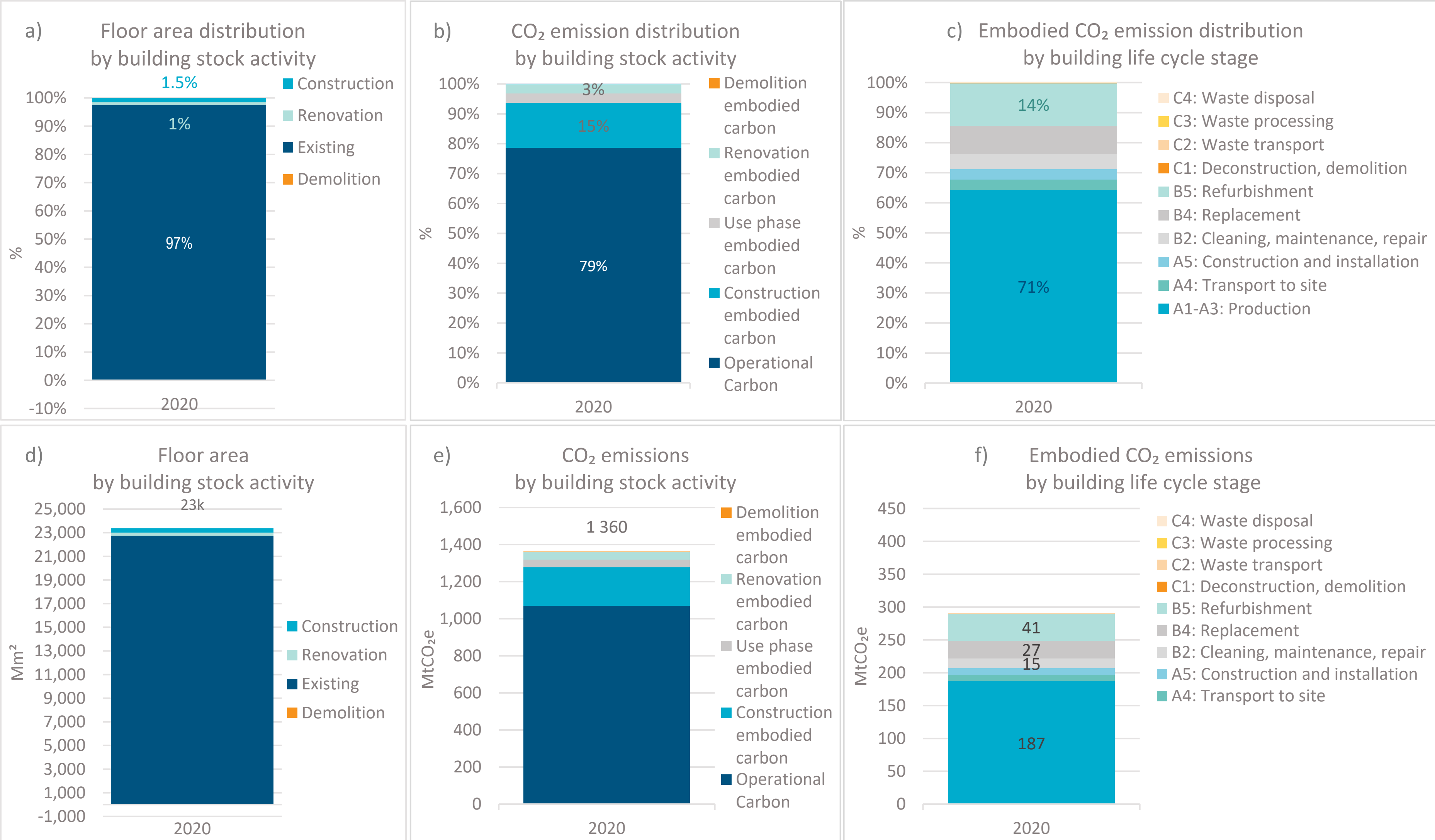


**Figure 20 Building stock activity and $CO_2$ emission results for Europe for the baseline year**



## 3.3 Key takeaways from the baseline analysis

**Energy efficiency of buildings operation will still have an important role** to make sure the quality of buildings is improved, as suggested by the relatively high share of operational emissions in the baseline (79%) for the whole building stock.

**Upfront emissions due to manufacturing of construction products and construction of buildings (A1-A5) is the second largest source of emissions (15% of overall life cycle emissions at building stock level). This confirms the relevance of the approach taken by the Commission in its proposals to revise the Construction Products Regulation and the Energy Performance of Buildings Directive, and the need to introduce WLC provisions starting with new constructions**. These are the emissions which have immediate climate impacts, long before the operation and use of the buildings. Neglecting these may trigger a premature spending of carbon budget beyond which operational carbon savings realised in 20-30 years from now will no longer be enough.

**Use phase embodied carbon (B1-B4) has not been quantified at EU building stock level until now, and the relative importance of these emissions (14% of building stock embodied emissions) may seem to be relatively high in comparison to the renovation embodied carbon (B5)**. A plausible explanation is that renovation embodied carbon only affects a very small percentage of the building stock (current renovation rate in the EU is around 1%), while the replacement, maintenance and cleaning activities are of a much higher volume, as they are ongoing and apply to the entire building stock. However, as the decarbonisation scenarios (see Chapter 5) suggest, renovation embodied carbon will exceed use phase embodied carbon as soon as renovation rates and depths take up in line with the implementation of the renovation wave strategy.

**The ratio of embodied/operational emissions is different when comparing the whole life carbon footprint of an individual building and all carbon emissions stemming from the entire building stock in one year**. The difference is due to the time horizon of embodied and operational carbon. Operational carbon emissions are ongoing and accrue over the lifetime of the building, whereas embodied carbon in the building stock is emitted in short bursts during the construction and renovation activities. Embodied emissions are the result of distinct, rather than ongoing, processes and are accounted for in the year when these emissions have been released (i.e. the year of the production, construction, renovation or demolition). The difference is significant because the baseline assessment is only a snapshot of the building stock in the year 2020, rather than a cumulative overview of the lifecycle emissions of buildings. Moreover, another straightforward reason is the much higher number of buildings in operation (their floor area) than newly constructed, renovated or demolished buildings in a given year. 97.3% of the floor area is not touched by renovation, new construction or demolition. The bulk of the building stock is in use and heated, as well as occasionally maintained and repaired. This has a significant impact on the emission profile of the stock. The discrepancy of embodied/operational emissions ratios at individual building and building stock levels confirms the need for carbon mitigation solutions and policy interventions applied at both individual and building stock levels.

**Results vary significantly in terms of different regional archetypes, overall embodied and operational carbon emissions, as well as the contribution of different building elements.** The outcome of the baseline analysis indicates a clear need for an increased level of detail in modelling the EU27 building stock and, potentially, moving away from a regional representation towards national archetypes and upscaling. A more granular analysis will guide all Member States towards a timely and coherent framework to be able to regulate whole life carbon emissions based on robust evidence and scientific research.

Finally, construction activity and economic output are closely linked. The baseline analysis is not attempting to quantify or model the impact of recent events, such as the Covid pandemic and the present energy crisis. The study team could not rely on robust observed trends to be able to account for these events in the building stock upscaling.

# 4. EU BUILDING STOCK EMISSIONS IN A BUSINESS-AS-USUAL SCENARIO

The business-as-usual (BAU) scenario projects the development of building WLC emissions based on current policies and expected market developments[37]. Using the baseline emissions as a starting point, this section outlines what levels of operational and embodied carbon emissions can be expected from the EU building stock between 2020 and 2050. It provides the reference for comparison and assessment of more transformational emission pathways (Chapter 5) that will set out the trajectory of what is actually needed to achieve the goal of net-zero.

This scenario answers the question of "how do building stock emissions evolve if we continue at our current pace of improvement?" The analysis takes into account relevant policy and market developments which are expected to impact future carbon emissions. These trends include European and national building policies, industry initiatives as well as other framework conditions related to carbon intensity and energy mixes, economic growth, demographics, urbanisation and built space utilisation.

**Overview of the business-as-usual scenario:**

- Whole life carbon emissions associated with the EU building stock are expected to decrease by 32% in 2050 (compared to the baseline).
- Overall decrease in WLC emissions is driven by operational emissions reductions due to renovations and space heating decarbonisation. Importantly, these reductions are projected against a 40% increase of the building stock floor area.
- In parallel, embodied emissions are expected to increase over time, in line with the carbon cost of increased renovations.
- Gains in operational emissions are higher than increases in embodied carbon so that WCL emissions are expected to decrease steadily over the coming decades.
- However, the current rate of progress will not achieve the net-zero target.

## 4.1 Building stock developments in the business-as-usual scenario

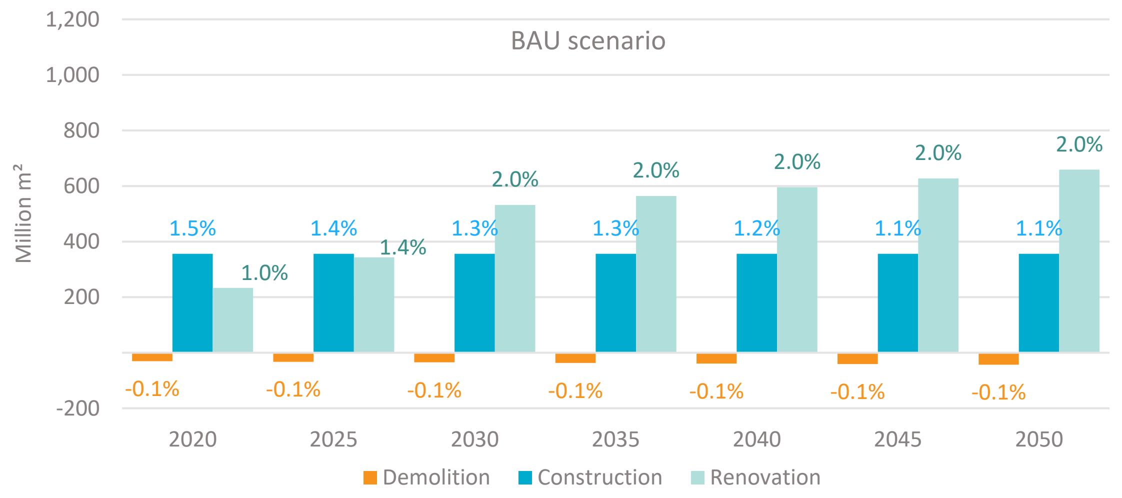
The starting point for projecting carbon emissions is to understand how the EU building stock would change over the future decades. Figure 2121 shows the distribution of floor area being constructed and renovated annually.

The construction activity remains constant adding 356 million m² annually. The renovation rate increases from 1% to 2% until 2030 which reflects the Renovation Wave assumption to at least double the renovation rates in the next ten years. From then on, the renovated floor area remains at 2% of the total building stock per annum. In absolute terms, the annual renovated floor area increases from 235 to 659 million m² from the 2020 baseline to 2050. The demolition rate is kept

[37] Note that the latest revisions of the EU ETS and the recast of EPBD are not included in the Business-as-Usual scenario.

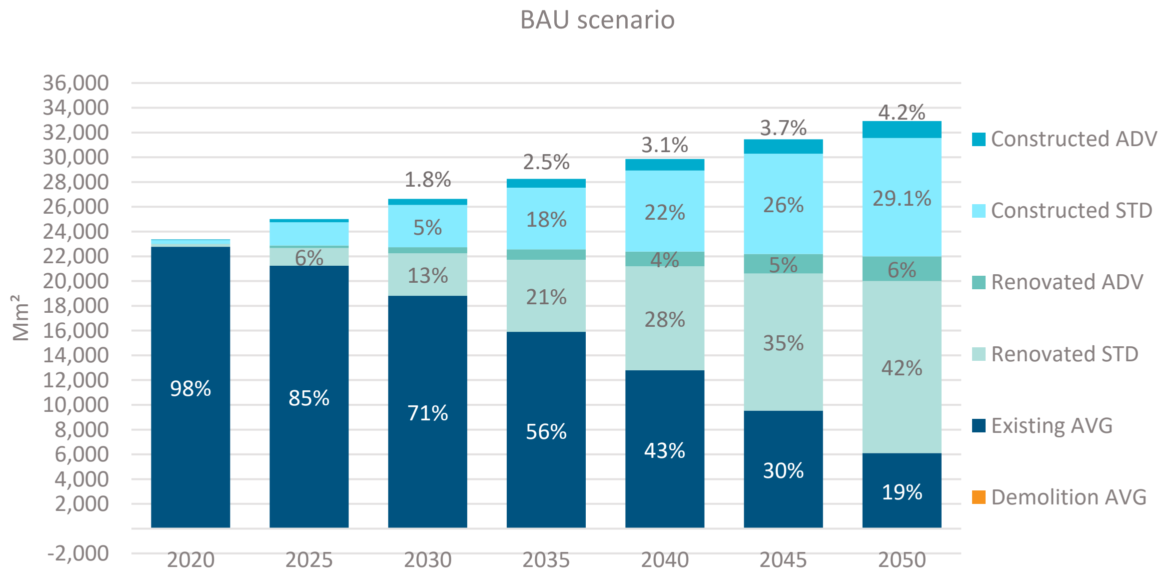
at 0.1% per annum. Due to more construction than demolition, the building stock grows by about 40%.

**Figure 21 Zooming in on annual construction, renovation, and demolition[38] that are mainly responsible for the release of embodied carbon emissions in the building stock**




By 2050, about 42% of the building stock have undergone standard renovation, while 6% are renovated to achieve advanced energy efficiency levels (deep renovation). Approximately 29% of the stock are newly built according to current national energy efficiency regulations and 4% implement the equivalent of a passive house standard. In total, the building stock in 2050 consists of 33% of buildings constructed after 2020. This is visualised in Figure 2222.

**Figure 22 Cumulative construction, renovation, and demolition activities at building stock level. Cumulative demolition indicated at the bottom.**




[38] Annual demolition is so small that it is barely visible. As it is a negative value it would be indicated under the x-axis.

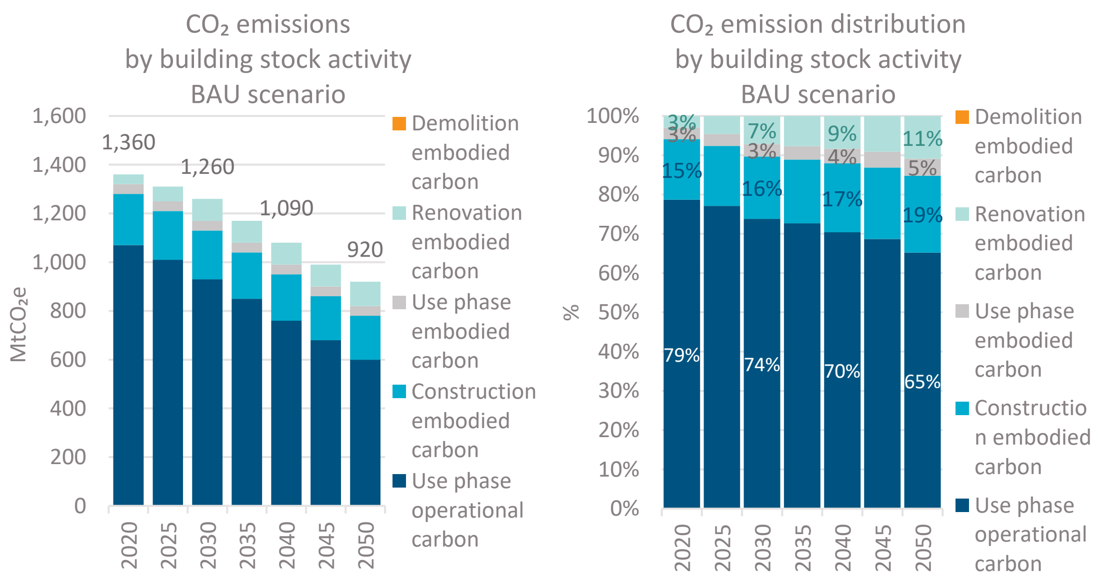
The EPBD requires that new buildings must be nearly zero-energy buildings (NZEB) and the ongoing recast of the EPBD may result in further tightening of requirements to zero-energy buildings (ZEB), which could imply that advanced standard will become a regular practice in the future. This business-as-usual scenario reflects the implementation of the EPBD in the Member States and the building technical measures that achieves compliance with the required energy performance levels. In other words, the business-as-usual modelling was built mainly on the basis of the technical implementation of policies, rather than on the long-term ambitions (policies, targets, strategies). As soon as stricter measures are implemented, alternative future scenarios would include forthcoming updates of the performance requirements for standard and advance performance new buildings according to future standards.

## 4.2 Building stock emissions in the business-as-usual scenario

Whole life carbon emissions are expected to be lower by 32% in 2050 (compared to the baseline of 2020) driven by operational emission reductions (Figure 233 below). The reduction of about 440 $MtCO_2e$ is relevant as it is being projected against a 40% increase of the building stock floor area. The 44% savings in use phase operational carbon (470 $MtCO_2e$) are due to renovations, but also space heating decarbonisation, mainly fuel switch in space heating. In parallel, embodied emissions are expected to increase slightly over time due to the embodied carbon cost of increased renovation rates and despite industrial decarbonisation.

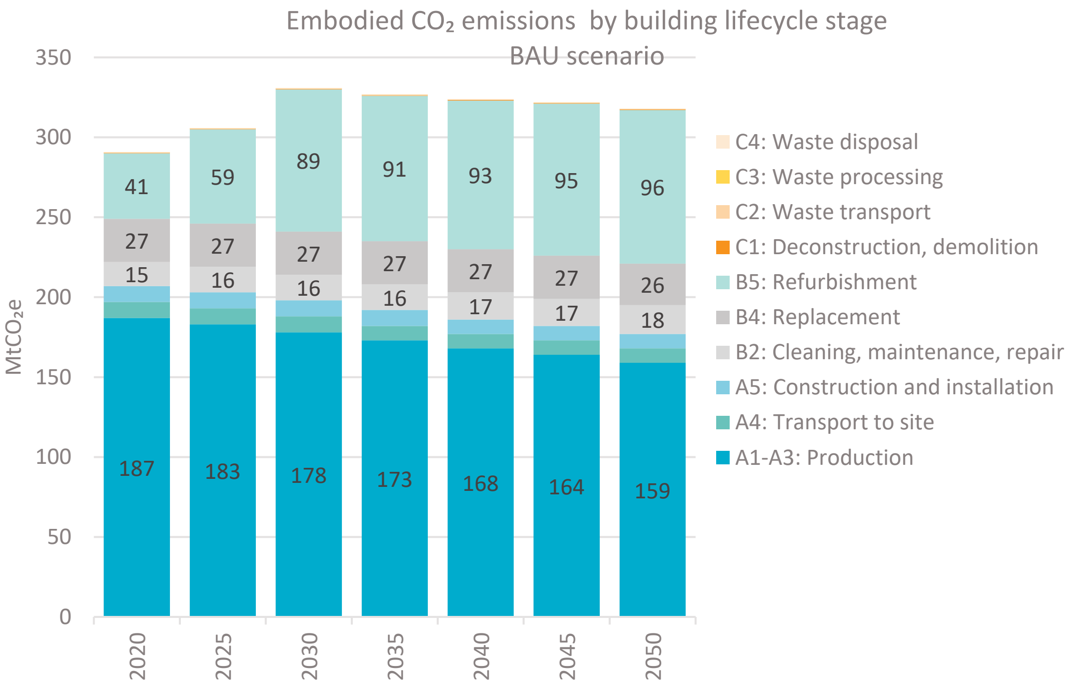
**While gains in operational efficiency and carbon savings are higher than the surge of embodied carbon so that whole life carbon emissions are expected to decrease steadily over the coming decades, the current rate of progress will not achieve the net-zero target.**

Figure 23 $CO_2$ emissions by building stock activity




Looking at embodied emissions over the next 30 years, (see Figure 244 below), the business-as-usual scenario shows that upfront emissions (A1-5) related to new constructions are decreasing due to industrial decarbonisation of key material supply chains. The use phase embodied carbon (B2 maintenance, B4 replacement) increases marginally and concomitantly with the overall increase of the building stock floor area. On the flip side, renovation-related embodied emissions (B5) double from about 40 to 89 $MtCO_2e$ in the short period between 2020 and 2030, which is in line with the assumptions that the renovation rate will increase towards 2030. From then on, the renovation rate remains at 2% but relative to a growing building stock which means that renovation embodied carbon emissions will continue growing slowly but steadily towards 2050. Emissions related to demolition are nearly insignificant.

**Figure 24 Building stock embodied emissions by building life cycle stages in the BAU scenario**




## 4.3 Embodied emissions by materials

Materials used in the construction and renovation of buildings are dominating resource consumption. However, material efficiency strategies and the use of low-carbon and recycled materials hold substantial potential for reducing emissions on a large scale. Transitioning to a future of low-carbon built environment requires a better understanding of the material build-up of the stock, carbon hotspots and of the strategies that take a whole building life cycle and systems-thinking approach.

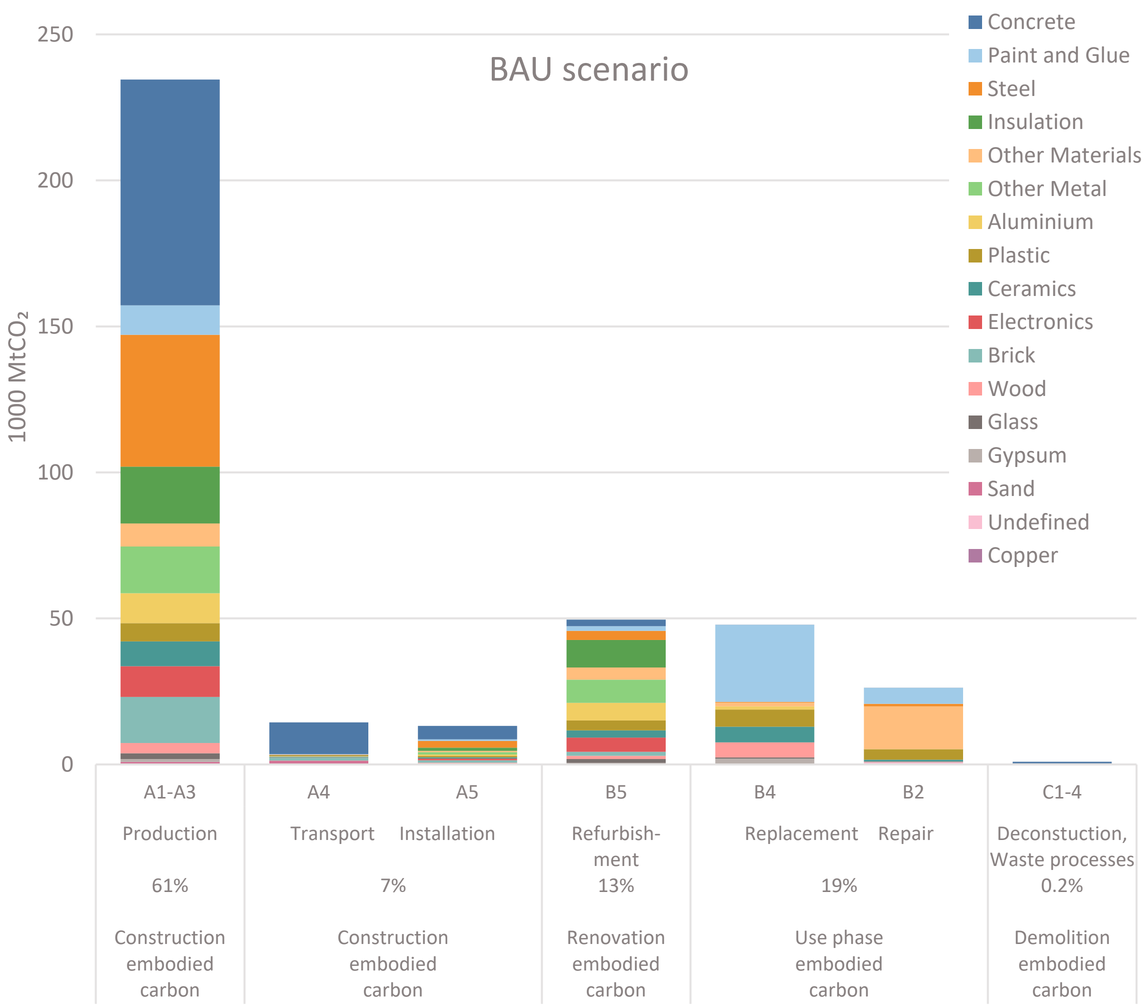
The material embodied emissions shown in the following figures have been developed through the upscaling of individual buildings life cycle emissions to the stock level. These represent the embodied carbon impacts arising from the construction, renovation, demolition and use of buildings.

According to the analysis, construction (A1-3, A4-5) is the most significant source of embodied emissions within the building life cycle with manufacturing of concrete, steel and insulation being responsible for over half of these emissions. In the baseline year of 2020, most embodied carbon, representing 61%, (235 $MtCO_2e$) of the building stock's total embodied emissions, has been released during the production of materials while only adding 1.4% new construction floor area to the building stock. Another 7% were emitted for the transport and installation of materials linked to the construction of new buildings.

Renovation activities in 2020 affected about 1% of the floor area and were responsible for about 13% or 50 $MtCO_{2}e$ of embodied carbon. Given that repair (B2) and replacement (B4)[39] activities are ongoing and are spread across almost the entire floor area (98%) of the building stock, they make up a remarkably large volume of emissions (19%, 28 $MtCO_{2}e$) which is more than the renovation related embodied carbon (13%). Among the materials relevant for replacement and maintenance (B4), paint and glue are surprising carbon hotspots.

Demolition (life cycle stages C1-C4) affect only 0.1% of the floor area and thereby its associated embodied carbon emission is only marginal (0.2% of the total embodied emissions).

**Figure 25 Building stock embodied emissions ($MtCO_{2}e$) in 2020 by material and building lifecycle stages**




[39] Note that these are not renovation but smaller unplanned works. Renovation is covered in B5 refurbishment.

Figure 266 illustrates the projected evolution of the largest contributions of material embodied emissions between 2020 and 2050 side-by-side. This business-as-usual scenario does not assume any carbon reduction measures related to the design of the building or the substitution of materials beyond the general decarbonisation of the energy system and the energy delivered to industry processes that produce/manufacture construction and renovation relevant products. Embodied carbon reduction solutions are modelled separately in the TECH-Build and LIFE-Build decarbonisation scenarios. Under business-as-usual, the renovation embodied emissions (B5) will more than double (111% increase) and reach 104 $MtCO_2e$ by 2050 due to the projected increase of renovation activities. The annual construction activity remains constant which implies that construction related material embodied emissions (A1-A3 production of construction products) will decrease slightly from 254 $MtCO_2e$ to 252 $MtCO_2e$ which is due to the decarbonisation of the industry for relevant building materials.

