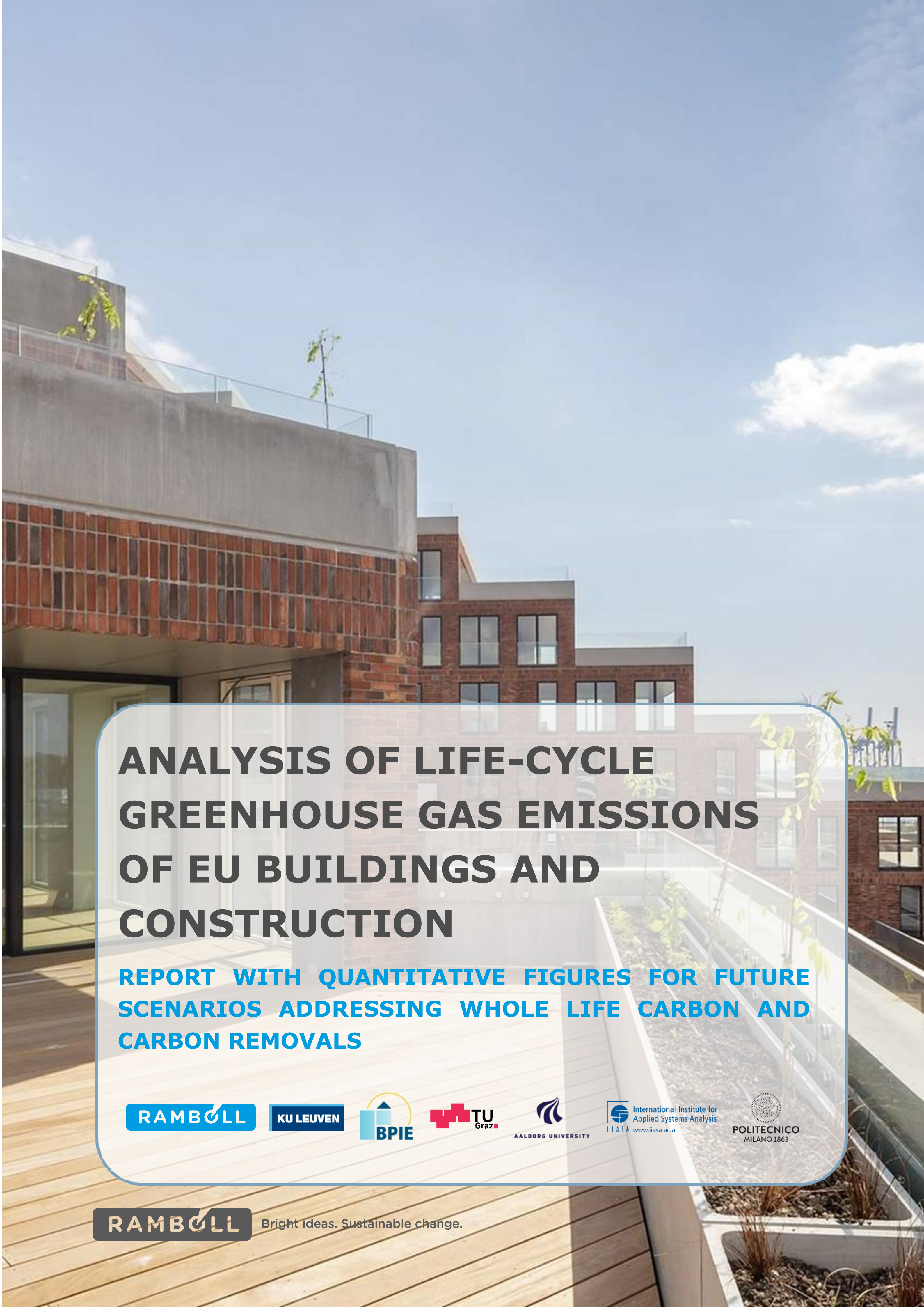

ANALYSIS OF LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF EU BUILDINGS AND CONSTRUCTION

REPORT WITH QUANTITATIVE FIGURES FOR FUTURE SCENARIOS ADDRESSING WHOLE LIFE CARBON AND CARBON REMOVALS

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Project name	Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction
Recipient	European Commission – DG GROW
Document type	Final Deliverable
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Contents

Glossary

Abbrevation	Description
ABL	Apartment blocks
BAU	Business as usual
BSO	Building Stock Observatory
CES	Cost-effectiveness studies
CRRS	Carbon reduction and removal strategies
DHW	Domestic Hot Water
EC	European Commission
EDU	Education
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEA	Health
HOR	Hotels and Restaurants
HVAC	Heating, Ventilation and Air Conditioning
IA	Impact Assessment
IAM	Integrated Assessment Model
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFH	Multifamily houses
MS	Member State
NPI	National Policies Implemented
OC	Operational Carbon
OFF	Offices
OTH	Other non-residential buildings
RSP	Reference Study Period
SFH	Single family houses
TRA	Trade
WLC	Whole Life Carbon (or Whole Life Cycle)

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

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 Life Cycle Assessment (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*".[2] 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, repairing, and re-equipping. It may include elements of retrofitting.
- **Renovation** refers to the process of returning something to a good state of repair.[3]

[1] Ramboll, KU Leuven, BPIE. (2024) Supporting the Development of a Roadmap for the Reduction of Whole Life Carbon of Buildings. European Commission, Directorate-General for Environment. https://data.europa.eu/doi/10.2779/849252

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

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

KEY MESSAGES

- Reducing operational and embodied[4] GHG emissions from buildings is a key element for reaching the EU's target of climate neutrality by 2050. The European Union (EU) has put in place comprehensive policies to ensure the life cycle related GHG emissions of buildings in the European building stock are decreasing. Various strategies are being promoted to enable emission reduction and removal from buildings across EU Member States (MS). However, the actual potential of these strategies to effectively reduce and/or remove emissions across the whole life cycle (WLC) of buildings - and the building stock at large - remains unknown.
- Here we show a comprehensive bottom-up life cycle analysis of EU buildings and construction, investigating various scenarios for rapid decarbonization until 2050 - see sections 2.7 and 3.3 for scenario definitions and detailed results, respectively. Under a business-as-usual (BAU) exploratory scenario WLC emissions of EU buildings and construction reduce from 808 MtCO2e in the baseline year 2020, to 751 MtCO2e in 2050 – a reduction of 7% compared to the 2020 baseline. The ALL/HIGH exploratory scenario, which assumes that strategies are deployed with highest levels of diffusion and market share across all MS, WLC emissions reduce to 136 MtCO2e in 2050, a reduction of 83% compared to baseline year (2020).
- In line with relevant EU policy ambitions and targets, the optimistic current policy scenario CPOL/A and optimistic additional policy scenario APOL/A are achieving WLC emissions for EU buildings and construction of 158 MtCO2e (CPOL) and 87 MtCO2e (APOL/A) in 2050, which corresponds to reductions of annual emission levels by 80% (CPOL/A) and 89% (APOL/A) compared to 2020, respectively. The conservative current policy scenario CPOL/B, limited by diffusion rates considering Members States differentiated capacities to implement certain strategies, achieves annual emission reductions of 66% by 2050 compared to 2020, landing at 278 MtCO2e of WLC emissions from EU buildings and construction in 2050.
- This study demonstrates that rapid decarbonization of EU buildings and construction is possible when activating comprehensive strategy packages that radically improve building energy performance through rapid increase of renovation rates to four times the baseline rates in the short term, to 2030 and 2040, respectively. Improving and decarbonizing production of conventional construction materials across MS is necessary to achieve emission reduction targets. Furthermore, shifting to low carbon material alternatives and avoiding emissions by increasing the intensity of use of floor space that is built, thereby freeing up resources for rapid refurbishment, are required to effectively reduce WLC emissions. We furthermore show how both starting points as well as feasible decarbonization pathways are substantially different across MS.
- This analysis provides evidence for policymakers on promising decarbonization strategies, helping to focus climate action where it matters most. For example, the analysis showed the overarching relevance of pursuing sufficiency-related 'avoid' strategies to enable decarbonization within the limits of technological shift & improve solutions' scaling potential.

[4] It should be noted that in the current EU GHG accounting and reduction scenario-modelling embodied emissions of buildings are not allocated to "buildings" but to the sectors producing the construction materials (mainly "industry").

- Finally, this analysis underlines the importance and possibility of radically reducing emissions from EU buildings and construction to ensure a fair contribution to global decarbonization efforts and respect for limited cumulative emission budgets.

1. INTRODUCTION

1.1 Background

According to the IPCC, climate mitigation in buildings needs to be advanced at each of the design, construction, renovation, use and disposal stages of the life cycle[5]. Globally, 37% of the energy and process related carbon dioxide emissions are linked to building construction and operation[6]. Material-related, embodied emissions ("embodied carbon") play an increasingly important role in achieving rapid decarbonization. Previous estimates suggested that the embodied greenhouse gas (GHG) emissions contribute around 10 – 20 % of emissions in the whole life cycle of buildings. However, more recent studies show the relative increase of embodied GHG emissions, which now make up 50% and more of new buildings' whole life cycle GHG emissions[7]. This seems logical, because when the operational emissions become smaller in newer, more energy-efficient buildings, the *relative* share of embodied emissions increases. At the same time, however, an observed *absolute* increase of embodied emissions highlights their increasing relevance in view of achieving climate targets both globally as well as in Europe. A relevance expected to continue to rise as more buildings are constructed and renovated to higher efficiency standards[8].

Furthermore, in Europe, GHG emissions must be radically cut across all sectors to achieve the EU climate objectives of a 55% reduction in net GHG emissions by 2030 (compared to 1990 levels) and climate neutrality by 2050. Annual GHG emissions occurring across the whole life cycle of buildings and construction in the EU building stock were estimated to account for approximately 1,360 MtCO_2e in 2020, around 41% of total EU27 GHG emissions[9]. To enable effective decarbonization of EU building stock activities, the study showed, a structural transformation is needed that goes beyond the use phase of buildings but considers GHG emissions across the whole life cycle. While further improvements are required regarding energy efficiency measures via renovation and energy standards for new buildings, a deliberate reduction of the embodied GHG emissions is also required during building design, material production, construction, replacement and renovation, as well as end-of-life treatment. Avoiding resource use and building with less primary raw material by extending existing building use through adaptive renovation as well as improving resource efficiency and the use of reused and recycled materials are amongst the effective ways to address whole life GHG emissions. At the same time, there is active debate about the potential for the building sector to become a carbon sink, e.g., through carbon uptake and

[5] IPCC, 2023: "Section 4". In: "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." IPCC, Geneva, Switzerland, p 105, https://doi.org/10.59327/IPCC/AR6-9789291691647

[6] United Nations Environment Programme (UNEP) and Global Alliance for Buildings and Construction (GABC), 2022. "2022 Global Status Report for Buildings and Construction. Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector.". https://wedocs.unep.org/bitstream/handle/20.500.11822/41133/Building_Construction_2022.pdf

[7] Röck M, Ruschi Mendes Saade M, Balouktsi M, Nygaard Rasmussen F, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T,Passer A,2020. „Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation. Applied Energy." https://doi.org/10.1016/j.apenergy.2019.114107

[8] United Nations Environment Programme and Yale Center for Ecosystems + Architecture, 2023. "Building Materials and the Climate: Constructing a New Future." United Nations Environment Programme. https://wedocs.unep.org/xmlui/handle/20.500.11822/43293

[9] Ramboll, BPIE, KU Leuven, 2023. "Supporting the Development of a Roadmap for the Reduction of Whole Life Carbon in Buildings." European Commission - DG ENV. https://c.ramboll.com/whole-life-carbon-reduction

fixation via nature-based solutions and biogenic materials for construction and renovations[10]. Beyond the material dimension, other approaches, like sufficiency and circularity strategies, flexible forms of use and extended producer responsibility are also likely to have to play an increasing role in the debate around decarbonising building construction and operation.

1.2 Objectives and research questions

This report is part of the Preparatory Action "Analysis of life cycle greenhouse gas emissions of EU buildings and construction", which takes the form of a study for the European Commission DG GROW. The report presents the results of **Task 4: Modelling of future whole life carbon scenarios**, aimed at "modelling of future scenarios to address whole life carbon and carbon removals" of EU building stock development.

The objectives of this task are to model future scenarios addressing whole life carbon, by applying the strategies identified earlier in this study[11]. The results demonstrate the effects of applying the chosen strategies within the perspective of reaching climate neutrality and resilience in 2050 without harming significantly other environmental goals.

This task aims to offer insights in response to the following research questions

- What is the whole life cycle GHG emission baseline for EU buildings and construction?
- Which reductions can be achieved considering carbon reduction and removal strategies?
- Which strategies are particularly promising, which may be underperforming?
- What are potential gaps in EU policy (current/additional) from a whole life cycle perspective?

1.3 Approach and advances

The present analysis substantially advances previous modelling efforts on various key aspects:

- This study developed a whole set of new building archetypes for representing the EU building stock using dedicated archetypes per Member State, representing the different activities in the building stock (existing building use, new building construction, renovation of existing buildings) considering their respective construction periods, and modelling a total of nine different building subtypes including residential buildings (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL)) and non-residential, commercial buildings (Offices (OFF), Trade (TRA), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Other non-residential buildings (OTH)).
- For each of these archetypes the modelling underlying this study defined comprehensive life cycle inventories and conducted an advanced life cycle impact assessment using the MMG-SLiCE[12] building life cycle model. The modelling considers both life-cycle related GHG

[10] Van Roijen E. *et al.* , 2025. "Building materials could store more than 16 billion tonnes of CO2 annually." *Science*. https://doi.org/10.1126/science.adq8594

[11] Marton, C., Steinmann, J., and Petrou, D. "Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction - Mapping of the Most Promising Carbon Reduction and Removal Strategies, Taking into Account National Contexts." European Commission - DG GROW, Ramboll, KU Leuven, BPIE, 2023. https://ec.europa.eu/docsroom/documents/58195.

[12] Röck, M., Passer, A., Allacker, K. (2024) SLiCE: An Open Building Data Model for Scalable High-Definition Life Cycle Engineering, Environmental Hotspot Analysis and Dynamic Impact Assessment." *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2024.01.005.

emissions ("whole life carbon") and carbon removals in line with EN 15978 and following the latest EN15804+A2 methodology. The analysis furthermore includes an analysis of whole life carbon 'hotspots', i.e., the life cycle stages, elements and materials with the highest contributions to overall life cycle impacts.

- We advanced the modelling of strategies for carbon reduction and removal (CRR), based on the compilation of key strategies[13], considering their potential impacts in reducing or removing emissions at building level as well as potential diffusion, i.e. market share, that strategies may achieve in different Member States by 2030, 2040, and 2050, respectively.
- Upscaling of building archetype data to building stock baseline as well as modelling of future scenarios for building stock development until 2050 has been upgraded from previous efforts and now utilizes the new PULSE-EU building stock model, advancing the foundational PULSE-AT[14] model to a multi-country scope covering the EU27.
- We deploy a validation model to provide relevant context to critically review and verify the validity of the modelling results obtained from the main modelling pipeline combining SLiCE building archetype modelling, custom modelling of CRR strategies, with upscaling and scenario modelling via PULSE-EU. The established MESSAGEix-Buildings model and the STURM stock turnover model are deployed for generating those additional validation runs.

The report is structured as follows: section 2 describes the methodological framework of the bottom-up building stock model and the modelling of future scenarios; section 3 presents the results of the modelling (building and stock level) focusing on the scenario analysis outcomes for pre-defined policy scenarios; section 4 presents discussion, validation, contextualization, and limitations.

1.4 Scenario modelling

Figure 1 illustrates the methodological steps of the scenario modelling presented in this report. A consistent bottom-up modelling has been deployed with top-down validation based on the detailed life cycle assessment of representative building archetypes per Member State.

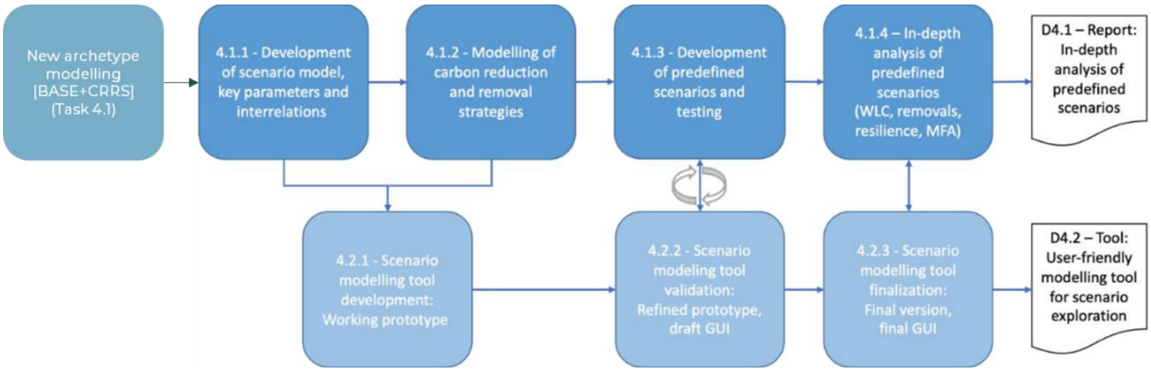

Figure 1: Methodological steps of the baseline analysis presented in this report

[13] Marton, C., Steinmann, J., and Petrou, D. "Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction - Mapping of the Most Promising Carbon Reduction and Removal Strategies, Taking into Account National Contexts." European Commission - DG GROW, Ramboll, KU Leuven, BPIE, 2023. https://ec.europa.eu/docsroom/documents/58195.

[14] Alaux, N., Schwark, B., Hörmann, M., Ruschi Mendes Saade, M, Passer, A. (2024) Assessing the Prospective Environmental Impacts and Circularity Potentials of Building Stocks: An Open-Source Model from Austria (PULSE-AT). *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13558.

Based on the analysis of the composition of building stock (characterization), the study team defined new archetypes required for representing the building stock in different Member States, considering the composition of both existing buildings as well as new construction and refurbishment activity. Dedicated archetypes were developed per Member State for representing different types of activities (i.e., existing buildings, refurbishment variants, new building construction). The study combines different models for both building and building stock analysis. It deploys a building Life Cycle Assessment (LCA) modelling of representative building archetypes, using the Scalable Life Cycle Engineering (SLiCE) data model[15] in combination with KU Leuven's MMG+_KU Leuven building LCA tool[16]. For investigation of implications at the macro-scale building stock level, the PULSE-EU model (Prospective Upscaling of Life cycle Scenarios and Emissions) has been advanced to represent key parameters and interrelations relevant for projecting building stock activities and upscaling emission levels and material flows from individual buildings to the Member State and EU27 building stocks, respectively. To investigate different scenario narratives for future development of EU buildings and construction and explore the related whole life cycle GHG emissions, this study models the potential effects of dedicated carbon reduction and removal strategies. A selection of scenarios has been pre-defined together with the client and stakeholders, the results for which are presented in-detail in this report. For validation of macro level results, this study deploys the MESSAGEix-Buildings model, developed by IIASA. MESSAGEix-Buildings[17] is a bottom-up building sector model to assess energy, material demands, and GHG emissions of buildings at the regional and global scales under different socioeconomic, technology, climate, and policy scenarios.

This report (D4.1) presents quantitative figures for future scenarios addressing whole life carbon and carbon removals, with breakdown to the building types/typologies, covering both EU and national/regional levels. Results are presented as totals for the EU27 as well as per Member State, expressed per m² floor area and per capita. Given the number of variables influencing the scenario results, the data presented in this report are also available via the scenario explorer tool (D4.2) that enables selection, viewing and analysis of various scenario combinations[18].

[15] Röck, M., Passer, A., Allacker, K. (2024) SLiCE: An Open Building Data Model for Scalable High-Definition Life Cycle Engineering, Environmental Hotspot Analysis and Dynamic Impact Assessment. *Sustainable Production and Consumption*. https://doi.org/10.1016/j.spc.2024.01.005.

[16] Allacker, K. "Sustainable Building - The Development of an Evaluation Method," 2010. https://doi.org/D/2010/7515/70 & Lam, Wai Chung, and Damien Trigaux. "Environmental Profile of Building Elements [Update 2021]." VITO, KU Leuven, OVAM, CSTC, WTCB, SPW, BE, December 2021.

[17] Mastrucci, A., van Ruijven, B., Byers, E. *et al. Global scenarios of residential heating and cooling energy demand and CO2 emissions. Climatic Change 168, 14 (2021). https://doi.org/10.1007/s10584-021-03229-3*

[18] Röck M, Eissa S, Lesné B, and Allacker K. "Scenario Modelling Tool - Analysis of Life-cycle Greenhouse Gas Emissions and Removals of EU Buildings and Construction" European Commission DG GROW, 2024. DOI: https://doi.org/10.5281/zenodo.13315281. Available online via: https://ae-scenario-explorer.cloud.set.kuleuven.be

2. METHODOLOGY: BOTTOM-UP BUILDING STOCK MODEL

Understanding and effectively decarbonizing the European building stock requires a comprehensive, data-driven approach. Figure 2 presents the bottom-up modelling framework developed to characterize and analyze the EU building stock using archetype-based representations. This foundational step enables robust projections of whole life carbon impacts and informs targeted policy interventions.