**Figure 26 Building stock embodied emissions ($MtCO_2e$) in 2020 and 2050 respectively, by material and building life cycle stages, decreasing by total amount of embodied emissions**

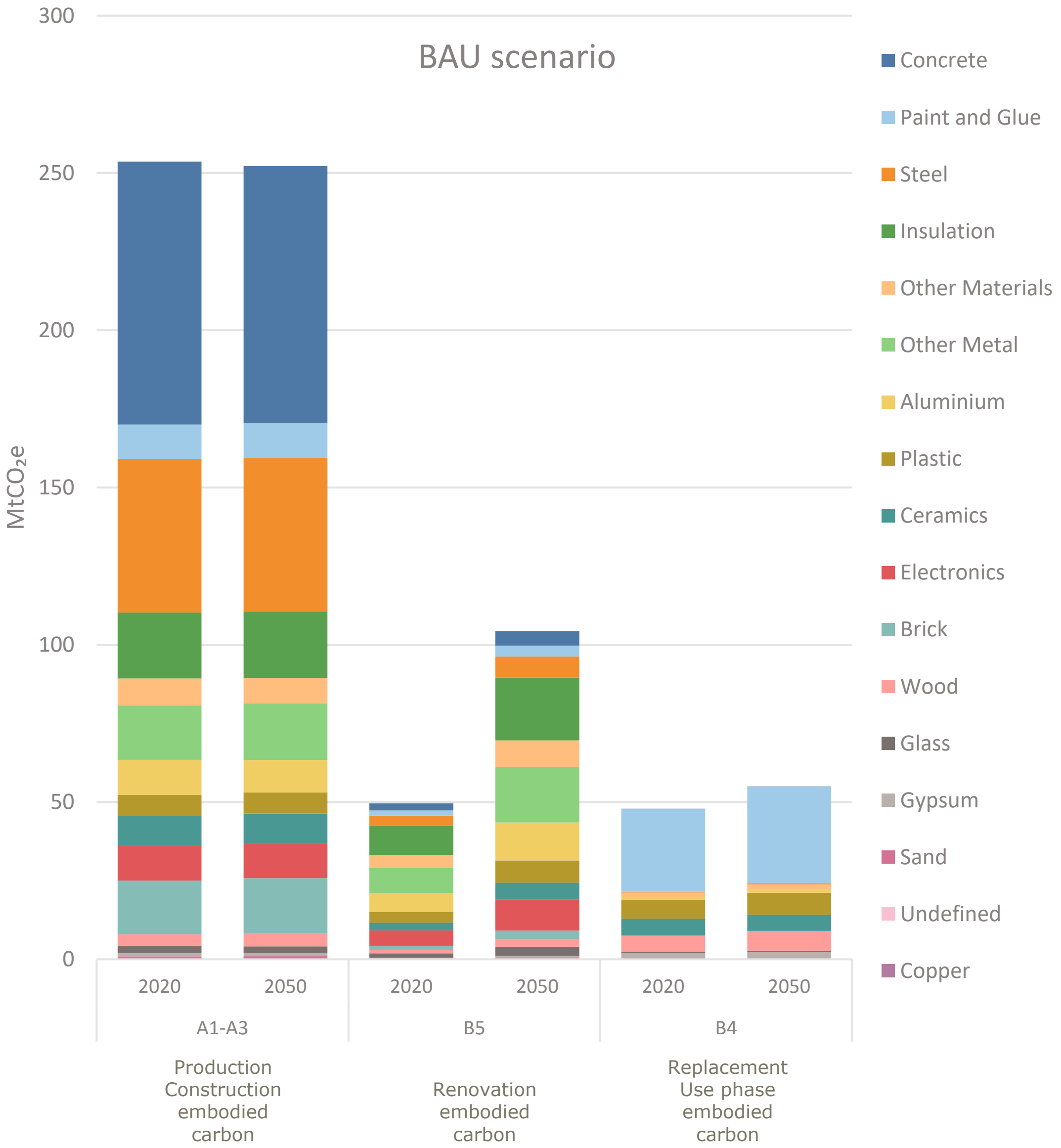


Figure 27 compares the material emissions associated with different lifecycle stages and, more specifically, it illustrates the increase of the renovation emissions between 2020 and 2050 (see renovation stage (B5) below).

**Figure 27. Building stock embodied emissions projections (MtCO₂e) by materials for selected building life cycle stages in 2020 and for B5 in 2050 as a shadow for the business-as-usual scenario.**

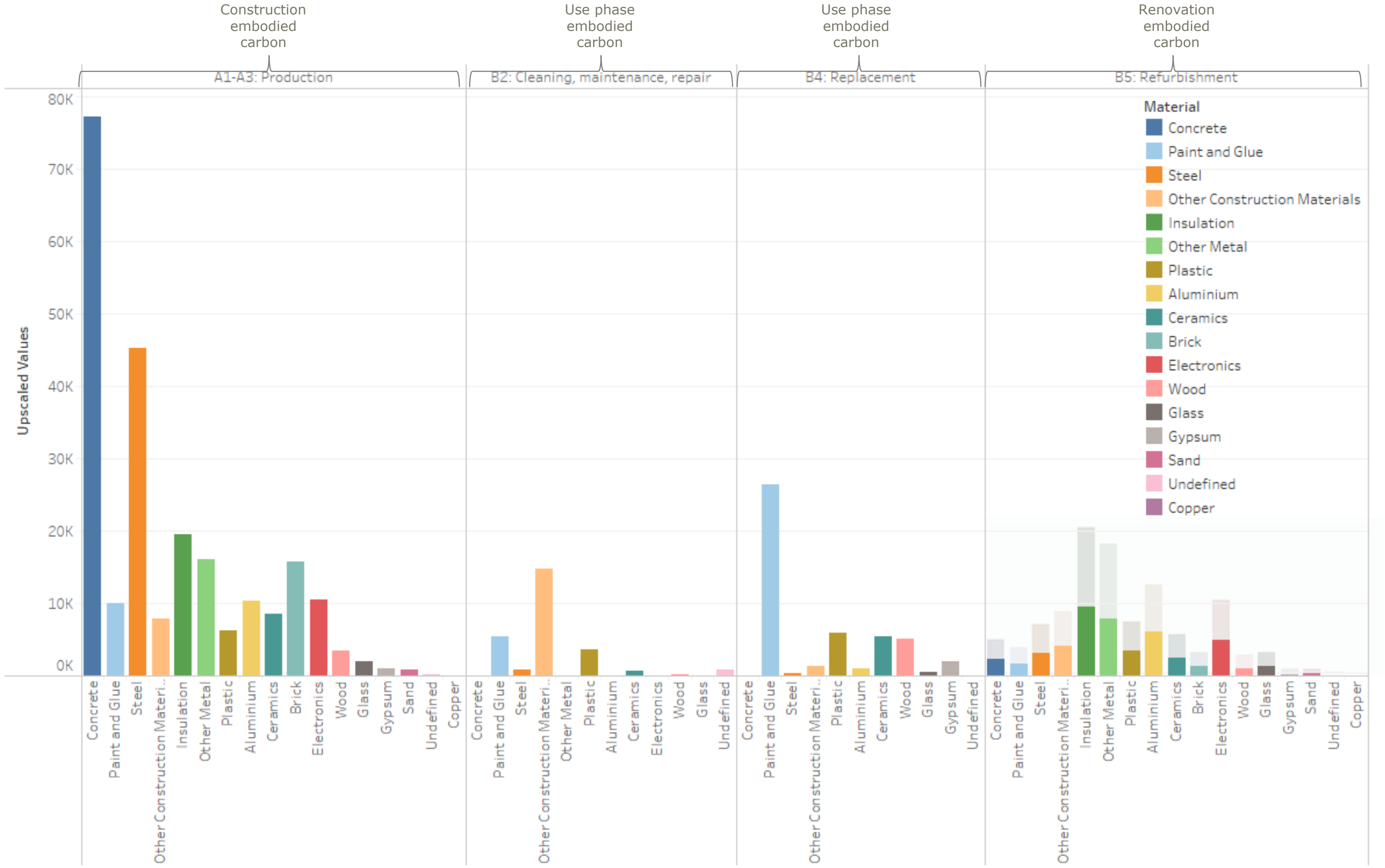
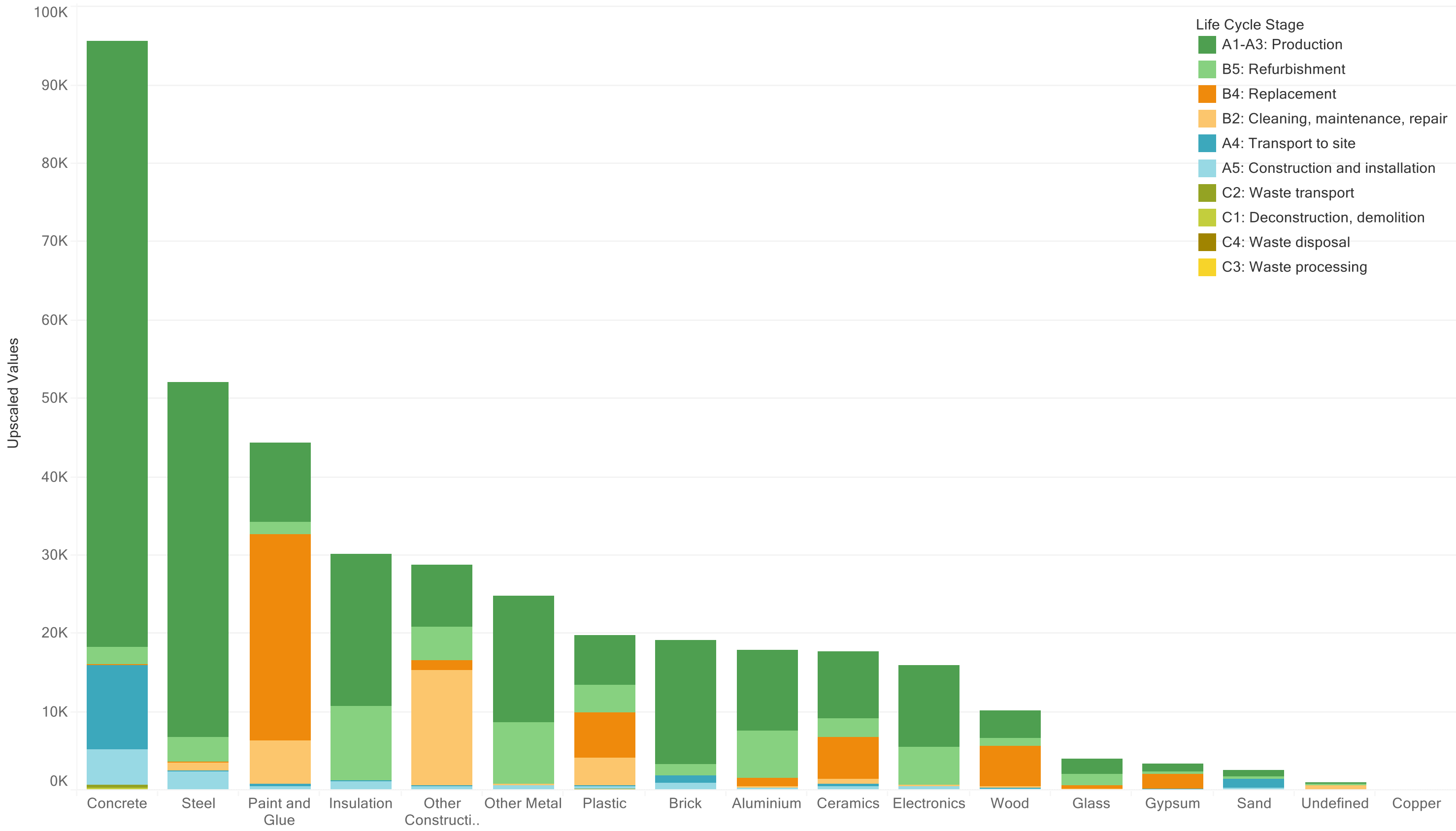


**Figure 28 2050 overview of material embodied emissions relevant to different life cycle stages of buildings for the business-as-usual scenario.**



## 4.4 Key takeaways from the business-as-usual scenario

**The business-as-usual scenario estimates a sectoral WLC decrease of 440 $MtCO_2e$ by 2050 and remaining residual emissions of 920 $MtCO_2e$ which suggests that buildings are not on track to achieve the decarbonisation transition needed to contain global temperature rise**. The analysis also shows that net-zero will not be achieved through the reduction of operational carbon emissions only. Energy efficiency improvements will result in substantial operational carbon savings of 44%, equivalent to 470 $MtCO_2e$. However, these gains will partly be offset by the embodied emissions from materials used in new constructions and the renovation of existing building stock, which are projected to increase by 40 $MtCO_2e$. This implies that further and more comprehensive transformational measures targeting both operational and embodied emissions will be required.

**The decarbonisation of space heating and manufacturing of construction products has a considerable impact on the operational and embodied carbon associated with the building stock**. However, actions in relation to how we construct, manage and use our buildings are also needed, to further reduce emissions. By treating the building sector as a priority per se, the carbon intensity of buildings can be reduced further. It will also avoid negative externalities and costly investments in energy infrastructure. Achieving 44% savings in use phase operational carbon is a result of combining 30% decarbonisation in space heating (including grid decarbonisation) with the improvement of the building stock.

**Material embodied emissions are expected to increase over time and despite production efficiency gains, process innovation and industry decarbonisation**. Although the study does not take into account the expected impact of policies currently being revised such as the Construction Products Regulation and Ecodesign for Sustainable Products Regulation or recently concluded policies such as the EU emission trading system, it suggests that the increase in embodied carbon is outweighed by the improvements in operational efficiency and operational carbon emissions. Nonetheless embodied carbon remains an important source of emissions to be addressed and absolutely necessary in order to achieve climate neutrality targets.

**The four material categories with the greatest impact on the overall embodied emissions of the EU stock are concrete, steel, paint/glue and insulation**. The latter two are to an important part driven by use phase maintenance and replacement cycles. Low-carbon solutions to reduce embodied emissions from these materials exist and these are explored in the TECH-Build and LIFE-Build scenarios. Importantly, these scenarios focus on achieving the required whole life carbon targets at building and building stock levels which will avoid the temptation to use the business-as-usual results of this study to pick these specific materials to target as "bad" or "good". This implies that EU whole life carbon roadmap should not exclude or prescribe the exclusive use of specific materials but rather flesh out the cumulative measures to be taken across the sector, with a whole-life and systems-thinking approach.

### Differences between individual building and building stock perspectives – two sides of the same coin

As discussed above, the ratio of embodied/operational emissions is different when comparing the whole life carbon footprint of an individual building and all carbon emissions stemming from the entire building stock in one year.

The baseline analysis (Chapter 3) revealed that, at **individual building level**, the embodied carbon share averages 43% of the whole life carbon emissions of new buildings, and an even higher 66% for very high energy performance buildings. At the same time, **the building stock analysis** suggested a share of approximately 21% embodied carbon emissions at the EU level in the baseline year (2020) and a remaining ratio of 79% associated with the operation of the building stock. The business-as-usual projection highlights that the relative importance of embodied and operational emission at the stock level will even out to around 35% embodied and 65% operational annual emissions by 2050, mostly due to an increase in renovation rates and overall decarbonisation of energy grids and industry.

Whereas the embodied/operational carbon profile of individual buildings is better understood and reveals substantially higher relative embodied carbon levels, especially for new constructions, the building stock level analysis and projections are what matters from the EU’s carbon budget and overall decarbonisation perspective. The substantial impact of WLC emissions in either perspective confirms the urgent need for carbon mitigation solutions and policy interventions targeted at both individual building as well as EU or national building stock levels.

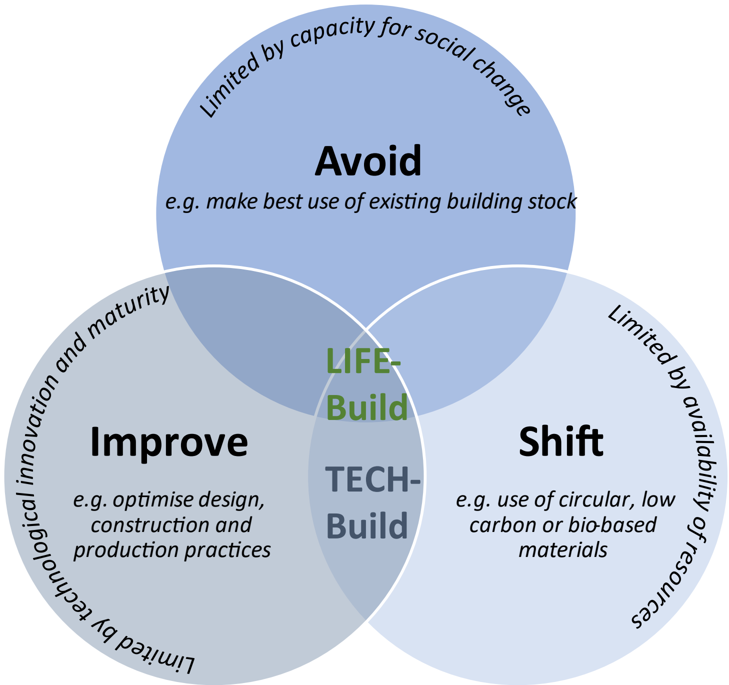
# 5. PATHWAYS TO DECARBONISE THE EU BUILDING STOCK

The business-as-usual scenario analysis developed in this study, with the assumptions set out in section 2.4, is unambiguous in pointing out that EU 2050 emission targets will be missed at the current rate of progress and assuming existing policies. Therefore, it is essential to understand how the sector can reduce its emissions in line with the EU's ambition of climate neutrality. This chapter presents two scenarios[40] to transform the building sector and its value chain aiming for substantially reducing the WLC emissions of EU buildings.

The **TECH-Build** scenario answers the question: how much can we reduce lifecycle emissions in buildings by implementing material efficiencies and technological solutions at the level of individual buildings and that of the building stock?

The **LIFE-Build** scenario answers the question: what changes to lifestyle and social norms are necessary *in addition* to technological solutions to reduce WLC as closely to the goal of net-zero as possible?

**Figure 29 Overview of the TECH-Build and LIFE-Build scenarios**




## 5.1 Building stock developments in the TECH-Build and LIFE-Build scenarios

This section describes building stock developments based on future construction, renovation and demolition floor area projections. These projections are assessed against existing scenarios and sources, such as Eurostat data for building permits and population growth (see Chapter 4 and Appendix III). The operational carbon projections of the TECH-Build scenario are aligned to the best extent possible with the EU Fit-for-55 MIX scenario[41], even though there may be differences among

[40] The scenario design is described in detail in Section 2.4. Both scenarios employ the embodied carbon reduction solutions described in Sections 2.3 and 2.4. A detailed description of the modelling framework of each solution is included in Appendix II

[41] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

the results of this study and that of the Ff55 MIX impact assessment which is due to the use of different models.

### 5.1.1 Activity levels for new construction, renovation and demolition

Similar to the business-as-usual (see Figure 30), the TECH-Build scenario assumes the construction rates by reference to historic data on building permits (see Figure 31). The scale of new constructions in the TECH-Build scenario is being kept the same as in business-as-usual because the scenario explores the impact of technology ("Improve" or "Shift") solutions without considering "Avoid" solutions such as building less. In contrast, the LIFE-Build scenario includes solutions to explicitly avoid the need for new construction. Therefore, the construction rate in Figure 32 is reduced over time. The assumptions for this rely on increasing the space use intensity and renovating/repurposing existing buildings instead of building new (see embodied carbon reduction solutions 1a, 1b and 2 in Appendix II).

**Figure 30 Annual activity rates as percentage of the building stock floor area in the BAU scenario**

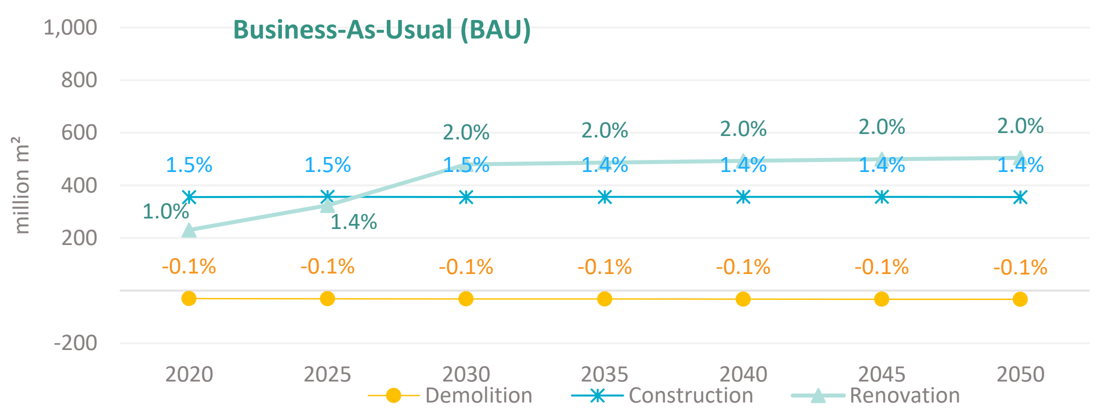



**Figure 31 Annual activity rates as percentage of the building stock floor area in TECH-Build scenario**

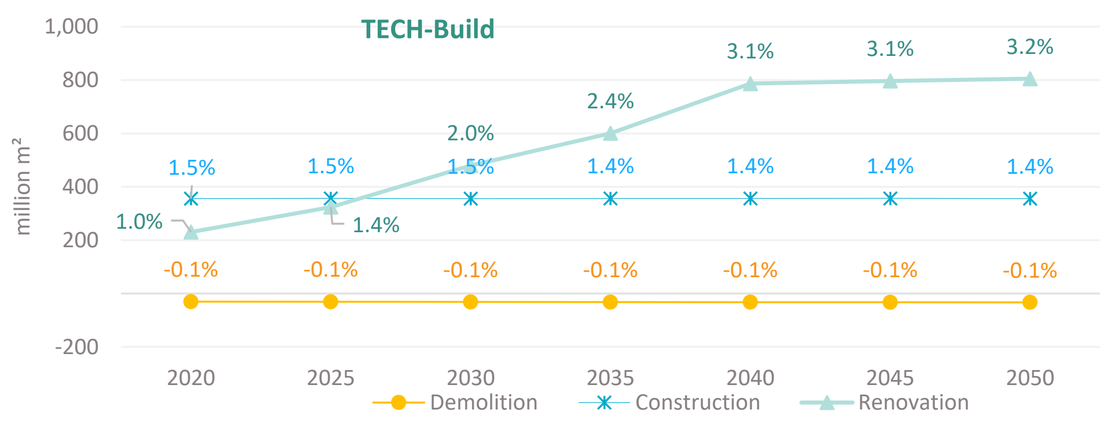
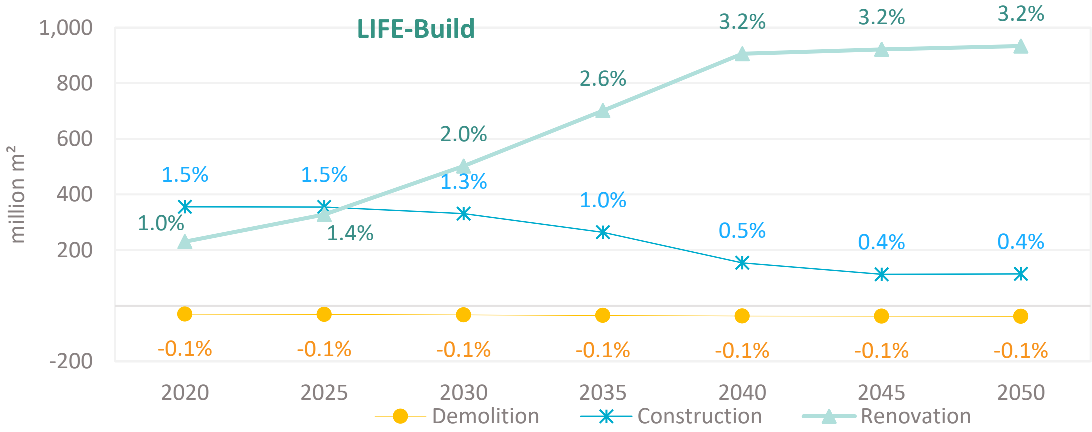


**Figure 32 Annual activity rates as percentage of the building stock floor area in LIFE-Build scenario**




The construction activity in the TECH-Build remains constant adding 356 million m² of new floor area annually. The renovation rate doubles between 2020 and 2030 and, as opposed to the business-as-usual scenario, it keeps growing consistently towards 2040 reflecting the comprehensive energy efficiency and embodied carbon reduction solutions being pushed to their limits (see Figure 3131). In absolute terms, the annual renovated floor area increases from 230 million m2 to 805 million m² from 2020 to 2050.

The LIFE-Build and TECH-Build scenarios assume a similar renovation ambition. Due to higher renovation rates assumed under both scenarios, the entire (98%) building stock will undergo energy efficiency renovations by 2050.

The best way to reduce lifecycle carbon emissions is through prevention. This is the principle at the core of the LIFE-Build scenario which is the most visible through space and construction demand reductions. Under this scenario, new construction steadily decreases from 356 million m2 (1,5% annual rate) in 2020 to 115 million m2 (0,4% annual rate) in 2050 (see Figure 3232). This is the result from a 20%[42] reduction of square meter per person throughout the buildings stock, and limiting new construction to situations where it is absolutely necessary, such as replacing structurally damaged buildings.

### 5.1.2 Energy performance of renovations and new constructions in the ambitious scenarios

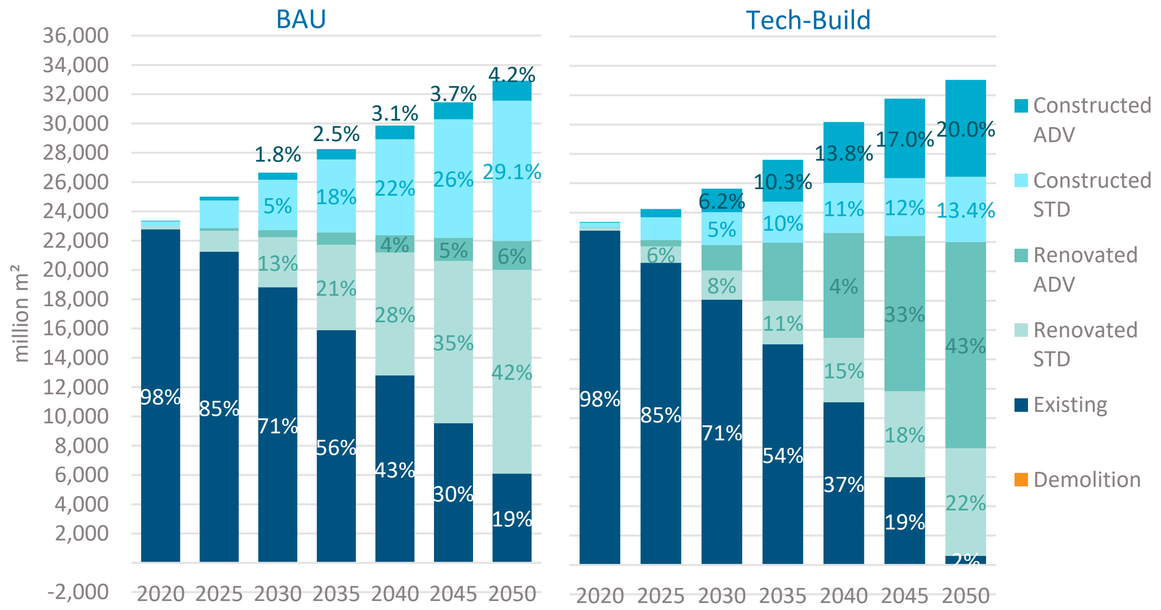
Figure 3333 and Figure 344 below show the evolution of the EU building stock over the next 25-30 years. The projections about the volume of renovations and newly constructed buildings, as well as their energy performance levels are the results of the assumptions applied for the construction and renovation rates described above. This is an intermediary step in the modelling to finally arrive at the quantification of related building stock emissions.

The share of buildings with advanced energy performance (*Constructed ADV* and *Renovated ADV*) within the new and renovated stock are significantly higher in the ambitious scenarios than in the business-as-usual scenario (see Figure 33). In the business-as-usual, about 42% of the building stock will have undergone standard renovation, while 6% of the stock is renovated to achieve advanced energy efficiency levels by 2050. In this scenario, the renovation rate is aligned with the ambitious goals set by the Renovation Wave strategy. However, the proportion of deep renovations

[42] Absolute values depend on the country.

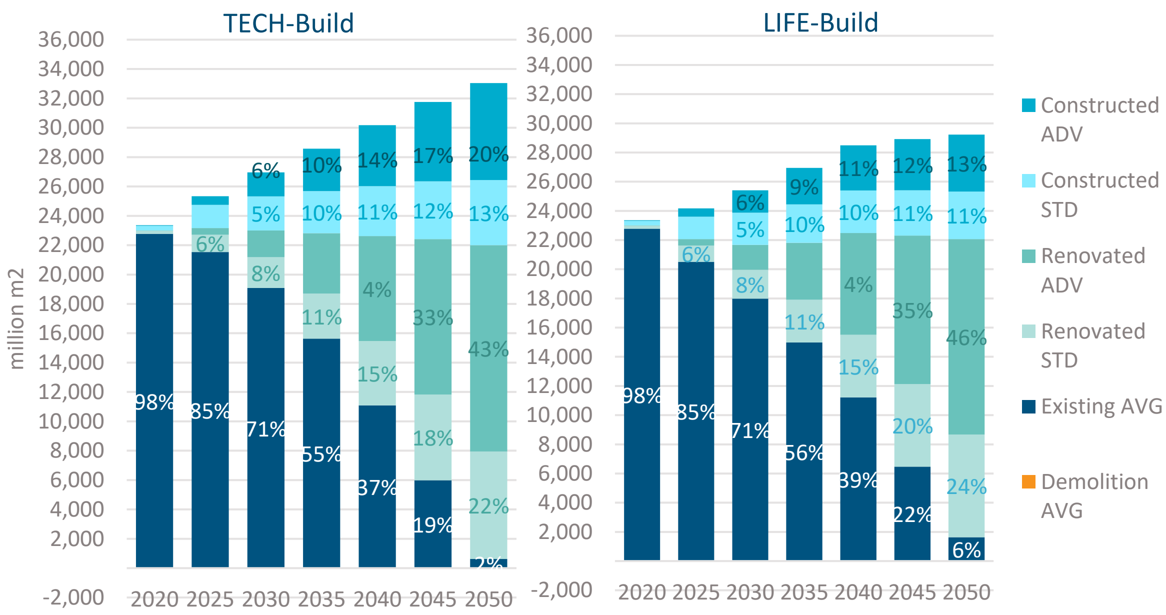
is slightly lower than as foreseen in the Renovation Wave, yet still surpasses the current levels observed in the building stock. In comparison, the TECH-Build scenario replaces standard renovations and constructions by advanced performance new buildings and deep renovations. As such, the majority of renovations by 2050 are deep renovations (43% *Renovated ADV* compared to 22% *Renovated STD*). In the LIFE-Build scenario, the deeply renovated floor area is even higher (46% Renovated ADV) due to the increased utilisation of existing assets delivering the same function as a new build.

**Figure 33 Cumulative construction, renovation, and demolition activities at building stock level – BAU compared to TECH-Build. Cumulative demolition is indicated at the bottom**




The volume of new constructions is similar in business-as-usual and TECH-Build scenarios adding a total floor area of about 10,000 million m2 by 2050. The LIFE-Build scenario assumes a lower construction activity adding 6000 million m2 new floor area to the stock by 2050 (see Figure 344). Renovation rates are higher in the TECH-Build scenario which result in significantly lower unrenovated floor area by 2050 compared to the business-as-usual scenario. The higher renovation rate and depth contribute to meaningful reductions of operational and overall whole-life carbon emissions from the building stock (see section 5.2 below). In addition to energy efficiency renovations, the LIFE-Build scenario also models renovations aiming to reuse or repurpose existing assets. By taking the additional step to maximise the use of existing assets and avoiding demand for new constructions in the LIFE-Build scenario, lifecycle emissions of the stock can be pushed even lower.

**Figure 34 Cumulative construction, renovation, and demolition activities at building stock level – TECH-Build compared to LIFE-Build. Cumulative demolition is indicated at the bottom**



## 5.2 TECH-Build scenario results

The sections below present the results of the TECH-Build scenario based on the assumptions set out in chapter 2.4.

**Highlights of the TECH-Build scenario – building stock emissions:**

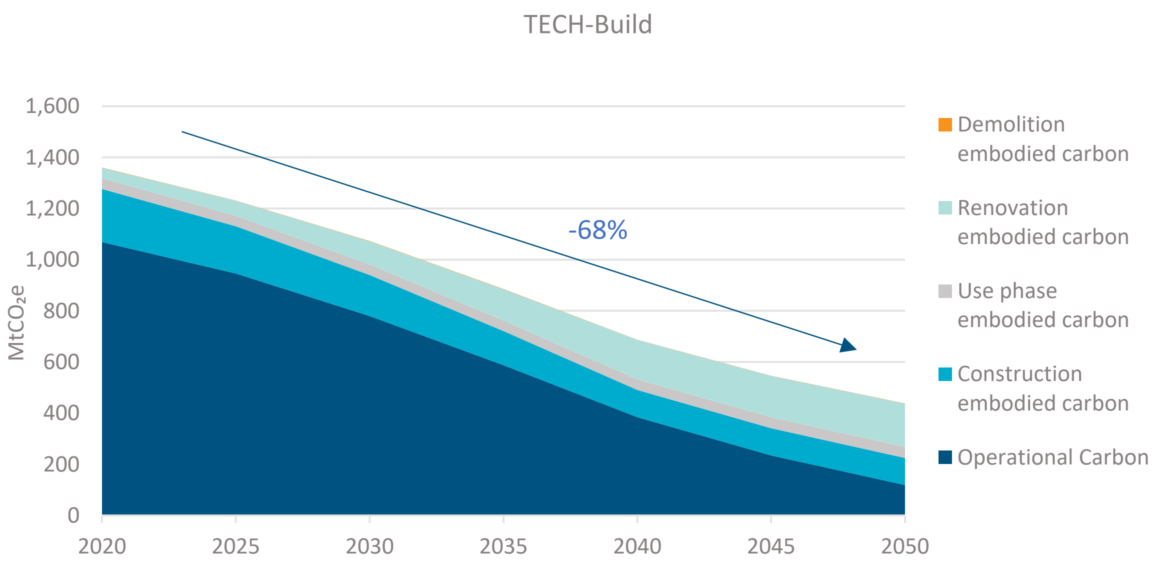
- Reductions of building stock WLC emissions of 68% are possible by 2050 compared to the baseline year if technology solutions to reduce embodied and operational emissions are pushed to their limits
- Across the building stock, operational emissions are expected to fall by about 90% relative to the baseline
- Embodied carbon would overtake and exceed operational carbon between 2040 and 2045
- The absolute amount of embodied carbon will decrease slightly by 2025 but then will increase. The main reason for this increase is higher renovation rates and depths which results in an estimate of four times higher renovation embodied carbon in the TECH-Build scenario than in the business-as-usual scenario. A decrease in the long term could be considered by exploring the mitigation options related to embodied carbon in the renovation sector.
- Upfront carbon emissions (Module A), associated with new construction, have the highest potential for mitigation and show the biggest embodied carbon savings
- Until 2030, new constructions are the largest source of embodied carbon; as of 2035 the renovation embodied carbon emissions take over

**EU building stock emissions – TECH-Build scenario**

The TECH-Build scenario illustrates the potential for reducing lifecycle emissions if state-of-the-art low-carbon material and design solutions are implemented consistently across the entire building stock. The TECH-Build scenario suggests that the best available embodied carbon reduction solutions applied to the largest extent possible can cut lifecycle emissions by more than two thirds (68%, 992 $MtCO_2e$) compared to the baseline year of 2020 (see Figure 355). These reductions are even more significant as they are projected against an increase of about 40% of the building stock floor area.

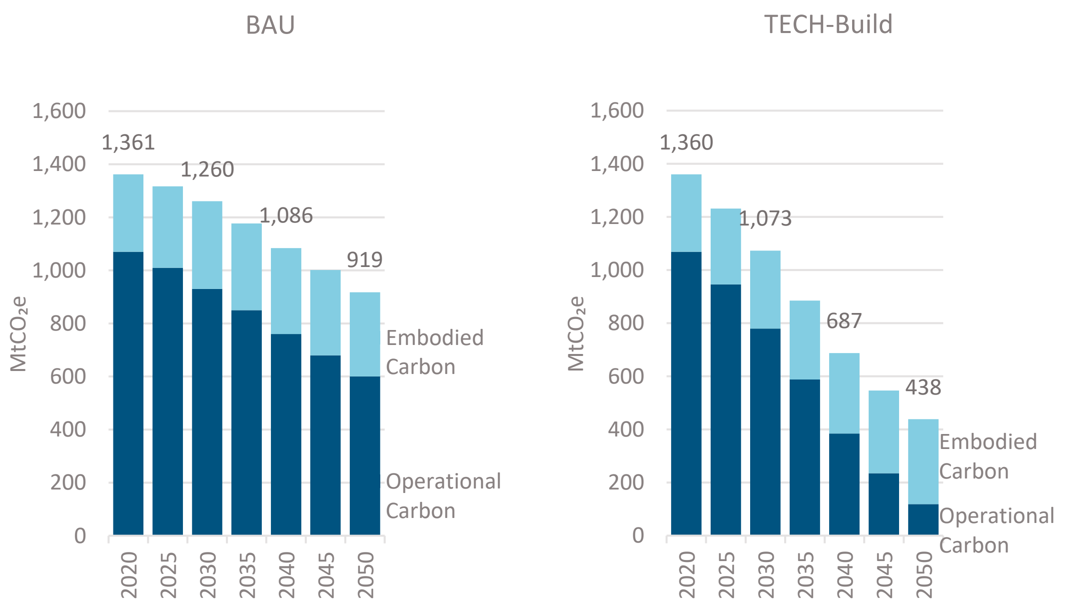
The TECH-Build scenario is nevertheless a comprehensive transformation of the EU building stock which requires robust policy support. EU and Member State policy must ensure that solutions are available to all and employed to the largest extent possible defined by their technical or planetary boundaries.

**Figure 35 TECH-Build scenario building stock whole life carbon projections**




Like in the business-as-usual scenario, the reductions in the TECH-Build scenario are due to operational carbon savings. However, driven by a higher rate and depth of renovations compared to business-as-usual, operational emissions are decreasing by about 90% in the TECH-Build scenario.

**Figure 36 Business-as-usual and TECH-Build scenario comparison: $CO_2$e emissions**



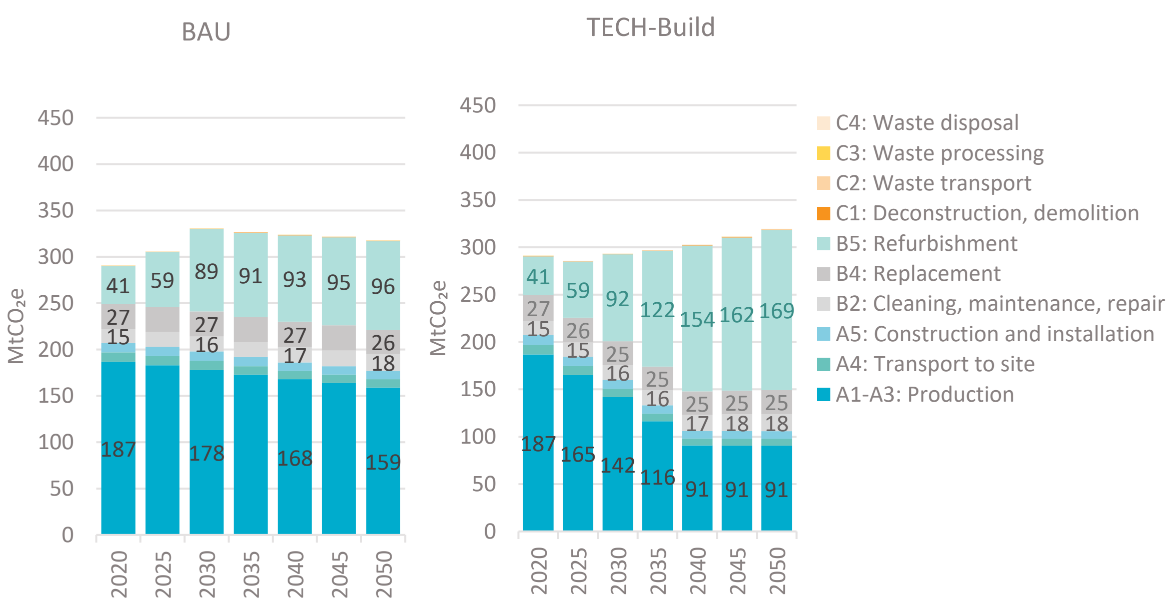

In parallel, the relative importance of embodied emissions is expected to increase over time and is anticipated to exceed operational carbon emissions sometime between 2040 and 2045. Initially, embodied carbon emissions are projected to decrease ever so slightly by 2025. However from that point on, they will increase consistently due to increasing rate and depth of energy renovations. With limited data on options to mitigate embodied carbon in renovation, the full extent of embodied carbon emission reductions from renovations could not be modelled, as described in detail in 2.5.

Given the current assumptions, embodied carbon emissions will be about four times larger than operational emissions by 2050 (Figure 366). Renovation embodied carbon, in particular, increases fourfold from 41 $MtCO_2e$ in 2020 to 169 $MtCO_2e$ in 2050 (Figure 37). The embodied carbon emissions related to renovations are reduced by 20% per m² on average, but the total emissions increase due to the increased renovated floor area and much deeper renovations.

The impact of new constructions is the prevailing source of embodied carbon in the building stock until 2030 (Figure 377). As of 2035, renovation activities become the largest emitters of embodied carbon emissions. This development is again related to the increase of the annual renovation rate to over 3% while new construction activity stays constant at about 356 million m2 floor area per annum in this scenario (1.5%-1.1% average annual growth rate of the stock). The assumptions used for modelling the TECH-Build scenario, with the limitations as described in 2.5, results in upfront emissions associated with new construction having the highest potential for mitigation.

An interesting finding is the potentially substantial carbon emissions stemming from insulation, paints and glues, which are driven by replacement and maintenance cycles during the use phase. In this study, no low carbon solutions linked to these materials are modelled and, thus, these emissions are not assumed to decrease. As new construction is an embodied carbon hotspot, the modelling exercise focused primarily on new built. Moreover, there is a lack of research, data, and comprehensive scenarios, specifically focus on carbon mitigation solutions for renovations and maintenance. These activities, however, involve significant use of insulation, paint, and glue. It will thus be important that future research to address these emissions.

**Figure 37 Embodied $CO_2e$ emissions by building lifecycle stages BAU and TECH-Build**




The scale of the reductions in upfront carbon emissions linked to the construction and production of buildings (Module A) confirms the regulatory approach taken by the proposal for the revision of the Energy Performance of Buildings Directive on the introduction of WLC provisions starting with new constructions. At the same time, the TECH-Build scenario makes clear that this does not mean that renovation embodied emissions should get less priority. Quite the contrary, **future building regulations ought to ensure the embodied emissions of both new constructions and renovations are minimised**.

**The fourfold increase of renovation embodied carbon (from 41 $MtCO_2e$ to 169 $MtCO_2e$) in the building stock in this scenario is linked to the more limited mitigation potential assumed for these embodied emissions, as well as the lack of data for more accurate modelling. Still it does raise the important question of where to draw the balance between in use energy efficiency gains including envelope and heating decarbonisation, and embodied carbon investments.** The analysis makes clear that the building stock will need to be renovated in order to cut operational carbon emissions in line with sufficiency and energy efficiency first principles. What the scenario also reveals is that this has an important embodied carbon cost implication, and without embodied carbon measures for renovations, the EU building stock will not achieve its climate targets. Renovations are a solution to the climate crisis, but they could also become a main source of emissions if renovations do not consider embodied emissions from materials and services.

When considering primarily well-established innovations in the industrial sector aimed at reducing energy intensity, the levels of embodied emissions in the business-as-usual and TECH-Build scenarios remain relatively similar. In the business-as-usual scenario, embodied emissions reach a peak of 330 MtCO2e, while in the TECH-Build scenario, they peak slightly lower at 320 MtCO2e.The deployment of embodied carbon reduction solutions achieves important reductions in upfront embodied emission in TECH-Build. However, the increase in embodied carbon associated with renovations offsets these savings. While the study was not necessary able to capture all relevant low carbon solutions for renovation projects, this suggests that efforts to reduce embodied carbon in the building stock will need to target both new construction and renovations. Due to limited research and data on renovation embodied carbon, the study could not further investigate the ways to reduce these impacts. As explained in section 2.5, the focus of the embodied carbon reduction solutions is primarily on new constructions. Additional research and data collection will be required to better capture the whole life carbon mitigation potential of renovations.

## 5.3 LIFE-Build scenario results

The sections below present the results of the LIFE-Build scenario based on the assumptions set out in chapter 2.4.

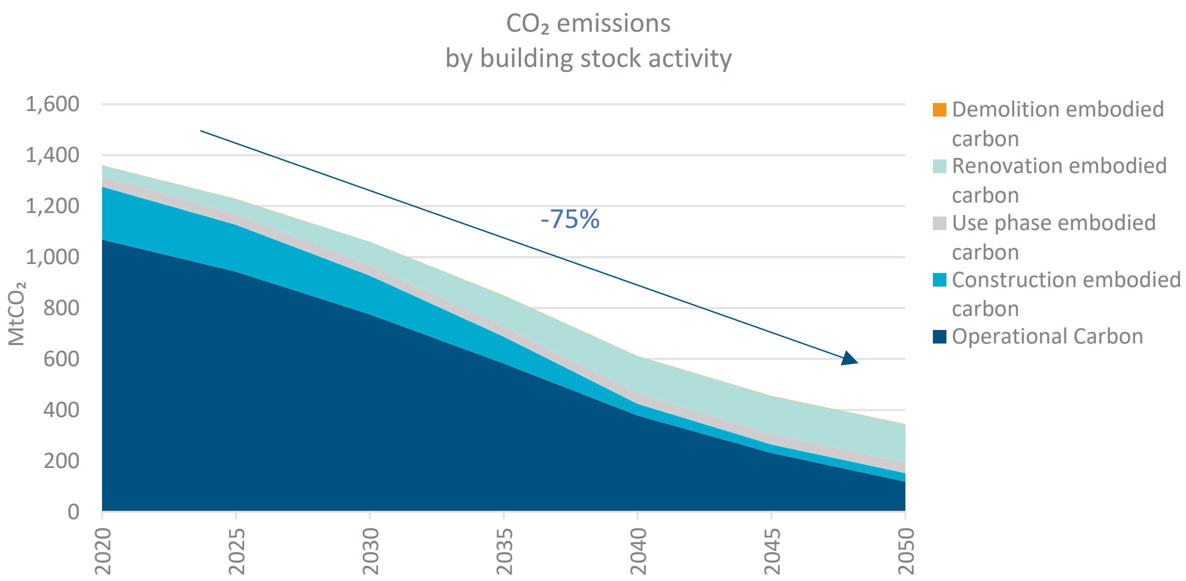
**Highlights of the LIFE-Build scenario:**

- Reduction of lifecycle emissions of 75% are possible by 2050 relative to the baseline year, if transformational technology solutions are combined with lifestyle and sufficiency measures
- By 2050, the LIFE-Build scenario cuts further 94 $MtCO_2e$ emissions compared to the already very ambitious TECH-Build
- Operational emissions are expected to fall by about 90% relative to the baseline, same as in TECH-Build
- Embodied carbon emissions will overtake and exceed operational carbon emissions as of 2040-2045
- Yet, the absolute amount of embodied carbon will decrease consistently between 2020 and 2050 – a significant change compared to the TECH-Build, which saw overall increasing embodied carbon emissions
- Upfront emissions (Module A) associated with new construction hold the most significant carbon reduction potential, 72 $MtCO_2e$, or a threefold reduction compared to TECH-Build
- Given the way the scenarios have been modelled in this study, the LIFE-Build scenario integrates sufficiency measures alongside the TECH-Build scenario, resulting in a reduced demand for new built. These measures help avoiding the need for energy services and materials for buildings that are not being built. By modelling the sufficiency measures on a building stock that has already made significant reductions in carbon emissions through technical improvements, the modelling accounts for the impact of sufficiency in addition to the TECH-Build measures. However, if sufficiency measures are applied to a building stock which have not yet reduced its whole life carbon emissions substantially through technical means, the resulting carbon savings would be even higher. Additionally, sufficiency measures play a vital role in ensuring that technological solutions deliver their intended performance and prevent rebound effects.

**EU building stock emissions – LIFE-Build scenario**

The LIFE-Build scenario demonstrates how sufficiency measures can significantly contribute to reducing the annual lifecycle emissions associated with the European building stock. This pathway represents an even more comprehensive transformation than TECH-Build. In addition to technological measures implemented consistently across the entire building stock, it also assumes sufficiency and lifestyle changes that go against the trend in residential buildings of increasing per-capita floor area observed over the recent decades.[43] The policy implications of the LIFE-Build scenario are therefore potentially far-reaching and require bold sufficiency policies which tackle the causes of anthropogenic emissions by avoiding the demand for new constructions and their related materials.[44] In addition, this would tend to suggest a major shift in priority for the construction industry from new buildings to renovations. This shift may also involve reallocating skilled workers from new construction projects to renovations, presenting a viable solution to address the anticipated surge in demand for renovations. The expected reduction potential of the LIFE-Build scenario is about 75% by 2050 compared to baseline emissions in 2020 (Figure 38).

**Figure 38 LIFE-Build scenario building stock whole life carbon projections**

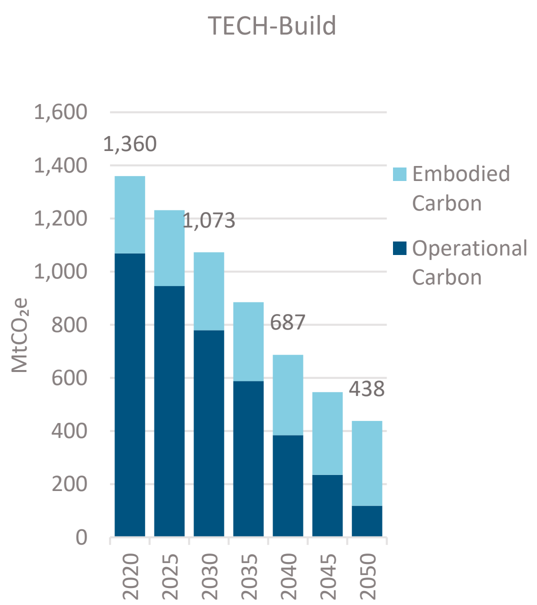


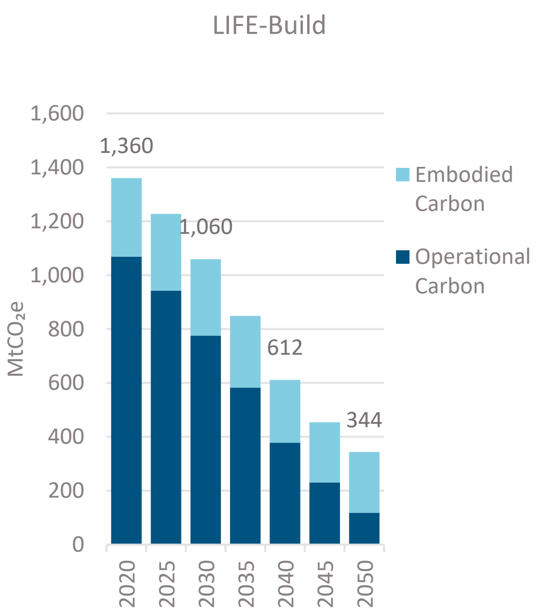

The LIFE-Build scenarios shaves off a further 94 $MtCO_2e$ emissions from the residual emissions remaining in TECH-Build in 2050 (Figure 39).

**Figure 39 TECH-Build and LIFE-Build scenario comparison: operational and embodied $CO_2e$ emissions developments**

[43] Ellsworth-Krebs (2020) Implications of declining household sizes and expectations of home comfort for domestic energy demand. Nature Energy, 5(1). https://doi.org/10.1038/s41560-019-0512-1

[44] EEB (2021) Sufficiency and Circularity. The two overlooked decarbonisation strategies in the 'Fit for 55' Package, https://eeb.org/wp-content/uploads/2021/10/Decarbonisation-EU-Building-Stock_EEB-report-2021.pdf



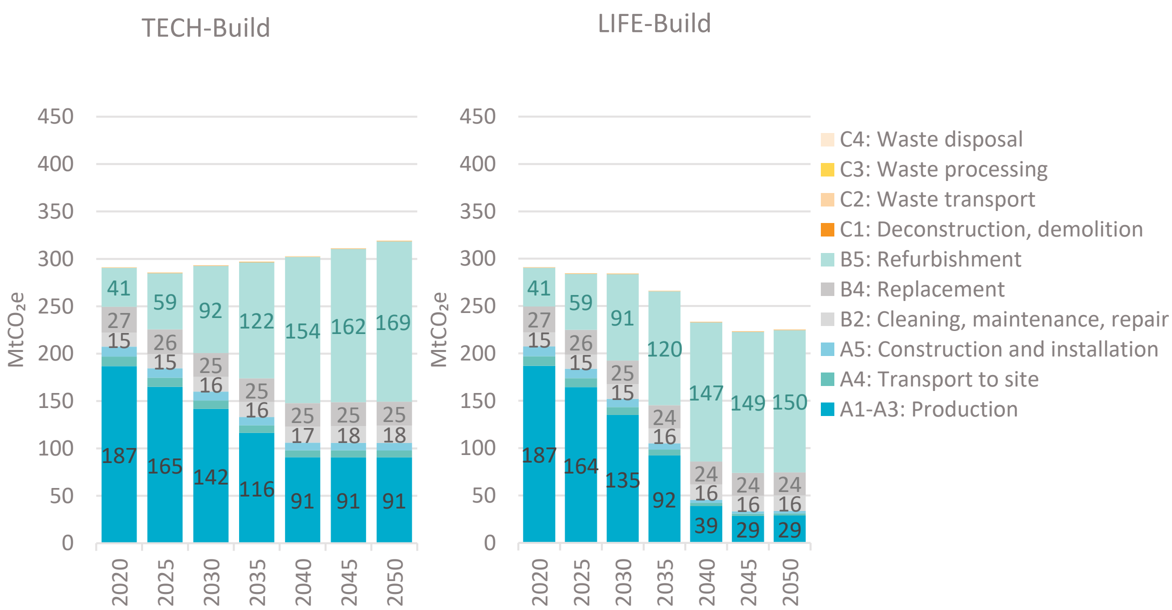

Both technology-driven and lifestyle pathways achieve about 90% operational carbon savings. The main difference between the two scenarios lies in the remaining embodied emissions. Whereas TECH-Build saw an overall increase of embodied carbon emissions towards 2050, embodied carbon is consistently decreasing in LIFE-Build in line with decreasing construction activities. Upfront emissions (Module A) in LIFE-Build are reduced by 72 $MtCO_2e$ compared to TECH-Build (i.e. a threefold reduction) (see Figure 4040).

It is important to note that the scope of the avoid measures applied in this study mainly target upfront emissions from new constructions. These measures involve optimising space use and prioritising renovations instead of demolition and new construction. With the implementation of construction technologies and solutions aimed at reducing embodied carbon, it is anticipated that upfront emissions will already be reduced to approximately 100 $MtCO_2e$ by 2050 in the TECH-Build scenario. This is a relatively low base of emissions to which the avoid measures (preventing new constructions) would apply.

This does not imply that sufficiency measures are not relevant. Sufficiency measures which tackle the cause of emissions by avoiding the demand for materials related to energy services and buildings are more effective today than in a highly decarbonised future.

Sufficiency reduces the need for constructing new floor area, thereby reducing related carbon emissions, which are known to be a significant carbon hotspot. By reducing the need for immediate and transformative technical measures, sufficiency measures provide additional time for these technical measures to mature gradually and be widely adopted. It also allows for the development of the necessary capacity within the supply chain. Sufficiency therefore helps to prevent material shortages for essential and unavoidable new construction and renovations. Sufficiency measures are also essential to ensure future technological solutions deliver their promised performance, preventing performance gaps between 'as designed' and 'as built', and avoiding rebound effects. Sufficiency measures focus on optimising the actual use and operational performance of buildings, thus minimising discrepancies between intended design and realised outcomes. Moreover, these measures help avoiding rebound effects by encouraging behaviour and lifestyle changes, promoting efficient resource use, and ensuring that energy-saving measures or low carbon technologies are not offset by increased consumption or comfort demands (including floor area per person).