The bottom-up model relies on defining representative building archetypes for each EU Member State, capturing key variables such as different types of use, building geometry, materials, energy performance, HVAC systems. Using statistical data from sources like the Building Stock Observatory and AmBIENCe, the model distinguishes between existing, new, and renovated buildings. Each archetype is assessed through LCA using the SLiCE framework, ensuring a detailed understanding of emissions across the full life cycle of buildings. This archetype-based structure supports scenario modelling to evaluate the impact of future policy and technology pathways.

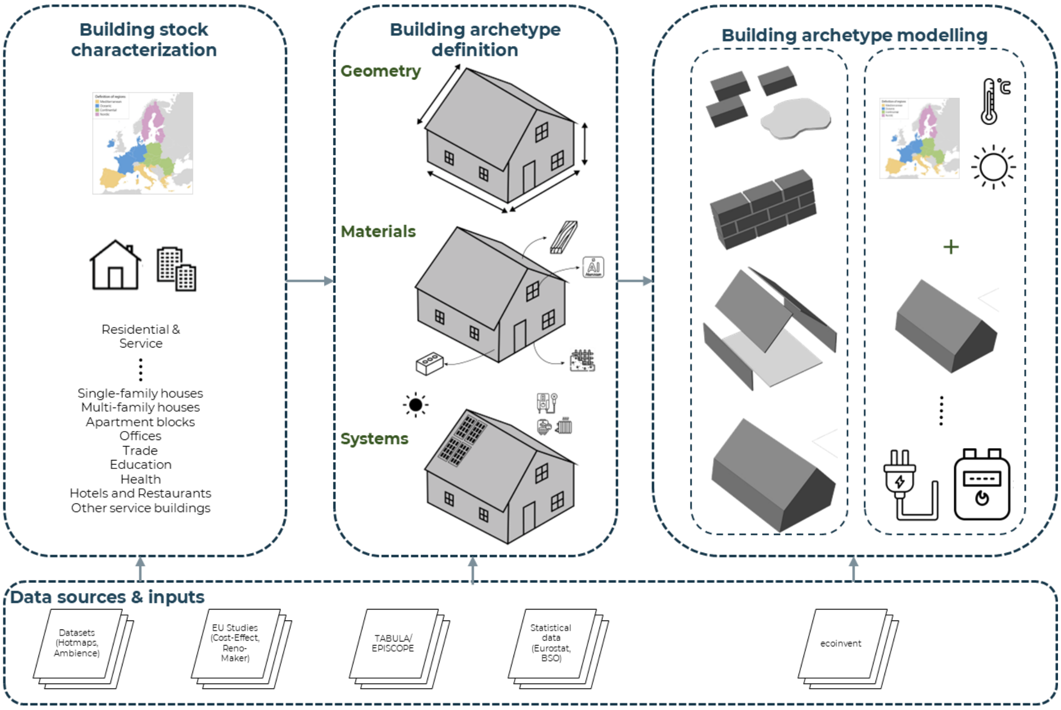

Figure 2: Overview of the bottom-up building stock modelling with key steps of building stock characterization, building archetype definition (geometry, materials, systems), as well as modelling of building archetype inventories and related life cycle impact assessment.

This methodology provides a powerful evidence base for EU-wide and national policy design. By grounding life cycle carbon modelling in archetype-specific data, it enables policymakers to identify and prioritize the most impactful carbon reduction and removal strategies across building types and countries. The modular nature of the framework ensures flexibility in updating data and assumptions as policies evolve or new data becomes available.

2.1 Building stock characterization

To build up the stock model, first the existing building stock has been characterized and the building archetypes have been defined. Building archetypes are virtual representations of various buildings in the stock that share similar characteristics. A bottom-up, archetype-based approach is commonly applied for modelling building stocks at the macro scale (e.g. Europe) to enable both the detailed modelling and analysis of representative buildings as well as the investigation of macro-level dynamics[19]. Archetypes are defined based on a 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 order to characterise and model the EU building stock, representative buildings (archetypes) are defined on EU Member State level by dividing the current building stock into clusters in line with the classification used in the Building Stock Observatory (BSO)[20]. The main characteristics selected to cluster the building stock and define the building archetypes, as indicated in Figure 3, are: sector (residential, service); building type (e.g. single-family house, multi-family house, as well as office, trade, education, etc.); building age class (the original construction period). With regards to the latter, it should be noted that the archetypes represent the current state of a building; older buildings could therefore be defined either as-built or as having undergone renovation. In light of the more detailed data available in the AmBIENCe dataset for residential buildings constructed before 1945, the classifications 1850-1918 and 1919-1944 have been retained.

Building stock attributes are sourced from BSO, referring to statistical data in order to provide a comprehensive understanding of the existing EU built environment. Data relative to the non-residential sector are used as they are, while further elaborations were necessary for residential buildings belonging to the pre-1945 age class. As AmBIENCe provides more precise information for these construction periods, often articulating them in several sub-periods, it is used as a source, following an adjustment procedure to ensure the information fits the age classes used.

The existing building stock is represented by 66 basic building archetypes per EU Member State, resulting in a total of 1782 archetypes – see Figure 3. On top of these baseline archetypes, additional archetypes are modelled for representing new construction variants and different renovation options. The new construction archetypes are building on baseline archetypes from age class 2011-2021, modified to meet latest energy performance requirements. Here we also include modelling of new archetype variants adjusted to represent a shift to bio-based material alternatives, drawing on prior modelling of bio-based building elements renovation. Throughout the modelling of future scenario, data on new and renovation archetypes are further modified to represent future building practice based on application of selected carbon reduction and removal strategies (CRRS).

[19] 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.

[20] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en

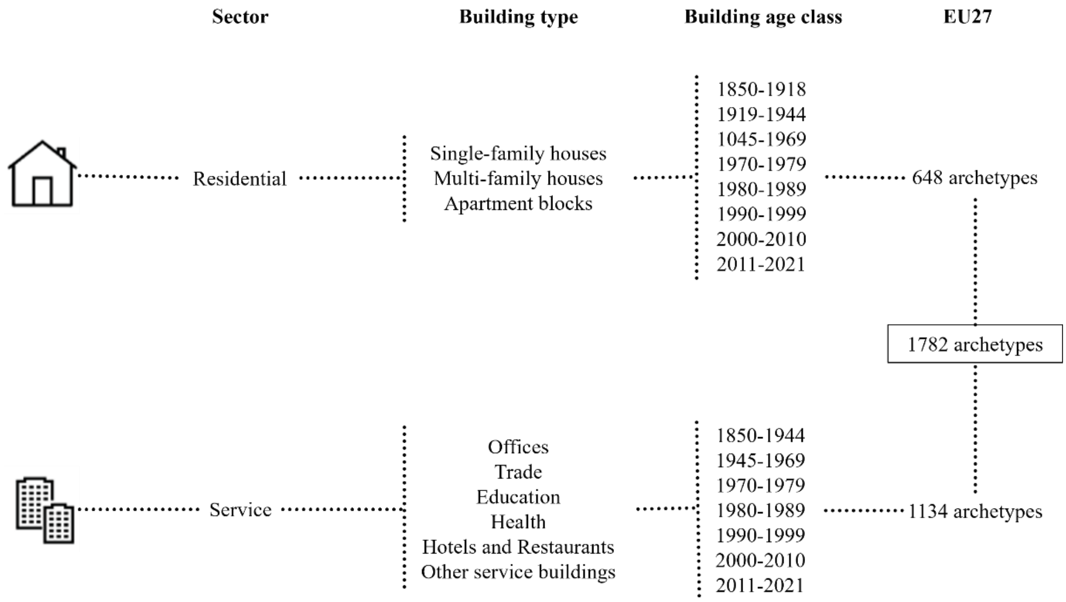

Figure 3: Key attributes for the base archetype definition

2.2 Building archetype definition

2.2.1 Archetypes for existing buildings

The EU building stock characterization dataset builds on the synthesis of information found in key data sources on the European building stock composition and relevant building characteristics. The primary data sources are Hotmaps[21], AmBIENCe[22], and the Cost-effectiveness studies (CES)[23]. These three sources are identified as possessing the most complete and cohesive information. Furthermore, as AmBIENCe is a synthesis of Hotmaps and TABULA/EPISCOPE [24], the information in the latter source can be skilfully cross-referenced and complemented with the information contained in Hotmaps. In addition to these three main sources of information, other data sources are used to supplement or verify the information in the EU building stock characterization dataset. The additional sources consulted include TABULA/EPISCOPE, the EU Building Stock Observatory (BSO)[25], Buildings' renovation makerspace studies[26], Eurostat[27], and Odyssee[28].

A total of 157 attributes are used to describe each building archetype, holding three main categories of information (Table 1): 1) building geometry and occupational properties; 2) building materialization and 3) HVAC system related properties. A full list of attributes has been included in

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

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

[23] EU countries' cost-optimal reports 2018 https://circabc.europa.eu/ui/group/092d1141-bdbc-4dbe-9740-aa72b045e8b3/library/809a0742-2eb9-4797-bf16-a2d269d5c6d0 Accessed on:01/07/2024

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

[25] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en

[26] https://buildingsrenovation-makerspace.jrc.ec.europa.eu/

[27] https://ec.europa.eu/eurostat/en/

[28] https://www.odyssee-mure.eu/

Supplementary information Section 7.1.1, providing an overview of the definition and methodology to collect the attribute.

Table 1: Main groups of archetype characteristics and related attribute examples

Main groups of characteristics	Examples of attributes
Building geometry & occupation	building gross floor area, volume, shape factor, storeys below and above ground, storey height, envelope area, window/wall ratio, number of users, area per person
Building element characteristics	storey floors, external and internal walls, roofs, windows: material characteristics and energy performance characteristics, (structural) materials ratio and thickness, insulation material and thickness, thermal conductivity, density, U-value
HVAC systems	system technology, energy demand and energy sources for space heating, space cooling, domestic hot water (DHW)

In order to collect attribute information for each building archetype in a harmonized manner, a set of rules has been defined, establishing a common procedure for data collection and data gap filling.

In a first step, the attribute value collection activity involves the extraction of relevant information from the appropriate primary sources; in a second step, the data collected are recalculated, where necessary, to align with the defined construction periods. Once this process was finalized, a clear overview of the existing data gaps emerged. In a third step, the data gaps were filled by employing secondary sources. To achieve transparency as to the origin of the information and assess data quality, each data item is accompanied by a short description indicating its source and any calculations or assumptions made. Furthermore, a detailed review of the attribute data of building element characteristics was conducted, as these data retrieved from primary and secondary sources are not always fully reliable and representative. The review was carried out relying on national sources and expert judgement. Hereinafter, attribute information gathering and data gap filling are described according to the main group of characteristics to which these belong.

Attributes relative to **building geometry** are derived from two sources: general statistical data from AmBIENCe and specific information from actual building cases provided by the CES. The AmBIENCe data offers broader geometrical information like reference building wall area, while the CES data complements this with information such as reference building storey height, which is otherwise unavailable. The attributes relative to **occupational properties** are based on CES and supplemented with Eurostat population data to calculate the surface area per person. It is worth mentioning that any information collected from CES has been treated on a case-by-case basis, due to a lack of standardization in the data provided. A two-step process is carried out to ensure that CES data are used appropriately: firstly, it was necessary to check which reference buildings are available in the CES and to what degree they matched the defined archetypes in this study. Secondly, the available data were examined and, where appropriate, processed to conform to the archetype definition in the present work. This proves particularly relevant where the CES included multiple archetypes per building type in a given country. To proceed, the building most closely aligned with the useful floor area of the corresponding AmBIENCe archetype was selected.

The **building element characteristics** are of crucial importance for the assessment of the environmental impacts of the existing building stock, as these define each archetype in terms of materials, performance and construction technologies. At statistical level, detailed information is lacking and had to be complemented with specific real-case building data which are, however, not necessarily representative of the entire building stock. As a consequence, attributes belonging to this group are challenging to define and call for particular attention in order to avoid the risk of distorted outcomes. To close the gap, the attribute filling is carried out in a series of steps.

Firstly, Hotmaps is used to define the composition of floors, walls, roofs and windows in terms of percentage of different materials (e.g., a specific archetype can be characterized by 50% concrete walls and 50% masonry walls) and constructive solutions (e.g., solid wall and/or cavity wall). The construction technologies are then detailed in terms of layer thickness and performance properties (e.g., conductivity, density, U-value) using AmBIENCe. When AmBIENCe reports a set of different characteristics for reference building envelope elements, they were all taken into consideration for the archetype definition. Secondly, in order to fill data gaps, additional information was retrieved through a data review by regional experts, with the goal of maximising the collection of data on the constructive and material heterogeneity of the existing building stock and to validate the uncertain information previously gathered. Thirdly, some attributes were subjected to a review process, with the aim of handling outliers (e.g. in terms of U-value) and critical materials (e.g., asbestos use in compliance with regulatory constraints). In this stage, special attention was given to building insulation, by calculating the thickness of the material layer to obtain the stated U-values for walls, ground floors and roofs. Data gaps were filled in post-processing step by using inputs from neighbouring countries.

AmBIENCe serves as the reference source for **HVAC systems**, providing comprehensive data for the period from 1850 to 2021. The AmBIENCe data details the most common system technologies, their prevalence in the building stock, and their respective efficiencies and fuels used for space heating, space cooling, and domestic hot water. Typically, more than one heating and domestic hot water technology is present for each archetype. Given their importance for building energy demand, the archetypes have been multiplied by the number of HVAC systems present. In total the existing building stock is represented by 4493 archetypes, consisting of 2184 archetypes representing the residential sector and 2309 representing the service sector.

2.2.2 Archetypes for new buildings

New building archetypes are used for modelling new construction activity on building stock level. New archetypes are defined for all nine building types and all EU Member States assuming the same building geometry and materialization of the latest building age class. For each of these 243 archetypes, three energy performance standards are defined: 1) compliant with standard energy performance in line with national NZEB requirements (implementations 2021 latest); 2) advanced energy performance in line with Passive Standards in accordance to what had been defined per region in the DG ENV study "Supporting the development of a roadmap for the reduction of whole life carbon of buildings"; and 3) sub-standard performance in line with the energy performance of the latest building age class. Predefined shares for new buildings according to each of these energy performance standards are used in the baseline year[29]. Building HVAC systems are adapted to be in line with energy performance requirements in the respective Member State (e.g. adaption of system efficiency, phasing out of space heating by gas, etc.). In total 1973 archetypes for new buildings are defined.

In addition, archetypes are generated for the modelling of the increased use of bio-based materials (CRRS 4.1). A distinction is made between mass timber and hybrid timber archetypes. The archetypes for new buildings are used as a basis and the materialization of the external walls,

[29] European Commission. (2019). Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU.

internal walls, storey floors and roofs are based on Mouton et al. (2023)[30], leading to 3946 additional archetypes for new buildings constructed in bio-based materials.

2.2.3 Archetypes for refurbishments

In addition, archetypes are generated for modelling refurbishment activities of different intensity. Dedicated archetypes are defined based on the definition of CCRS 9 ("Reduce operational carbon emissions") as defined earlier in this study[31].

The modelling of refurbishment archetypes utilizes data from both existing building archetypes for modelling the operational emissions (B6) as well as new building archetypes for modelling embodied emissions (B5) of the respective refurbishment activity. Following the logic of light, medium, and deep renovations, the CRR strategy defined the target energy savings as well as the related scope of the intervention (i.e. building elements replaced or upgraded during renovation).

The modelling of B6 operational emission reduction departs from the respective existing building archetype performance to model the specific effect of renovating existing buildings with different building use typologies, from different construction periods, as well as from different countries. Building on those existing building archetypes, we categorize the energy performance levels of buildings in the stock and model renovation option with the following levels of reduction in final energy consumption: Light renovation (expected energy savings <30%): reduction factor = 0.25; medium renovation (expected energy savings 30-60%): reduction factor = 0.50; deep renovation (expected energy savings >60%): reduction factor = 0.75. The related operational emissions are adjusted in the same way for the baseline year and are subject to systemic decarbonization of energy grid (e.g. electricity decarbonization) in subsequent years of the modelling of future scenarios. In addition, we model the embodied emissions (B5) of the renovation considering the elements in scope for that intervention and considering their embodied emissions as defined in the new building archetypes. We build the B5 embodied emissions assuming a full nested life cycle considering the end-of-life of elements taken out of the existing building (C1, C2, C3, C4) as well as the production and processing of elements newly added to the building during renovation (A1-3, A4, A5). Depending on the existing building energy performance and the renovation depth (light, medium, deep), the scope of the intervention varies from a replacement and upgrade of insulation in external walls and roofs, to incorporating replacement and upgrade of windows, as well as, potentially, the replacement and upgrade of technical systems to incorporate low carbon energy provisions such as heat pumps. For those interventions where technical systems are replaced and upgraded to low-carbon electricity-based systems, data records are adjusted to model future decarbonization of electricity across Europe.

Use of the different refurbishment archetypes in the building stock model is defined by the combination of refurbishment rates and depths considered in the modelling for different future scenarios. Further details on the integration of the building archetypes in the building stock and future scenario modelling are presented in Section 2.5 on upscaling to baseline building stocks and Section 2.7 on modelling of future scenarios, respectively.

[30] Mouton, L., Allacker, K., Röck, M. (2023). Bio-based Building Material Solutions for Environmental Benefits over Conventional Construction Products - Life Cycle Assessment of Regenerative Design Strategies (1/2). *Energy And Buildings*, Art.No. 112767. doi: 10.1016/j.enbuild.2022.112767

[31] Marton, C., Steinmann,J., and Petrou, D.. "Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction - Mapping of the Most Promising Carbon Reduction and Removal Strategies, Taking into Account National Contexts." European Commission - DG GROW, Ramboll, KU Leuven, BPIE, 2023. https://ec.europa.eu/docsroom/documents/58195.

2.3 Building archetype life cycle modelling

For modelling the life cycle inventory (LCI), the selected archetypes are defined in detail based on data from D2.1, TABULA/EPISCOPE[32] complemented with expert insights from the consortium team. These element definitions have undergone a review process by the project consortium to maximize the representation of the heterogeneity of existing buildings and to validate uncertain information. Once defined, the archetypes are modelled in detail to conduct a whole life carbon assessment using the LCA method.

The LCI are established using a modular life cycle approach according to EN 15978 and using a hierarchical approach for building decomposition. More specifically, the modelling of buildings is structured in a hierarchical way from building to element to component to material level (presented in Figure 4). Building archetype inventory definition and life cycle modelling are carried out using the Scalable Life Cycle Engineering (SLiCE) data model[33]. This model is a proven instrument for the detailed modelling and life cycle-based assessment of the environmental performance of materials used in buildings and building elements. The SLiCE building modelling framework enables a detailed analysis of environmental hotspots by providing insight into the timing of emissions per life cycle stage and per year, as well as detailed information on the contribution of materials at various scales: building, element, and work-section.

The archetypes are assessed in the SLiCE data model through coupling with the MMG+_KU Leuven LCA tool[34] (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.

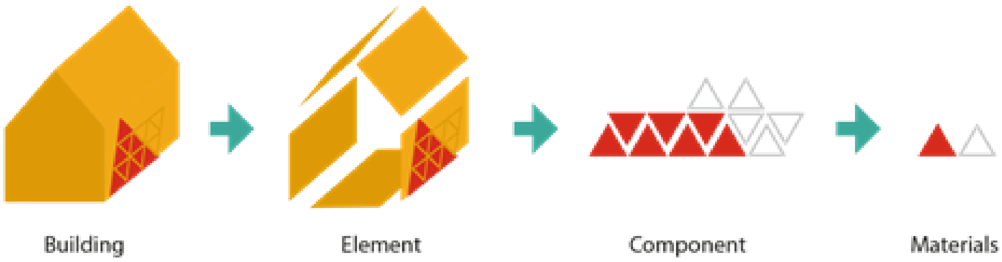

Figure 4: Hierarchical structure of the MMG method and SLiCE model

2.3.1 Operational energy use

The operational energy use modelled at building level includes energy use for space heating, space cooling, domestic hot water, and ventilation, where applicable.

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

[33] Röck, M., Passer, A., Allacker, K.(2024) SLiCE: An Open Building Data Model for Scalable High-Definition Life Cycle Engineering, Environmental Hotspot Analysis and Dynamic Impact Assessment. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2024.01.005.

[34] Allacker, K. "Sustainable Building - The Development of an Evaluation Method," 2010. https://doi.org/D/2010/7515/70 @& Lam, Wai Chung, and Damien Trigaux. "Environmental Profile of Building Elements [Update 2021]." VITO, KU Leuven, OVAM, CSTC, WTCB, SPW, BE, December 2021.