**Figure 40 Embodied $CO_2e$ emissions by building lifecycle stages BAU and TECH-Build**



# 6. KEY TAKEAWAYS FROM THE SCENARIO ANALYSIS

## 6.1 Comparison of scenario results to recorded emissions and future budgets

When comparing the results of this study to existing references, it is important to consider the novelty of the approach of this study which quantifies emissions at the scope of the building stock across the EU, and the assumed mitigation options. The comparison to the EU climate target faces the following challenges:

- **The scopes of emissions differ.** The results of this study relate to emissions along the entire lifecycle caused by activities related to buildings located in Europe. Yet, some materials used to construct and renovate these buildings (or their raw materials) may to some extent be imported[45]. Therefore, the **accounting of this work,** which is more closely aligned with consumption-based principle[46], **includes emissions generated outside the EU's borders but linked to products consumed within the EU**. Reported emissions in national inventories rely on official statistics based on EU GHG accounting, including domestic emissions generated within the EU.
- **Assumptions differ.** Both the modelling of the building stock emissions and of the EU economy-wide GHG emissions rely on assumptions on the future development of key variables. Some of these assumptions differ between the TECH-build and the LIFE-build scenario on the one hand, and previous EU economy-wide modelling exercises on the other hand. For instance, the projected future renovation rate varies, and so do the assumed mitigation options. Additionally, the impact of carbon removal through biomass and carbon capture and storage, which reduces the future net-emissions from the EU economy, is not included in the quantification of building stock emissions in this study.
- **Limitations apply to the coverage of building stock emission reductions.** As described in Section 2.5, additional emission reductions from sufficiency and renovations are expected to contribute to a further reduction than what is currently quantifiable.

**Table 5 summarises the EU buildings' WLC emission reductions resulting from this work.** For information, the total emissions of the EU are also reported and based on reported GHG emissions for 2019[47], while future emission levels have been modelled in support for the policy development of the Fit-for-55 package[48] and the Clean Planet for All[49].

[45] This can be considered relevant for raw materials used in production as well as technical services, which make up 10% of embodied carbon from an average new building. For some of these products, an EU carbon border adjustment mechanism (CBAM) is foreseen to align carbon pricing instruments of the EU with those applying to imported materials. This aims at incentivising low-carbon imports in the future.

[46] A bottom-up building LCA perspective, as used in this study's archetype modelling is different from both consumption-based and production-based emission accounting. Therefore, neither production-based nor consumption-based emission scopes are fully aligned with the scope of this study. For more explanation see a related analysis by Truger et al. (Truger et al., Life cycle GHG emissions of the Austrian building stock: a combined bottom-up and top-down approach, IOP Conf. Ser.: Earth Environ. Sci. 2022, https://doi.org/10.1088/1755-1315/1078/1/012024)

[47] 2019 is used instead of 2020 to mitigate the effect the COVID pandemic had on EU and global economies and also GHG emissions. Recent GHG quantifications show that the reduction effect occurred mainly in one-off nature, while the modelling of this study is based on general trends rather than specific data for 2020.

[48] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

[49] European Commission. In-depth assessment in support of the Commission Communication COM(2018) 773 (Clean Planet For All). 2018. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

**Table 5 Indicative WLC emissions reductions vs 2019 levels in BAU, TECH-Build and LIFE-Build**

| | Year | EU27 economy-wide emissions (excluding LULUCF) | Building stock emissions as modelled in | | |
|---|---|---|---|---|---|
| | | | BAU | TECH-Build | LIFE-Build |
| **Absolute emissions ($MtCO_2e$)** | **2020** | 3,360[50] | 1,360 | | |
| **Reduction relative to 2020 values** | **2030** | -33%[51] | -8% | -22% | -23% |
| | **2050** | -88%[52] | -32% | -68% | -75% |

The comparison – within the limits described above – shows that the **reduction trajectory in a future under business-as-usual conditions would be insufficient to achieve the level of reduction necessary for staying on track of the EU targets.**

Both the **TECH-Build** and **LIFE-Build** scenarios achieve high mitigation potential. Both would benefit notably from further mitigation options addressing the embodied carbon emissions from renovations, which underlines that further research is needed to quantify the potential in renovation projects in order to reduce whole life carbon. Finally, the LIFE-scenario underlines that lifecycle changes can help with reducing emissions further, and avoid some of the more costly technical options. As such, lifestyle changes are an important enabling factor, which facilitate higher ambition.

**A comprehensive transformation of both technological and lifestyle conditions for reductions as captured in the LIFE-Build scenario are as such contributing strongest to** the climate targets.

## 6.2 Residual emissions and carbon removals

**Carbon removals are still a fundamental part of achieving EU climate targets in what concerns the buildings sector**. Even though both TECH-Build and LIFE-Build reduction pathways have been designed to get the building stock as close to net-zero WLC emissions as possible by implementing all relevant technical and social measures available at present, the results of the modelling suggests that it is still not yet possible to achieve carbon neutral buildings without the removal of residual emissions.

[50] EEA (2022). National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism. Available at: https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18

[51] According to the results of scenario MIX in https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en For details on the results of the MIX scenario see: E3Modelling work to support the Fit-for-55 package. https://energy.ec.europa.eu/excel-files-mix-scenario_en

[52] According to the range of scenario results (1.5TECH, 1.5LIFE,1.5LIFE-NB) in European Commission. In-depth assessment in support of the Commission Communication COM(2018) 773 (Clean Planet For All). 2018. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

**Carbon capture technologies that reach a good level of maturity today in specific material production processes have been included in the embodied carbon reduction solutions implemented in both TECH-Build and LIFE-Build scenarios.** This is consistent with the material industry pathways, which unavoidably rely on these technologies to reach net-zero by 2050. But the modelling did not reflect how the production of certain construction materials, in combination with biomass use as a renewable energy source and CCS, can lead to carbon removals.

**Also bio-based construction materials provide the opportunity for carbon removals at least temporarily**. Maximising their use in a sustainable manner, with long lifetimes of products made from bio-based materials, and end-of-life processing that prevents GHG releases, can play an important role to balance remaining emissions of the building stock. However, these effects are not quantified in this work as the biogenic carbon content was not accounted for (see Section 2.5). Moreover, technologies will need to be ramped up for low-carbon biobased solutions to have sufficient impacts.

**Yet, it can be concluded that carbon removals should be considered in a comprehensive, economy-wide, lifecycle carbon strategy, while every effort should be made to reduce lifecycle carbon through design, material and sufficiency initiatives.** The implementation of carbon removals in the building sector versus the transformation of the building stock will depend on various factors, including the carbon prices associated with the emissions. However, it is likely that the greater the residual emissions after transforming the building stock, the higher the costs of implementing carbon removals will be. This represents an important argument for realising the highest possible reduction in building stock emissions, rather than relying on economy wide removals.

## 6.3 Translation of scenario results into embodied carbon benchmarks

The scenarios quantify WLC emissions at the building stock level within the time horizon of 2050. The pathways provide important insights for policymakers to explore and steer future mitigation and strategies.

The building sector pathways and strategies can be translated into **building-level carbon values** to support the planning of future regulatory limits and net-zero carbon verification scheme requirements. Specifically, this is relevant for the development of embodied emissions and of WLC in total, who are not yet targeted by existing legislation. Table 6 shows the trajectory of construction (A1-A5) and renovation (B5) embodied carbon in the TECH-Build scenario that can provide useful signposts for policymakers and market practitioners as for the phased implementation of WLC threshold values.

**Table 6 Trajectory of building level upfront embodied carbon and renovations in $kgCO_2e/m^2$ of useful floor area (UFA) in TECH-Build scenario**

| Year | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| **Upfront construction embodied carbon (A1-A5) ($kgCO_2e/m^2_{UFA}$)** | | | | | | | |
| **Average** | **810.41** | **706.55** | **603.12** | **500.66** | **398.48** | **398.48** | **398.48** |
| Best practice | 344.21 | 296.27 | 248.54 | 201.26 | 154.10 | 154.10 | 154.10 |
| **Renovation embodied carbon (B5) ($kgCO_2e/m^2_{UFA}$)** | | | | | | | |
| **Average** | **273.81** | **260.30** | **246.60** | **233.62** | **222.06** | **222.06** | **222.06** |
| Best practice | 46.81 | 44.51 | 41.93 | 39.49 | 37.32 | 37.32 | 37.32 |

*Based on results obtained from archetype modelling.* ***Average*** *represents the average across all new construction archetypes (all regions and building typologies) after implementing technological reduction measures.* ***Best practice*** *represents the lowest value observed in any individual archetype.*

**For construction embodied carbon ($kgCO2e/m^2UFA$), average 'upfront embodied carbon' emissions (related to life cycle stages A1-A5) across building types and regions decrease by around 25% until 2030 and by more than 50% until 2050.** Interestingly, it also shows that current best practice low-carbon construction in 2020 – as obtained from baseline archetype modelling – are already below the projected possible 2050 average for upfront embodied. This suggests low-carbon buildings already exists today and a substantial potential to improve current average building practice is possible.

**The trajectory for reducing embodied carbon of renovation activities is a lot less steep: on average, the embodied carbon of renovation reduces by less than 20% until 2050 in the current modelling**. However, this is also an indication of the initial focus of this study on understanding new construction whole life embodied carbon and strategies for its reduction. Additional strategies relating to renovation embodied carbon can and should be investigated in future studies to better understand the decarbonisation potential of renovations[53].

**Nonetheless, as the comparison of the scenario results with EU emission targets illustrates, further measures will have to be investigated.** Innovative reduction approaches – relating to production improvements, material shifts and most certainly also sufficiency measures – to avoid resource use and carbon emissions and to enable a steeper reduction of both embodied and operational carbon and align the European building sector with climate goals.

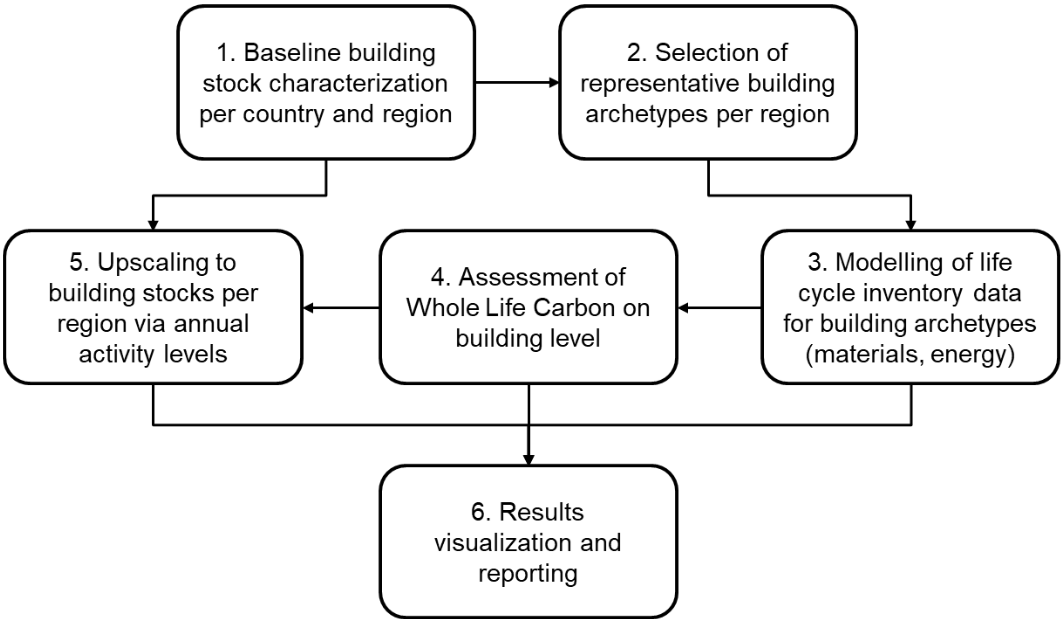
[53] As described in Section 2.5, the assessment of the carbon reduction potential from material alternatives such as using bio-based materials (e.g. timber in structures as well as insulation from straw, hemp, or woodchips) and reuse of materials from existing buildings in renovation projects needs to be further researched to be able to present a more complete outlook on embodied emissions from renovations.

# APPENDIX I – BUILDING ARCHETYPE MODELLING

## A. Overall methodological approach

This study quantifies the carbon emissions associated with the use, construction, refurbishment, and demolition of European buildings and the EU27 building stock. The approach follows the steps illustrated in the figure below. Step 1 to 5 are described in the present Chapter (one sub-section for each step) from a methodological standpoint, while Step 6 is addressed in the discussion of results (Chapters 3, 4 and 5)

**Figure 41 Overall methodological approach for assessing the baseline**




## B. Characterisation of the baseline building stock

In order to select representative building archetypes and upscale their whole life carbon assessment to the building stock level, a first step of the analysis consists in the characterization of the baseline building stock per country and region.

### Clustering of building stocks by regions

To enable an efficient modelling of the European building stock within the framework of this project, we grouped the building stock into regions (often also called geoclusters). To identify appropriate ways of grouping different Member States (MS) into regions, we reviewed existing approaches for establishing regions for buildings in an EU context. Three important references are:

- Energy Performance in Buildings Directive (proposal)[54]
- Basket of products indicator on housing[55]

[54] EPBD proposal (https://ec.europa.eu/energy/sites/default/files/proposal-recast-energy-performance-buildings-directive.pdf) and Annexes (https://ec.europa.eu/energy/sites/default/files/annex-proposal-recast-energy-performance-of-buildings-directive.pdf)

[55] Baldassarri C, Allacker K, Reale F, Castellani V, Sala S. Consumer Footprint: Basket of Products indicator on Housing. 2017. doi:10.2760/05316.

- Existing studies modelling embodied emissions of EU building stock retrofit and bio-based material availability for construction purposes[56] [57]

**Figure 42 Map of Europe showing the grouping of Member States to geocluster regions applied in this study, in line with EPBD**


The definition of regions in this study follows the EPBD approach, grouping MS into four regions. An overview map is shown in Figure 42**Error! Reference source not found.**. More specifically, the country distribution is as follows:

- Mediterranean region (MED): CY, HR, IT, EL, MT, ES, PT
- Oceanic region (OCE): BE, DK, IE, DE, FR, LU, NL
- Continental region (CON): AT, BG, CZ, HU, PL, RO, SI, SK
- Nordic region (NOR): EE, FI, LV, LT, SE

## Building stock data for the baseline year

### *Overall approach to building stock modelling*

For a building stock model to be reasonably accurate, it needs to capture the main characteristics of the real stock it aims to represent. What these characteristics are depends on the goal of the model, its desired level of detail and the type of assessment for which it will be used. Our approach to developing such a model is to (1) classify the buildings in the stock based on a set of attributes, (2) develop archetypes to represent the building types obtained through this classification, and subsequently, (3) scale up these archetypes based on floor area.

[56] Pittau F, Lumia G, Heeren N, Iannaccone G, Habert G. Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. J Clean Prod 2019;214:365–76. doi:10.1016/j.jclepro.2018.12.304.

[57] Göswein V, Reichmann J, Habert G, Pittau F. Land availability in Europe for a radical shift toward bio-based construction. Sustain Cities Soc 2021;70. doi:10.1016/j.scs.2021.102929.

***Scope of the building stock model***

The building stock model employed in this study covers both residential and non-residential buildings and includes both existing (to assess buildings in-use as well as refurbishment strategies) and new buildings (to assess needs for additional housing or working space in the future). covers the full building stock of the EU27.

The model differentiates four main building types:

- Residential buildings
    a. Single family houses (SFH)
    b. Multi-family houses (MFH)
- Non-residential buildings
    a. Office buildings (OFF)
    b. Other non-residential buildings (ONR)

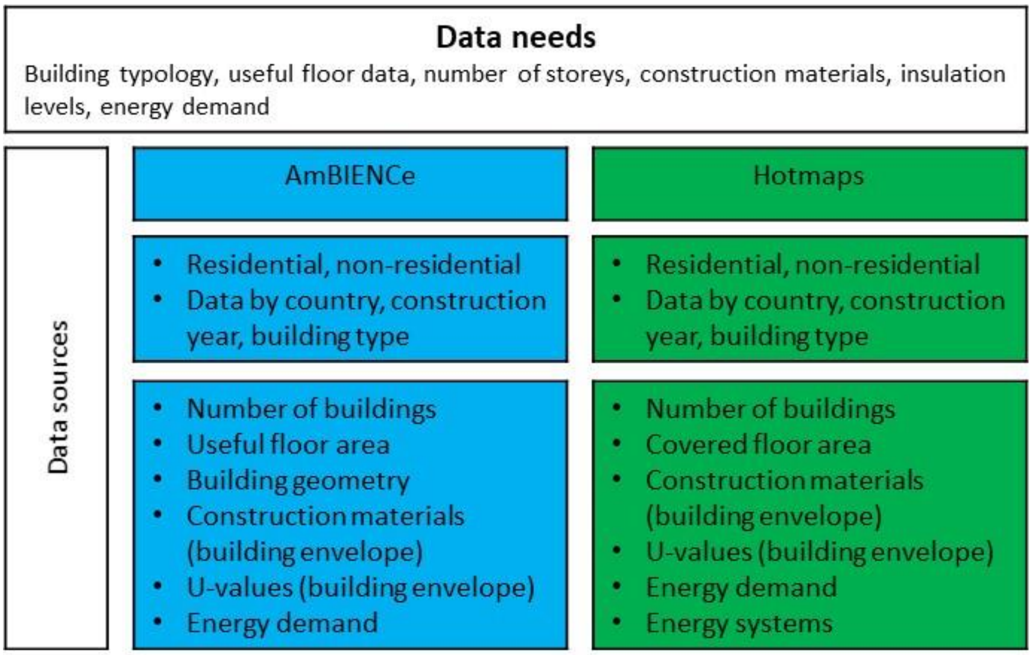
These are modelled with dedicated building archetypes that are further differentiated and specified by the four regions mentioned above, i.e., Oceanic, Mediterranean, Continental and Nordic. Various sources have been used to select representative archetypes for the regions, i.e., TABULA/EPISCOPE, AmBIENCe and Hotmaps (see below). All these projects include archetypes for residential and/or non-residential buildings at Member State level. The challenge hence was to deduct regional archetypes out of these national archetypes. The exact data within each of these sources is explained in more detail further on.

***Data needs for the selection and modelling of archetypes***

As explained in the previous section, the selection of the representative regional archetypes for our stock model is based on national building stock data (i.e. national archetypes defined in the AmBIENCE and Hotmaps projects). The selection focuses on the following attributes: building type; construction period; total floor area; construction material composition; and insulation level of the various elements of the building envelope. By analysing the data sources on the EU building stock in the baseline year 2020, as described in the next section, archetypes have been selected based on these attributes. The selection of representative building archetypes is explained in more detail in section C.

Beyond these attributes, the AmBIENCe and Hotmaps databases however also provide information on other building characteristics such as building typology (e.g. detached SFHs versus terraced SFHs), useful floor area, surface area of the elements comprising the building envelope, and number of storeys. The representative regional building archetypes hence well represent the insulation level, construction period and materials used in the specific region. However, since the other characteristics were assumed to be as defined in AmBIENCe and Hotmaps for the selected archetypes, they might be less representative for the full region. A detailed explanation of the identification of the regional archetypes follows.

**Figure 43 Data needs and the data availability from main sources to select representative buildings archetypes**

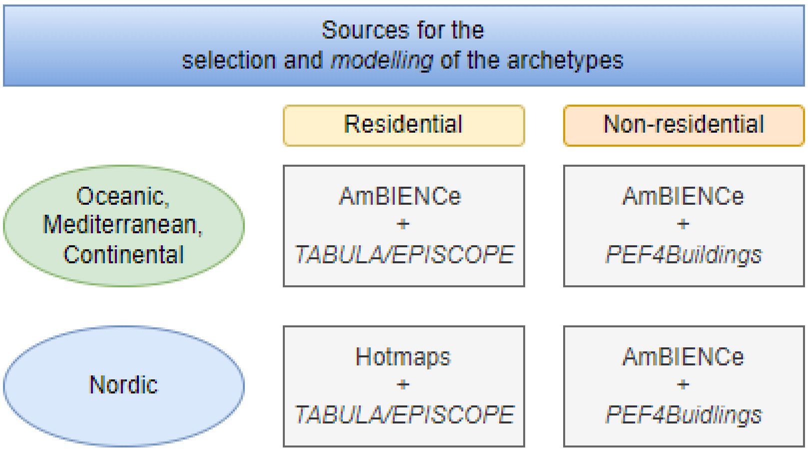



***Data sources for the selection and modelling of archetypes***

Data collection was carried out to obtain the necessary information about the EU building stock in the baseline year 2020. The data collection effort was informed by the stock modelling projects mentioned above, as well as a recent review study on building stock modelling in an EU context authored by members of the project team[58]. An overview of the selected data sources, which were used for the archetype selection process, is given in **Error! Reference source not found.**.

[58] Röck M, Baldereschi E, Verellen E, Passer A, Sala S, and Allacker K. "Environmental Modelling of Building Stocks – An Integrated Review of Life Cycle-Based Assessment Models to Support EU Policy Making." Renewable and Sustainable Energy Reviews (2021). https://doi.org/10.1016/j.rser.2021.111550.

**Figure 44 Data sources used for the selection (non-italics) and modelling (italics) of the archetypes**




The **TABULA** (Typology Approach for Building Stock Energy Assessment) project (2009-2012) focused on the development of residential building typologies for 13 European countries, based on size, construction period and energy supply system type[59]. The follow-up project **EPISCOPE**[60] (2016-2021) aimed at increasing the effectiveness and transparency of energy refurbishment processes, the TABULA/EPISCOPE building database has been extended to include 21 European countries. Both projects were financed by Intelligent Energy Europe.

AmBIENCe[61] and Hotmaps[62] made use of these data and widened the scope to include non-residential buildings. The **AmBIENCe** (Actively Managed Buildings with Energy Performance Contracting) project (2019-2022) aimed to "extend the concept of Energy Performance Contracting to Active Buildings and making it available and attractive to a wider range of buildings". The **Hotmaps** project (2016-2020) aimed at developing an open-source toolbox for mapping heating and cooling for the EU28 countries. Both projects were financed by Horizon 2020.

AmBIENCe and Hotmaps are used in this study as a starting point to identify representative archetypes on which to build the stock model. These representative building archetypes are defined for the four regions and three building types (SFH, MFH, OFF), considering the total useful floor area and estimates of energy performance and material compositions. TABULA and EPISCOPE are then used in a second step for modelling the life cycle inventory of the selected archetypes.

Due to lack of representative build-ups of elements for non-residential buildings, the life cycle inventory of the non-residential buildings makes use of a real-world case study used in the **PEF4Buildings**[63] study conducted in 2017 by some of the authors of the present report on behalf of the European Commission, DG for Environment. The study aimed to test the application of the PEF method (Product Environmental Footprint), related PEF pilot guidance documents prepared by the EC and knowledge/experiences from several PEF pilots on construction materials to two office buildings.

[59] https://episcope.eu/fileadmin/tabula/public/docs/tabula-info.pdf

[60] https://episcope.eu/fileadmin/episcope/public/docs/EPISCOPE-ProjectInformation.pdf

[61] https://ambience-project.eu/about/

[62] https://www.hotmaps-project.eu/

[63] European Commission, Directorate-General for Environment, Spirinckx, C., Mirabella, N., Damen, L., et al., *Study and related guidance documents on the application of the PEF method to a new office building*, Publications Office, 2018, https://data.europa.eu/doi/10.2779/23505

SELECTION OF BUILDING ARCHETYPES

As shown in **Error! Reference source not found.**, the largest share of the data for the selection of building archetypes is obtained from the AmBIENCe research project, which involved the development of a database, and was finalised in 2021. Two additional main sources were used: TABULA/EPISCOPE and Hotmaps[64].

The AmBIENCe database is publicly accessible and available in the form of a downloadable Excel file. It divides the stock in several segments, each represented by a reference building (archetype). The segments in AmBIENCe are defined by country, building use and construction period (ranging from 1850 to 2021). Inherently the material use is considered as the materials differ per construction period and country. AmBIENCe considers five reference buildings for multi-family houses and five reference buildings for single-family houses (each time one reference building per construction period defined). The reference buildings are characterised through building geometry data, energy use and information about elements of the building envelope.

AmBIENCe data were lacking for the residential buildings in the Nordic region. Therefore, data from the Hotmaps project were consulted for this region. The data in the Hotmaps project, last updated in February 2022, is available in the form of an Excel file downloadable from a publicly accessible GitLab folder. The data are organised by country, building type (single-family house, multi-family house, etc.) and construction period, ranging from *before 1945* until *after 2010*. The available information covers construction materials and thermal transmittance values for elements of the building envelope; constructed, heated and cooled floor areas; as well as heating and cooling systems.

AmBIENCe and Hotmaps seem to contain similar data. There are however some key differences which are relevant for the archetype selection:

- Residential buildings – single family houses: the AmBIENCe database only covers detached houses. Hotmaps, on the other hand, includes both detached houses and terraced houses, but defines them as a single category.
- Non-residential buildings: Hotmaps does not provide the same level of detail that is present in AmBIENCe. In particular, the former describes construction materials only at the regional level, rather than the country-level.

The AmBIENCe and Hotmaps reference buildings have not been directly used as archetypes for the stock model in this study, because this would be too data intensive to be feasible within the time frame of the project. Instead, a more limited set of archetypes have been defined by selecting a limited number of buildings from this list that well represent the stock. The approach used for this selection is further explained in section C. Figure 43 summarises the data needs for the selection of representative building types and the data availability by source.

MODELLING OF BUILDING ARCHETYPES

As shown in Figure 41, once the representative archetypes have been selected, the TABULA/EPISCOPE project is the main source used to develop the life cycle inventories for residential buildings, providing data on the build-ups of the building envelope elements, refurbishment activities and operational energy use. Specifically, TABULA/EPISCOPE is used to obtain information about the buildings' energy demand and source for heating. TABULA/EPISCOPE does not include information on electricity use for lighting and appliances. A detailed description of how these elements have been modelled is given in section D.

[64] https://ambience-project.eu/wp-content/uploads/2022/02/AmBIENCe_D4.1_Database-of-grey-box-model-parameter-values-for-EU-building-typologies-update-version-2-submitted.pdf

Due to lack of representative build-ups of elements for non-residential buildings, the life cycle inventory of the non-residential buildings makes use of a real-world case study, i.e. the BelOrta building case study of the PEF4Buildings study. A detailed description of how these non-residential elements have been modelled is given in section D.

***Construction periods and archetypes for the baseline year***

For the modelling of the stock in this project, the aim was to represent the stock by one existing, as originally constructed building, differentiated per building type (i.e. SFH, MFH, OFF, ONR), and for each of the regions (i.e. MED, OCE, CON, NOR). These represent as built, un-renovated buildings. Refurbishment archetypes are also covered in the model, but in a separate step (see section D for the description of the modelling of the refurbishment archetypes). Additionally, dedicated archetypes were selected and modelled to represent new buildings added to the stock, again differentiated per building type, and for each of the four regions.

The representation of the existing building stock by just one 'average' archetype per building type and region is a necessary simplification of the modelling of existing buildings as the focus of this study is on the modelling of current and future building stock activities, different refurbishment options and new building variants. Building stock studies focusing more on modelling the existing building stock, rather than its future development, can further differentiate the modelling in that regard, e.g., by modelling archetypes for different construction periods. This has for example been done in the JRC study on Consumer Footprint: Basket of Products Indicator on Housing[65].

The databases consulted to characterise the existing stock indeed cover various construction periods. The construction periods moreover vary by country in TABULA/EPISCOPE and in AmBIENCe, while in Hotmaps the same seven construction period categories are used for all countries. The variation in construction periods of the different data sources and our need of one each existing and new archetype is summarised in Table 7.

In order to accurately represent the existing stock in the four regions with a limited number of archetypes, an analysis of the variation in type of construction per construction period, for the various countries has been performed. The most recent building period in all the data sources was used to select the archetypes for new buildings, while all other construction periods were used as the basis for selecting the archetypes to represent the existing stock. More specifically, the buildings were analysed in terms of useful floor area, U-value of the elements in the envelope, and construction materials used. This allowed to select the archetypes that best represent the existing stock.