The energy use for **space heating** and **space cooling** is based on the dynamic equivalent heating degree day (Trigaux, 2017)[35] and dynamic equivalent cooling degree day (Goossens, 2021)[36] methodology applied on building archetype level. Country-specific weather data representative for the current climate from PVGIS[37] are used. In case a ventilation system is present in the building, electricity use is estimated based on the volume of the building and system efficiency in line with the EPBD calculation method.

The energy use for **domestic hot water** is calculated based on the number of users for residential buildings and for non-residential buildings with a resident function (i.e. Health buildings and Hotels and restaurants). A detailed description of the calculation can be found in Trigaux (2017)[38]. For the other non-residential buildings, a water usage of 6 l/day is assumed for 250 days per year in line with Level(s) indicator 3.1[39].

2.3.2 Life cycle scenarios

For the assessment of the life cycle embodied impacts of buildings, various scenarios (e.g. regarding transportation or end-of-life treatments) and some default values (e.g. regarding component service life) are defined.

National scenarios are set up for transportation (considered in A4 and C2 of the EN15978:2011 standard) and end-of-life treatment (taken into account in C1, C3 and C4 of the EN15978:2011 standard). The B-PCR[26] serves as a structure for these scenarios and a literature review has been conducted to define values on national level as no comprehensive database was available. Any outstanding data gaps are filled through a procedure based on geographical proximity, as data from similar countries within a region are used as a proxy; in their absence, EU-wide data are used.

Similarly, replacement rates of building elements and building components are defined on a national level based on a literature review. When multiple data points were available, the average is taken as representative value. Any remaining data gaps are filled with a similar approach, using the mean of values referring to countries in the same region or, lacking those, other regions, as a proxy.

Scenarios for cleaning and maintenance during the use stage have been defined according to the MMG method and in line with EN 15978:2011.

2.4 Building archetype environmental impact assessment

2.4.1 Material and energy intensity

The LCA method used is in line with current European LCA standards and methods EN 15804+A2 and EN 15978. The LCI data are based on generic LCI data from ecoinvent 3.6. To guarantee geographical representativeness, for the production of materials, the study team always opted for processes that are representative for the European market. National datasets are selected for the different building end-uses (e.g. electricity or gas burned in a gas boiler). The building archetypes

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

[36] Goossens, D. "Berekenen van de energievraag voor verwarming en koeling van kantoorgebouwen tijdens de vroege ontwerpfase." (2021).

[37] https://re.jrc.ec.europa.eu/pvg_tools/en/#TMY

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

[39] Donatello S., Dodd N. & Cordella M., 2021. Level(s) indicator 3.1: Use stage water consumption user manual: introductory briefing, instructions and guidance (Publication version 1.1)

are assessed using a reference study period (RSP) of 50 years. It is assumed that the material production processes (and related GHG emissions and other environmental impacts) do not change over time during the RSP (e.g. for any maintenance or replacement activities). The rationale for this static life cycle impact assessment (LCIA) modelling is that the results are used for understanding impacts in the baseline year and are hence treated as if occurring 'today'. For projections and scenario analyses in subsequent steps of this study, the impact assessment results will be modified to model future changes of impacts from energy production and material production.

2.4.2 GHG emissions

The life cycle GHG emissions and carbon removals are assessed based on three distinct indicators: GWP-fossil, GWP-biogenic and GWP-LULUC (GWP related to land use and land use change) to ensure a transparent and clear representation of GHG emissions as well as the carbon storage potentials. A fourth indicator, GWP-total expresses the sum of the other three GWP indicators.

When looking at bio-based materials such as timber, CO_2 is taken up during the growth of the tree, leading to a temporary carbon removal benefit. However, when harvested, the stored carbon is usually released at the material's end-of-life, particularly if the timber is landfilled or incinerated, rather than remaining in the natural carbon cycle and/or contributing to soil carbon storage. Within this study and in line with EN15804+A2, the baseline carbon removal assessment is conducted using the standardized static '-1/+1 approach'. This means that carbon uptake (-1) is assumed when timber is harvested for use in the building (module A1-3) and is released again (+1) at end of life (when it is removed from the building) (module C1-C4). From a whole life cycle perspective there is hence no impact at all (no benefits nor burdens).While this approach is commonly treated as net zero in life cycle assessments, it fails to reflect key issues: a) it takes decades for newly planted trees to recapture the carbon released from harvested trees, meaning the short-term climate impact is not neutral; b) the EU forest carbon sink is in decline, driven by climate change and increasing extraction rates. In some regions, forests are already becoming net carbon sources due to unsustainable management practices and environmental stressors.

Given these challenges, it is crucial to consider long-term carbon storage solutions that extend the life of bio-based materials and align with sustainable forest management strategies to ensure timber use contributes meaningfully to climate mitigation (e.g. the ongoing work under the Carbon Removal and Carbon Farming Regulation).

The SLiCE results of the GWP-biogenic indicator are based on the characterization factors in Simapro. However, these are based on an economic allocation, whereas according to the EN15804 standard, a mass-based allocation is preferred. To address this, the GWP-biogenic results from Simapro have been used, except for the CO_2-related part. This CO_2-related part is implemented using the biogenic carbon content defined for each ecoinvent process multiplied by the conversion factor (i.e. 1 kg C = 44/12 kg CO_2) and the material quantity. This 'correction' factor is added to the GWP-biogenic obtained from Simapro. This implementation has been used for the respective A1-3, C3 and C4 stages and substages. Specifically for SLiCE-based modelling considering end-of-life GWP-biogenic: in C3 and C4, this is implemented as the impact of the C3 and C4 process, respectively (without considering biogenic carbon) + the factor calculated based on the biogenic carbon content. These carbon contents are defined based on the production processes while they should be defined based on the end-of-life processes, which is a limitation of the current SLiCE MMG model. A future update to ecoinvent version 3.8 will solve this manual implementation as in this updated version mass allocation is embedded.

2.4.3 Carbon removals

In order to gain additional insights into potential atmospheric carbon stored, a second quantification based on carbon dioxide removal factors was conducted. The method is based on Deliverable 2.1. Report with quantitative baseline figures for whole life carbon and carbon removals. Carbon storage was assessed based on **bio-based and mineral materials**. Hereby, bio-based and mineral building materials were again extracted from the SLiCE datasets and assigned with material relevant factors for carbon dioxide removal. To obtain a wider range for these of removal factors, minimum and maximum values for the expected carbon dioxide removal were determined. In this way, the inherent uncertainty of the data analysed should be better considered, whereby we would like to point out that a minimum and maximum analysis based on individual ranges is not a fully developed uncertainty analysis.

With **bio-based materials** such as wood or agricultural crops, carbon is extracted from the atmosphere as the tree grows and stored in solid form. When the tree is used to produce products, this stored carbon is transferred into an artificial carbon pool, in the case of wood into the harvested wood products pool, for which the inflow can be accounted for as carbon sink and the outfly be accounted for as a carbon source, based on the current IPCC National GHG Inventory calculation guidelines[40]. Similarly, in the relevant standards for the sustainability assessment of buildings EN 15804 and EN 15978, the biogenic carbon is assigned a negative value when entering a product system and booked out again at the end of the life cycle when leaving the product system. This is the so-called '-1/+1 method', which is used in this report for quantifying carbon storage via bio-based materials.

For minimum and maximum values of carbon storage, we relied on the information on the carbon fraction and moisture content available in relevant ecoinvent[41] processes and on the information provided in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[42], where the biogenic carbon content and the conversion factors to biogenic CO_2 are provided for semi-finished wood-based materials. Depending on which source provided a lower or higher value of biogenic carbon dioxide storage in the specific material, it was assigned to the maximum respective the minimum value.

During their life cycle, **mineral materials** show the removal of atmospheric carbon through the process of carbonation, which can reabsorb some of the mineral-bound carbon released in the production of the materials. During the time mineral materials are installed in a building, a small amount of the previously emitted carbon is absorbed back into the material. At the end-of-life this material is demolished, which allows for some additional carbon can be stored by increasing the surface area of the material. As already applied in Deliverable 2.1 Report with quantitative baseline figures for WLC and carbon removals, the mineral building materials available in the updated SLiCE datasets for all EU countries were extracted based on the techflow_names_mmg information, including the information for element_type_generic_name, in order to obtain information about where an element is installed in the building. For these combinations of mineral material and element location, calcination emissions due to production, carbonation during the use phase and carbonation

[40] C.M.T. Johnston, V.C. Radeloff, Global mitigation potential of carbon stored in harvested wood products, Proc. Natl. Acad. Sci. U.S.A. 116 (29) 14526-14531, https://doi.org/10.1073/pnas.1904231116 (2019).

[41] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230.

[42] Rüter, S., Matthews, R. W., Lundblad, M., Sato, A., & Hassan, R. A. (2019). Chapter 12: harvested wood products 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC: Geneva, Switzerland, 49

at the end-of-life were quantified based on the valid standards EN 16757:2022 D[43] and CEN/TR 17310:2019 D[44]. It is very important to note that the calcination emissions in the production phase represent only the chemically bound carbon and do not include the emissions from the upstream chains or fuels, etc. We have done this to show only the material-specific carbon flows and to give insights into the ratios on how much of the chemically bound carbon can be back absorbed by the material.

Following Figure 5 was also part of Deliverable 2.1 Report with quantitative baseline figures for WLC and carbon removals and schematically shows these carbon dioxide fluxes as they can be observed for bio-based and mineral building materials which we were able to quantify via the '-1/+1 method'. Additional insights into the applied standards and formulas and the obtained CDR factors for bio-based and mineral materials are provided in section 7.1.6 in the appendix of this report.

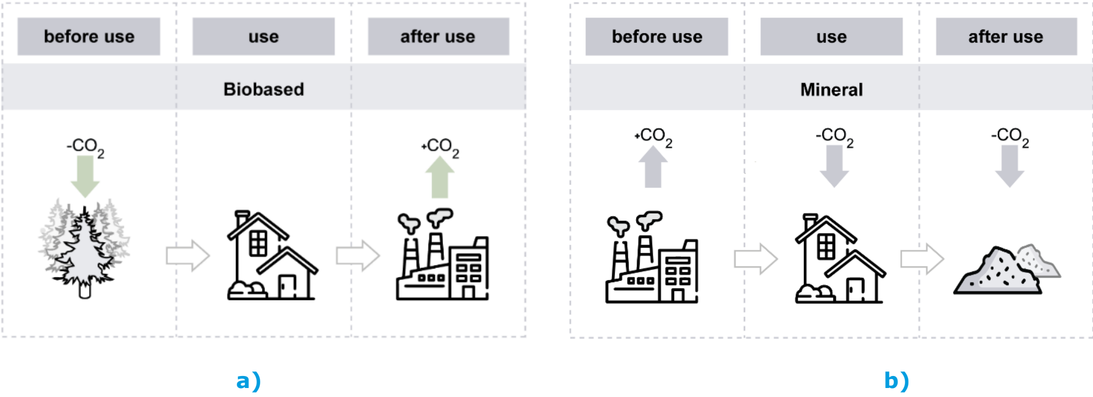

Figure 5: '-1/+1 method' to account for a) biogenic and b) mineral carbon dioxide removal fluxes in this report

2.5 Upscaling to baseline building stocks of EU27 Member States

2.5.1 Baseline building stock characterization per MS

The building stock modelling framework is shown in Figure 6. The first input data is the "EU 27 Building Stock Dataset" which contains data about the building archetypes (e.g. geometry, energy consumption), which are also used by the SLiCE model to create whole-life carbon emission results, and the stock composition in 2020 (e.g. number of buildings, built area, etc.), which was collected as described in Section 2.2. This allows for characterizing the existing building stock. Based on this data, the PULSE-EU model is used to project future building stock activities (e.g. demolition, renovation, new construction, maintenance and replacement) from 2020 to 2050. These activities are linked to carbon emission data using the results from the SLiCE model, as described in Section 2.3. Both the building stock activities and the emissions data can be influenced by the carbon reduction and removal strategies (CRRS), for which the implementation is further explained in Section 2.7.

[43] CEN 2022. EN16757:2022 D Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements

[44] CEN 2019. CEN/TR 17310:2019 D Carbonation and CO2 uptake in concrete

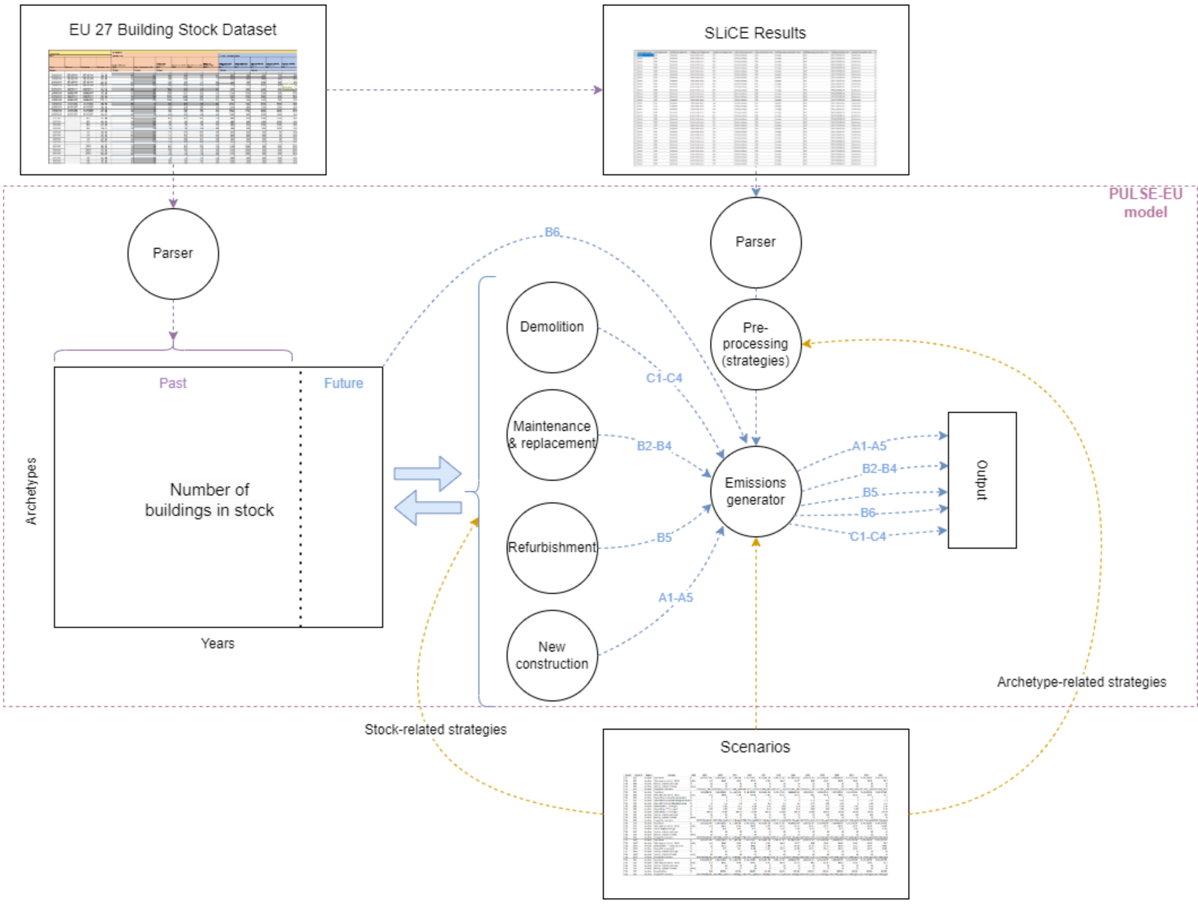

Figure 6. Overview of the building stock modelling framework

The existing building stock is characterized by its total useful floor area, which is taken from the Building Stock Observatory (BSO)[45] for different building archetypes. The shares of occupied dwellings or building units, vacant dwellings or building units and secondary residences are also taken from the BSO. These data are for all buildings represented by these archetypes, which is why we recalculate the number of buildings in the stock by dividing the total useful floor area by the useful floor area per building of the given archetype. The useful floor area per building is taken from the AmBIENCe project. As the data from the BSO include the year 2020, but 2020 is also our first project year, we exclude buildings built in 2020 from the data to avoid double counting. To do that, we assume a linear distribution of the buildings built between 2011 and 2020 over the years and cut off the share for 2020. In terms of naming conventions, archetypes from this time are then renamed 2011-2019 for consistency.

An important aspect of the existing stock is the number of habitants of residential buildings, which we call building capacity. It is the capacity of each building archetype to provide housing to a certain number of occupants. This data is used for calculating the number of new residential buildings but was not provided in the data sources. The number of inhabitants of residential buildings has therefore been recalculated in the following way:

[45] https://building-stock-observatory.energy.ec.europa.eu/database/

1. First, the population data from EUROSTAT for every Member State in 2019[46] are used.
2. Then, the latest EUROSTAT[47] data indicating shares of the population living in different types of residential buildings are used. This provides a distribution per building typology (e.g. single-family house, multi-family house and apartment block).
3. To be able to associate a number of habitants to an archetype, a further division per construction period (e.g. 2011-2019) was needed. The split between construction periods is based on the number of dwellings that each archetype has. These data are taken from Hotmaps.
4. Finally, it is divided by the number of archetypes and by the occupancy (e.g. percentage of use).

The following sections explain the temporal dynamics of the building stock that determine its evolution from 2020 to 2050. Construction and renovation activities are performed on the useful floor area, and not the number of buildings. As such, the useful floor area is the right metric to compare with the BSO and other statistical sources. Due to geometrical differences between the archetypes and real buildings, the number of buildings in the stock might not always fit with national or European statistics. Demolition activities are performed on the number of buildings, due to their difference in implementation.

2.5.2 Upscaling SLiCE archetype results per Member State via PULSE-EU

The calculations related to **demolitions**, which represent the first step of the annual activity calculations of the model, are based on a Weibull function, which is the state-of-the art of the literature for modelling demolition. It calculates the percentage of a typology that is demolished based on use and age. As the building stock model is not probabilistic, the probability is interpreted as the proportion of buildings that will be demolished. If in a specific year, 2.3 buildings need to be demolished, only 2 buildings will be demolished, and the fractional part (0.3) will be carried to the next year. If in the next year, 3.7 buildings will be demolished, then 3.7 + 0.3 = 4 buildings will be demolished. This ensures that even buildings with a very low probability of demolition can be demolished as well. All buildings except medium and deep renovated ones can be demolished (it is considered unlikely within the time frame). Buildings can also be repurposed and therefore saved from demolition depending on the scenario parameters. The scale and shape parameters of the Weibull function are taken from the MESSAGEix-Buildings model[48]. As Croatia was missing, the data of Slovenia were used as proxy. The data for Austria is taken from previous work[49]. An overview of the Weibull parameters is provided in Table 9 in the SI. As the Weibull function requires buildings to have a specific age, but we model archetypes built within time periods, they are not naturally associated to an age, or a construction year. In other words, we know how many buildings were built between 2011 and 2019, but we don't know exactly how many of them were built in 2011, 2012, 2013, etc. To be able to provide each building with a specific construction year, we distribute the buildings of a time period based on the historic population evolution, using the difference

[46] https://doi.org/10.2908/TPS00001

[47] https://doi.org/10.2908/ILC_LVHO01

[48] Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M., & Pachauri, S. (2021). Global scenarios of residential heating and cooling energy demand and CO2 emissions. Climatic Change, 168(3–4), 1–26. https://doi.org/10.1007/S10584-021-03229-3/FIGURES/7

[49] Alaux, N., Schwark, B., Hörmann, M., Ruschi Mendes Saade, M., & Passer, A. (2024). Assessing the prospective environmental impacts and circularity potentials of building stocks: An open-source model from Austria (PULSE-AT). Journal of Industrial Ecology, 14(1). https://doi.org/https://doi.org/10.1111/jiec.13558

between two years as a weighing percentage. The number of demolished buildings is then multiplied by the C1-C4 emissions provided in the SLiCE input data.

Renovations, the second step of the model, are thermal refurbishments only and are calculated by specifying a renovation rate (which refers to the useful floor area) in the scenario parameters for three renovation packages (low, medium and deep renovations). A renovation package is understood as a set of measures that can reduce the energy use of buildings by 25% (light), 50% (medium) or 75% (deep) with every medium and deep renovation carrying a change in heating system. Not all buildings have these three renovation packages. For instance, very energy efficient buildings can only be renovated with a light renovation package. Buildings built after 2010 are not eligible for renovation, because we consider this unlikely in the time frame. Every building can only be renovated once. We assume that buildings which are repurposed, and therefore saved from demolition (as mentioned in the previous section), are renovated with a deep renovation package. If they don't have a deep renovation package, they cannot be saved from demolition. Current renovation rates for the baseline are taken from EUcalc[50]. The specified renovation rates are assumed to apply to all typologies, construction material types and heating types in an equal way. A distribution of renovation across construction periods is performed (see Table 10 in the SI). If one time period is fully renovated, the remaining renovation needs are redistributed on the other epochs in the same typology (but there is no redistribution across typologies). If there are no more buildings of a typology to renovate, it stops. The same occupancy level is considered for renovations as for non-renovated buildings (no other data were available). The number of renovated buildings is then multiplied by the B5 emissions provided in the SLiCE input data.