**Table 7. Classification of construction periods of TABULA, AmBIENCe and Hotmaps**

| Archetype classification in this study | TABULA / EPISCOPE | AmBIENCe | Hotmaps |
|---|---|---|---|
| Existing<br>New | Construction periods from <1850 to >2016, different for each country | Construction periods from 1850 to 2021, different for each country | <1945<br>1945-1969<br>1970-1979<br>1980-1989<br>1990-1999<br>2000-2010<br>>2010 |

[65] Baldassarri C, Allacker K, Reale F, Castellani V, and Sala S. Consumer Footprint: Basket of Products Indicator on Housing, 2017. https://doi.org/10.2760/05316.

## C. Selection of representative building archetypes

The second step of our methodology consists in selecting a limited number of building archetypes. As mentioned, archetypes are representative buildings created by a composite of several characteristics found within a category of buildings with similar attributes. Building archetypes are virtual representations of various buildings that share similar characteristics in the stock.

### Residential buildings

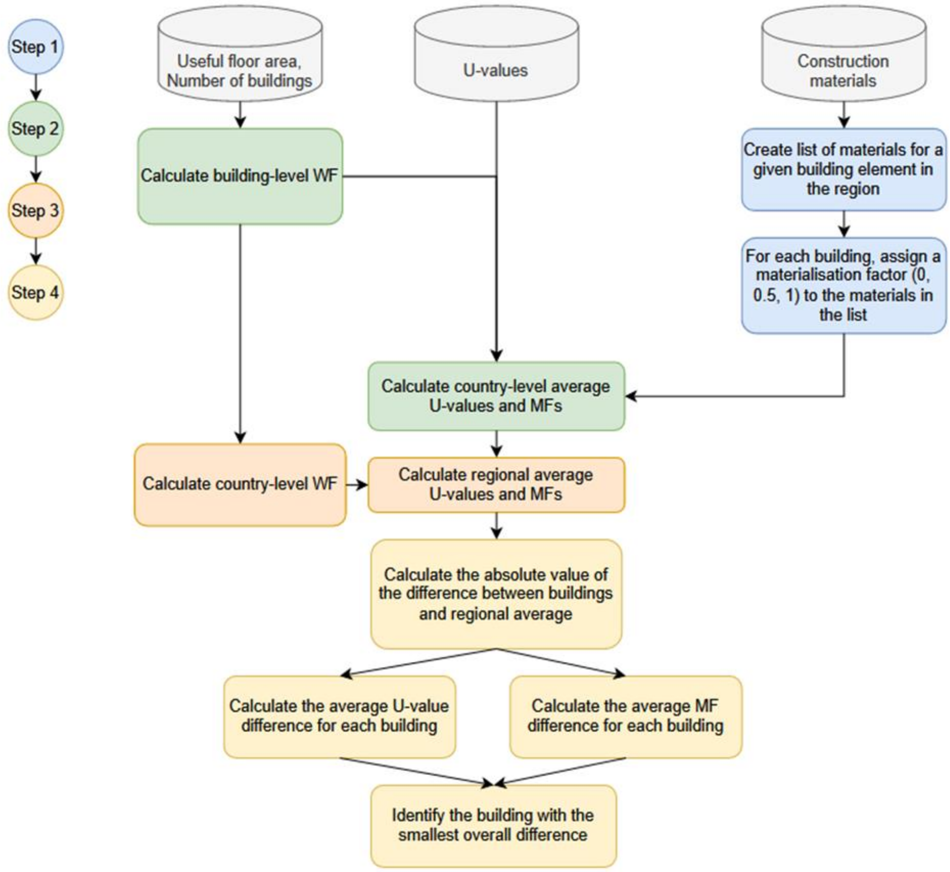
As explained above, based on AmBIENCe and Hotmaps data, representative building archetypes are identified for each region (Oceanic, Continental, Mediterranean, Nordic), building type (SFH, MFH) and age (existing, new), for a total of 16 archetypes.

Based on TABULA/EPISCOPE data, these representative buildings are then further developed to include refurbishment measures. More specifically, two renovated building archetypes (for each existing building) are included. To cover also advanced new buildings, an ambitious energy performance standard (for each new building) is included as well. As a result, the final number of buildings used in the baseline for the residential buildings in the stock model is 60.

***Existing buildings***

The archetype selection for existing buildings was carried out according to the process illustrated in **Error! Reference source not found.**.

**Figure 45 Overview of the method used to select representative building archetypes. The input data were obtained from AmBIENCe (Continental, Oceanic, Mediterranean regions) and Hotmaps (Nordic region) for each Member State, construction period and building type.**




Building stock data for all Member States are obtained from AmBIENCe and Hotmaps and grouped by region (i.e., Continental, Oceanic, Mediterranean region or Nordic) as mentioned in section B. The datasets included in the study span construction periods from 1850 to 2021. The most recent construction period in this dataset is 2010-2021, with a small variation in the starting year of this construction period depending on the Member State (e.g., in Austria the most recent construction period is 2010-2021, while in Germany the most recent construction period is 2016-2021). This final construction period with varying starting year is further indicated as 2010/2015-2021.

For all analysed countries, the most recent construction period (2010/2015-2021) is used to represent new buildings. These are not included for the selection of the representative archetypes for existing buildings. The archetypes of the existing buildings are hence defined based on the data from 1850 until 2010/2015.

The goal was hence to use the available data to select, for each of the four regions and of the two residential building types (SFH and MFH), an archetype representative for original (non-refurbished) existing buildings and one representative for new buildings. The archetypes for our study could not directly be taken from AmBIENCe nor Hotmaps as these only provide archetypes per Member State, not per region as required for our study; and for each Member State these consist of various archetypes (i.e., one for each construction period). The archetypes of the various Member States of a certain construction period differ in thermal insulation of the building envelope and materials used for the element build-ups.

To define a region-based archetype based on these Member State archetypes, the following approach is taken. First, an average building at the regional level is calculated based on the data from each Member State. For the calculation of the average regional level building, the following attributes were considered: thermal transmittance values, or U-values (W/m²K), and main construction materials of the building elements.

This average building is however not selected as region-based archetype, but is used to select the archetype (from AmBIENCe or Hotmaps) from a certain Member State that best represents the average, both in terms of U-value and main construction materials used. For determining the archetype that best represents the fictitious regional average building, each individual archetype (from AmBIENCe or Hotmaps) was compared with this average. The archetype from AmBIENCe or Hotmaps with the smallest deviation with respect to the regional average is selected as representative building for that specific region. This approach of selecting the archetype from AmBIENCe or Hotmaps that best represents the regional average instead of using the regional average directly is chosen in order to allow the stock model to be refined and extended with more archetypes in future using the AmBIENCe and Hotmaps data.

***New buildings***

Archetypes for new buildings are identified following a process similar to that used for existing buildings, but then focussing on the data from the construction period 2010/2015-2021. As there is only one most recent construction period, the calculation hence includes only one SFH archetype and one MFH archetype per country. It is therefore unnecessary to calculate a country-level average, and the regional average can be calculated directly.

**Non-residential buildings**

The process described above is also applied to identify the representative archetypes for non-residential buildings. For the purposes of this project, non-residential buildings are divided in two categories: offices (OFF) and other non-residential buildings (ONR). The latter category includes the following building types, as defined in AmBIENCe: education (EDU), health (HEA), hotels and restaurants (HOR), other (OTH), trade (TRA).

***Office buildings***

Office buildings data in AmBIENCe is structured so that the construction periods are the same for all countries, ranging from 1850 to 2010. Once again, the 2010/2015-2021 dataset was used to select the representative archetype for new office buildings, while the other construction periods were used for the selection of the existing office building archetypes. No distinction was made in either AmBIENCe or Hotmaps between private and public offices, which were therefore assumed identical in our study.

***Other non-residential buildings***

The other, non-residential (ONR) category includes several building types. The process to identify the representative archetypes is similar to the process of the residential and office buildings and is performed as follows.

Regional averages of U-values and materials used (via a materialisation factor are calculated separately for each of the five non-residential, non-office building types (EDU, HEA, HOR, OTH, TRA), following the same process that was used for residential buildings. A representative archetype was thus selected for each of these building categories.

The regional averages computed for each non-residential building type are used to calculate the characteristics of a final regional average building for the ONR category.

The selected archetypes for each sub-category are then assessed against this average to establish which archetype shows the smallest variation and can therefore be used as a representative product for the whole ONR category.

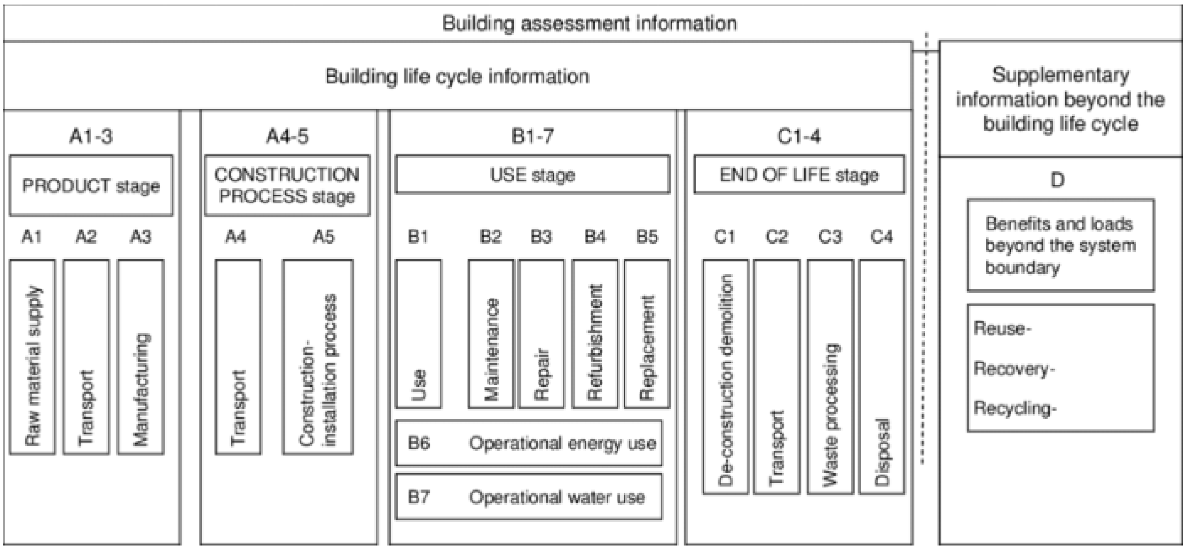
Finally, the archetypes selected at this step are upscaled to represent the complete EU building stock. Details of the upscaling are described in section F.

## D. Modelling of life cycle inventory data for building archetypes

Once the representative building archetypes are defined, the related buildings are modelled in detail to conduct a whole life carbon assessment, using standardised life cycle assessment (LCA) methodology.

The establishment of life cycle inventories (LCI) is conducted using a hierarchical approach for building decomposition, explained in the following section, as well as the modular life cycle approach of building assessment information according to EN 15978 – as shown in Figure 46.

**Figure 46 Life cycle stages for building assessment information (acc. EN 15978).**

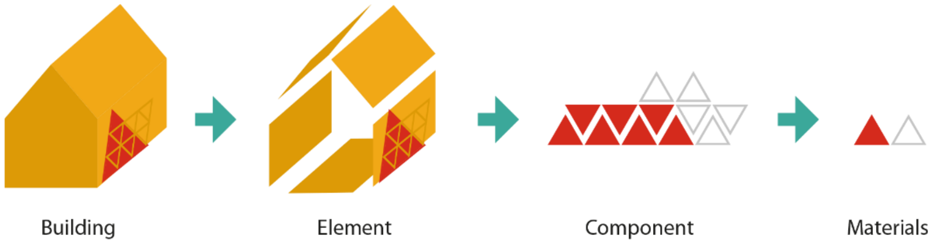



The following section explains the modelling of the building archetypes in terms of establishing a bill of quantities for construction productions and building elements as well as information on technical systems and building operational energy use. The section furthermore explains how different building stock activities are modelled with dedicated building archetypes for new buildings, existing buildings, and refurbishment, respectively.

### Material and energy modelling

The building archetype inventories are modelled using the KU Leuven MMG-LCA method (where MMG stands for the Dutch version of "Environmental profile of buildings"). The MMG method was developed to assess the environmental impact of building elements and buildings in a Belgian context[66] and has been extended to modelling environmental impacts at neighbourhood and building stock level in recent research projects.

**Figure 47 Hierarchical structure of the MMG method[67]**




The modelling of the building archetypes is structured in a hierarchical way, which is presented in Figure 47. At each level, environmental impacts are calculated for the respective life cycle stages and transferred onto the next level. Firstly, materials are modelled by defining their thermal conductivity (λ) and density (ρ), their impacts for life cycle stages A1-A3, and by selection of suitable scenarios for stages A4, A5, C2 and C4. Next is the component level, in which multiple materials are selected and their quantity per unit of component is defined. In addition, scenarios for B2, B4 and C1 are selected. Then, building elements (e.g. walls, floors) are composed of various components in a similar way, i.e. by defining the quantity of component per unit of building element. At this level, the U-values of the building elements are calculated based on the λ and thickness of the components and the thermal resistances of the surfaces. Lastly, buildings as a whole are defined as a compilation of building elements and technical systems. This level includes, on one hand, specifying the building geometries (e.g. m² of building element areas, number of doors etc.), and on the other hand, creating combinations of specific building element compositions (e.g. wall type 1, floor type 3 etc.). Hence, a building is defined by combining one building geometry with one building element combination, and by filling in parameters related to technical systems and energy use (B6).

Deconstruction and demolition activities, as well as end of life treatment of the building elements, are modelled as part of the respective life cycle of the buildings. These are included for both existing and new buildings and represent current common practice. The end-of-life scenarios for the various materials in the building elements and technical systems are following the MMG method.

Operational energy use modelled includes energy use for space heating, domestic hot water (DHW), and ventilation, where applicable. Cooling is modelled for the office archetypes but not for SFH and MFH archetypes, as cooling related energy use is unregulated and not captured in the statistical data at building stock level, which is used for upscaling later. A detailed description of the calculation of the energy use of these different aspects can be found in Trigaux (2017)[68].

The approach for modelling building inventories (bill of materials and LCI) in MMG uses the information provided for TABULA/EPISCOPE building archetypes and is based on the method developed by Eeckhout (2020), translated to the most recent version of MMG by the KU Leuven team. Overall, the archetypes are modelled based on the information available in the TABULA/EPISCOPE webtool and complemented with the national typology brochures, external sources and expert judgement to fill in data gaps. In fact, as the focus of TABULA/EPISCOPE is energy performance, the information included in the webtool is limited to what is required to perform energy calculations.

[66] Ibid.

[67] Lam W.C., Trigaux D. Environmental profile of building elements [update 2021]. 2021.

[68] Trigaux, D. "Elaboration of a sustainability assessment method for neighbourhoods." (2017).

In this study, the energy use for space heating of the existing residential buildings is assumed to equal the energy use mentioned in the national brochures of TABULA/EPISCOPE of the respective archetypes. The energy use for domestic hot water is calculated based on the household size (number of users).

The energy source for heating and domestic hot water are taken from TABULA/EPISCOPE's description of the installations. The installation efficiencies are based on TABULA/EPISCOPE's description of the installations, as well as taken from the Flemish EPC[69], where no other information was available. For the offices, the energy use for space heating and cooling is calculated with the Belgian EPBD (Energy Performance of Buildings Directive) method. In the existing office buildings, cooling is only foreseen in the Mediterranean (MED) region. The energy use for DHW for the offices is estimated in the same way as for the residential buildings.

This project further benefited from novel methodological developments by Röck et al. (2023) which extend functionality of the MMG LCA tool towards a scalable life cycle (SLiCe) building modelling framework for building assessment across spatial and temporal dimensions: The SLiCe building modelling framework enabled a more detailed analysis of the carbon hotspots by providing specific insights into the timing of emissions per life cycle stages and per year as well as detailed information on the contribution of elements, work-sections and materials at all levels of the building and building stock analysis.

***Handling of data gaps for the modelling of life cycle inventory data***

Significant data gaps have been encountered while establishing the inventory of the representative building archetypes. To deal with them in a consistent manner, a strategy was developed based on source priority and a gap-filling methodology.

The main data source this project relies on TABULA/EPISCOPE. This is also the data source prioritised over other sources whenever there is a discordance in data.

Using data from TABULA/EPISCOPE as main source for the modelling at building level ensures consistency as TABULA/EPISCOPE is also used to model the different refurbishment measures (see further) in our model. However, TABULA/EPISCOPE being geared towards an assessment of energy performance levels, it only contains information about the building envelope. Moreover, this information is often incomplete, as the source lacks data about material thickness and does not provide a complete build-up of the elements it describes. Therefore, it was necessary to rely on other sources in order to establish a complete inventory.

To fill data gaps for the modelling of the archetypes, a layered, iterative approach was established based on three levels of detail:

- In a first version of establishing the buildings' inventory, the modelling is limited to the information available in TABULA/EPISCOPE, supplemented, if necessary, with data derived from AmBIENCe. The AmBIENCe project (Actively Managed Buildings with Energy Performance Contracting, funded by Horizon 2020) aimed to extend the concept of Energy Performance Contracting to Active Buildings and make it available and attractive to a wider range of buildings". It is useful in particular in order to establish the thickness of the materials constituting the envelope. Overall, this first version therefore includes building elements which are part of the envelope as well as technical system related to heating and domestic hot water, but it does not consider internal elements and finishes.

[69] https://www.vlaanderen.be/en/epc-for-a-dwelling

- In the second version of the inventory, the focus is on the build-ups of the internal elements, which are modelled based on assumptions related to other similar archetypes and/or countries, for which the information is readily available.
- In the third version, the model is refined and expanded to include the most accurate information possible, based on an extensive literature review.

Eventually, where appropriate, we engaged relevant stakeholders by consulting local building experts in order to ensure that the information used in the inventory is a reasonable and robust description of the building type it aims to represent.

### Existing buildings

#### *Building geometry parameters*

Building geometry data about the external elements and overall building characteristics are taken from TABULA. This includes the surface areas of external elements (walls, floors, roofs and windows) as well as the number of housing units and storeys, storey heights, useful floor area and protected volume. The MMG model takes into account the distinction between elements adjacent to either the outside or to unheated spaces.

Geometry data about internal elements (i.e. surface area of internal walls, number of doors and stairs) and foundations are missing in TABULA. The calculation of the internal wall surface area is based on an assumed average room area and the storey height taken from TABULA. Internal door openings are subtracted, and half of the derived internal wall area is assumed to be loadbearing. The number of internal doors is derived from the number of estimated rooms, which is based on the assumed average room area. The number of stairs is calculated by multiplying the number of storeys with the number of circulation cores (i.e. one for SFH, and one for every two apartments on a storey for MFH). The number of steps is derived from the storey height and an assumed step height of 18 cm. Further, for MFH it is assumed there is 15 m² of common space (i.e. circulation core) per storey. The useful floor area is then calculated by subtracting the area of common space from the total floor area. Similarly, storey floor area is derived by subtracting the ground floor area and area of the stairs from the total floor area. Lastly, the length of foundations equals the sum of the length of external walls and the length of loadbearing internal walls. Only for the large MFH, pile foundation is assumed.

#### *Building element compositions*

In the webtool of TABULA, the elements of the archetypes are defined in two sub-typologies, i.e. construction elements and service systems. For construction elements the information in the webtool is generally limited to the U-value, a brief description of the main structure, and whether the element is insulated or not. Hence, information about the thicknesses, typical finishes or the specific insulation material is missing. Moreover, there is no information about the composition of internal construction elements.

Part of this missing information has been retrieved from the national typology brochures provided in TABULA. For some countries, the national brochure specifies which insulation material is applied in the walls, floors and roofs[70]. The full building element compositions, however, are defined based on technical documentation, literature sources and expert knowledge about how the countries typically built during the different construction periods. When full building element compositions are established, the insulation thicknesses are adapted so that the U-values match the values in TABULA. Consequently, the insulation thicknesses can vary from what is defined in TABULA. The

[70] https://episcope.eu/fileadmin/tabula/public/docs/brochure/BE_TABULA_TypologyBrochure_VITO.pdf

composition of internal construction elements is fully based on knowledge of typical compositions in the countries.

Regarding the service systems, TABULA/EPISCOPE includes descriptions of the systems for space heating and Domestic Hot Water (DHW), the ventilation system, and the photovoltaic (PV) system for the different construction periods. In addition, the respective energy carriers and system efficiency are included. Hence, service systems were taken entirely from TABULA/EPISCOPE and translated to the MMG model based on systems that were already available in the MMG database. For SFH, the building models are equipped with the following systems: water supply and disposal, space heating and domestic hot water, ventilation, and electrical services (e.g. elevators, PV systems). For MFH, the buildings include as many of these as there are housing units in the building archetype.

***Energy performance levels***

The existing building energy performance levels are included in the modelling of the archetypes by identifying the energy demand estimates per $m^2$ floor area and representative U-values of the main building envelope elements (e.g., external walls, roofs, windows).

The yearly energy demand data, obtained from TABULA/EPISCOPE, are then used to estimate energy use for heating and domestic hot water, as described in further detail in section 0.

**Refurbishment measures**

***Energy performance level of the refurbishment options in TABULA/EPISCOPE***

Firstly, the refurbishment options as defined in TABULA/EPISCOPE are investigated. On the TABULA/EPISCOPE website[71] and in the executive summary of the TABULA/EPISCOPE typology approach[72], two refurbishment scenarios are defined as follows:

- Usual/standard refurbishment (STD): Package of measures for upgrading the thermal envelope and the heat supply system which are commonly realised during refurbishment; typically reflecting the national requirements in case of refurbishments.
- Advanced/ambitious refurbishment (ADV): Package of measures for upgrading the thermal envelope and the heat supply system which are usually only realised in very ambitious refurbishments or research projects; typically reflecting the level of passive house components.

For both scenarios, the energy performance level aimed at is different for each country[73]. An overview of country-specific definitions is provided in the TABULA/EPISCOPE webtool[74].

The refurbishment measures in TABULA/EPISCOPE are defined in terms of construction elements on the one hand and service systems on the other hand. Specifically, the following elements are considered for refurbishment: external walls, roofs, ground floors, windows, space heating and domestic hot water systems, ventilation systems, and additional PV systems. Internal elements are not considered to be renovated.

The measures for construction elements include refurbishments and replacements. Specifically, the measures for walls, floors and roofs are refurbishments that are typically defined as *"add XX cm of insulation"*. The tool also states which share of the surface area of the respective construction

[71] https://episcope.eu/building-typology/country/

[72] https://episcope.eu/fileadmin/tabula/public/docs/report/TABULA_ExecutiveSummary.pdf

[73] Ibid.

[74] https://webtool.building-typology.eu/#bm https://webtool.building-typology.eu/#bm

elements is refurbished. For windows and doors, the measure consists of replacing the existing component. For service systems, the existing system is replaced by a more recent one, and/or additions to the existing system, e.g., instalment of PV-panels.

Similar to the modelling of the existing buildings, the refurbished buildings are modelled by complementing the TABULA/EPISCOPE information with the national brochures, external sources, and expert judgement. For construction elements, the insulation material and the way in which it is applied and finished are based on typical refurbishment methods applied in the country. The insulation thicknesses are adjusted so that the building elements achieve the energy performance level that is aimed for. Consequently, insulation thicknesses differ again from the values in the TABULA/EPISCOPE tool. Furthermore, it can be that some elements are not renovated, even if their current state does not fulfil the requirements. This depends on the typical refurbishment practices of the countries.

The service systems for space heating and domestic hot water are assumed to be the ones defined in the latest TABULA/EPISCOPE construction period. If the building has another, older system, this is replaced by the new system. Otherwise, if the building already has the same system as the one applied in the latest period, the existing system is kept unchanged. For systems that are renovated, the heat generator and, if required, the piping is replaced. It is assumed that the existing radiators remain in place.

The ventilation system is derived from the requirements for the refurbishment scenarios. Instalment of a PV system is modelled only for the deep refurbishment archetypes.

In general, both refurbishment scenarios are applied to archetypes representing existing buildings from past construction periods. For the most recent periods, it can be that the buildings already fulfil the current national regulations, hence the medium refurbishment is not relevant and consequently not considered.

For **residential buildings**, the energy use for heating was derived from the values after refurbishment for the different refurbishment variants, as provided by TABULA/EPISCOPE for the respective archetypes.

For **office buildings,** the energy use for space heating and cooling is calculated with the EPBD method. In the renovated office buildings, cooling is foreseen in all regions.

For both **residential buildings and offices**, the net energy demand for domestic hot water (DHW) and the electricity use for lighting and appliances are assumed to remain the same as before the refurbishment.

### New buildings

#### ***Building geometry and materialisation***

For new buildings, again, geometries of the building archetypes from the latest period in TABULA/EPISCOPE are used, combined with construction elements and service systems that represent current construction practices. Specifically, similar to the modelling of refurbishment measures, two energy performance levels are considered, namely according to current national energy regulations and according to the passive house standard. Therefore, the building elements are derived by adjusting the insulation thicknesses so that the U-values achieve the respective requirements. For the systems for space heating, domestic hot water and ventilation, the same systems as for the two refurbishment scenarios are assumed. Furthermore, it is assumed that a photovoltaic system of the same kind as in the deep refurbishment scenario is installed.

For **residential buildings**, the approach for the operational energy modelling is similar to that of the refurbishments. The net space heating energy demand is taken from the last TABULA/EPISCOPE period. The net energy demand for domestic hot water is again taken from the archetypes from the last TABULA/EPISCOPE period.

For **office buildings,** the energy use for space heating and cooling is calculated with the EPBD method. In the new office buildings, cooling is foreseen in all regions.

For both **residential buildings and offices**, the net energy demand for domestic hot water and the electricity use for lighting and appliances are calculated in the same way as for existing buildings.

## E. Assessment of whole life carbon on building level

The fourth step of our approach consists of the actual assessment of whole life carbon of building archetypes, i.e. the life cycle GHG emissions. The assessment covers all building archetypes representative for the European building stock in their respective region and includes existing buildings, new buildings and refurbishments as explained in the previous sections.

### Functional unit

The functional unit is described along four main questions – What? How much? How well? How long? – as proposed in the PEF Guidance Documents and previously applied in the PEF4Buildings project.

*What?*

The objects of assessment are the specific archetype buildings, for which the impacts are expressed per m² of useful floor area (UFA). The buildings include the following element classes (numbers between brackets refer to related building element classes according to the BB-SfB code):

- Floors on grade [(13) floor on grade]
- Foundations [(16) foundation, (17) pile foundation]
- External walls [(21) external walls, (28) load-bearing structures]
- Internal walls [(22.1) load bearing and (22.3) not-load bearing internal walls]
- Common walls [(22.8) party walls]
- Storey floors [(23) storey floors]
- Stairs [(24) stairs]
- Roofs [(27.1) flat and (27.2) pitched roofs]
- External openings [(31) windows]
- Internal openings [(32) internal doors]
- Technical systems [(53) water supply and (52) water disposal, (56) space heating and (53.3) DHW, (57) ventilation]
- Electrical systems [(6) services, mainly electrical]

How much?

Whole life carbon assessment is conducted for each of the representative building archetypes.

How well?

Building geometries, building element compositions and U-values, and service systems of the existing buildings are defined and modelled such that each of the building archetypes can be considered representative for a certain building type (SFH, MFH, OFF) in a given region (CON, MED, NOR, OCE). Individual archetypes are modelled for representing existing buildings (EXB), two options for their refurbishment (REF), as well as new buildings (NEW) in two distinct energy performance classes. The archetypes are modelled in line with the respective energy performance, namely along current regulatory standards (STD) and advanced passive house performance (ADV).