Calculating the number of **new constructions** is the third step of the model. The dynamics behind the construction of new buildings differs between residential and non-residential buildings. The number of new useful floor area of residential buildings was calculated as follows:

1. First, the evolution of the population from 2020 to 2050 was taken from EUROSTAT[51] and assumptions on the future evolution of the average living area per person (m^2/cap) in the same period (which is derived as explained below). This results in an amount of useful floor area that is needed for housing every year. It is assumed that the average living area per person corresponds to the total useful floor area of buildings in use divided by the total population of this specific year. This might cause differences to other models or data sources, if the considered area is different, or if the vacant stock is included in this area.
2. Second, the capacity of the building stock to provide housing is calculated. This is done by calculating the total useful floor area of residential buildings which are in use. This of course depends on how many buildings are demolished and on the vacancy rate, and can thus be influenced by various scenario parameters.
3. The difference between the demand for living area and the building stock capacity corresponds to the newly built area.
4. We did not find recent plausible assumptions for the future evolution of the average living area per person. However, we have some evidence on the amount of buildings currently built. The building permits are reported in the EUROSTAT[52]. Statistical data from countries

[50] http://tool.european-calculator.eu/intro

[51] https://doi.org/10.2908/PROJ_23NP

[52] https://doi.org/10.2908/STS_COBP_A

such as France[53] or Germany[54] show that there can be about a 20% difference between the number of building permits and the built area (since not all permits are actually built).

5. The country-specific increase of m2/cap from 2020 to 2050 has therefore been calibrated, with the aim to achieve 80% of the building permit area. A linear evolution of the m²/cap from 2020 to 2050 has been assumed. As reference value the average over a ten-year period (2014-2023) was used, which we believe is more robust to calibrate the model. As model value, the average over the first four model years (2020 - 2023) was used, as this overlaps with the reference period. To avoid extreme values and stay within the increases in m²/cap that were observed in the past and are plausible[55], the increase in m²/cap was limited to a lower value of 0.5% and an upper value of 100%. The relative increase in m²/cap in 2050 compared to 2020 for each Member State is provided in the SI in Table 11 and the difference between the reference values and the model can be seen in the SI in Figure 27.

For non-residential buildings, about 80% of the delivered building permits (averaged between 2014 and 2023) are taken as a reference. However, in our current modelling, the evolution of the population is the only driver for the number for calculating new non-residential buildings. To account for this modelling limitation, which does not include all drivers behind the construction of non-residential buildings, we artificially increase this number to reach 80% of delivered permits. This has the exact same effect as applying a construction rate but has the advantage of allowing for the implementation of scenario parameters, such as reducing vacancy.

Unless specified by the scenario parameters, the typology distribution and occupancy of new buildings are assumed to be the same as the latest construction decade (2011-2019), which means for instance that the share of new single-family houses remains unchanged. Archetypes of new buildings are assumed to use current construction techniques, and additional full or hybrid timber archetypes can be used in specific scenarios. Regarding energy performance of new buildings, the reference shares of nearly-zero energy buildings are taken from previous reports[56] but can also be influenced by the scenarios. The number of buildings constructed is then multiplied by the A1-A5 emissions provided in the SLiCE input data.

Emission data for **maintenance** (B2), **replacement** (B4) and **operational energy use** (B6) are provided on an annual basis for 50 years in the SLiCE input data, as required in the life cycle assessment of buildings. However, at the stock level, the annual maintenance, replacement and energy use are calculated by the model, assuming that, for every year, these operations are needed for occupied or secondary buildings (empty dwellings are not considered for use phase operational and embodied carbon emissions). Therefore, a yearly average of the 50 years from the emission data is performed for B2, B4 and B6. This average is then used for upscaling. Maintenance (B2) and replacements (B4) can be affected by the scenarios (material-related strategies) and, apart from renovation, operational energy use (B6) can be affected by the future intensity of the electricity or district heating mix, as well as changes in temperature set points.

[53] https://www.insee.fr/en/statistiques/serie/001717752

[54] https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Tabellen/baufertigstellungen.html

[55] Thema, J., Cordroch, L., Parschau, J., Graser, G., & Wiese, F. (2024). Where and how do people live? Modelling the occupation of the German building stock by households. ECEEE SUMMER STUDY PROCEEDINGS.

[56] European Commission. (2019). Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU.

2.5.3 Calibration of model results

Due to differences observed between the operational emissions (B6) of the SLiCE input data and other sources, such as the BSO, a calibration of the B6 emissions for the baseline year (2020) is performed. These differences arise from several factors, including the use of a semi-static energy performance method in our building model, and the varying building layouts and orientations across the building stock. The calibration is performed using reference emissions for 2020 from the BSO. Direct emissions are overtaken as provided. However, due to differences in modelling scope for indirect emissions, they could not be directly overtaken (we only model heating, cooling and ventilation but not electrical appliances). The scope 2 from the BSO is hence reduced by a certain share to exclude non-heating related electricity. This share is taken from EUcalc because this is specified (in the BSO the split of indirect emissions per type of use is unfortunately not provided). The reference B6 emissions calculated for the EU27 are provided in Table 12 in the SI. Our results for 2020 are then scaled by a calibration factor to reach the reference values. Since numbers of buildings are rounded during upscaling, it might be that our results for 2020 slightly differ from these reference values, as can be seen in Table 12. This calibration of operational emissions is applied to every year from 2020 to 2050 (meaning that the operational carbon emissions of every year are multiplied by the ratio of the calibrated value to the original value). It is based on the GWP total indicator but applied to all indicators.

2.6 Carbon reduction and removal strategies (CRRS)

The modelling of future scenarios in this study is based on the combination of different settings for the implementation of carbon reduction and removal strategies (CRRS). The scenarios are modelled through different settings of key parameters such as "diffusion" of a strategy, meaning different ambition levels for the uptake of individual CRRS across Member States. Details on the selection and definition of CRRS have been established in earlier reports of this study[57]. An elaborated version has furthermore been published as a journal article by Alaux et al.[58]

The following CRRS and related measures are considered in the modelling:

Avoid

- **Increase repair and renovation:** This strategy emphasises the preservation and enhancement of existing structures and spaces. This approach seeks to reduce emissions by avoiding the use of new materials, while also retaining cultural and historical value of existing buildings.
- **Increase material efficiency:** This strategy considers emissions savings from optimizing the use of construction materials. This involves lightweight construction methods and prefabrication and modular construction. By implementing efficient material practices, this strategy aims at mitigating emissions associated with resource extraction, manufacturing, transportation and construction, i.e. embodied emissions.

[57] Marton, C., Steinmann, J., and Petrou, D. "Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction - Mapping of the Most Promising Carbon Reduction and Removal Strategies, Taking into Account National Contexts." European Commission - DG GROW, Ramboll, KU Leuven, BPIE, 2023. https://ec.europa.eu/docsroom/documents/58195.

[58] Alaux, N, et al. (2024) Whole-Life Greenhouse Gas Emission Reduction and Removal Strategies for Buildings: Impacts and Diffusion Potentials across EU Member States. *Journal of Environmental Management* 370: 122915. https://doi.org/10.1016/j.jenvman.2024.122915.

- **Reduce construction waste:** This strategy focuses on reducing emissions by minimising construction and demolition waste (CDW). By preventing the generation of waste, this strategy promotes resource conservation and contributes to emissions savings by reducing the need for the production and disposal of construction materials.
- **Reduce space per capita:** This strategy focuses on improving sufficient use of buildings by decreasing average individual space demand. The number of users and the floor space per user determine the amount of built area that is required. If the overall area that is occupied per user can be reduced, the demand for new construction also decreases.

Shift

- **Increase circularity and reuse:** This strategy aims at mitigating emissions by emphasising the reuse, recycling, and repurposing of construction materials, components, and products. These strategies aim at extending the service life of entire building elements or increase the degree of recycled content in construction products, both leading to lower demand for new materials and primary resources. By embracing circular material flows, these efforts contribute to embodied emissions reductions by reducing material production and disposal.
- **Increase bio-based solutions:** This strategy focuses on replacing conventional construction materials with bio-based alternatives, such as those derived from agricultural plants and trees. These materials have a lower embodied carbon footprint due to their natural growth processes and offer carbon sequestration capabilities, leading to potential carbon removals.
- **Increase carbon dioxide removal:** This strategy relates to using additional carbon dioxide removals (CDR) solutions not yet in scope of other strategies. It involves implementing technologies and practices that actively capture and durably store atmospheric CO_2 and contribute to negative emissions. Focus is on CDR solutions applied in scope of the building as such and not its surroundings (the wider built environment).

Improve

- **Reduce operational energy:** This strategy aims at improving the energy efficiency of buildings during their operational phase as an essential element of reducing the WLC emissions from the EU building stock. This strategy includes seven renovation measures contributing to reducing operational carbon emissions, organized per type of energy saving that is achieved. The strategy is also linked to the uptake of energy efficient options for new buildings.
- **Improve conventional materials:** This strategy focuses on the embodied emissions from conventional construction materials, which contribute to a significant share of the building sectors' total carbon footprint. By introducing substitute materials and improving manufacturing processes, this strategy seeks to lower the impacts associated with commonly used construction materials like concrete, steel, and aluminium.
- **Reduce transport emissions:** This strategy focuses on curbing embodied emissions by improving the transportation logistics associated with construction materials. This entails, amongst others, reducing the distance materials travel to construction sites by favouring local sourcing and employing low-carbon transportation alternatives.
- **Reduce construction process:** This strategy addresses construction machinery and equipment used on site, the main contributors to emissions in the construction phase. Currently, construction machines generally run on fossil fuels, usually diesel. Implementing

fuel switching, using more efficient machines and optimising site logistics to reduce machine idling and fuel consumption can help mitigate emissions from construction sites.

2.7 Modelling of future scenarios for EU buildings and construction

2.7.1 Methodological framework for scenario modelling

The scenario modelling framework created considers different CRRS, the capacity of each Member State (MS) to implement these strategies and their ambition to do so. This framework is flexible and can be used for generating both the policy narratives, as well as the other explorative scenarios. It builds on previous work, especially report D1.2 on the most promising CCRS considering national contexts. An overview of this framework is shown in

Figure 7 and is described in detail in the SI.

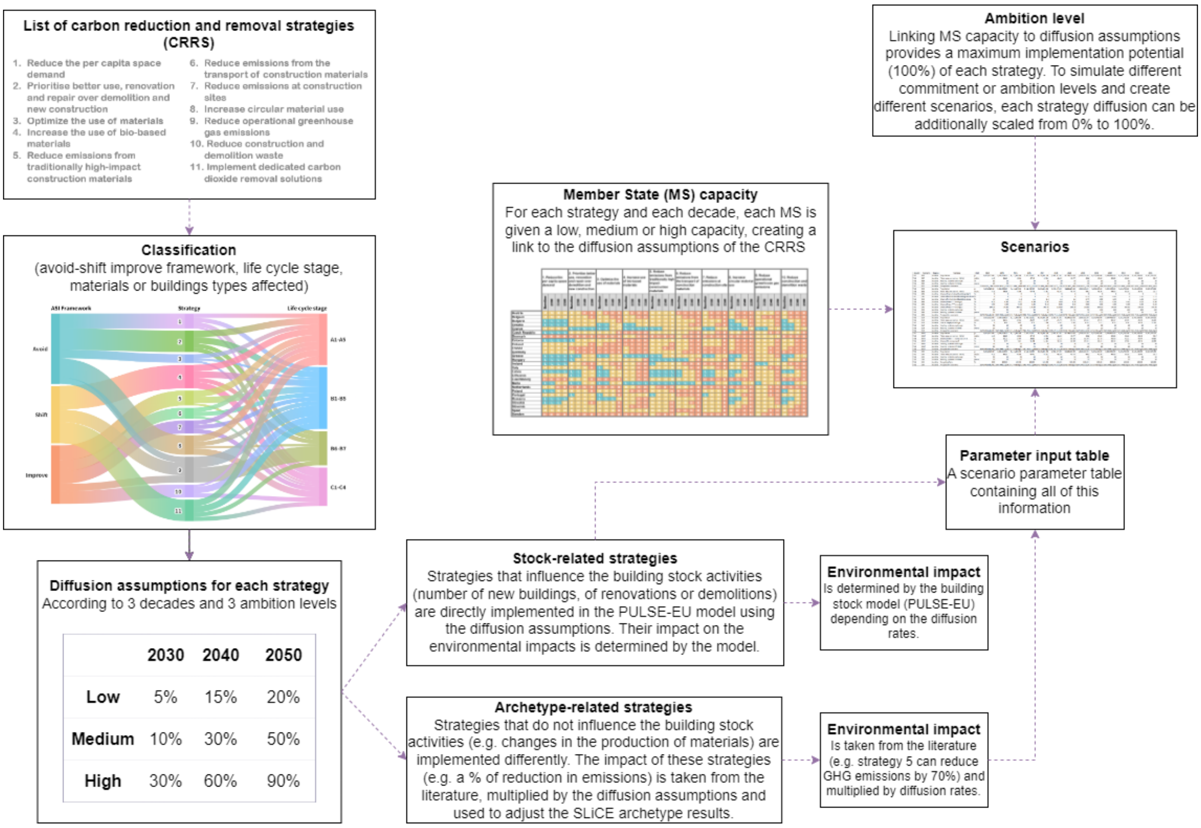

Figure 7: Overview of the scenario modelling framework (based on Alaux et al.[59]).

2.7.2 Pre-defined policy scenarios (CPOL, APOL)

The pre-defined policy scenarios assessed represent aspirational scenarios, i.e. modelled to represent a certain policy ambition. These consist of current policies (CPOL) and additional policies (APOL). Explorative scenarios, deviating from those policy targets, are moreover presented in order

[59] Alaux, N, et al. (2024) Whole-Life Greenhouse Gas Emission Reduction and Removal Strategies for Buildings: Impacts and Diffusion Potentials across EU Member States. *Journal of Environmental Management* 370: 122915. https://doi.org/10.1016/j.jenvman.2024.122915.

to better understand the “solution space”, meaning emission reduction pathways reasonable within the modelling implemented in this study considering the various types of CRRS (see next section).

As described in section 2.6, the CRRS have been categorized into **avoid (A)**, **shift (S) or improve (I)** strategies. The implementation of the CRRS related to these ‘ASI’ measures are modelled based on the scope, impact, and diffusion potential identified from scientific literature and expert consultation as established via the collection of available data and information on whole life cycle GHG emissions and carbon removals.

The pre-defined policy scenarios and related narratives focused on in this report are as follows:

- **CPOL/A: Optimistic current policy scenario.** Assuming current policies are fully delivering, and policy targets are being met as planned.
- **CPOL/B: Conservative current policy scenario.** Implementation of current policies but assuming transposition and implementation may encounter socio/technical challenges.
- **APOL/A: Optimistic additional policy scenario.** Based on the latest EU policy ambition outlined in the CLIMA 2040 target study[60], aiming for 90% reduction of GHG emissions in scope by 2040. In this scenario, remaining direct CO_2 emissions compensated using biofuels in 2050.
- **APOL/B: Conservative additional policy scenario.** Implementation of additional policies, but assuming transposition and implementation may encounter socio/technical challenges.

2.7.3 Exploratory scenarios: Solution space

To explore the solution space, two theoretical extreme scenarios are also assessed. They define the boundaries of the solution space in this modelling:

- **BAU: Business-as-usual scenario.** This scenario is a projection of the baseline activity rates until 2050 and is only affected by population development. There is no implementation of the strategies. This is a reference scenario that is created to be able to assess the influence of the scenario narratives on reducing carbon emissions.
- **ALL/HIGH: High diffusion across all MS.** This scenario shows the maximum theoretical implementation potential of the strategies, meaning that all strategies are fully implemented in the Member States to a high diffusion level, to estimate the maximum carbon reduction potential that is achievable in the current modelling.

2.8 Validation model - MESSAGEix Building

This study deploys the MESSAGEix-Buildings modelling framework, developed by IIASA, to validate the results of the SLiCE-PULSE models. MESSAGEix-Buildings[61] is a bottom-up building sector model to assess energy, material demands, and GHG emissions of buildings at the regional and global scales under different socioeconomic, technological, climate and policy scenarios. We use two

[60] Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society (COM/2024/63 final). Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en (Last accessed 13/08/2024)

[61] Mastrucci, A., van Ruijven, B., Byers, E. *et al. Global scenarios of residential heating and cooling energy demand and CO2 emissions. Climatic Change 168, 14 (2021). https://doi.org/10.1007/s10584-021-03229-3*

modules of the MESSAGEix-Buildings framework: CHILLED (Cooling and Heating gLobaL Energy Demand model), a bottom-up engineering model to estimate space heating and cooling energy demand; and STURM (Stock TURnover Model of global buildings), a stock turnover model based on dynamic Material Flow Analysis (MFA) to assess new constructions, demolitions and refurbishment activities.

This framework is flexible in both temporal and spatial resolution, allowing for a highly granular representation of key household dimensions—such as location, income, and tenure—and building characteristics, including housing type, energy efficiency standards, and fuel use. The model can be soft-linked with the Integrated Assessment Model (IAM) MESSAGEix-GLOBIOM to incorporate energy price feedback, enabling a joint assessment of energy demand-side and supply-side aspects.

In this study, we apply the model to analyse material and energy demands, and associated GHG emissions, for residential and non-residential buildings across the 27 EU Member States. The analysis runs from the base year (2020) to 2050, with a 5-year time step. For results validation, key outputs of the SLiCE-PULSE and MESSAGEix-Buildings model are compared for residential and non-residential buildings focusing on three selected scenarios: BAU, CPOL/A, CPOL/A+ALL (see Section 3.4). The CRRS are modelled following the same logic and assumptions as in SLiCE-PULSE (Sections 2.6-2.7). Some adaptations and omissions were necessary for a limited set of strategies that cannot be fully represented in the current version of MESSAGEix-Buildings, such as vacancy reduction (Avoid) and biobased insulation (Shift). More details on the modelling of the EU building stock and relevant impacts are presented in the subsequent sections.

2.8.1 Building stock modelling

The European implementation of MESSAGEix-Buildings represents Member States as specific model regions. The dimensions considered in the model are the following: location (urban and rural), residential and non-residential building subtypes, vintage and energy efficiency standards for existing, refurbished, and new buildings, construction system and materials, and heating systems. For validation, the scope, resolution, and data are aligned with the primary model (SLiCE-PULSE) wherever possible. This includes:

- Characterizing existing building stocks through subtypes, age structures, and energy performance.
- Future stock evolution trends based on floor area changes.
- Synchronizing demolition and renovation activities using consistent service life assumptions and renovation rates.

The model was calibrated using available data on activity rates, where possible on a country level basis. Due to the nature of the model and data structures some differences persist with the primary model, namely in the accounting of materials, energy demand, and embodied and operational emissions, as described in the next paragraph.

2.8.2 Building materials, energy, and emissions modelling

Six key **construction material** types are included in the analysis: concrete, steel, aluminium, copper, wood, glass. Materials for insulation and renovation are excluded. Material intensity coefficients in the baseline, representing the amount of material per unit of floor area, are sourced from the literature[62] [63]. The material intensity coefficients are described in detail in previous reports[64]. This represents a subset of the construction materials considered in the SLiCE-PULSE model.

Energy demands for space heating, cooling, and domestic hot water for different building subtypes are calculated using the embedded CHILLED energy demand model. In the case of heating, the share of different energy carriers (biomass, gas, oil, coal, electricity and district heating) is considered. This differs from SLiCE-PULSE, where a more limited set of energy carriers is included. Explicit accounting of energy carriers enables detailed calculation of operational direct emissions (e.g. from fuel combustion in buildings, including gas, oil, and coal) and indirect emissions (from electricity and district heating).

For **GHG emission** calculations, we account here for two main stages of the life cycle of buildings, namely the construction stage and operational stage, and focus on fossil emissions. GHG emissions are calculated by applying embodied and operational emission factors to material demands for new construction and energy demands respectively. Emission factors for material production are based on the SliCE archetypes results (Section 2.3). Operational emission factors for energy use are derived for different energy carriers from the MESSAGEix-GLOBIOM integrated assessment model (IAM). In the BAU scenario, emission factors for electricity and district heating reflect the future evolution of the energy supply system under the National Policies Implemented (NPi) scenario, reflecting a continuation of current policies. Non-CO_2 emissions are currently not included in the calculation. Due to differences observed in the base year results, a calibration was run to ensure improved consistency across the two models and with observed data (Section 2.5.3).

[62] Marinova, S., S. Deetman, E. van der Voet, and V. Daioglou. 2020. Global construction materials database and stock analysis of residential buildings between 1970-2050. Journal of Cleaner Production 247: 119146.

[63] Deetman, S., S. Marinova, E. van der Voet, D.P. van Vuuren, O. Edelenbosch, and R. Heijungs. 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. Journal of Cleaner Production 245: 118658.

[64] European Commission. 2024. Analysis of Life-Cycle GHG emissions and removals of EU buildings and construction - Baseline Analysis Report

3. RESULTS: WLC EMISSIONS AND REMOVALS (2020-2050)

3.1 Building archetype baseline

In the following, first the total GHG emissions results are presented as annualized values for whole life cycle GHG emissions per building type. Annualized values express the cumulative GHG emission results divided by the years of the reference study period (RSP) of 50 years. Figure 8 presents the embodied and operational whole life carbon emissions per m² useful floor area (UFA) and year for the new building archetypes (excluding new timber archetypes) based on impact assessment following EN15804+A2.

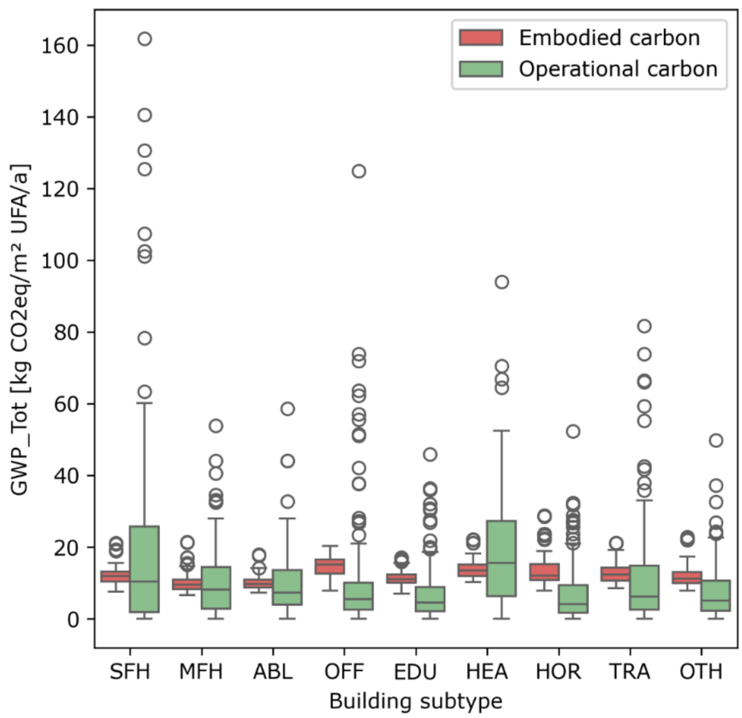

Figure 8: EU27 averages and distribution of whole life cycle embodied and operational carbon emissions per m² and year (GWP total, annualized) for new building archetypes (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

As presented in Figure 8, embodied GHG emissions across the whole life cycle are around 10.1 to 14.9 kgCO2eq/m²/a on average, with values ranging from about 6.7 to 28.9 kgCO2eq/m²/a. The analysis per building use type shows that whole life embodied GHG emissions per m² and year tend to be lowest for ABL (10.1 kgCO_2eq/m²/a on average), highest for OFF (14.9 kgCO_2eq/m²/a on average). Operational GHG emissions across the whole life cycle are around 7.1 to 21.0 kgCO_2eq/m²/a on average, with values ranging from as little as 0.1 kgCO_2eq/m²/a up to almost 161.9 kgCO_2eq/m²/a (considering outliers).

Figure 9 presents the embodied and operational whole life carbon emissions per m² useful floor area (UFA) and year for the new building archetypes across the EU Member States. The analysis for the whole life embodied carbon per country tends be lowest on average for Slovakia (9.1

kgCO_2eq/m²/a) and highest for Spain (17.0 kgCO_2eq/m²/a). Variations across countries can be related to varying building layouts, element materializations and life cycle scenarios. Higher variations across countries are found for the whole life operational carbon ranging from on average 4.5 for Denmark to up to 29.5 kgCO_2eq/m²/a for Romania caused by the carbon intensity of the different energy mixes and the HVAC systems used (i.e. heating by gas or electricity).

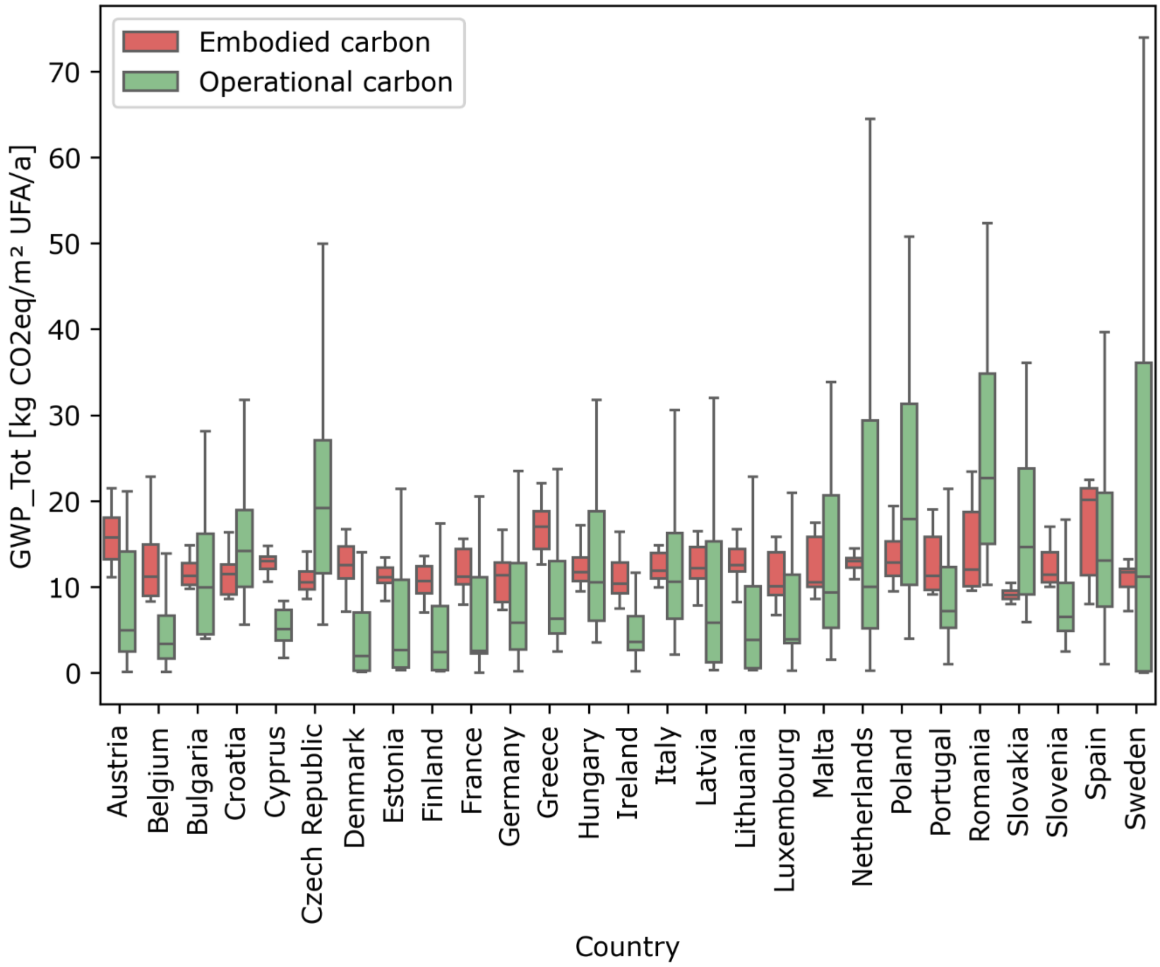

Figure 9: Member State level average and distribution of whole life cycle embodied and operational carbon emissions per m² and year (GWP total, annualized) for new building archetypes.

Figure 10 illustrates the whole life embodied carbon per square meter of useful floor area for the most prevalent building typologies: new single-family houses (SFH), multi-family houses (MFH), office buildings (OFF), and healthcare buildings (HEA) across EU Member States. The variations observed across different countries can be attributed to differences in building materials, the efficiency of building layouts, and life cycle scenarios, such as varying replacement rates. Within individual countries, the spread is related to the limited number of variants, with variations primarily linked to differences in energy performance and building system. For SFH in specific, the differences are limited, while for other building types this results in higher disparities in some countries compared to others. Notably, Nordic countries exhibit a broader range of embodied carbon due to a greater variety of system variants, except for single-family houses.

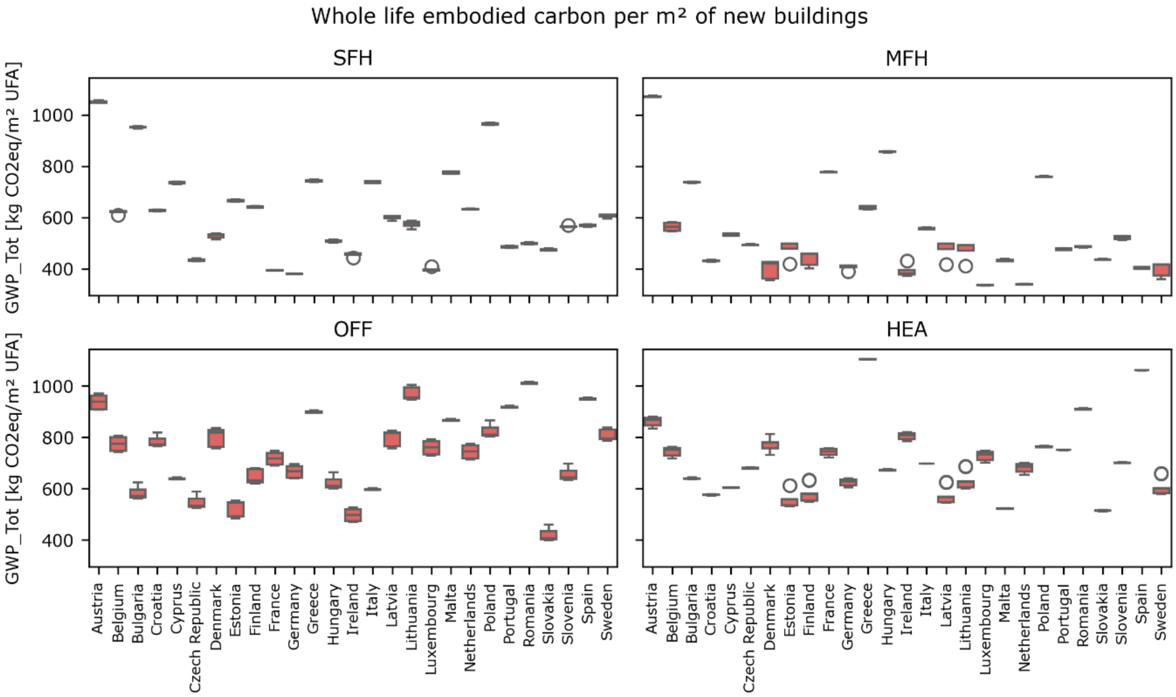

Figure 10: Boxplot of Member State level whole life cycle embodied carbon emissions per m² for the new building archetypes (excluding timber archetypes) for each Member State based on impact assessment following EN15804+A2. Results displayed for a selection of relevant building use subtypes: Single-family houses (SFH), Multi-family houses (MFH), Offices (OFF) and Health buildings (HEA). Outliers are indicated with a circle.

3.1.1.1 *Life cycle stages*

Figure 11 illustrates the whole life cycle embodied carbon (GWP Fossil) across the different life cycle stages. The Production stage (A1-A3) has the highest contribution across all building types and shows a range between 359.1and 539.38 kgCO2eq/m²UFA on average, with minimum and maximum values spanning from 219.3 up to 1132.8 kgCO2eq/m²UFA. Across all building types, the production has a share between 67% and 74% to the total whole life cycle embodied carbon. The Replacement stage (B4) is the second most important life cycle stage on average ranging between 42.7 kgCO2eq/m²UFA for TRA and 106.9 kgCO2eq/m²UFA for HEA, and minimum and maximum values from 19.6 to 208.6 kgCO2eq/m²UFA. The contribution of this stage to the total embodied carbon ranges from 7% for TRA to up to 16% for HEA. The third most contributing life cycle stage is the Transport to construction site stage (A4) with on average between 31.0 and 56.4 kgCO2eq/m²UFA, with minimum and maximum values ranging from 5.8 to 169.1 kgCO2eq/m²UFA. Across all archetypes, A4 contributes on average between 6% and 9% to the whole life cycle embodied carbon.

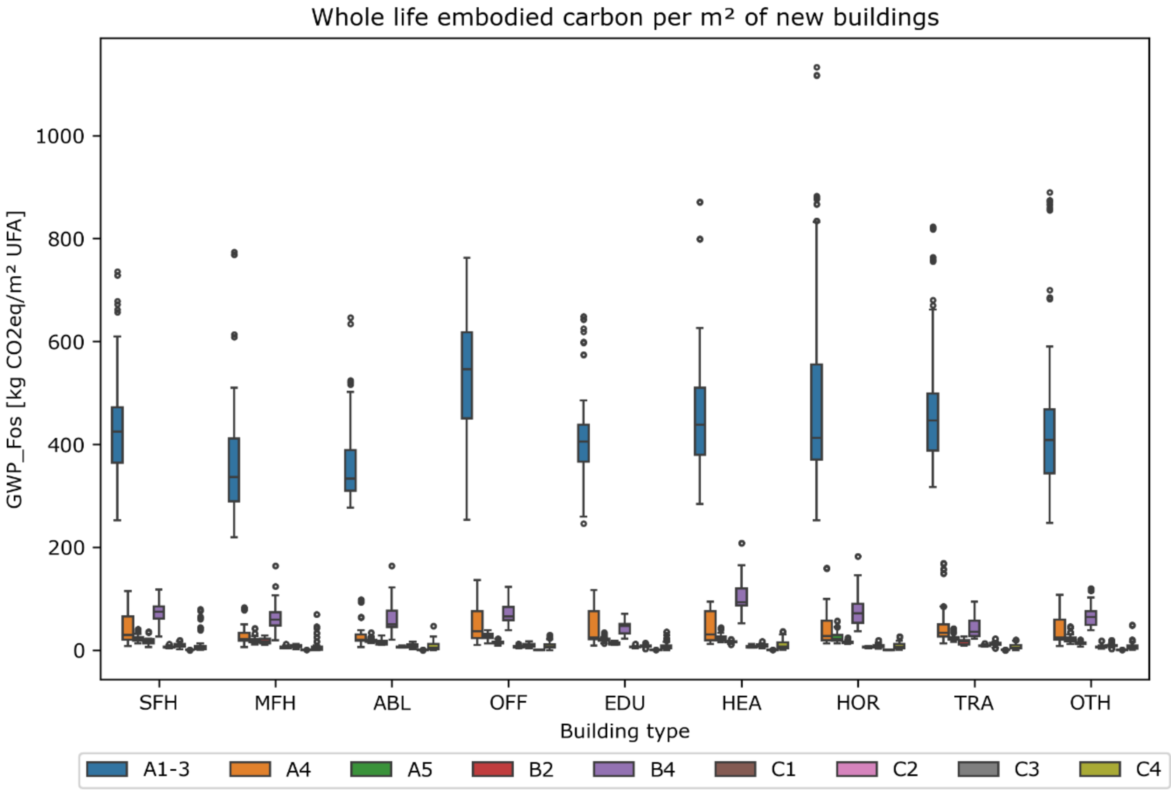

Figure 11: Boxplot showing distribution of whole life embodied carbon (GWP Fossil) per m² useful floor area for new building archetypes (not including new timber building archetype variants) grouped per building use type and life cycle stage. Outliers are indicated by circles. (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)). The different boxes indicate life cycle stages acc. to EN15978 (A1-3: Production stage; A4: Transport to site; A5: Construction and installation process; B2: Cleaning and maintenance; B4: Replacement; C1: Deconstruction and demolition process; C2: Transport to waste processing; C3: Waste processing; C4: Disposal).

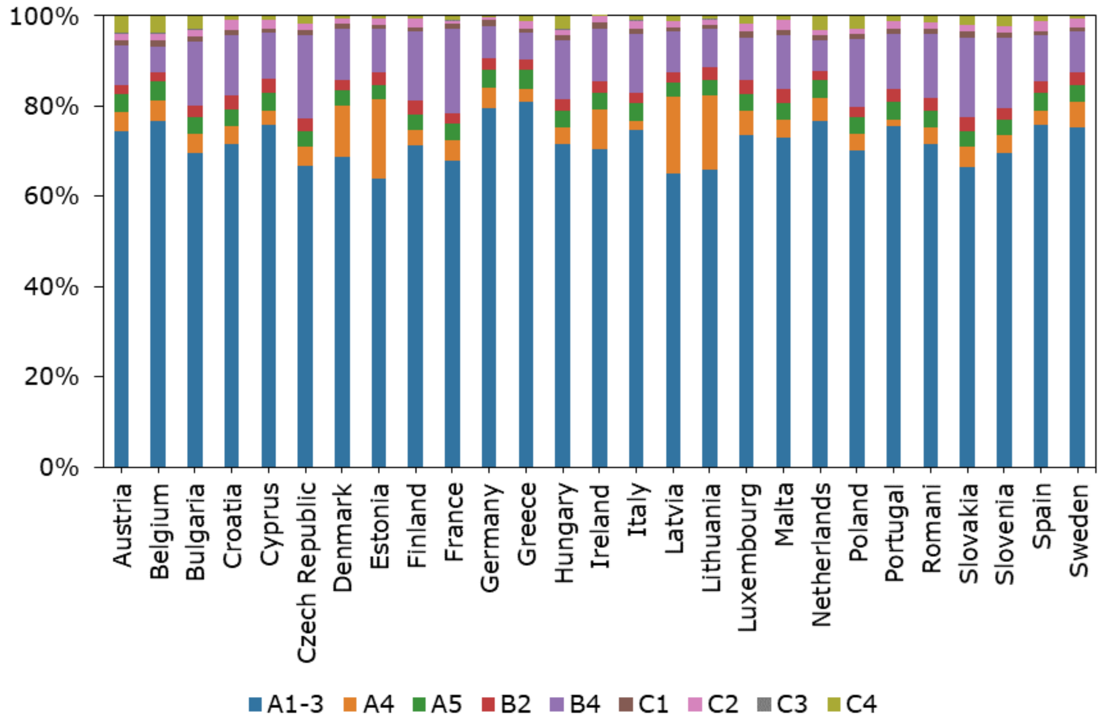

Figure 12: Average share of life cycle stages (in %) to whole life embodied carbon (GWP Fossil) for new building archetypes (excluding new timber building archetypes) grouped EU Member State.

Figure 12 illustrates the average relative contribution of different life cycle stages to the whole life embodied carbon (GWP Fossil) across various EU Member States. Notable cross-country variations are observed in A4, with the Nordic countries exhibiting higher contributions (11% to 17%) compared to other countries (2% to 9%), attributed to the national scenarios implemented for A4. B4 displays a broader range of variation across countries (from 6% to 19% share), influenced by national scenarios for replacement frequencies of different building elements and the national scenarios for A4.

3.1.1.2 Building elements

Figure 13 presents the Upfront embodied carbon (GWP Fossil, A1-5) per m² useful floor area for the new building archetypes (excluding timber archetypes) grouped by building use type and element class. The contribution of the different element classes differs across building types. For the residential sector, the substructure is the most important element class with on average 130.1 to 182.2 kgCO2eq/m² UFA. For SFH, the external walls (i.e. 121.4 kgCO2eq/m²UFA on average) and roofs (i.e. 68.8 kgCO2eq/m²UFA on average) are the two most important element classes in addition to the substructure, while for MFH and ABL these are the storey floors (i.e. 67.1 to 74.7 kgCO2eq/m²UFA on average), external walls (47.5 to 53.1 kgCO2eq/m²UFA on average) and electrical services (i.e. 46.4 to 48.8 kgCO2eq/m²UFA on average). For the non-residential sector, the substructure is on average the most important element class for the building types with limited storeys (i.e. OTH, EDU and TRA ranging between 130.1 and 258.1 kgCO2eq/m²UFA on average), while for OFF this is the electrical services (144.5 kgCO2eq/m²UFA on average) and external walls (i.e. 128.9 kgCO2eq/m²UFA on average), for HEA the electrical services (120.0 kgCO2eq/m²UFA on average) and, substructure (97.6 kgCO2eq/m²UFA on average), and the storey floors (90.1 kgCO2eq/m²UFA on average) and for HOR the electrical services (161.2 kgCO2eq/m²UFA on average), substructure (112.1 kgCO2eq/m²UFA on average), and the storey floors (90.2 kgCO2eq/m²UFA on average).