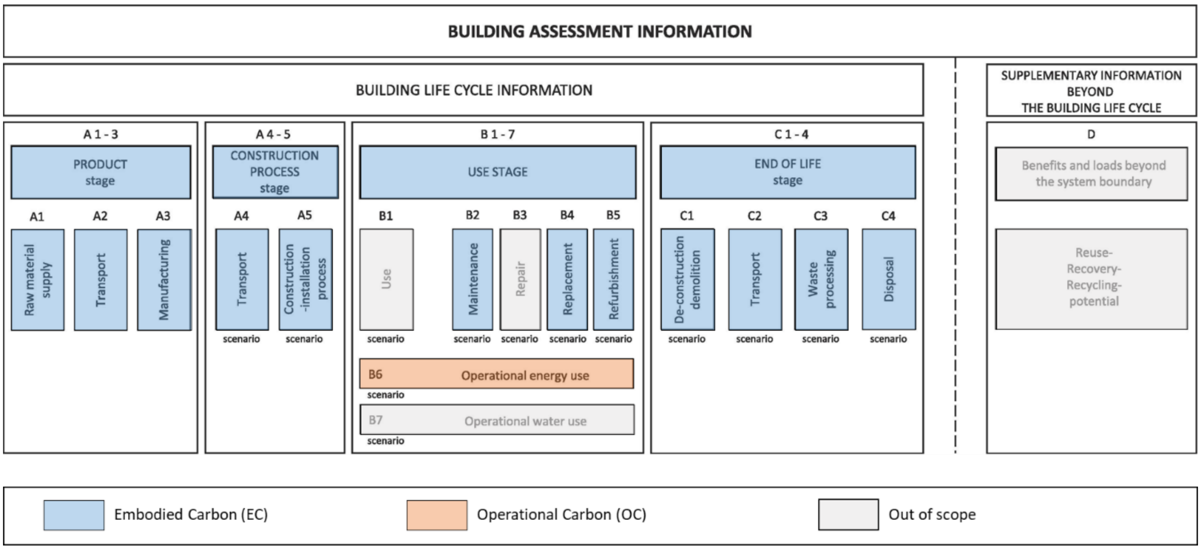
How long?

The reference study period (RSP) applied for modelling the building archetypes is 50 years. It is important to understand that, in the present study, the application of the RSP is relevant for the results on building level when expressing results across different life cycle stages. For the upscaling of whole life carbon results to building stock level, the underlying assumptions of buildings' service life is embedded in the building stock activity data and specific activity levels related to retrofit, demolition or new construction – as explained in section B. Impact assessment results are hence applied based on the carbon impacts for a building stock level activity in a given year, e.g., m² floor area of new building construction in 2020, drawing from the building level results of the different building archetypes.

### System boundaries

Figure 48 presents the system boundaries of the LCA conducted in this study. The life cycle stages are in line with EN 15978 and some are further subdivided in sub-stages. It is a cradle-to-grave assessment in which both embodied and operational impacts are considered. Specifically, the following stages are included: A1-A3 (production), A4 (transport to site), A5 (construction and installation), B2 (cleaning and maintenance), B4 (replacement), B5 (refurbishment), B6 (operational energy use), and C1-C4 (end-of-life stage). Benefits and loads beyond the system boundary (module D), as well as building use (B1), repair (B3) and operational water use (B7) are out of scope for this study.

**Figure 48 Life cycle stages and modules included in this whole life carbon assessment**




### Impact assessment

#### *Compliance and background database*

The MMG LCA method is in line with current European LCA standards and methods EN 15804+A2 (construction products) and EN 15978 (buildings). The life cycle inventory (LCI) data is based on generic LCI data from Ecoinvent 3.3. Both data and methods are adjusted to be representative for the EU context. In order to guarantee geographical representativeness for the production of materials, priority was given to processes representative for Europe. If no European processes were available in the dataset in the Ecoinvent database, the electricity mix for production was replaced by the European mix for the available processes. For the transport of the raw materials to the factory, we always opted for transport processes representative for Europe. The electricity mix in the underlying processes (e.g., production of raw materials used in the production process) is not modified to the European version. A sensitivity analysis shows that changing the electricity mix in the underlying processes has no significant influence on the results.

***Consideration of biogenic carbon***

When looking at bio-based materials such as timber, $CO_2$ is uptaken during the growth of the tree, leading to an environmental benefit. The carbon stored in the tree, i.e., the biogenic carbon, is not considered in this study. However, it is important to note that biogenic carbon is typically released at end-of-life when the timber is landfilled or incinerated. This biogenic carbon release is however also not considered in our scope as the Ecoinvent database is used with a 0/0 approach[75] for modelling biogenic carbon uptake and release[76].

## F. Upscaling of results to building stocks

The fifth step of our methodology is the upscaling of the individual building level emissions to illustrate the emission profile of the EU building stock. The upscaling multiplies the archetypes selected in section C to represent the complete floor area in EU buildings. The same step translates activity levels, i.e. changes in existing building use and building refurbishment including energy renovations, building deconstruction or demolition, and new building construction activities.

### Translation of building LCA results to building stock level activities

The useful floor area is the basis for translating the building LCA results to the building stock level. Per-square meter emissions for the different building stages are mapped to the buildings stock activities as shown in Table 8 and multiplied by the total floor area affected by the activities.[77]

We assume that all construction, renovation, and demolition activities are finished at the beginning of the year. This is assumed in order for operational emissions to be also applied to new and renovated buildings in the same year, but not to demolished buildings.

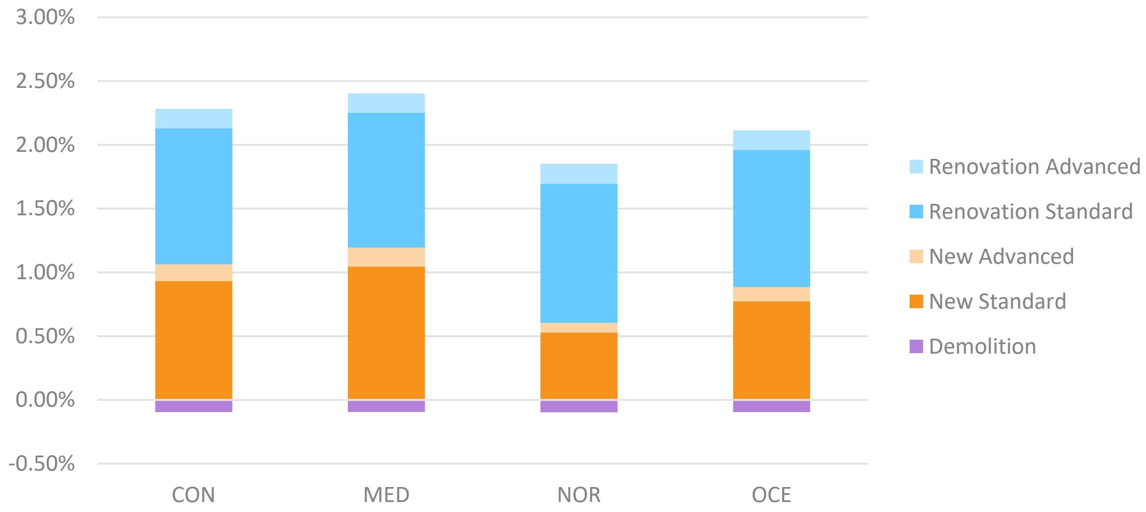
Building stock life cycle emissions are connected to the following building stock activities: construction, renovation, and demolition (LCA modules A *Production and Construction*, B5 *Planned refurbishment* and C *Deconstruction and demolition*). The emissions are calculated per floor area. The floor area affected by these activities is determined by the rates of construction, renovation, and demolition. The emissions are then upscaled based on floor area undergoing these activities. As these are immediate emissions, these are fully accounted when the specific building activity occurs. The level or rate of these activities are based on latest observation researched for the EUCalc Reference Scenario.

[75] "[The] '0/0 approach' or 'carbon neutral approach', is based on the assumption that the release of CO2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO2 during the biomass growth. As a consequence, there is no consideration of biogenic CO2 uptake (0) and release (0).", see Hoxha et al. (2020)

[76] Hoxha, E., et al. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. Buildings and Cities, 1(1), pp. 504–524. DOI: https://doi.org/10.5334/bc.46

[77] The quantitative building stock data for floor area and the CO2 emissions can be found in the supplemental data file: "activity data for baseline year.xlsx"

**Figure 49 Construction, renovation, and demolition rates in different EU climate regions in the baseline year 2020; Source: EUCalc Reference Scenario**




Life cycle emissions not associated with the above three activities are ongoing maintenance, repair, and smaller replacements (LCA modules B2 *Cleaning and maintenance*, B4 *Replacement*, and B6 *Operational energy use*). These emissions are distributed over the service life (50 years) of the building.

**Table 8. Life cycle stages and their consideration in different activities at building stock level.**

| Life cycle stages | | Activities in year X | | | |
|---|---|---|---|---|---|
| | | Existing building operation; | Building refurbishment and energy retrofit; | Building deconstruction, end-of-life | New building construction |
| Building results for upscaling used from | | Existing buildings archetypes (EXB) | Refurbishments archetypes (REF) | Existing buildings archetypes (EXB) | New buildings archetypes (NEW) |
| Production stage | A1-A3 | No | (included in B5) | No | Yes |
| Transport to site | A4 | No | (included in B5) | No | Yes |
| Construction and installation | A5 | No | (included in B5) | No | Yes |
| Use | B1 | - | - | - | - |
| Cleaning, maintenance | B2 | Yes: annual amount | No | No | Yes: annual amount |
| Repair | B3 | - | - | - | - |
| Replacement | B4 | Yes: annual amount* | No | No | Yes: annual amount |
| Planned refurbishment | B5 | No | Yes | No | No |
| Operational energy use | B6 | Yes: annual amount | Yes: annual amount | No | Yes: annual amount |
| Operational water use | B7 | - | - | - | - |
| Deconstruction, demolition | C1 | No | (included in B5) | Yes | No |
| Waste transport | C2 | No | (included in B5) | Yes | No |
| Waste processing | C3 | No | (included in B5) | Yes | No |
| Waste disposal | C4 | No | (included in B5) | Yes | No |
| Beyond system boundary | D | - | - | - | - |

**Existing building archetypes (EXB):** the B4 module of existing buildings is the replacement of elements along the building life cycle (i.e. over 50 years). This can include, among others, technical systems, windows or insulation materials which are commonly replaced sometime between 20-30 years after their initial installation. Such replacement cycles are in line with the default service lives provided in Level(s), and with good practices for usual building-level LCA studies.

Given the policy context and the EU's Renovation Wave aim to at least double the annual refurbishment rate from 1% to 2% over the next decade, it can be assumed that large building parts (such as technical services, i.e. heating systems, windows or insulation layers) will be increasingly replaced with more efficient ones, and therefore replacements with also need to be considered in the light of "refurbishment activity". Building policies require the improvement of such building parts (or elements) so that, for example, the windows are replaced with those that offer better thermal and acoustic insulation.

The replacement of building elements by more energy efficient ones are associated with refurbishment activity (B5) and considered at the rate of the refurbishment. The replacements of building elements not related to changing the energy performance of the building are included in module B4. This differentiation allows for a more accurate representation of B4 and B5 at stock level. Moreover, this will allow for a more accurate accounting of the embodied carbon footprint of measures related to the implementation of renovation wave strategy.

**Refurbishment archetypes (REF):** Embodied emissions associated with B5 module (refurbishment emissions) include the end-of-life (nested C1-4) from removed elements as well as the production and installation (nested A1-5) of the newly added building items. C1-C4 emissions are from end-of-life of the elements added during refurbishment. B2 and B4 are a combination of emissions related to cleaning, maintenance (B2) and replacement (B4) for the un-refurbished state (year 1-30) and the refurbished state (years 31-60).

**Box 1. Additional clarifications regarding the term "renovation" and its use in this document**

The present study uses the term "renovation" to indicate an improvement of the building energy performance. This interpretation is in line with EU building policies which refer to building renovation as improvements of the building envelope or the technical building systems. However, it should be noted that the LCA and building professional community more commonly use the term "refurbishment" in reference to the same activity.

Academic literature defines the terms renovation, refurbishment and retrofit differently although in non-building-professional language and therefore in policy discussion they may be used equivalently. The different meanings are:

- **Retrofitting** means "*providing something with a component or feature not fitted during manufacture or adding something that it did not have when first constructed*".[78] It is often used in relation to the installation of new building systems, such as heating systems, but it might also refer to the fabric of a building, for example, retrofitting insulation or double glazing.
- **Refurbishment** on the other hand implies a process of improvement by cleaning, decorating, and re-equipping. It may include elements of retrofitting.
- **Renovation** refers to the process of returning something to a good state of repair.[79]

### Validation and alignment of floor area and emission levels

To ensure robust and meaningful results, we compare intermediate results with existing scientific literature. Given that the floor area is the main link between the archetypes and the stock level upscaling, it is compared across several data sources including the HotMaps, the EU Building Stock Observatory (EU BSO), Ambience and ENTRANZE projects. The total floor area varies amongst these sources due to the fact that data was collected at different points in time. The total floor area of the EU building stock is overall consistent across these data sources, but the split of residential and non-residential building floor area in some countries appears to be quite different. The HotMaps data were selected as the reference source for our upscaling as it is the most recent source and applies a robust methodology. The EUCalc floor area stems from older observations (2015) and therefore this is updated with the more recent HotMaps data (breakdown of floor area per country and building type) for the baseline year 2020.

The comparison of results with existing reports of operational and embodied carbon emissions shows that our results are well in range with existing literature. To compare the operational carbon footprint of the stock, we have relied on a recent EEA study[80] which was identified to have a similar

[78] Eames M. et al. (2014) Retrofit 2050: Critical challenges for urban transitions

[79] https://www.designingbuildings.co.uk/wiki/Renovation_v_refurbishment_v_retrofit

[80] Greenhouse gas emissions from energy use in buildings in Europe; https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emissions-from-energy/assessment

scope including both primary and secondary emissions from buildings. The EEA study estimates that operational emissions span between 1000 and 1400 $MtCO_2e$, while our baseline calculation amounts to about 1300 $MtCO_2e$, which is well in line with the range of current estimates. As yet, a reliable and robust report accounting embodied emissions at EU buildings level does not exist. As a proxy, we have compared the emissions related to steel[81] and concrete[82] production. Cement and steel account for approximately 340 $MtCO_2e$[83] according to EU data, whereas our calculations suggest about 330 $MtCO_2e$, which is again well in range with current estimates

## G. References

[1] Eurostat. Building permits - annual data (STS_COBP_A). Eurostat Data Brows 2023. https://ec.europa.eu/eurostat/databrowser/view/STS_COBP_A__custom_4663650/default/table?lang=en.

[2] Eurostat. Population on 1st January by age, sex and type of projection (PROJ_19NP). Eurostat Data Brows 2021. https://ec.europa.eu/eurostat/databrowser/view/proj_19np/default/table?lang=en.

[3] Eurostat. Demographic balances and indicators by type of projection (PROJ_19NDBI). Eurostat Data Brows 2021. https://ec.europa.eu/eurostat/databrowser/view/proj_19ndbi/default/table?lang=en.

[4] European Commission. EU Reference Scenario 2020 Energy, transport and GHG emissions - Trends to 2050 2021;First edit:184. https://doi.org/10.2833/35750.

[5] European Commission. COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Accompanying the document REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021. Comm Staff Work Doc 2021;SWD:176.

[6] Costa L, Waibel G, Hausner B, Gül E. WP1 - Lifestyle module documentation. Berlin: 2020.

[7] EUCalc Consortium, Potsdam Institute for Climate Impact Research (PIK), Imperial College London, CLIMACT, Building Performance Institute Europe (BPIE), ÖGUT, et al. EUCalc scenario selected to support the BAU scenario 2018. http://tool.european-calculator.eu/app/buildings/building-types-area/?levers=1j12112ffl11211mp2b111fffffpppppp11f411111e3211r211l21n221&other=1j12112ffl11211mp2b111fffffpppppp11f411111e3211r211l21n221.

[8] Sandberg NH, Sartori I, Heidrich O, Dawson R, Dascalaki E, Dimitriou S, et al. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy Build 2016;132:26–38. https://doi.org/10.1016/j.enbuild.2016.05.100.

[9] Joint Research Center (JRC), Anders D, Concetta L, Stefania B, Thilde FA, Martijn K, et al. Background data collection and life cycle assessment for construction and demolition (CDW) waste management. 2022. https://doi.org/10.2760/772724.

[10] Eurostat. Number of households (LFST_HHNHTYCH). Eurostat Data Brows 2022. https://ec.europa.eu/eurostat/databrowser/view/lfst_hhnhtych/default/table?lang=en.

[81] The EU steel industry currently accounts for 221 Mt GHG emissions annually (including both direct and indirect emissions). https://ec.europa.eu/info/sites/default/files/swd-competitive-clean-european-steel_en.pdf

[82] "The CO2 emissions of the cement clinker production in the European Union1 covered by the EU ETS reached a maximum of 172 Mt in the year 2007 and have been on a plateau of around 120 Mt since 2009"; https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2022-01-04_climate-change_02-2022_decomposition_of_co2_emissions_in_the_european_cement_sector_0.pdf

[83] Acknowledging that this comparison is not ideal as the emissions for concrete and steel in the EU may not be entirely associated with buildings. At the same time there may be other materials used that don't have emissions that well quantified.

# APPENDIX II – DEFINITION OF THE EMBODIED CARBON REDUCTION SOLUTIONS FOR MODELLING

## A. Solutions included in Scenario TECH-Build

**Carbon solution 3: Re-use existing building components and materials**

### Description

Re-using components or materials from existing buildings substantially lower the GHG emissions from these items, as they do not have to be manufactured again. This solution describes re-use of materials that may have been altered, refinished or resized, but not reprocessed (for this, see solutions 7c, 11a, 11b on recycled material inputs).

### Modelling approach

In the model, we assume that re-used components and materials can be used in new construction and renovation for residential buildings and offices. All building components can be impacted, although steel, bricks and concrete elements are most suitable for this solution. The GHG reduction potential at product-level is assumed to be 99% for bricks,[84], and 40% for steel[85]. Currently, 4% of steel is re-used[86], with minor application for bricks. For steel, this share is assumed to be increased up to 29% in 2050[87], with a linear increase up to 2040, when the maximum is reached. For lack of similar numbers, this development is also assumed for bricks.

### Scope, limitations, considerations for interpretation

N/A

**Carbon solution 4: Design for adaptability, resilience and extended lifespan**

### Description

Buildings designed for flexibility, resilience and extended lifespan can reduce the need for new construction in the future as their internal structure can be adapted to changing use patterns for a long use.

### Modelling approach

This solution applies to new construction projects. As the impacts of reduced need for new construction lie in future beyond the timeline of this study, the solution is not modelled.

[84] Nußholz, J.; Nygaard Rasmussen, F.; Milios, L. (2019). Circular building materials: Carbon saving potential and the role of business model innovation and public policy, Resources, Conservation and Recycling, Volume 141, https://doi.org/10.1016/j.resconrec.2018.10.03

[85] Brütting, J.; Desruelle, J.; Senatore, G.; Fivet, C. (2019). Design of Truss Structures Through Reuse. Structures, Volume 18, https://doi.org/10.1016/j.istruc.2018.11.006.

[86] Hopkinson, Peter & Chen, Han-Mei & Zhou, Kan & Wang, Yong & Lam, Dennis. (2018). Recovery and Re-Use of Structural Products from End of Life Buildings. Proceedings of the Institution of Civil Engineers - Engineering Sustainability. 172. 1-36. 10.1680/jensu.18.00007.

[87] IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

### Scope, limitations, considerations for interpretation

N/A

**Carbon solution 5: Design for disassembly**

#### Description

Designing buildings for disassembly enables the constituent element(s) of a building or assembly to be taken apart at the end of its useful life in a way that allows components and parts to be re-used, recycled or recovered. As a consequence, the environmental and economic value of the materials is maintained.

#### Modelling approach

This solution applies to new construction projects. As the impacts of reduced need for new material production lie in future beyond the timeline of this study, the solution is not modelled.

#### Scope, limitations, considerations for interpretation

N/A

**Carbon solution 6: Design based on light construction method instead of massive construction**

#### Description

In many construction projects, there is a substantial potential for using lighter construction methods that result in a lower weight of the building structure and foundation because less and lighter material is used. Primarily, this reduces the amount of structural steel and concrete used in a building. This in turn can reduce the amount of foundation needed leading to an overall reduction in the amount of material used as well as the material-related GHG emissions.

#### Modelling approach

In the model, we assume that light construction can be applied to all building typologies in new construction projects. The reduction impact stems from lower material demand for steel (-15%) and concrete (-20%). This reduction potential is based on multiple sources that describe different reduction potentials for the key construction materials based on similar strategies but different scopes and scales[88]. These include the reduction in overspecification as well as light design for entire buildings or only top stories, which are all summarized in this solution under light building design. Based on expert judgement and validation with building design practitioners, the mentioned values have been defined as averages considering the varying degrees of light design options. Our modelling assumes that the maximum implementation for new buildings designed according to light construction methods is 85% of all new building. This share will be achieved in 2040[89] after a linear increase.

[88] G. Habert, S. A. Miller, V. M. John, J. L. Provis, A. Favier, A. Horvath and K. L. Scrivener. Environmental impacts and decarbonization strategies in the cement and concrete industries https://doi.org/10.1038/s43017-020-0093-3; Azzouz, A., Borchers, M., Moreira, J. and Mavrogianni, A. (2017). Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK. Energy and Buildings, 139, pp.547–568. doi:10.1016/j.enbuild.2016.12.089; Dunant, C.; Drewniok, M. et al. (2018). Regularity and optimisation practice in steel structural frames in real design cases. Resources, Conservation and Recycling, Volume 134. https://doi.org/10.1016/j.resconrec.2018.01.009; Moynihan Muiris C. and Allwood Julian M. (2014). Utilization of structural steel in buildings. Proc. R. Soc. A.4 http://doi.org/10.1098/rspa.2014.0170

[89] IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Scope, limitations, considerations for interpretation

Light construction is cannot be realized together with the use of bio-based materials (other than timber) in walls (as defined in solution 10). Their reduction potentials therefore cannot simply be added on the building stock scale. However, ins some cases this is not a concern as the two solutions in parts address different building types and therefore do not apply to the same archetype. Additionally, restrictions apply to areas of increased earthquake risk.

A full implementation earlier than 2040 is assumed to be possible. However, this is balanced by extremely optimistic assumptions for the implementation of carbon capture and storage in material production. Therefore, an average of 2040 has been used.

### Carbon solution 7a: Use industry by-products instead of clinker in cement

Description

To reduce the $CO_2$ footprint, a part of the cement (ordinary portland cement) can be replaced by fly ash from coal fired power plants, ground granulated blast furnace slag (GBFS) from steel production or other materials. These materials have much lower $CO_2$ emissions then standard cement and therefore reduce the GHG intensity of the concrete components in the building.

Modelling approach

In the modelling, we assume that replacement of clinker can be used in all building types for new construction as well as renovation. The impact occurs in concrete components. Compared to conventional cement, the substitution materials lower the GHG intensity by 45% per m3 of concrete according to an average of multiple case studies and other publications[90]. This substitution already takes place in current practice with an average substitution ratio of 25%[91] which can technically be increase up to a maximum of 40%. This represents a 60% increase that is assumed to take place in linear form up to 2040.

Scope, limitations, **considerations for interpretation**

The availability of current commonly used industry by-products such as fly ash or GBFS is expected to decrease as a result of the decarbonisation of energy generation and industry processes. However, other substitution materials can be expected to be introduced to replace these.

### Carbon solution 7b: Use alternative cementitious materials instead of cement in concrete

Description

Standard concrete is made from cement, stone & sand (aggregate) and water. To reduce the GHG intensity of concrete, the use of ordinary Portland cement can be replaced fully by alternative cementitious materials and binders (ACMs) such as calcium sulfoaluminate, calcium aluminate, and alkali-activated binders. These materials often require lower production temperatures than ordinary

[90] Ahmed Al-Mansour , Cheuk Lun Chow, Luciano Feo, Rosa Penna and Denvid Lau, Green Concrete: By-Products Utilization and Advanced Approaches. Sustainability 2019 11(19):5145 https://www.researchgate.net/publication/335952329_Green_Concrete_By-Products_Utilization_and_Advanced_Approaches; Roland Hunziker, Chris Carroll: Net-zero buildings Where do we stand? 2021 07: https://www.arup.com/-/media/arup/files/publications/n/net_zero_buildings_where_do_we_stand.pdf; G. Habert, S. A. Miller, V. M. John, J. L. Provis, A. Favier, A. Horvath and K. L. Scrivener. Environmental impacts and decarbonization strategies in the cement and concrete industries https://doi.org/10.1038/s43017-020-0093-3

[91] GNR PROJECT Reporting CO2 Emission report for 2019 https://gccassociation.org/gnr/

Portland cement (OPC) and have lower calcium contents, reducing the emissions associated with $CO_2$ released from calcium carbonate during calcination.

#### Modelling approach

In the modelling we assume that alternative cementitious materials can be used in all building types for new construction as well as renovation. The impact occurs in concrete components. Compared to conventional cement, an 41% reduction of GHG intensity is achieved per m3 of concrete[92]. ACMs are currently only used in marginal amounts. Based on consultation with industry roadmaps and expert stakeholder consultation, we assume that in 2040 a maximum of 3% of cement clinker use will be replaced by ACMs following a linear uptake of the solution.

#### Scope, limitations, considerations for interpretation

The ACMs mentioned are examples that have limited use in the current construction industry. This solution includes possible new materials still currently under research.

### Carbon solution 7c: Use recycled concrete and other by-products for new concrete

#### Description

To reduce the GHG intensity of concrete further, the aggregate part of the cement can be replaced by recycled concrete aggregate (RCA) and recycled concrete fines (RCF). Alternatively, other industry by-products can be used as aggregate. RCA and RCF are made from deconstructed concrete material that has been crushed into a granular product of a given particle size.

#### Modelling approach

In the modelling we assume that recycled concrete as aggregate can be used in all building types for new construction as well as renovation. The impact occurs in concrete components. Compared to concrete mixed with conventional aggregates, a reduction in GHG intensity of 8% per m3 of concrete[93]. From current levels of around 2% by concrete weight used for new concrete mixing[94], we assume a linear increase to 11% recycling use by 2040[95].

#### Scope, limitations, considerations for interpretation

N/A

### Carbon solution 7d: Reduce concrete demand by use of void formers in concrete slabs

#### Description

Concrete slabs are planned as flat shapes with uniform thicknesses. This is done in part to fit them into standard formworks and to optimise construction time, even when the concrete is in many areas not needed from a structural point of view. Void formers made from lightweight and cheap material can be used to fill the areas where less concrete is needed. This way the standard formwork can be kept, but the concrete use is also reduced.

[92] G. Habert, S. A. Miller, V. M. John, J. L. Provis, A. Favier, A. Horvath and K. L. Scrivener. Environmental impacts and decarbonization strategies in the cement and concrete industries https://doi.org/10.1038/s43017-020-0093-3

[93] G. Habert, S. A. Miller, V. M. John, J. L. Provis, A. Favier, A. Horvath and K. L. Scrivener. Environmental impacts and decarbonization strategies in the cement and concrete industries https://doi.org/10.1038/s43017-020-0093-3

[94] European Cement Research Academy, Technichal report A-2015/1860 Closing the loop: what type of concrete re-use is the most sustainable option?

[95] Ermittlung von Ressourcenschonungspotenzialen bei der Verwertung von Bauabfällen und Erarbeitung von Empfehlungen zu deren Nutzung https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4040.pdf

#### Modelling approach

In the modelling we assume that void formers can be used in all building types for new construction as well as renovation. However, they can only be used in horizontal concrete slabs and are therefore limited to projects which use uniform concrete slabs. At the component level, compared to conventional slabs, they realise a reduction of GHG emission intensity of 34%[96] by reducing the material use. It is assumed that this solution will be implemented in 4% of horizontal slabs from 2040 on[97], following a linear increase up to this maximum.

#### Scope, limitations, considerations for interpretation

N/A

### Carbon solution 7e: Use carbon-cured concrete

#### Description

Carbon-cured concrete defines the process of injecting captured carbon dioxide ($CO_2$) into the concrete during mixing, where the $CO_2$ becomes chemically converted into a mineral. This process can offset some of the emissions which occurred during cement production. Once injected, the $CO_2$ undergoes a mineralization process and becomes permanently embedded.

#### Modelling approach

In the modelling we assume that this solution can be applied to all building types in new construction as well as renovation projects. However, the implementation is limited to prefabricated concrete elements, which are assumed to represent about 20% of the concrete used. Building elements with carbon-cured concrete have a 4% reduced GHG impact, according to first demonstration projects[98]. Given the technical uncertainty, it is assumed that from 2040 onwards, 1% of prefabricated concrete elements are made with carbon-cured concrete.