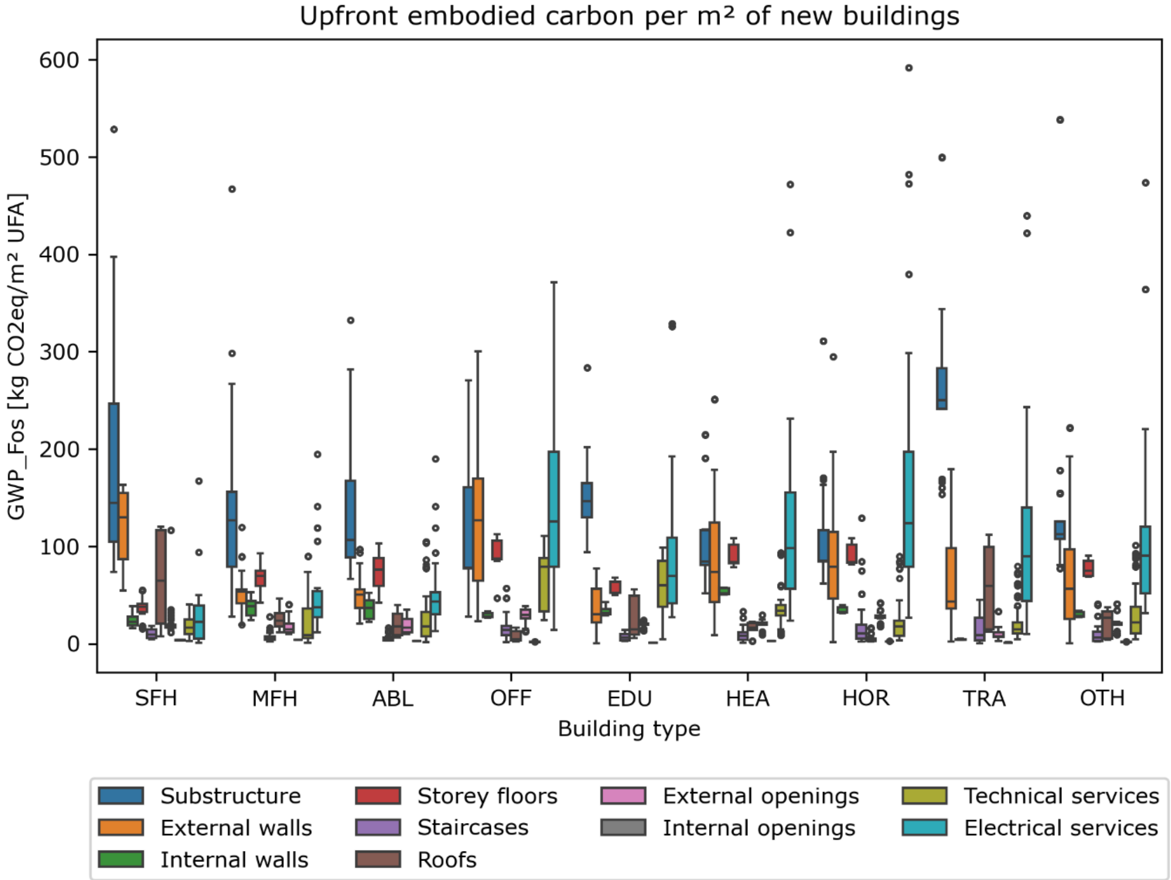

Figure 13: Upfront embodied carbon (GWP Fossil) per m² useful floor area for new building archetypes (excluding new timber building archetypes) grouped per building use type and element classes (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

3.1.1.3 Materials

Figure 14 presents the distribution of whole life embodied carbon (GWP Fossil) per m² useful floor area for the different building types grouped by material category according to the material categories included in the MESSAGEix-Buildings model of IIASA. The materials in the JRC CDW report[65] are classified in a more differentiated way (higher number of material classes), leading to a more differentiated perspective regarding the contribution of different material classes. Only NEW archetypes (excluding new timber archetypes) are included in this analysis.

The 'Other' category has overall the highest contribution, linked to different materials grouped in this category, (ranging between on average 135.1kgCO2eq/m² to up to 242.6 kgCO2eq/m²) except for the TRA, and ABL where 'Concrete' has the highest contribution. Excluding, 'Other', and in line

[65] "Background Data Collection and Life Cycle Assessment for Construction and Demolition Waste (CDW) Management - Publications Office of the EU." Accessed October 10, 2023. https://op.europa.eu/en/publication-detail/-/publication/623326e6-8274-11ed-9887-01aa75ed71a1/language-en.

with D2.1 Report with quantitative baseline figures for WLC and carbon removals the highest contribution at building level is from 'Concrete'. Across most building types, the second and third largest contribution is from 'Steel' and 'Brick' materials. For HEA, HOR, TRA and OTH, 'Brick' has on average a higher overall contribution compared to 'Steel'. For SFH, 'Plastic' comes forward as on average the most important material after 'Other'.

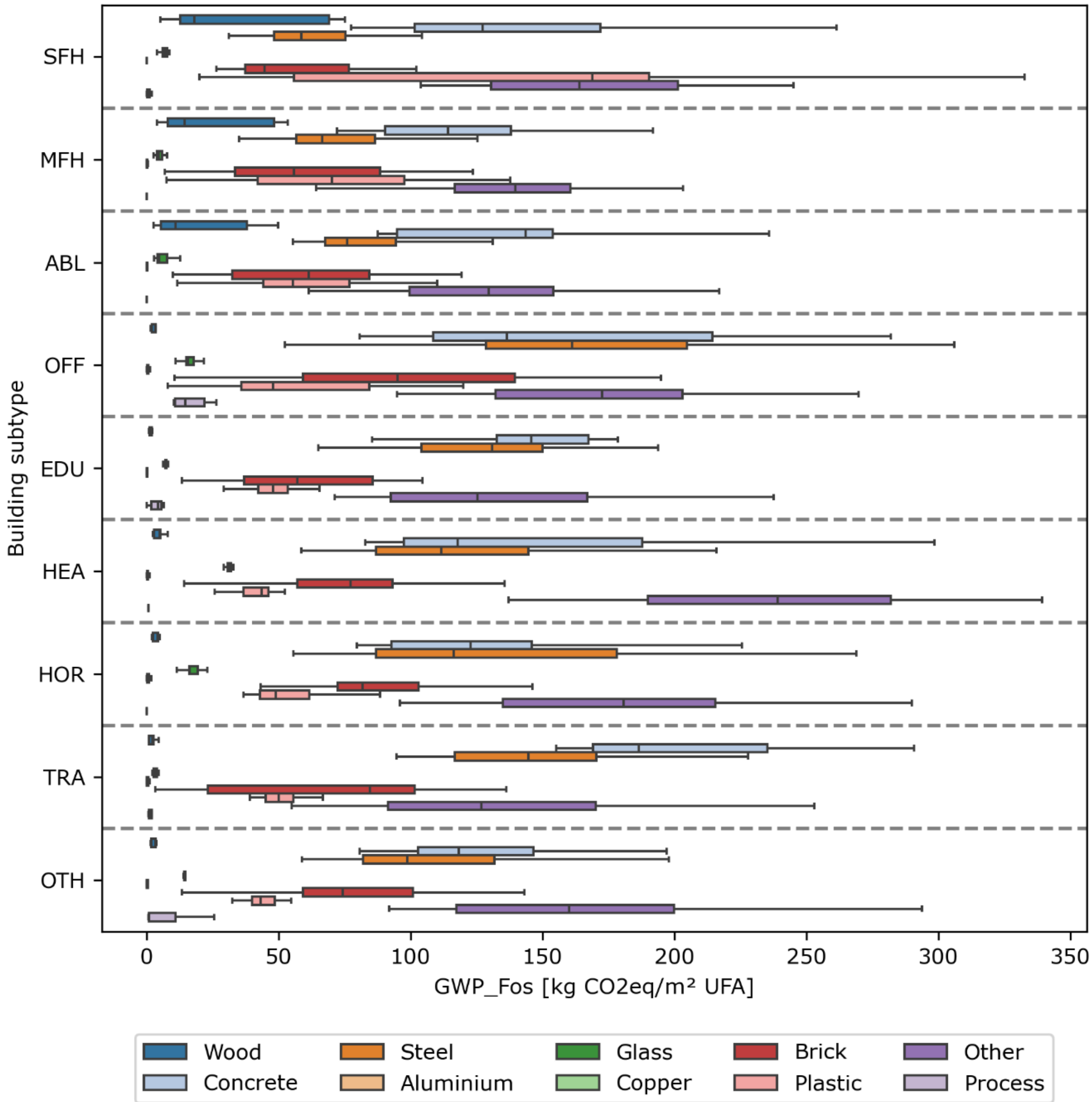

Figure 14: Whole life cycle embodied carbon (GWP Fossil) per m² per building type and material class. Showing results for new baseline building archetypes (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

3.1.1.4 Carbon Dioxide Removal Quantification on Archetype level

Herein, the results of the carbon removal quantification on archetype level are presented. First, it must be noted that these results are not obtained via LCA in the classical sense, but rather via a quantification of the carbon dioxide fluxes based on the materials entering and leaving the building system boundary. Figure 15 starts by showing the biogenic carbon dioxide stored via **bio-based**

materials in module A1-3 in the NEW archetypes modelled for the 27 Member States. These results show the ranges of biogenic carbon that physically reach the archetypes and is stored within the archetype for the reference service life of the elements. We hereby show the ranges of biogenic carbon dioxide storage for conventional construction, mass timber construction and hybrid timber construction for comparison.

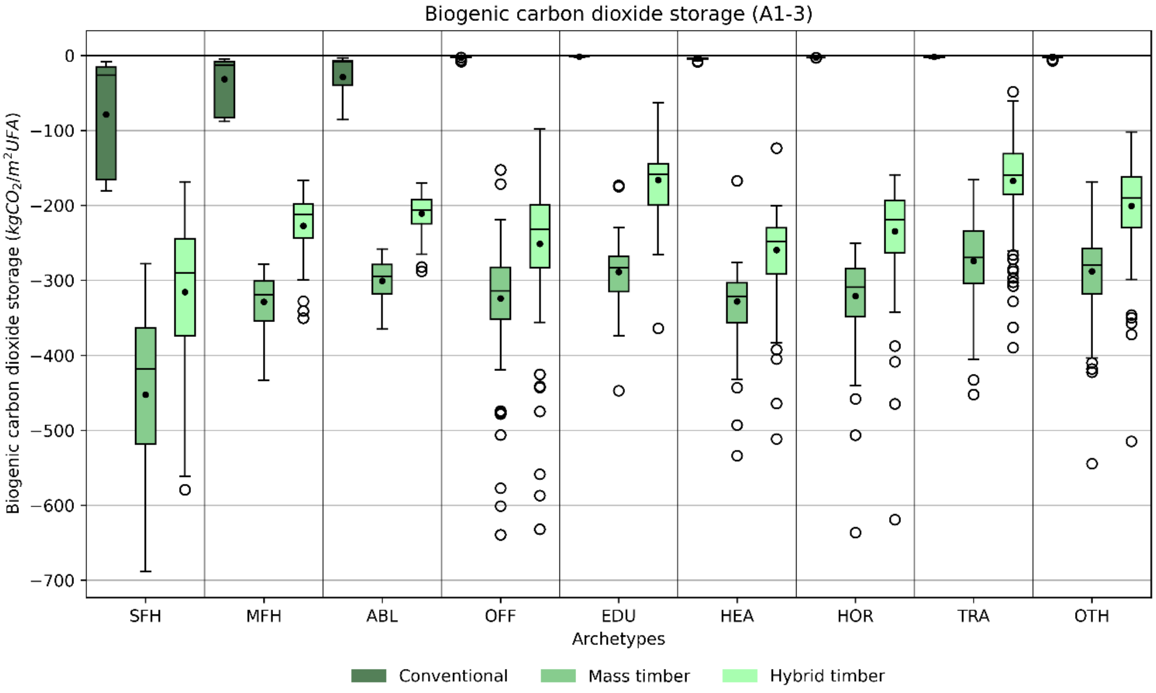

Figure 15: Average biogenic carbon dioxide storage (A1-3) for all NEW archetypes in the 27 Member States, for conventional, mass timber and hybrid timber construction. Results in [kgCO2/m2UFA]. Note: Figure shows A1-3 biogenic carbon dioxide storage, which is rereleased in module C3, according to the '-1/+1 method'. (Single-family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

We observe a range of average biogenic carbon dioxide storage for the conventional archetypes from -1.60 for EDU to about -78.75 $kgCO_2/m^2$UFA for SFH for the mean values, represented by the dot in the boxplots. As expected, the biogenic carbon dioxide storage is much higher for the mass timber construction archetypes, ranging from -274.16 $kgCO_2/m^2$UFA for the TRA archetype up to around -452.45 $kgCO_2/m^2$UFA for the SFH archetype, when looking at the mean values determined in the boxplots. For hybrid timber construction, we observe -166.10 $kgCO_2/m^2$UFA for EDU archetypes and -315.64 $kgCO_2/m^2$UFA for the SFH archetype, again looking at the mean values in Figure 15. The values for biogenic carbon dioxide storage we observe in this report are within the range of the literature [66,67,68] although it has to be noted that the values for the timber construction archetypes herein tend to be slightly higher.

A few critical comments need to be made on these results. First, the plotted results only concern the biogenic carbon dioxide storage quantified in A1-3, i.e. only the material that actually enters the building for storage, which according to the '-1/+1 method' can be accounted for with a negative value. We hereby show only the '-1' from the '-1/+1 method', which is not in line with current standardization, but this is presented as such to show the order of magnitude of biogenic carbon dioxide reaching the system boundary of the building archetypes. These results thereby always represent temporary carbon storage over time, which, according to the latest standards, will be released back into the atmosphere at the end of the life cycle. We have included an additional Figure 18, in which we show the biogenic carbon fluxes for all relevant life cycle stages, including the emission of the biogenic carbon in C3. Furthermore, the result in Figure 15 also do not include module A5 or B4, which also show biogenic carbon fluxes over the life cycle. Those fluxes are included in Figure 18.

Figure 16 shows the average **carbonation** for **mineral materials** in the **use phase module B1** for all the NEW archetypes modelled in the 27 EU Member States. We again differentiate between conventional, mass timber and hybrid timber construction in order to provide a comparison in this respect. Please notice that the y-axis in comparison to prior Figure 15 has been scaled down for the range of the observed results for the use stage carbonation.

[66] Hoxha, E., Passer, A., Ruschi Mendes Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G. (2020) Biogenic Carbon in Buildings: A Critical Overview of LCA Methods. Buildings and Cities 1, Nr. 1: 504–24. https://doi.org/10.5334/bc.46.

[67] Maierhofer, D., Van Karsbergen, V., Potrč Obrecht, T., Ruschi Mendes Saade, M., Gingrich, S., Streicher, W., Erb, K-H., and Passer, A. (2024) Linking Forest Carbon Opportunity Costs and Greenhouse Gas Emission Substitution Effects of Wooden Buildings: The Climate Optimum Concept. Sustainable Production and Consumption 51: 612–27. https://doi.org/10.1016/j.spc.2024.08.021.

[68] Andersen, C., Ernst, M., Garnow, A., Sørensen, C., Grau et al. (2023) Whole Life Carbon Impact of 45 Timber Buildings. 1 ed. København: Department of the Built Environment, Aalborg University. 187 p. (BUILD Rapport; No. 10, Vol. 2023).

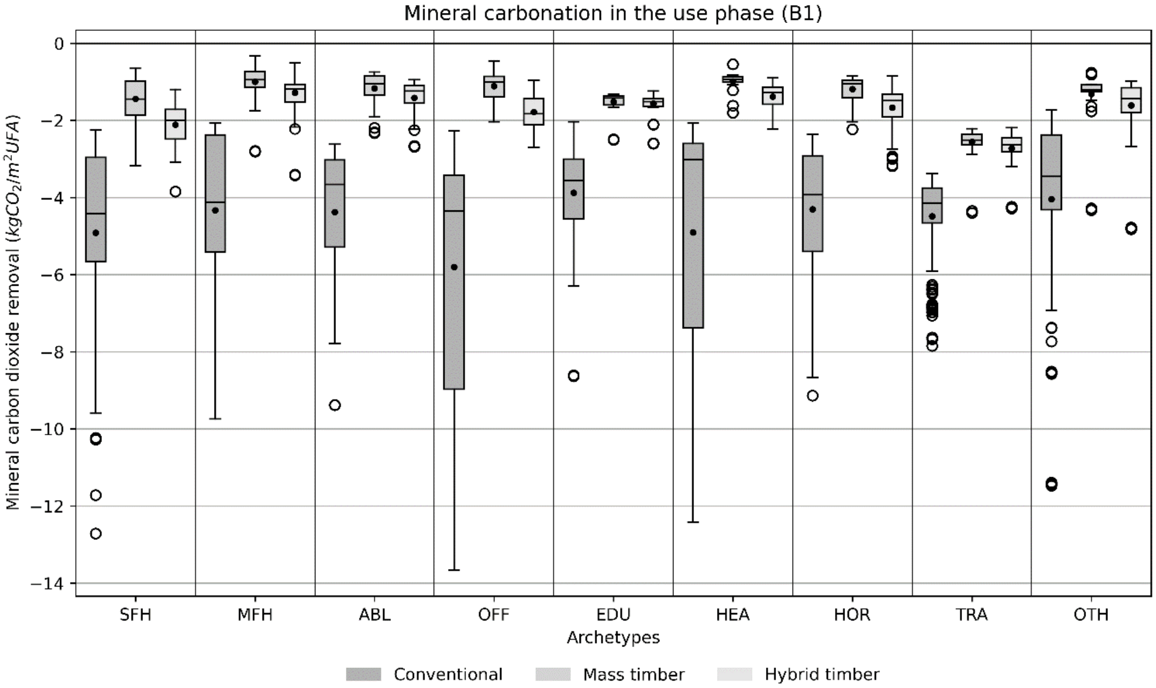

Figure 16: Average use stage mineral carbonation (B1) for all NEW archetypes in the 27 Member States, for conventional, mass timber and hybrid timber construction. (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

We observe carbonation of mineral materials in the use phase in module B1 for the conventional archetypes from -3.88 $kgCO_2/m^2$UFA for EDU up to -5.80 $kgCO_2/m^2$UFA for OFF archetypes, looking at the mean boxplot results obtained. For the mass timber, the mineral carbonation in the use phase is lower due to the lower amount of mineral materials in the archetypes, and results in -0.98 $kgCO_2/m^2$UFA for HEA archetypes to -1.44 $kgCO_2/m^2$UFA for the SFH, which, in comparison to the conventional construction method, is expectedly lower. For the hybrid timber archetypes, we observe use phase mineral carbonation between -1.38 $kgCO_2/m^2$UFA for HEA archetypes up to -2.72 $kgCO_2/m^2$UFA for the TRA archetypes. In general, if comparing the results of the use stage carbonation in B1 with the upfront GHG emissions shown in Figure 13, we can notice that mineral material carbonation in the use phase when observing the single archetypes, only accounts for a small proportion of initial GHG emissions quantified in this project. It should also be noted that the carbonation of concrete in the use phase is an effect that should be avoided with regard to the load-bearing capacity of a building, as excessive carbonation of the concrete attacks the reinforcing steel and then impairs the load-bearing capacity. The relevant structural engineering standards (e.g. EUROCODES) already consider this, but it should be mentioned again in this context.

Figure 17 shows the amount of atmospheric carbon dioxide absorbed via **carbonation of mineral materials in module C3**, after the materials have been demolished, which results in an increase in surface area. The results are plotted again for all NEW archetypes modeled for the 27 Member States. We again show a differentiation between conventional, mass timber and hybrid timber construction. Please note that the y-axis again has been scaled according to the ranges of our results.

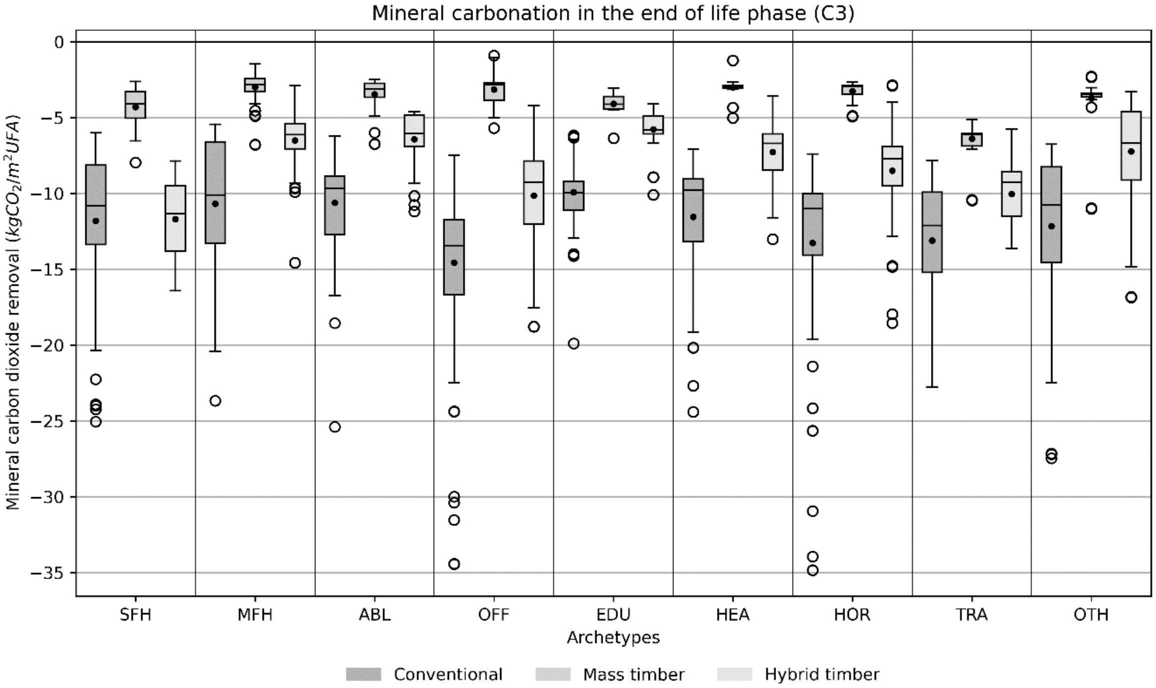

Figure 17: Average end-of-life carbonation (C3) of mineral materials for all NEW archetypes in the 27 Member States, for conventional, mass timber and hybrid timber construction. (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

For mineral carbonation in the end-of-life phase, when looking at the conventional archetypes, we observe between -9.92 $kgCO_2/m^2UFA$ for EDU and -14.56 $kgCO_2/m^2UFA$ for OFF archetypes. For archetypes representing mass timber, the carbonation of the mineral materials in these archetypes can be observed between -3.01 $kgCO_2/m^2UFA$ for HEA and -6.38 $kgCO_2/m^2UFA$ for TRA archetypes. Finally, when observing the mineral carbonation in the end-of-life phase in module C3 for the hybrid timber archetypes, we observe a range between -5.77 $kgCO_2/m^2UFA$ for EDU archetypes and -11.69 $kgCO_2/m^2UFA$ for SFH archetypes. As expected, carbonation is higher for the conventional construction methods, which is due to the higher quantity of mineral building materials applied in these archetypes.

The results for biogenic carbon dioxide release in module C3 and mineral calcination emissions in module A1-3 can be found in the Supplementary Material fof this report in Figure 33 and Figure 34. Modules A5 and B4 biogenic carbon dioxide results are not shown in boxplots as inflows and outflows cancel each other out (see also Figure 18).

In the course of the data analysis for the calculated carbon dioxide removal results for the updated European archetype datasets in this project, CDR results for all modeled archetypes have been obtained. These results are based on the plots already shown in D2.1, but in the course of the update for this report, they were extended with the defined MIN and MAX values, both for biogenic and mineral CDR factors, in order to provide more certainty for the calculated values. In this context, we have developed a whole collection of CDR results for all archetypes. Since they cannot all be presented in the report due to the high number of plots, we have created a PDF edition of the plots, which is provided as a supplementary file to the report.

Here we now give insights into one plot with archetypes that provide interesting results in terms of biogenic carbon dioxide storage and mineral carbonation. This should also be seen as a guideline for reading the plots provided. Figure 18 shows the results of the bio-based and mineral CDR mapping. The first three blocks in Figure 18 show conventional archetypes (i.e., 00 for the first code in the "00-00-00" archetype coding), the second blocks show mass timber archetypes (01 for the first code in the "00-00-00" archetype coding), and the third blocks show hybrid timber archetypes (02 for the first code in the "00-00-00" archetype coding).

Furthermore, in this report, we have transferred our approach taken in D2.1 Report with quantitative baseline figures for WLC and carbon removals for presenting the material flows in the before use, use and after use phases to the well-known modules of EN 15978 in order to gain a better understanding of the results. For mineral materials, calcination emissions before use are shown for modules A1-3, A5, and B4. Again, it has to be noted that these values represent only the chemically bound carbon that is released during the production of the materials and thus represent only a part of the emissions occurring in the production of such materials. Carbonation removals of mineral material during the use phase are represented in module B1 and module B4 for the materials entering the archetype via replacement. Mineral carbonation removal after use is presented in module C3 for end-of-life, but also for materials leaving the archetypes in module A5 due to loss on the construction site and B4 due to replacement. The results for the mineral calcination emissions and carbonation removals are shown in a greyish color tone for materials concrete, cement, cement mortar, cement plaster, and clay brick.

For the bio-based materials, the carbon dioxide storage due to the growth of the plant, i.e. before use in the building, is primarily shown in module A1-3, but also in module A5 if a material enters the construction site but is lost in the process of it, and in B4 due to the exchange of elements. At the end of the life cycle, positive biogenic carbon emissions are accounted for in module C3 if the material leaves the archetype. Also, in module A5, material leaves the system boundary and is assigned a positive biogenic carbon emission. For module B4, if a biogenic material is exchanged, a positive factor is also applied. It should be noted that for Module A5 and also for module B4, the nature of the -1/+1 method results in simultaneous inflows and outflows of material, which results in symmetric negative and positive results for biogenic carbon in these modules. The results for the biogenic materials are differentiated in sawn wood, wood-based panels, windows and doors, and others (which include linoleum, hemp, straw, hempcrete, and cork) and are shown in green color in the plots.

The height of the bars shown in the plots represents the quantified AVG values resulting from the assignment to the SLiCE data, which are the arithmetic mean between the MIN and MAX values obtained in the CDR factor development. For both the mineral and bio-based materials, the plot includes error bars that represent the quantified MIN and MAX values for the CDR factors.

First, we describe the conventional construction for Austrian NEW single-family archetypes, represented by the first code 00 in the "00-00-00" archetype code logic in Figure 18. For these archetypes, calcination emissions in module A1-3 are observable between +103.98 up to +122.88 $kgCO_2/m^2$UFA. In module A5, the mineral materials that are depicted as an inflow to the building but lost at the construction site are quantified with around +5.20 $kgCO_2/m^2$UFA of calcination emissions and -0.83 $kgCO_2/m^2$UFA of carbonation after use, as the material lost is leaving the construction site to carbonate. In the use phase in module B1, carbonation removal of at around -7.27 to -7.56 $kgCO_2/m^2$UFA is observable. For module B4, also material inflows and outflows occur which are associated with calcination and carbonation of mineral materials, yet these are very small and quantified with only -0.02 and +0.03 $kgCO_2/m^2$UFA. After demolition, carbonation removals of around -16.63 to -25.05 $kgCO_2/m^2$UFA can be observed in module C3 for these archetypes. In terms of biogenic carbon, storage of -21.16 $kgCO_2/m^2UFA$ is observable in module A1-3, which are again released in module C3 as +21.16 $kgCO_2/m^2UFA$. The biogenic fluxes observed in modules A5 and B4 for those archetypes are very small, between -1.06 and +1.06 $kgCO_2/m^2UFA$.

Second, we move to the NEW single-family archetypes representing mass timber construction via the first code 01 in the "00-00-00" archetype code logic in Figure 18. For the wooden archetypes representing mass timber, the mineral calcination emissions in module A1-3 are occurring with +78.56 $kgCO_2/m^2UFA$, while carbonation in the use phase in module B1 of -3.18 $kgCO_2/m^2UFA$ and after use in module C3 of -7.96 $kgCO_2/m^2UFA$. Modules A5 and B4 values for mineral materials are very low and are not described herein. Looking at the biogenic carbon fluxes for these archetypes, we observe between -353.16 to -385.88 $kgCO_2/m^2UFA$ of stored biogenic carbon dioxide in module A1-3. For module A5, which represents the losses of materials at site, we see that between -17.66 $kgCO_2/m^2UFA$ and -19.29 $kgCO_2/m^2UFA$ are entering and leaving the system boundary again as +17.66 $kgCO_2/m^2UFA$ and +19.29 $kgCO_2/m^2UFA$ respectively. In module B4, elements are exchanged, resulting in +9.66 $kgCO_2/m^2UFA$ emissions as well as -9.66 $kgCO_2/m^2UFA$ of storage. Biogenic carbon dioxide is released for the end-of-life in module C3, with values observable between +353.16 to +385.88 $kgCO_2/m^2UFA$.

The archetypes representing hybrid timber construction in Figure 18 are labeled with the first code 02 in the "00-00-00" coding logic. These archetypes show mineral calcination emissions in module A1-3 of +92.30 $kgCO_2/m^2UFA$. For module A5, calcination of +4.62 $kgCO_2/m^2UFA$ due to production and carbonation of -0.82 $kgCO_2/m^2UFA$ due to carbonation off site are observable. Module B4 again shows low values for mineral materials and are skipped herein. For end-of-life carbonation in module C3, these archetypes show -16.42 $kgCO_2/m^2UFA$ of carbonation observable. Biogenic carbon dioxide storage of -244.27 to -288.93 kgCO2/m2UFA is observable in the biogenic carbon dioxide fluxes. For module A5, the same logic of material inflow and material outflow due to loss at construction site applies as before, resulting in storage and emission from -12.21.45 $kgCO_2/m^2UFA$ and +12.21 $kgCO_2/m^2UFA$ up to -14.45 $kgCO_2/m^2UFA$ and +14.45 $kgCO_2/m^2UFA$. Model B4 similarly shows emissions and removals of +9,66 $kgCO_2/m^2UFA$ A and -9,66 $kgCO_2/m^2UFA$ for bio-based materials. In relation to end-of-life in module C3, emissions between +244.27 $kgCO_2/m^2UFA$ and +288.93 $kgCO_2/m^2UFA$ are observable for the hybrid timber archetypes.

The presented results are shown in following Figure 18. As already indicated above, we provide the same type of results plots for all the archetypes modelled for the 27 EU Member States as a separate document as a supplementary file to this report.

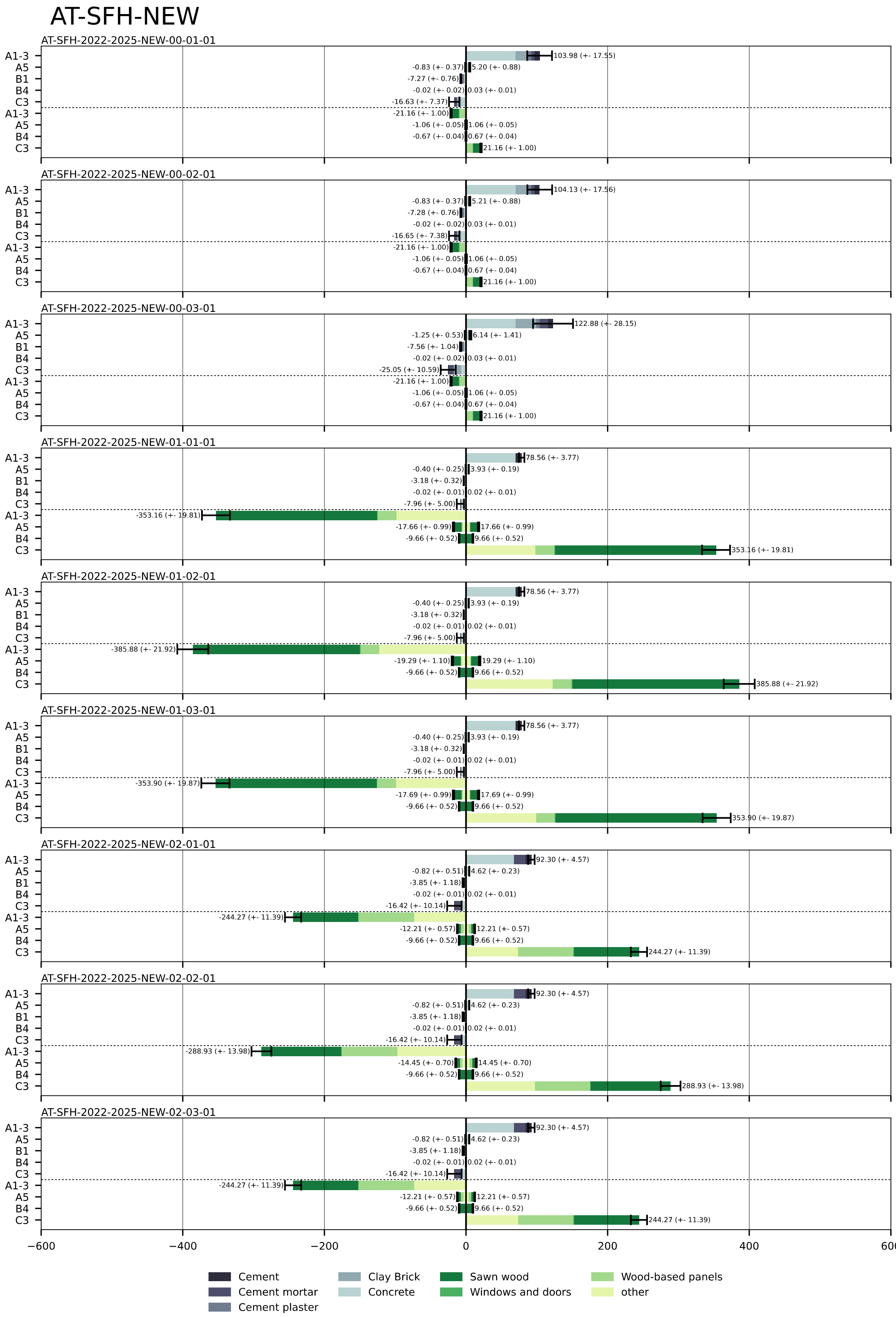

Figure 18: Mineral calcination and carbonation and biogenic carbon dioxide fluxes for the Austrian NEW single-family archetypes (AT-SFH-NEW), results in [kgCO2/m2 UFA]

3.2 Building stock baseline year (2020)

Figure 19 presents the building stock level whole life cycle carbon emissions in the baseline year 2020. It shows total carbon emission levels per Member State and illustrates the contribution of different life cycle activities to the overall building life cycle emissions per Member State in that year.

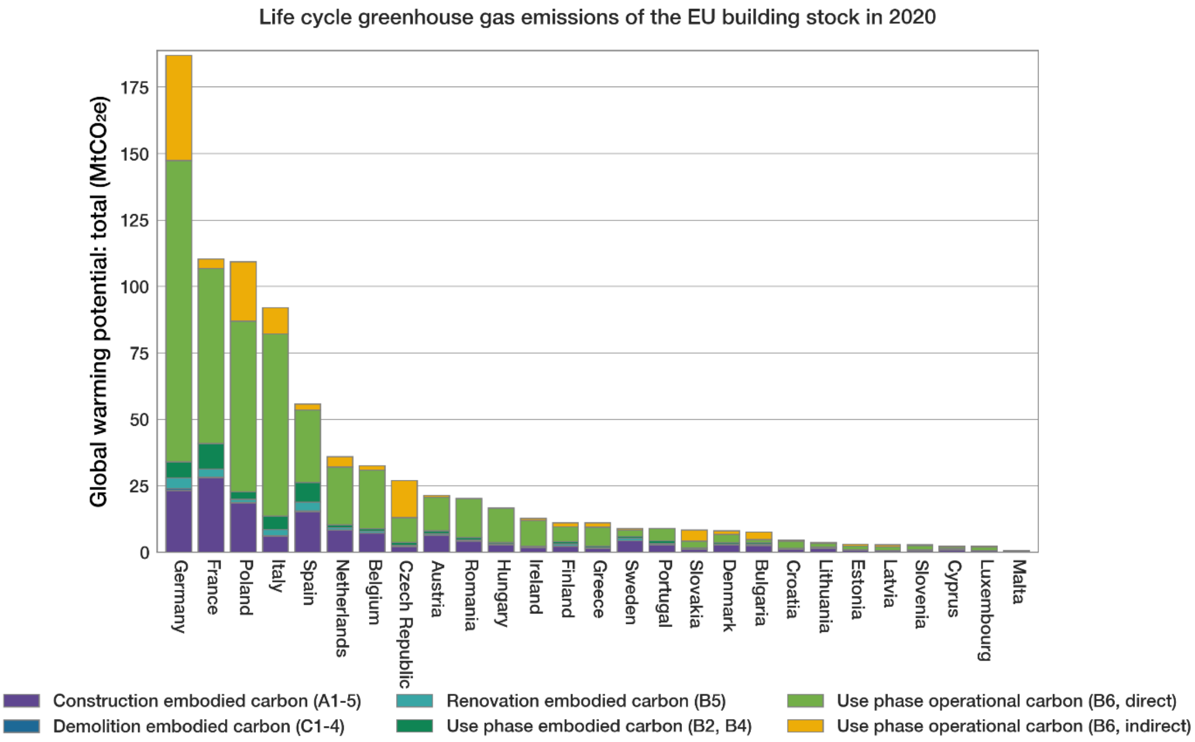

Figure 19: Building stock level whole life cycle carbon emissions (MtCO2e) in the baseline year (2020) by life cycle activity and per Member State.

We observe the five largest contributors to whole life cycle emissions of EU building construction and operation arising in Germany (approx. 187 MtCO2e), France (approx. 110 MtCO2e), Poland (approx. 109 MtCO2e), Italy (approx. 92 MtCO2), and Spain (approx. 56 MtCO2e), respectively. Across all Member States, we can observe use phase operational carbon emissions as the major contributor to national whole life cycle GHG emissions of buildings and construction. However, embodied carbon emissions of new construction pop out as a substantial aspect, contributing approximately 28 MtCO2e in France, approximately 23 MtCO2e in Germany, and as well as approximately 15-19 MtCO2e in Spain and Poland, respectively. Furthermore, use phase embodied carbon also play a relevant role in countries such as Germany, France, Italy and Spain. Renovation embodied carbon is naturally highest in countries with high renovation rates as they invest embodied carbon to reduce operational carbon emission in following years.

Further analyses of whole life cycle carbon emissions in the baseline year is presented in SI - **Error! Reference source not found.**. This includes a breakdown of the different embodied carbon emissions by key attributes - such as EU region, building stock activity, building type, element and material class.

3.3 Building stock scenario results (2020-2050)

3.3.1 Scenario results overview: Understanding the solution space

Figure 2 and Figure 20 present the key scenarios and whole life cycle carbon emission trajectories.

Table 2: Key scenarios their description (Further information in Section 2.7)

Scenarios	Description
BAU	Business-as-usual: Projection of baseline activity rates, future population development.
CPOL/A	Optimistic current policy: Meeting policy targets as planned, not limited by MS capacity.
CPOL/B	Conservative current policy: Limited by socio/technical challenges, MS capacity.
APOL/A	Optimistic additional policy: APOL/B plus biofuels for remaining direct emissions.
APOL/B	Conservative additional policy: Push to meet policy targets, not limited by MS capacity.
ALL/HIGH	High diffusion across all MS: Supporting MS push beyond currently determined capacities.