#### Scope, limitations, consideration for interpretation

This solution requires available infrastructure to obtain and supply the $CO_2$ for injection in the concrete mixing process.

### Carbon solution 8: Offsite construction and design for less waste on site

#### Description

Using a construction technique with prefabricated modularised elements, which are then erected on-site, minimizes construction waste and enables recycling instead of the waste material becoming landfilled.

#### Modelling approach

This solution is not modelled due to its low impact. The benefits for waste prevention at the construction site has a minor impact on the building embodied carbon levels, while the transport of pre-fabricated elements offsets parts of these emission reductions[99]

[96] Seungho Cho and Seunguk Na. Evaluation of the Flexural Performance and CO2 Emissions of the Voided Slab Advances in Materials Science and Engineering 2018 https://doi.org/10.1155/2018/3817580

[97] Following expert judgement by experienced project team members and consultations with industry experts.

[98] Case Study. Preforte & CarbonCure: A Success Story https://go.carboncure.com/rs/328-NGP-286/images/Preforte%20and%20CarbonCure%20Case%20Study.pdf

[99] Mao, C.; Shen, Q.; Shen, L.; Tang, L. (2013). Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. Energy and Buildings. Volume 66, https://doi.org/10.1016/j.enbuild.2013.07.033.

#### Scope, limitations, considerations for interpretation

N/A

### Carbon solution 9a: Full timber construction

#### Description

Timber has lower GHG emissions than concrete and most other construction materials. Building from timber can therefore significantly reduce GHG emissions. This solution is defined as full timber buildings, in which the structural elements of the building are made primarily of timber.

#### Modelling approach

The modelling assumes full timber construction is an option for single-family residential building in new construction projects. We apply a 0/0 approach to biogenic carbon content[100] and thus model a GHG reduction potential of 20% at a project level compared to conventional buildings. This number is derived from an average of multiple sources, of which some had to be converted to a 0/0 accounting approach[101]. The maximum implementation at the building stock level is defined by the available material from sustainable sources, without damaging ecosystems or risking natural carbon sinks. It is assumed that a 15% increase in timber used in construction is possible from current material volumes[102]. This maximum level is modelled to be reached in 2040, after a linear increase. However, this material availability has to be split between full and hybrid timber construction. Because of the overall higher reduction impact of hybrid timber buildings (see solution 9b below), 20% of the additional timber availability is allocated to full timber buildings.

#### Scope, limitations, considerations for interpretation

The most appropriate accounting principle for biogenic carbon is debated among academics and the various stakeholder of bio-based material value chains. As a result, the quantified assumptions of this modelling may differ from other studies. However, considering the whole-life cycle approach for buildings but in the limited timeline up to 2050 the 0/0 approach avoids omitting end-of-life emissions which will contribute to global warming in the future.

Given the limits in additional material availability, this solution is expected to reach its full potential earlier than 2040. However, this is balanced by extremely optimistic assumptions for the implementation of carbon capture and storage in material production. Therefore, an average of 2040 has been used.

[100] This approach means that biogenic carbon content is not credited at the upfront stage because it will cause emissions in the future. In contrast, the -1/+1 approach – the other common accounting approach – deducts the carbon stored in the products at the time of construction but adds it to the emissions at the end of life.

[101] E.g., Hafner, A.; Schäfer, S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level, Journal of Cleaner Production, Volume 167, 2017, pp. 630-642, https://doi.org/10.1016/j.jclepro.2017.08.203; Chen, C.X.; Pierobon, F.; Jones, S.; Maples, I.; Gong, Y.; Ganguly, I. Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A Case Study in China. Sustainability 2022, 14, 144. https://doi.org/10.3390/su14010144; Himes, A.; Busby, G. Wood buildings as a climate solution. Developments in the Built Environment 2020, 4. https://doi.org/10.1016/j.dibe.2020.100030; Liang, S.; Gu, H.; Bergman, R. Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building: A Case Study in Pacific Northwestern United States. Sustainability 2021, 13, 7831. https://doi.org/10.3390/su13147831.

[102] Trinomics, VITO, Wageningen University, Research,Technische Universität Graz and Ricardo (2021) Evaluation of the climate benefits of the use of Harvested Wood Products in the construction sector and assessment of remuneration schemes Report to the European Commission, DG Climate Action, under Contract N° 340201/2020/831983/ETU/CLIMA.C.3, Trinomics BV, Rotterdam. https://op.europa.eu/en/publication-detail/-/publication/eb9de1f4-2c93-11ec-bd8e-01aa75ed71a1

### Carbon solution 9b: Hybrid (timber and concrete) structures in new construction

#### Description

Timber has lower GHG emissions than concrete and most other construction materials. Building from timber can therefore significantly reduce GHG emissions. This solution is defined as hybrid structures made from concrete and timber. This combination uses the benefits of timber structures in terms of lower GHG emissions, while allowing for the benefits in stability and safety provided by concrete. Hybrid buildings allow for construction typologies similar to standard concrete structures (e.g. multi story) but result in lower material volumes and carbon intensity than conventional or full timber designs.

#### Modelling approach

The modelling assumes that hybrid construction is an option for office and other non-residential building types in new construction projects. Again, we apply a 0/0 approach to biogenic carbon storage and thus model a GHG reduction potential of 35% at a project level compared to conventional buildings[103]. This number is derived from an average of multiple sources, of which some had to be converted to a 0/0 accounting approach[104]. The maximum implementation at building stock level is defined by the available material from sustainable sources, without damaging ecosystems or risking natural carbon sinks. It is assumed that a 15% increase of timber use in construction is possible from current material volumes[105]. This maximum level is modelled to be reached in 2040, after a linear increase. However, this material availability has to be split between full and hybrid timber construction. Because of the overall higher reduction impact of hybrid timber buildings, 80% of the additional timber availability are allocated to this solution.

#### Scope, limitations, considerations for interpretation

The most appropriate accounting principle for biogenic carbon is debated among academics and the various stakeholder of bio-based material value chains. As a result, the quantified assumptions of this modelling may differ from other studies. However, considering the whole-life cycle approach for buildings but in the limited timeline up to 2050 the 0/0 approach avoids omitting end-of-life emissions which will contribute to global warming in the future.

Given the limits in additional material availability, this solution is expected to reach its full potential earlier than 2040. However, this is balanced by extremely optimistic assumptions for the implementation of carbon capture and storage in material production. Therefore, an average of 2040 has been used.

[103] The reduction potential of this solution is higher than the one presented for full-timber buildings because the construction with hybrid structures allows for a lighter design and optimises the use of material properties from concrete and timber. Importantly, this assessment has to be seen in light of the 0/0 approach, which means that timber materials are linked to notable emissions at the upfront stage.

[104] E.g., Hafner, A.; Schäfer, S. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level, Journal of Cleaner Production, Volume 167, 2017, pp. 630-642, https://doi.org/10.1016/j.jclepro.2017.08.203; Chen, C.X.; Pierobon, F.; Jones, S.; Maples, I.; Gong, Y.; Ganguly, I. Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A Case Study in China. Sustainability 2022, 14, 144. https://doi.org/10.3390/su14010144; Himes, A.; Busby, G. Wood buildings as a climate solution. Developments in the Built Environment 2020, 4. https://doi.org/10.1016/j.dibe.2020.100030; Liang, S.; Gu, H.; Bergman, R. Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building: A Case Study in Pacific Northwestern United States. Sustainability 2021, 13, 7831. https://doi.org/10.3390/su13147831.

[105] Trinomics, VITO, Wageningen University, Research,Technische Universität Graz and Ricardo (2021) Evaluation of the climate benefits of the use of Harvested Wood Products in the construction sector and assessment of remuneration schemes Report to the European Commission, DG Climate Action, under Contract N° 340201/2020/831983/ETU/CLIMA.C.3, Trinomics BV, Rotterdam. https://op.europa.eu/en/publication-detail/-/publication/eb9de1f4-2c93-11ec-bd8e-01aa75ed71a1

### Carbon solution 10: Use other bio-based materials

#### Description

Bio-based materials such as straw and hemp have substantially shorter growth periods and can be used as building materials in insulation or external wall structures instead of more carbon-intensive materials such as concrete or mineral or synthetic insulation materials. The use of rammed earth is also included in this solution as part of the walls, however, it represents a minor share of the total as the potential use cases are strongly limited, which limits the diffusion.

#### Modelling approach

In the modelling, we assume that bio-based insulation can be used in all building types for new construction. The reduction of GHG intensity of the insulation component is quantified at 25%[106]. With abundant availability of raw materials[107] we assume a shift to this material in a maximum of 75% of insulation use is possible by 2040, following a linear increase.

Bio-based external walls on the other hand are only applicable to new construction in residential buildings. However, the reduction potential at the component level is higher, at 75%[108]. Yet, the implementation is more limited by structural requirements and fire safety regulations. It is assumed that 5% of buildings are build using bio-based materials (and rammed earth) in walls in 2040, with a linear increase from a baseline of 0%[109].

#### Scope, limitations, considerations for interpretation

As for timber, the 0/0 approach for accounting for the biogenic carbon stored in the materials mentioned in this solution means that the biogenic carbon content is not accounted for at the time of harvest and subsequent use in construction.

### Carbon solution 11a: Use recycled steel in steel production

#### Description

Recycled steel reduces the environmental footprint during the end-product's lifecycle. It replaces the iron ore as input material in the steel production process.

#### Modelling approach

The modelling assumes steel from recycling processes can be used as a direct replacement of all steel uses in all building types, in new construction and in renovation projects. The GHG intensity of recycled steel is quantified at 85% lower than virgin steel[110]. This is already an established

[106] Torres-Rivas et al. Multi-objective optimisation of bio-based thermal insulation materials in building envelopes considering condensation risk. Applied Energy, Volume 224, 2018, Pages 602-614, https://doi.org/10.1016/j.apenergy.2018.04.079; Wijnants, L.; Allacker, K.; De Troyer, F. Life-cycle assessment of timber frame constructions – The case of rooftop extensions. Journal of Cleaner Production, Volume 216, 2019, Pages 333-345, https://doi.org/10.1016/j.jclepro.2018.12.278

[107] Göswein, V.; Reichmann, J.; Habert, G.; Pittau, F. Land availability in Europe for a radical shift toward bio-based construction, Sustainable Cities and Society, Volume 70, 2021, https://doi.org/10.1016/j.scs.2021.102929.

[108] Li, Hu & Luo, Zhixing & Xu, Xudong & Cang, Yujie & Yang, Liu. (2021). Assessing the Embodied Carbon Reduction Potential of Straw Bale Rural Houses by Hybrid Life Cycle Assessment: A four-case study. Journal of Cleaner Production. 303. 127002. 10.1016/j.jclepro.2021.127002

[109] Mutani G, Azzolino C, Macrì M, Mancuso S. Straw Buildings: A Good Compromise between Environmental Sustainability and Energy-Economic Savings. Applied Sciences. 2020; 10(8):2858. https://doi.org/10.3390/app10082858

[110] Guevara Opinska, L., et Al. 2021, Moving towards Zero-Emission Steel, Publication for the committee on Industry, Research and Energy (ITRE), Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament, Luxembourg

practice (20% recycled steel). A maximum of 27% is assumed[111], which represents a 35% increase that takes place in linear manner and is reached in 2040.

Scope, limitations, considerations for interpretation

N/A

### Carbon solution 11b: Use recycled glass in glass production

Description

The use of waste glass as an input for new glass production reduces the amount of energy needed for the production, thus reducing the $CO_2$ emissions related to the production.

Modelling approach

The modelling assumes glass from recycling processes can be used as a direct replacement of all glass uses in all building types, in new construction and in renovation projects. The GHG intensity of recycled glass is quantified at 30% lower than virgin glass[112]. As for steel, this is already an established practice (26% recycled flat glass production from recycled glass). A maximum of 35% recycled glass content is assumed based on the amount of construction waste and new demand for flat glass while also considering difficulties in purity for construction-grade glass[113]. This represents a 35% increase from the baseline. The increase is assumed to take place in linear manner and the maximum to be reached in 2040.

Scope, limitations, considerations for interpretation

N/A

### Carbon solution 12a: Use renewable energy in cement production

Description

The cement sector can support the reduction of carbon emissions by improving the uptake of renewable power generation. This requires an adjustment in the cement production technology that currently relies on fossil fuels for the most energy-intensive part of cement production. While cement production creates process emission from chemical reactions, the energy-related GHG emissions can be reduced through renewable energy sources and renewably generated electricity.

Modelling approach

The modelling assumes that cement produced with renewable energy can be used as a direct replacement of all cement uses in all building types, in new construction and in renovation projects. Due to the substantial process-related emissions, a shift to non-fossil energy is quantified to have a GHG intensity reduction of cement production of 30%[114]. Some non-fossil energy sources are

[111] IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

[112] Zier, M.; Stenzel, P.; Kotzur, L.; Stolten, D. (2021). A review of decarbonization options for the glass industry, Energy Conversion and Management: X, Volume 10. https://doi.org/10.1016/j.ecmx.2021.100083

[113] https://glassforeurope.com/recycling-of-end-of-life-building-glass/; https://glassforeurope.com/the-sector/key-data/

[114] International Energy Agency. (2018). Technology Roadmap: Low carbon transition in the cement industry. https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

already used in cement production (30% baseline). This is assumed to increase to a maximum of 50% in 2040[115], representing a 66% increase assumed to be linear.

#### Scope, limitations, considerations for interpretation

The share of renewable energy includes waste-to-energy uses as these are combined in non-fossil energy inputs in the available literature. Additionally, green hydrogen is a potential renewable energy source for cement production.

### Carbon solution 12b: Use renewable energy in steel production

#### Description

The predominant production method in the iron and steel industry is the use of fossil-based blast furnace or basic oxygen furnace processes. Using renewable energy or renewably generated electricity instead of fossil fuels can contribute to decarbonising iron and steel production processes.

#### Modelling approach

The modelling assumes that steel produced with renewable energy, including renewable based Hydrogen, can be used as a direct replacement of all steel uses in all building types, in new construction and in renovation projects. Renewable energy can lower the GHG intensity of steel production by 90%[116]. From current marginal shares of renewable energy, an increase to a maximum of 70% is assumed[117]. The increase is assumed to take place in linear shape up to 2040.

#### Scope, limitations, considerations for interpretation

N/A

### Carbon solution 12c: Use renewable energy in glass production

#### Description

75% of the $CO_2$ emissions from flat glass manufacturing derive from the use of natural gas to heat the melting furnace, while the remainder comes from the release of $CO_2$ from raw materials carbonates. By switching to renewable energy instead of gas for the heating of the melting furnace, $CO_2$ emissions can be significantly reduced.

#### Modelling approach

The modelling assumes that glass produced with renewable energy can be used as a direct replacement of all glass uses in all building types, in new construction and in renovation projects. Renewable energy can lower the GHG intensity of steel production by 70%[118]. From current marginal shares of renewable energy in glass production, a maximum of 50% renewable energy is assumed. Due to the limited data and projections, this assumption is based on the forecasted implementation in cement, assuming similar technical options. The maximum is reached in 2040 after a linear increase.

[115] International Energy Agency. (2018). Technology Roadmap: Low carbon transition in the cement industry. https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

[116] A. Otto et al., 2017. Power-to-steel: Reducing $CO_2$ through the integration of renewable energy and hydrogen into the German steel industry. Energies, 10 no. 451.

[117] International Energy Association. (2022). Iron & Steel Technology Roadmap https://www.iea.org/reports/iron-and-steel

[118] Zier, M.; Stenzel, P.; Kotzur, L.; Stolten, D. (2021). A review of decarbonization options for the glass industry, Energy Conversion and Management: X, Volume 10. https://doi.org/10.1016/j.ecmx.2021.100083

Scope, limitations, considerations for interpretation

N/A

**Carbon solution 13a: Carbon capture in cement production**

Description

Carbon capture  and storage (CCS) technology aims at capturing and storing the relatively high concentration of $CO_2$ in the flue gas from large, point-source emitters. In case of the cement industry, the aim is to capture both the $CO_2$ emissions related to burning of fossil fuels and the $CO_2$ emissions related to the process chemistry of limestone decarbonisation during cement production.

Modelling approach

The modelling assumes that cement produced with carbon capture technology can be used as a direct replacement of all cement uses in all building types, in new construction and in renovation projects. With CCS, the GHG intensity of cement can be reduced by 90%[119]. It is assumed that CCS implementation can be increased to cover 65% of remaining GHG emissions after fuel switch to renewable energy based on forecasted global cement production and carbon intensity with CCS[120]. Until 2030, only small progress is made, reaching 10% of the projected increase. The remaining increase takes place between up to 2040 in a linear shape.

Scope, limitations, considerations for interpretation

CCS technologies are still in demonstration or pilot stages, which makes the definition of accurate assumptions for their development complex. However, this is balanced by other solutions such as timber use or design based on light construction principles, which can reach their full potential earlier than 2040.

**Carbon solution 13b: Carbon capture in steel production**

Description

Carbon capture technology aims at capturing and storing the relatively high concentration of $CO_2$ in the flue gas from large, point-source emitters. In case of the iron and steel industry, the aim is to capture the $CO_2$ emissions related to the burning of coal in blast furnaces or basic oxygen furnaces.

Modelling approach

The modelling assumes that steel produced with carbon capture technology can be used as a direct replacement of all steel uses in all building types, in new construction and in renovation projects. With CCS, the GHG intensity of steel production can be reduced by 70%[121]. Due to limited data available for forecasts of CCS implementation in steel production, a similar diffusion than in cement is assumed, meaning that 65% of global steel stems from plants equipped with CCS in 2050. Again, until 2030, only small progress is made, reaching 10% of the projected increase. The remaining increase takes place up to 2040 in a linear shape.

[119] Markewitz, P.; Zhao, L.; Ryssel, M.; Moumin, G.; Wang, Y.; Sattler, C.; Robinius, M.; Stolten, D. (2019). Carbon Capture for CO2 Emission Reduction in the Cement Industry in Germany. Energies, 12, 2432. https://doi.org/10.3390/en12122432

[120] IEA. (2020) Energy Technology Perspectives 2020. Available at: https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf

[121] Guevara Opinska, L., et Al. 2021, Moving towards Zero-Emission Steel, Publication for the committee on Industry, Research and Energy (ITRE), Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament, Luxembourg

### Scope, limitations, considerations for interpretation

CCS technologies are still in demonstration or pilot stages, which makes the definition of accurate assumptions for their development complex. Assuming full implementation by 2040 is therefore uncertain. However, this is balanced by other solutions such as timber use or design based on light construction principles, which can reach their full potential earlier than 2040.

## B. Additional solutions included in Scenario LIFE-Build

The volume and space needs for future buildings is a key lever impacting the decarbonisation of the European building stock. Demographic trends and urbanisation is expected to significantly change demand for buildings. The number of people living in predominantly urban and intermediate regions will grow significantly, reaching 80% by 2040[122]. Concomitantly, the size of households is expected to shrink and likely to contribute to more carbon emissions per person than those bigger in size.

There are two measures considered in the model with the purpose of reducing the need for new construction. First, overall space demand is reduced by the efficient use of space in existing buildings. Second, vacant buildings and unused spaces are reused, refitted, or repurposed instead of constructing new buildings. These sufficiency or "avoid" measures are implemented on the building stock level.

**Carbon solution 1a: Optimize/reduce the use of space in offices and residential buildings.**

### Description

Increasing the usage intensity in existing buildings reduces the need for indoor space use and thereby reduces the need for new construction projects. The amount of newly constructed built area depends on the number of users and the space occupied by users. New construction projects are driven by the increased need for specific building types and the need for space for a particular activity. Importantly, building developments are also impacted by the location and a number of important economic, social and demographic factors, such as planning, affordability, financing, migration, etc.

### Modelling approach

The model assumes that the construction of residential buildings and offices can be reduced. The basis for the reduction is a more efficient space use and a smaller space demand per person for living (-10% total living space need[123]) and for working (-30% total office space need[124]). This would be a radical change in many people's lifestyles and habits. The reduction of the amount of space for working and living is assumed to be achieved in 2030 after a linear decrease starting from current levels of space use intensity.

[122] Source: Eurostat and 2022 Strategic Foresight Report: Twinning the green and digital transitions in the new geopolitical context (COM(2022) 289 final). See also: A long-term Vision for the EU's rural areas (COM(2021) 345 final) and Scenarios for EU rural areas 2040

[123] Gunther, J. et al. (2019). Resource efficient pathways towards Greenhouse-Gas-Neutrality-RESCUE. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_kurzfassung_eng.pdf

[124] Bedford, M. et al. (2013). Occupier density study 2013. Available at: https://www.bco.org.uk/Research/Publications/Occupier-Density-Study-2013.aspx

### Scope, limitations, considerations for interpretation

The scenario does not account for demographic changes, such as population growth or migration. The scenario only considers lifecycle emissions of energy efficiency renovations and not that of refitting/repurposing renovations. The measures, and their embodied emissions, that are needed to refit existing buildings are quantified in Carbon solution 2.

## Carbon solution 1b: Use existing assets that are currently unused instead of new buildings

### Description

Assets that are currently unused represent readily available space for commercial and residential use while requiring none or very little additional embodied GHG emissions. Using them would mean an optimised use of existing indoor spaces.

### Modelling approach

We found evidence that in urban areas 2% of the residential floor area and 8% of the office floor area would be unused and could be used instead of new built. However, this measure applies to only 25% of the residential buildings and all of the office building stock. This means that about 0.50% of the housing stock would apply for this solution. For modelling, it is assumed that 50% of the buildings are in urban areas.

### Scope, limitations, considerations for interpretation

It is likely necessary to renovate vacant space to make it fit for new use. These repurposing and refitting renovations are considered at the carbon solution 2: Renovate instead of building new.

## Carbon solution 2: Renovate instead of building new

### Description

The demand for structural materials can be significantly reduced when existing buildings are refitted for their new purpose instead of replacing them with new buildings. Existing buildings can be stripped down to their structural components, usually reinforced concrete, bricks, timber, or steel and used as the structure for a new building. While this major renovation process does not completely forgo the use of new structural materials, it does significantly decrease it. Additionally, repurposing vacant/abandoned buildings could reinvigorate neighbourhoods and answer community needs at the same time.

### Modelling approach

In the model, we assume that demolitions of all building types and uses can be avoided by repurposing existing buildings and renovating them to fit new purposes. Consequently, the same amount of floor area is assumed to be avoided new construction. This solution reuses a significant number of the structural components of the building that are often the most carbon intense, i.e. steel and cement. Therefore, the carbon emissions for refitting (independent of energy renovation or not) are assumed to make up 25% of the carbon emissions of a new construction and will be aggregated in the renovations carbon emissions.

This measure translates to a decrease in demolition and new construction, while increasing renovation. Avoiding demolition is the driver that sets the diffusion of this measure, i.e. only buildings that are decommissioned and set to be demolished (modelled as demolition) are available for repurposing. Other than that, this measure is applicable to all building uses. When applicable 75% of the GHG emission can be avoided compared to constructing a new building[125]. This maximum is assumed to be reached in 2040 after a linear increase.

### Scope, limitations, considerations for interpretation

As an embodied carbon reduction solution, the scope of renovation applied here relates to projects which make major adjustments to a building (e.g., to transfer an old industrial building into a residential one), while retaining long-lasting elements such as foundations and core structures. This solution does not include energy-efficiency renovations with the sole or main purpose of improving energy performance. Note: As the demolition is assumed to make up 0.1% of the building stock floor area the saving potential would be in the dimensions of 75% of 0.1%, hence not significant and will not be modelled.

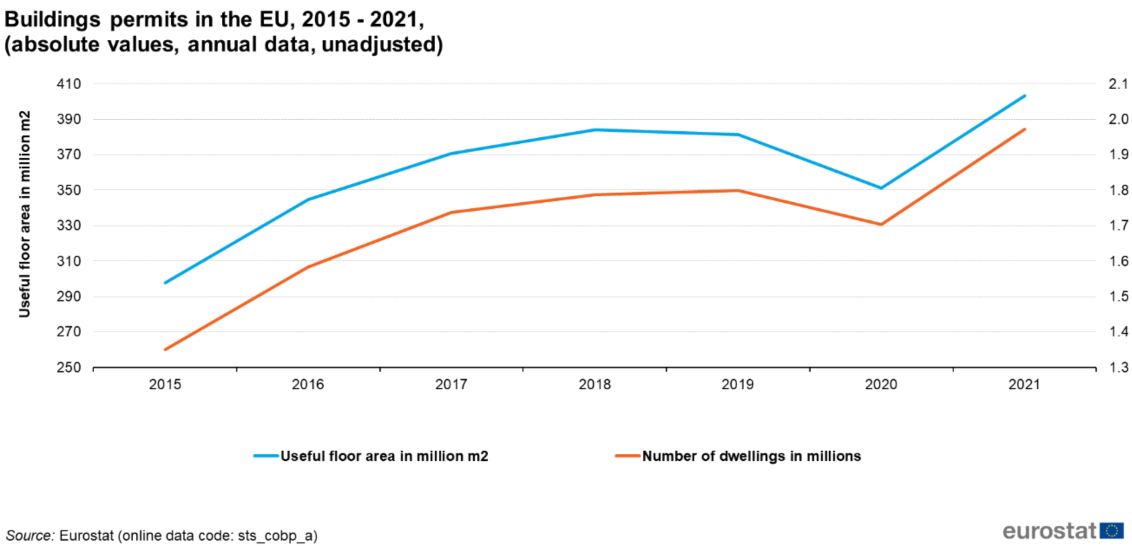
[125] Mendes Saade, M. R.; Guest, G.; Amor, B. Comparative whole building LCAs: How far are our expectations from the documented evidence? Building and Environment, Volume 167, 2020, https://doi.org/10.1016/j.buildenv.2019.106449

# APPENDIX III - BUILDING STOCK MODELLING IN A BUSINESS-AS-USUAL SCENARIO

## A. Assumptions for new construction

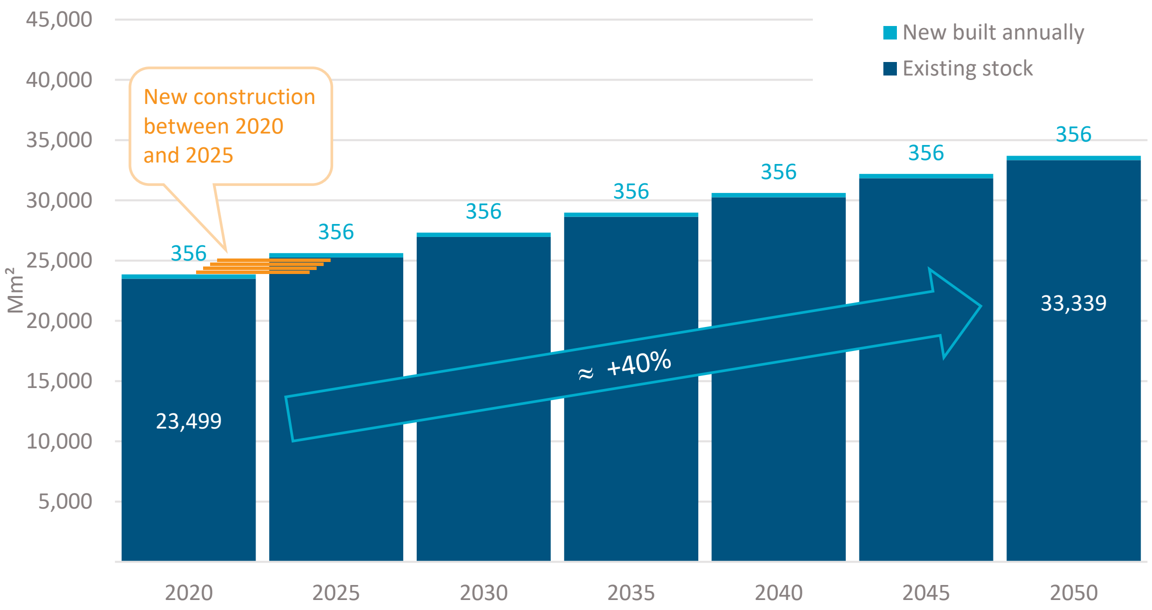
The scale of new construction is assumed by reference to Eurostat data on building permits issued across the EU.

**Figure 50 Building permits in EU, 2015- 2021; Source: Eurostat**




According to Eurostat, building permits for new construction in the EU have been fluctuating roughly around 350 Mm² between 2015 and 2021. Therefore, we are assuming the average future construction to continue to add 356 Mm² floor area per annum in going forward. New constructions are expected to add a total of 11.039 Mm² and increase the floor area of the stock by 40% by 2050.

**Figure 51 Projections of floor area growth**




The growth projection of the building stock shown in Figure 51 is based on the assumption that the current construction rate (i.e. observed building permits) will be maintained over time. This building stock growth is however disconnected from the population development shown in Figure 51. The EU population is projected to shrink by 1.4% overall, as shown in Figure 52 on the left.

The demographic development varies significantly across European countries. For example (see Figure 52 below on the right), the population is expected to grow in Sweden (+34%), Ireland (+35%), Germany (+0.02%) and France (+4%). On the other hand, the population will decrease in Italy (-15%), Poland (-27%), and Romania (-34%). As the population is a main factor[126] determining the space demand, the first group of countries is likely to push the development and new home construction, adding to the existing stock. Meanwhile, in the latter group of countries, buildings may become vacant, abandoned and, eventually, demolished. Further analysis will be necessary to quantify what exactly happens with the building stock when the supply of space exceeds the demand.

***What is the relevance of vacant properties?***

Operational carbon stems from the energy sources used to keep buildings warm, cool, ventilated, lighted and powered. Unoccupied buildings (vacant buildings or second homes) may not be heated, therefore they do not contribute to the operational carbon footprint of the stock. Quantifying operational carbon emissions with a greater accuracy will require a more comprehensive overview of the stock and that of vacant properties[127]. In the same time, addressing structural vacancy is an effective lever to reducing embodied emissions. Solving the vacancy problem avoids the need for new constructions and the related environmental costs and impacts on resources by the reuse of building space or materials.

[126] Another factor area shrinking household sizes. They increase the need for heated floor area, however only about a 4% decrease was reported for the last 12 years [10].

[127] Data compiled by the Organisation for Economic Cooperation and Development (OECD) in 2021 show that in selected EU countries the share of vacant dwellings is over 12% of the stock.

**Figure 52 EU-27 population development: drop in 2050 by about 1.4% compared to 2019; right: population increase expected in countries such as Sweden, France, Germany, Belgium.**

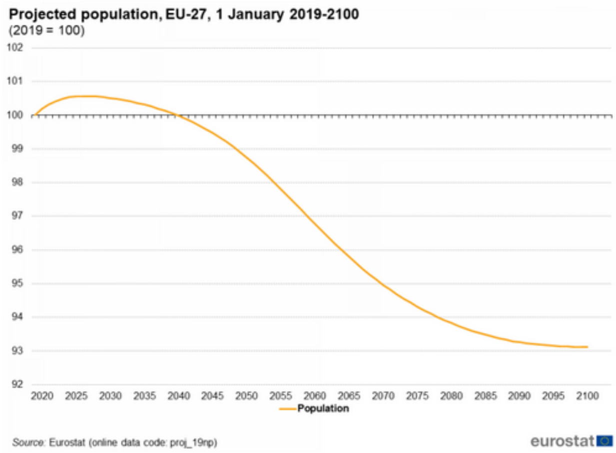



Figure 1: Projected population, EU-27, 1 January 2019-2100

(2019 = 100)

*Source:* Eurostat (proj_19np)

**Demographic balances, 1 January 2019-2100**
(thousands)

| | Population | Cumulative births | Cumulative deaths | Cumulative natural population change | Cumulative net migration | Total population change | Projected population |
|---|---|---|---|---|---|---|---|
| | 1 January 2019 | | | 2019-2099 | | | 1 January 2100 |
| EU-27 | 446 825 | 308 705 | 422 713 | -114 007 | 83 257 | -30 750 | 416 074 |
| Belgium | 11 456 | 9 089 | 10 420 | -1 331 | 1 730 | 399 | 11 854 |
| Bulgaria | 7 000 | 3 782 | 6 629 | -2 847 | 585 | -2 262 | 4 738 |
| Czechia | 10 650 | 8 037 | 10 012 | -1 975 | 1 533 | -442 | 10 207 |
| Denmark | 5 806 | 4 970 | 5 414 | -444 | 885 | 441 | 6 247 |
| Germany | 83 019 | 61 048 | 79 091 | -18 043 | 18 225 | 182 | 83 202 |
| Estonia | 1 325 | 882 | 1 262 | -379 | 199 | -180 | 1 145 |
| Ireland | 4 904 | 5 310 | 4 755 | 555 | 1 152 | 1 707 | 6 611 |
| Greece | 10 725 | 5 631 | 9 977 | -4 346 | 1 764 | -2 582 | 8 143 |
| Spain | 46 937 | 30 227 | 46 047 | -15 820 | 14 672 | -1 148 | 45 789 |
| France | 67 013 | 57 297 | 60 983 | -3 686 | 6 325 | 2 639 | 69 652 |
| Croatia | 4 076 | 2 144 | 3 749 | -1 604 | 304 | -1 300 | 2 776 |
| Italy | 60 360 | 33 738 | 59 564 | -25 826 | 16 882 | -8 944 | 51 416 |
| Cyprus | 876 | 834 | 811 | 23 | 220 | 242 | 1 118 |
| Latvia | 1 920 | 935 | 1 651 | -716 | -122 | -838 | 1 082 |
| Lithuania | 2 794 | 1 413 | 2 499 | -1 086 | -29 | -1 114 | 1 680 |
| Luxembourg | 614 | 533 | 620 | -87 | 254 | 167 | 781 |
| Hungary | 9 773 | 6 641 | 9 632 | -2 990 | 1 932 | -1 058 | 8 714 |
| Malta | 494 | 400 | 583 | -184 | 379 | 196 | 689 |
| Netherlands | 17 282 | 13 940 | 16 125 | -2 184 | 2 870 | 685 | 17 967 |
| Austria | 8 859 | 6 584 | 8 383 | -1 798 | 2 176 | 378 | 9 237 |
| Poland | 37 973 | 20 336 | 35 409 | -15 073 | 4 755 | -10 318 | 27 655 |
| Portugal | 10 277 | 6 067 | 9 745 | -3 678 | 1 382 | -2 296 | 7 981 |
| Romania | 19 414 | 10 424 | 17 196 | -6 772 | 138 | -6 634 | 12 781 |
| Slovenia | 2 081 | 1 361 | 1 986 | -626 | 433 | -193 | 1 888 |
| Slovakia | 5 450 | 3 429 | 5 081 | -1 651 | 547 | -1 104 | 4 346 |
| Finland | 5 518 | 3 329 | 5 183 | -1 853 | 1 051 | -802 | 4 716 |
| Sweden | 10 230 | 10 322 | 9 908 | 414 | 3 015 | 3 430 | 13 660 |
| Iceland | 357 | 446 | 362 | 84 | 182 | 266 | 623 |
| Liechtenstein | 38 | 30 | 37 | -7 | 18 | 11 | 49 |
| Norway | 5 328 | 4 896 | 5 154 | -258 | 1 977 | 1 719 | 7 047 |
| Switzerland | 8 545 | 7 773 | 8 292 | -520 | 4 017 | 3 498 | 12 042 |

Source: Eurostat (online data code: proj_19ndbi)

eurostat

Table 1: Demographic balances, 1 January 2019-2100

(thousands)

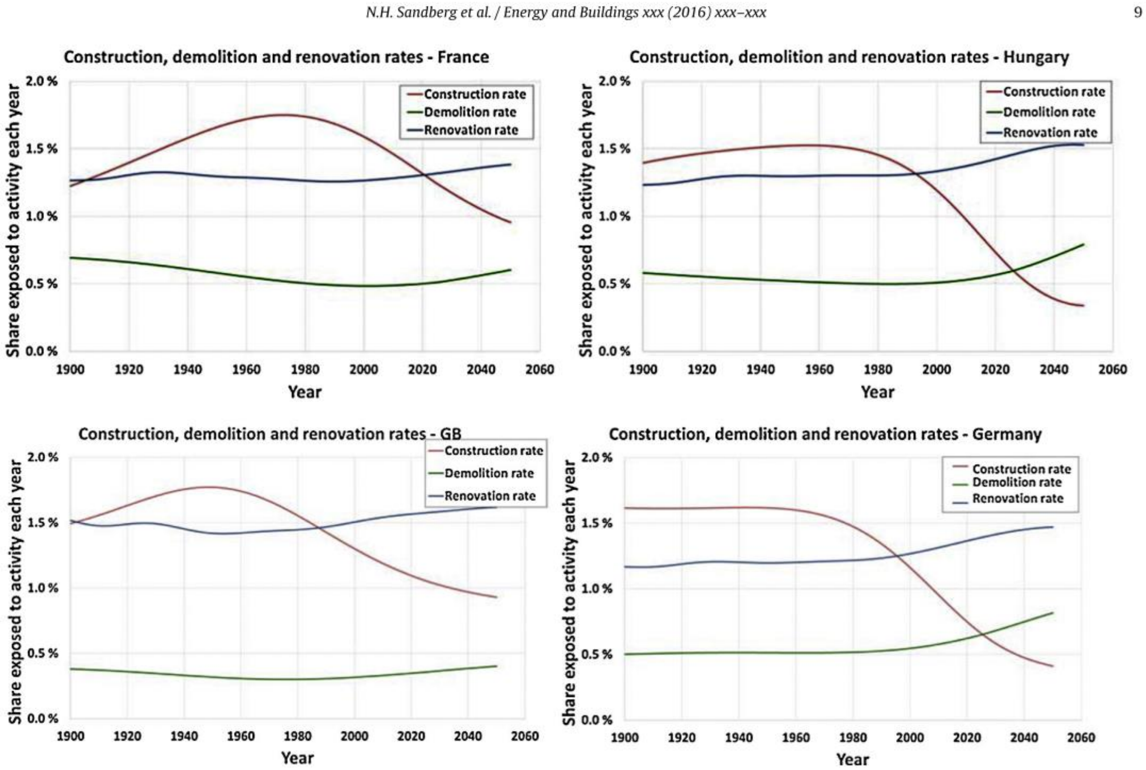
*Source:* Eurostat (proj_19ndbi)

***What have other building stock assessments assumed?***

The construction rate and the building stock size is not always transparently reported.

- The EU Reference [4] and MIX scenario[5] assume an annual construction of 1.4% in 2025 decreasing to 0.9% in 2050.
- The EUCalc scenario construction is based on the population development and the living space per person[6] and suggest a much lower construction rate of 0.4%[7]. At this rate, there will be no excessive buildings and the heating assumptions can be the same for all buildings.
- Figure 53 based on source [8] shows rates for construction between 0.5% and 1% in Germany and Hungary and between 1% and 1.5% for France and Great Britain. This validates the range but also shows there are differences of 0.5% points between countries.
- A recently published a JRC report on data for construction and demolition (CDW) waste [9] identified much higher construction rates of about 2% for residential buildings and up to 6% for non residential buildings. These rates appear very high and we are in the process of clarifying the comparability and background of these differences.

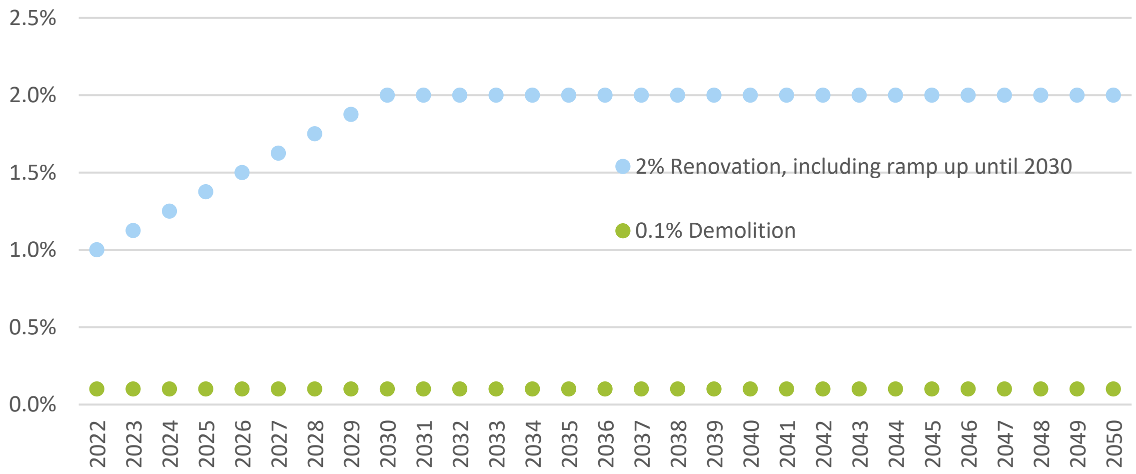
**Figure 53 Assumptions for rates for different countries according to [8]**



## B. Assumptions for renovations and demolitions

The starting point for defining the business-as-usual (BAU) renovation scenario is the current renovation rate, commonly assumed to be at the level of 0.9 – 1.0%. It is further foreseen that the renovation rate in the BAU scenario will linearly grow until doubled in 2030, which would fulfil the EU renovation targets set in the EU Renovation Wave.[128] This scenario furthermore assumes that the renovation rate will stabilise at 2% and stays at a constant rate from 2030 onwards. We assume that no building is renovated twice. The renovation scenario is presented in the graph below. The same annual renovation rate was assumed for all EU regions.

**Figure 54 Renovation and demolition rate assumptions**




The rate of demolition is assumed to stay constant throughout the 2022-2050 period and at the rate documented in the EUCalc[129] model, that is of 0.1% per year.

## C. Share of standard and advanced energy efficient buildings

To characterise the building stock, the previous D2.2 baseline analysis defined two levels of new construction:

- Standard energy performance levels (STD), representing buildings complying with current/recent minimum legal requirements
- Advanced energy performance levels (ADV) representing low energy buildings, roughly similar to NZEB and ZEB standards

Similarly, refurbishments were defined as follows:

- Usual/standard refurbishment (STD): package of measures for upgrading the thermal envelope and the heat supply system which are commonly realised during refurbishment; typically reflecting the national requirements in case of refurbishments.

[128] https://eur-lex.europa.eu/resource.html?uri=cellar:0638aa1d-0f02-11eb-bc07-01aa75ed71a1.0003.02/DOC_1&format=PDF

[129] http://www.european-calculator.eu/wp-content/uploads/2020/04/EUCalc_D2.8_Pathways-explorer-buildings.pdf

- Advanced/ambitious refurbishment (ADV): package of measures for upgrading the thermal envelope and the heat supply system which are usually only realised in very ambitious refurbishments or research projects; typically reflecting the level of passive house components.

The share of standard and advanced energy performance levels achieved by renovations and new constructions are determined on the basis of the EU Calc Reference scenario. The light and medium energy efficient renovations and constructions in the EU Calc scenario are related to the standard performance level, while the deep level relates to the advanced renovations and constructions used in this study.

**Table 9. Comparison between EUCalc and this analysis**

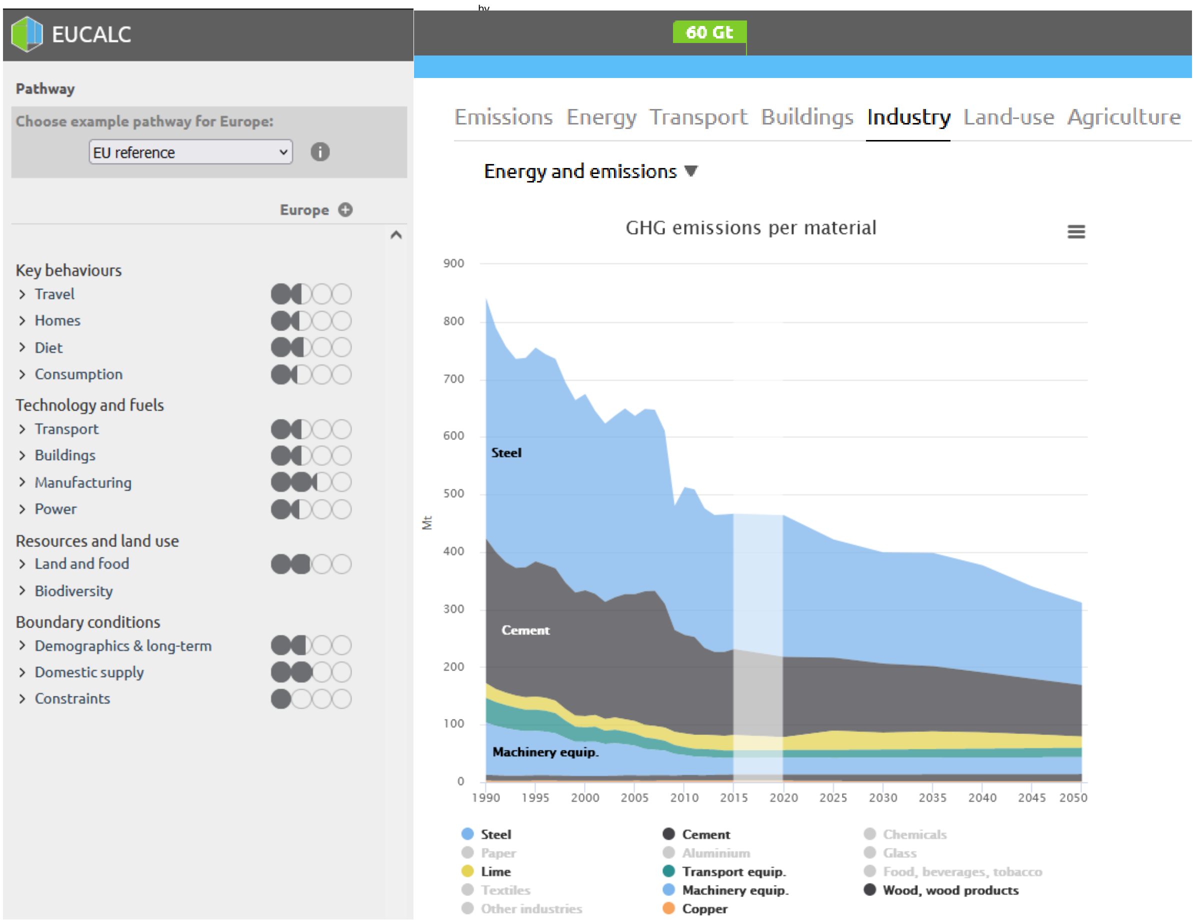
| EU Calc | | | This analysis | | |
|---|---|---|---|---|---|
| **Energy performance definition** | **Final energy savings** | **Share in annual construction and renovation activity** | **Energy performance levels** | **Final energy savings** | **Share in annual construction and renovation activity** |
| Light | -30% | 50% | Standard | depends on climate region and building type | 87.5 % |
| Medium | -40% | 37.5% | | | |
| Deep | >-60% | 12.5 % | Advanced | | 12.5 % |

## D. Decarbonisation of space heating and construction materials industry

Indirect actions, such as decarbonisation of space heating and industry, in addition to improvements in energy efficiency of buildings, can contribute significantly to reducing building related operational and embodied emissions. It should therefore be properly accounted for in the BAU scenario. The decarbonisation of the energy system includes the space heating and the energy delivered to industry processes that produce/manufacture construction and renovation relevant products (building materials, technical systems) and construction machinery. To reflect these reductions in the carbon intensity of processes we apply decarbonisation rates to space heating and energy in industry.

The EU Calc Reference Scenario provides the decarbonisation rates of space heating and energy in industry. It stipulates the energy demand and the related emissions for specific building material-related industry processes and for the space heating. Our BAU model selected specific building material-related industries to assess the applicable decarbonisation factor for construction and renovation industry. The model assumes that steel, cement, lime, transport, machinery, wood, copper already provide the proxy needed to calculate degrowth/decarbonisation rates. The ratio of GHG emissions per energy demand decreases over time reflecting a decarbonisation of the energy supply in these industries. This reduction is applied to the construction and renovation emissions in the scenario.

**Figure 55 . Carbon intensity of the construction industry for building-relevant materials; complete industry, source:** [7]



# APPENDIX IV – DETAILED SCENARIO RESULTS

**Figure 56 Building stock activity and $CO_2$ emission results for Europe for the Business-as-usual scenario**

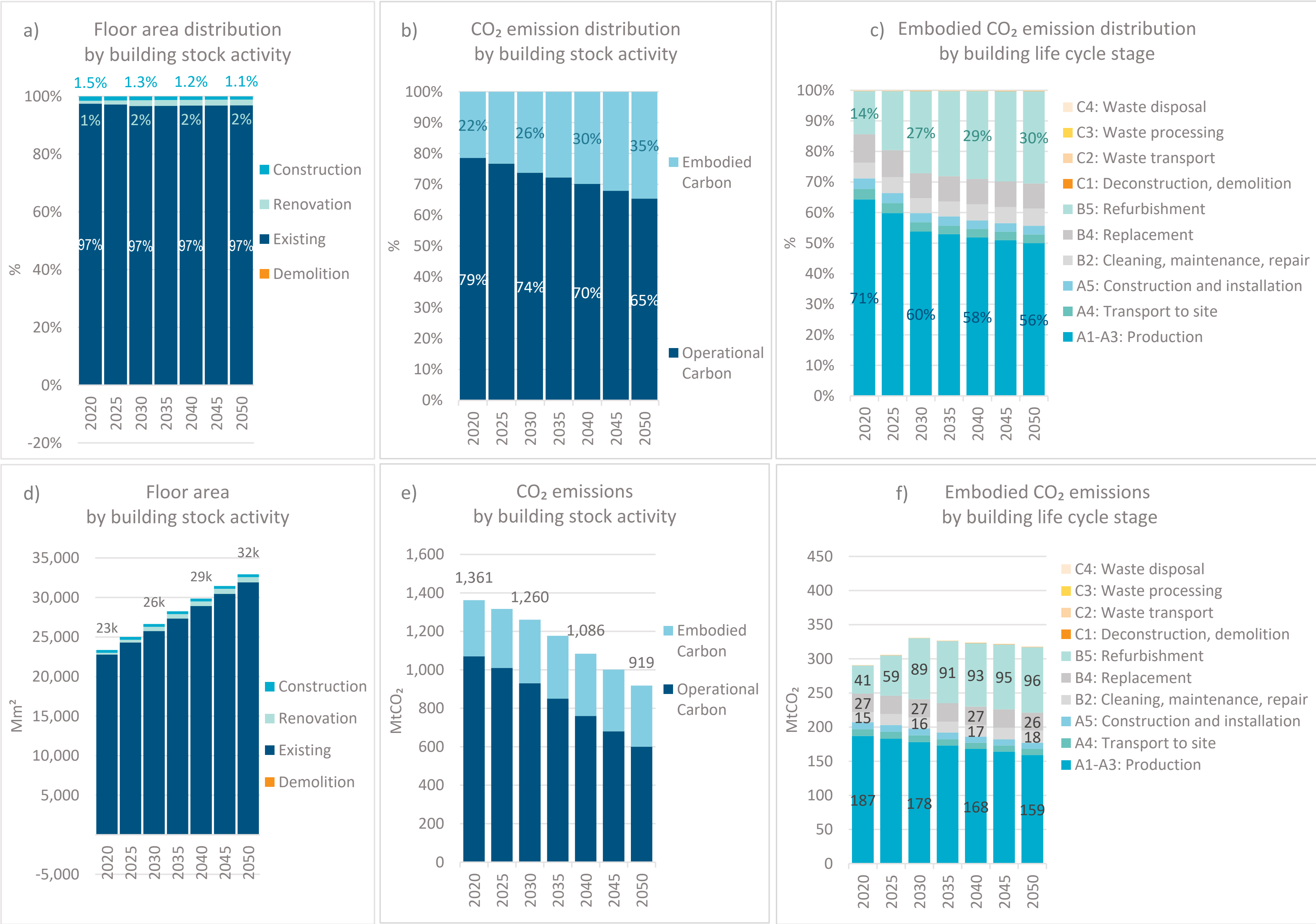


**Figure 57 Building stock activity and $CO_2$ emission results for Europe for the TECH-Build scenario**

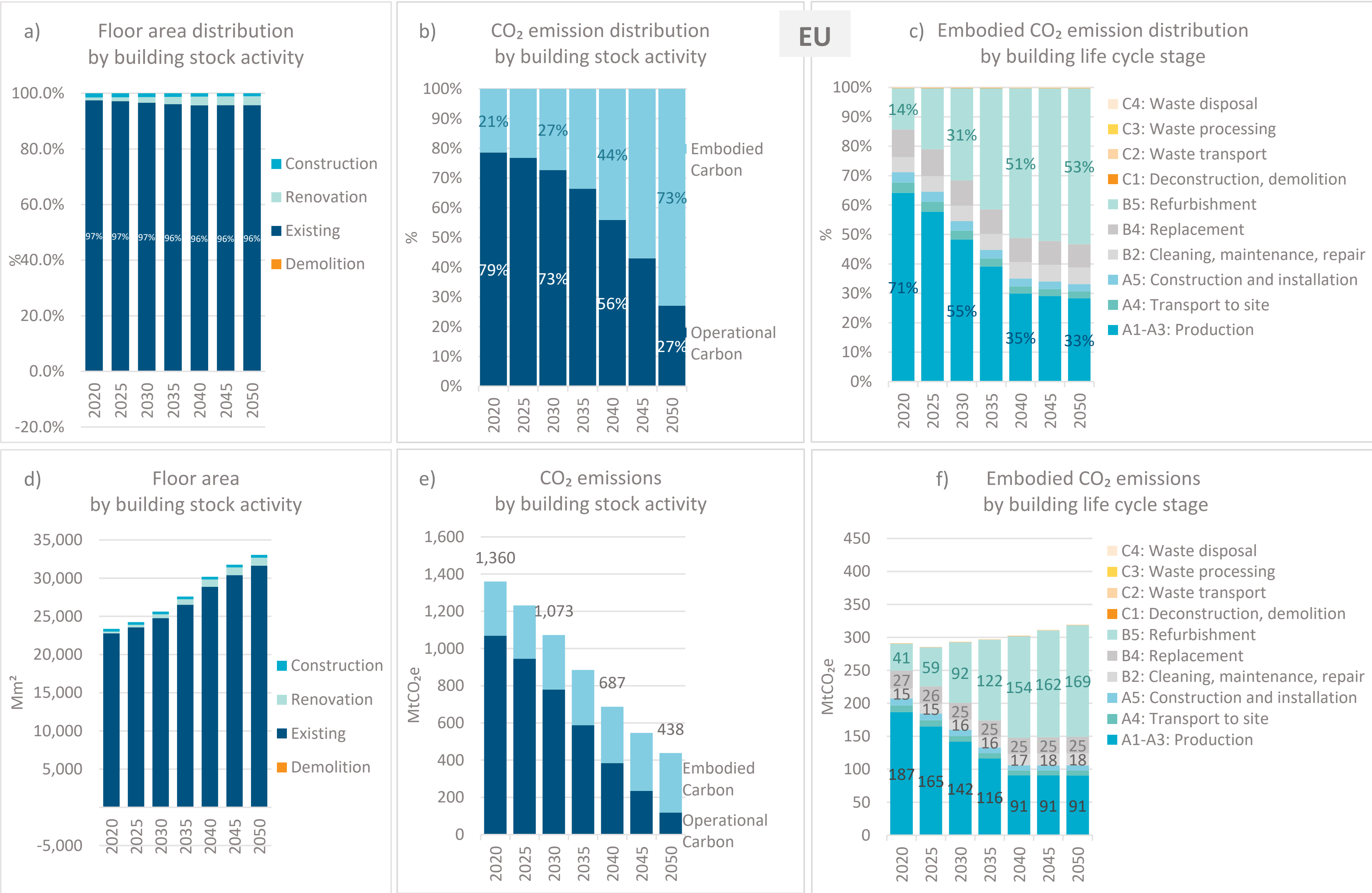


**Figure 58 Building stock activity and $CO_2$ emission results for Europe for the LIFE-Build scenario**