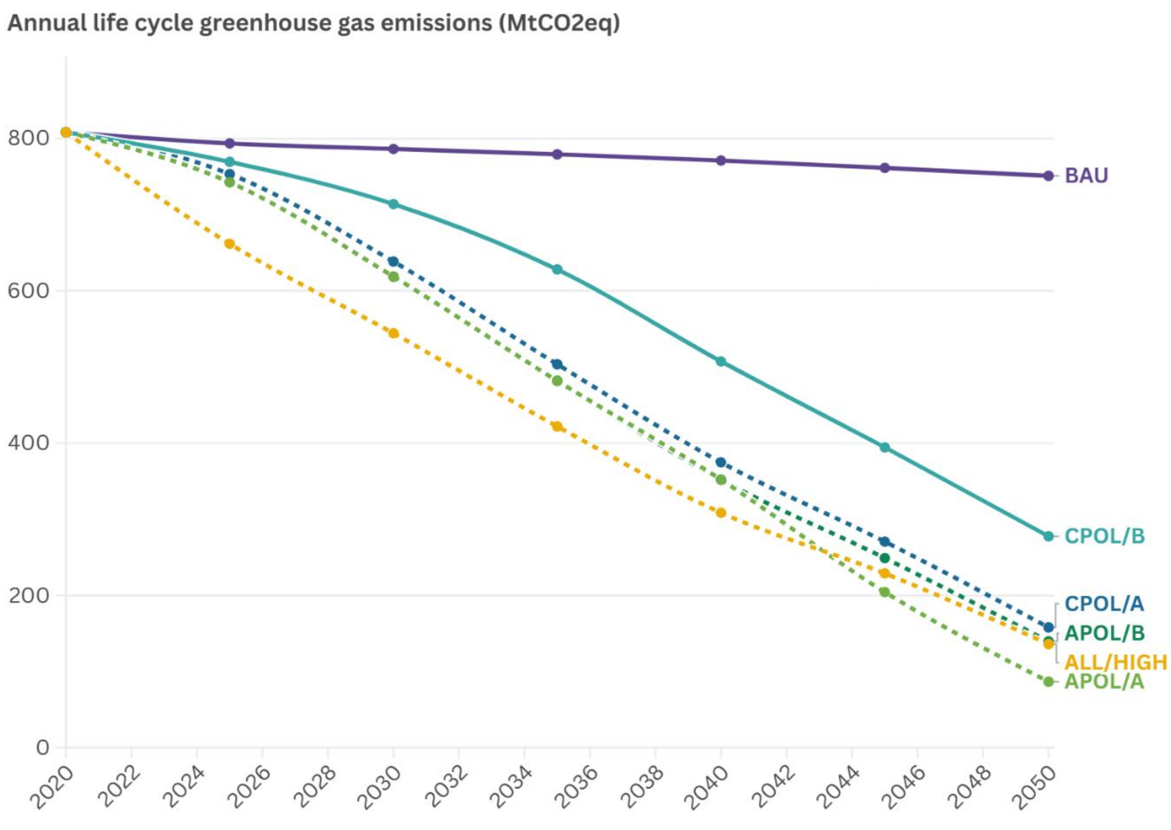

Figure 20: Annual life cycle emissions resulting from modelling the key scenarios. (Solid lines = limited by MS capacity; Dashed lines = Diffusion levels beyond established MS capacities)

Two exploratory scenarios indicate the solution space opened in the modelling in this study. On one hand, the business-as-usual (BAU) reference scenario indicates a 'worst case' emission trajectory where 2020 baseline activity rates (new construction, refurbishment, demolition) are further projected into future years, considering EU population projections to 2050. The BAU scenario does not factor in any of the CCRS. Observed emission reductions are only due to the improvements of the EU building stock through continued refurbishment activity and related advances in building energy efficiency and related operational emissions. On the other hand, the ALL/HIGH scenario shows the maximum theoretical implementation potential of the strategies, meaning that all strategies are fully implemented in all the Member States to a high diffusion level. This scenario shows the 'best-case' estimate of maximum carbon reduction potential that is achievable in the present modelling. The pre-defined policy scenarios CPOL/A, CPOL/B and APOL/B and APOL/A are within this solution space on the upper end of decarbonization trajectories modelled in this study. In addition, APOL/A considers the use of biofuels for compensating remaining direct emissions from building operation to achieve the even lower emission outcomes. While it is questionable if such fuels effectively reduce emission outcomes, current accounting rules seem to offer beneficial effects that support meeting policy targets focused on direct emissions from building operation via biomass.

Under a BAU exploratory scenario whole life cycle emissions of EU buildings and construction reduce from approximately 808 MtCO2e in the baseline year 2020, to approximately 751 MtCO2e in 2050 – a reduction of just around 7% compared to the 2020 baseline. In the ALL/HIGH exploratory scenario whole life cycle carbon emissions reduce to approximately 136 MtCO2e in 2050, which amounts to a reduction of 83% compared to the baseline. Following the related policy ambitions and targets, the optimistic current policy scenario CPOL/A achieves whole life cycle carbon emissions for EU buildings and construction of approximately 158 MtCO2e (CPOL/A) in 2050, which corresponds to reductions of annual emission levels by 80% (CPOL/A) compared to 2020. The conservative current policy scenario CPOL/B, limited by diffusion rates considering Members States differentiated capacities to implement certain strategies, achieves annual emission reductions of 66% by 2050 compared to 2020, landing at approximately 277 MtCO2e of whole life cycle carbon emissions from EU buildings and construction in 2050.

The additional policy scenarios APOL/A and APOL/B achieve whole life cycle carbon emissions for EU buildings and constructions in 2050 of approximately 87 MtCO2e and 140 MtCO2e, respectively. Compared to 2020 whole life carbon emission levels, this represents reductions of 89% (APOL/A) and 83% (APOL/B), respectively. Notably, the APOL/A scenario is achieved through the consideration of additional reduction of considered direct emissions via the use of biofuels, the burning of which is considered as climate neutral under current accounting standards. With this assumption modelled, the APOL/A scenario shows the lowest annual emission levels in 2050. Without such beneficial accounting effects from future use of biofuels, the explorative HIGH/ALL scenario offers the lowest whole life carbon emission levels for EU buildings and construction at approximately 136 MtCO2e in 2050, a reduction of 83% compared to the 2020 baseline.

Table 3 summarizes the cumulative and annual emissions under the key scenarios compared to the BAU. The results indicate that by 2050 annual emissions can be reduced up to 65% to 85% compared to the BAU scenario (no implementation of any of the CRRS), in cumulative terms for the period 2020-2050 the range is 27% to 44% reduction.

Table 3: Cumulative and annual emissions outcomes under CPOL/A and CPOL/B compared to BAU.

Scenarios	Cumulative emissions 2020-2050	Annual emissions in 2050
BAU	24 134 MtCO2e	751 MtCO2e

CPOL/A	65% (-35%)	21% (-79%)
CPOL/B	76% (-24%)	37% (-63%)
APOL/A	61% (-39%)	12% (-88%)
APOL/B	62% (-38%)	19% (-81%)
ALL/HIGH	57% (-43%)	18% (-82%)

3.3.2 Policy scenarios: Modelling the current policy ambition

3.3.2.1 Optimistic current policy scenario (CPOL/A)

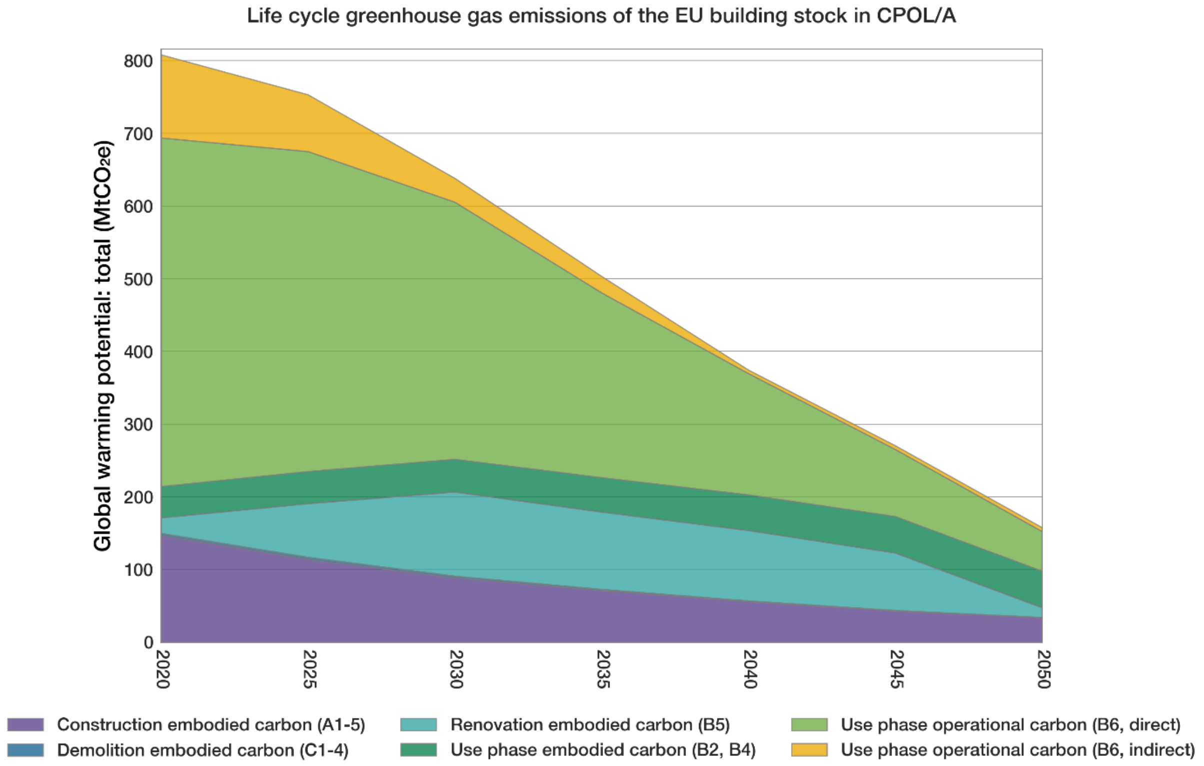

Figure 21: Optimistic current policy scenario (CPOL/A) whole life cycle emissions trajectory 2020-2050 by life cycle activity.

Figure 21 shows the trajectory of whole life cycle emissions 2020-2050 by life cycle activity. It illustrates the steep decline of whole life cycle emissions right after the baseline year, mostly driven by the substantial reduction of use phase operational carbon emissions. In CPOL/A, operational carbon emissions reduce from 594 MtCO2e in 2020 to just 60 MtCO2e in 2050, a reduction of annual emissions from EU buildings operation by 90%. These emission reductions are achieved through radical increases of renovation rates, which almost quadruples, rising fast from just around 1,0% p.a. in 2020 to approximately 3,6% p.a. by 2030, thereby enabling refurbishment of the overarching majority of existing building stock by 2050. The figure shows the resulting increase in renovation embodied carbon from 2020 to 2030 with subsequent high levels until 2045 and decline by 2050. Overall, CPOL/A shows a short-term increase of embodied carbon emissions from 214 MtCO2e in

2020 to 235 and 252 MtCO2e in 2025 and 2030, respectively. Before then continuously falling to 173 MtCO2e in 2045, and – with the building stock mostly renovated and related embodied emissions decreasing to below 2020 levels – going down to just about 98 MtCO2e in 2050, thereby achieving a reduction of annual embodied carbon emissions by 54% compared to the 2020 baseline. It is this 'investment' and interim increase of renovation embodied carbon that enables the radical reduction of operational carbon emissions from existing buildings in the stock. To enable the required increase of refurbishment rates and free up the necessary resources, new construction rates are considered to decrease in a CPOL/A scenario from around 1,0 % p.a. in 2020 to just above 0,4% p.a. in 2050. In practice, this means the number of floor area newly constructed under this scenario would reduce from approximately 630 million m² p.a. in 2020 to approximately 321 million m² p.a. in 2050 while at the same time, the floor area undergoing renovations would increase from initially approximately 611 million m² p.a. in 2020, to as much as 2.398 million m² p.a. in 2030, staying high throughout the following decade and arriving at approximately 1.785 million m² p.a. in 2045, before dropping to 274 million m² p.a. in 2050. New construction embodied carbon emission thus reduce from 146 MtCO2e in 2020 to approximately 34 MtCO2e in 2050, a 77% decrease of annual embodied carbon emission from new construction of EU buildings. Relatedly, also demolition rates are considered to drop, reducing by half from around 0,2% in 2020 to 0,04% in 2050. The Supplementary Information section offers further details on activity rates considered across the different scenarios for refurbishment, demolition, and new construction, respectively.

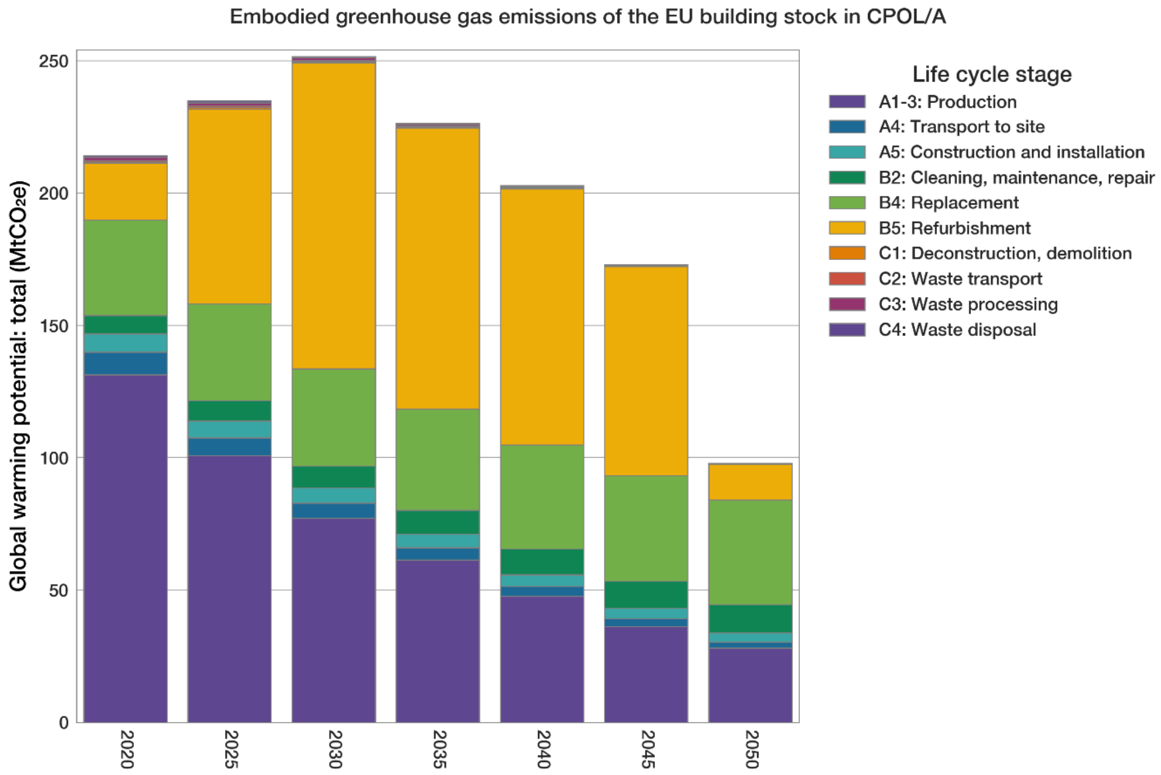

Figure 22: CPOL/A breakdown of embodied carbon emissions (MtCO$_2$e) by building life cycle stage (EN15978) for future EU building stock development (2020-2050).

Figure 22 further details the trajectory for whole life cycle embodied carbon emissions of EU buildings from 2020 to 2050 under a CPOL/A scenario. It shows the interim increase of embodied carbon emissions invested for refurbishment (B5) of the existing building stock, which show a steep increase and peak by 2030 at levels almost four times the baseline value of 2020 and remaining at high levels until 2040 before fading out and falling back to lower-than-baseline levels in 2050. At the same time, production embodied carbon emissions (A1-3) as well as related emissions from transport to site (A4) and construction and installation (A5) show a continuous decline due to substantial improvements of material production as well as reduction in new construction rates. Embodied emissions arising for existing building use (B2: maintenance; B4: replacement) reduce over time, mostly due to the implemented improvements of new material production. Emissions arising from end-of life processes (C1: deconstruction/demolition; C2: waste transport; C3: waste processing; C4: waste disposal) remain marginal throughout the modelling period.

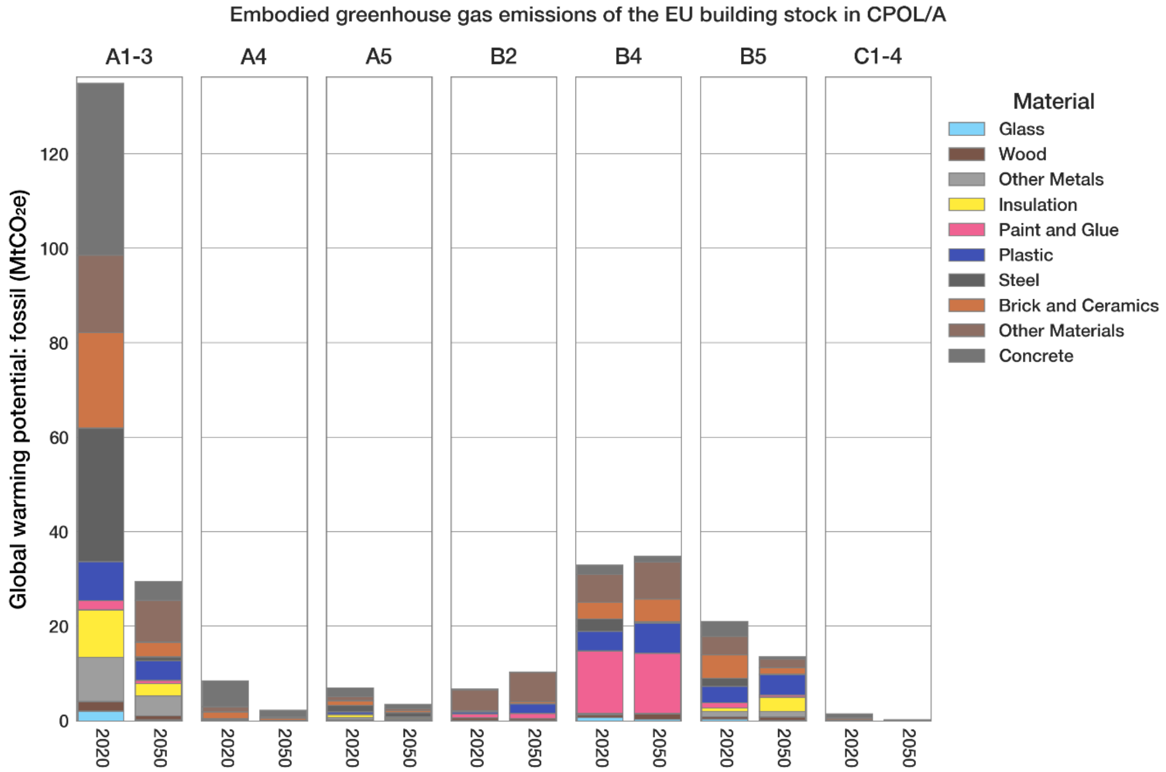

Figure 23: Whole life cycle embodied emissions comparison 2020-vs-2050 by material class and life cycle stages.

Figure 23 provides further insights on the radical emission reductions eventually realized also for embodied carbon emissions under a CPOL/A scenario. This scenario translates the current policy ambition of achieving substantial improvements in construction material production across the EU. It shows that embodied emissions of construction material production (A1-3) drop from around 135 MtCO2e in 2020 to approximately 30 MtCO2e in 2050. These emission savings are largely driven by improvements of emission intensity in production of conventional materials such as concrete, steel, and brick and ceramics. They are also the effect of a partial shift to low carbon alternatives for insulation and an overall improvement of production conditions due to a presumed decarbonization of energy grids and industrial processes across the European Union.

We take a step back now to investigate the per-capita values to better understand the differentiated starting points and trajectories of EU Member States considering their respective population levels. Table 4 shows the average whole life cycle embodied and operational emissions per capita, i.e. divided by the total population of the EU, under a CPOL/A scenario. At comprehensive table with detailed per-capita emissions for each individual MS is provided in Supplementary Information (SI: Results and discussion: Table 17). The EU average for whole life cycle GHG emissions from building construction and operation is 1,81 tCO2e/cap in the baseline year 2020. That is 0,48 tCO2e/cap embodied carbon emissions and 1,33 tCO2e/cap of operational carbon emissions, respectively. In 2050 these figures consequently reduce to 0,22 tCO2e/cap embodied carbon emissions and 0,14 tCO2e/cap of operational emissions, respectively. The 2050 EU average whole life cycle emission intensity is thus 0,36 tCO2e/cap under a CPOL/A scenario, an average reduction of 80% compared to the per-capita average of 2020. The SI Table 17 shows that these per capita values can vary substantially across EU Member States as both the population projection as well as the emission trajectories are different for individual MS. SI Table 17 provides an overview for embodied and operational carbon emission per capita for CPOL/A with individual values for all Member States. Therein, for example, 2020 baseline embodied carbon emission per capita range from 0,23 tCO2e/cap (EL) to 1,46 tCO2e/cap (CY). Baseline operational carbon per capita show an even stronger variation, ranging from 0,29 tCO2e/cap (SE) to 2,73 tCO2e/cap (LU), respectively. The 2050 values – while overall reducing – still suggest a strong inequality across Member States in 2050 for embodied emission values, ranging from 0,15 tCO2e/cap (IE, SK) to 0,81 tCO2e/cap (FI). Whereas operational emissions range from 0,03 tCO2e/cap (SE) to 0,2 tCO2e/cap (PL).

Note that these per capita values are a derivate of the total whole life cycle emissions at country level and are meant to better understand country level differences and inequalities. These are not building level per capita values, which should distinguish different building stock activities and types of building uses as well as consider the actual intensity of use of the building types in question.

Table 4: EU Average for embodied and operational carbon emissions per capita for CPOL/A (in tCO2eq/cap)

Member State	Emission type	2020	2030	2040	2050
EU	**Embodied**	**0.48**	**0.56**	**0.45**	**0.22**
	Operational	**1.33**	**0.86**	**0.38**	**0.14**

It is important to understand that CPOL/A is a scenario modelled to meet the ambition level of current EU climate policy. We here present the outcomes of modelling the whole life cycle emissions of EU building construction and operation and its future trajectories considering the various carbon reduction and removal strategies established earlier in this study. Strategies have been defined – among other differentiating characteristics – based on their scope of applicability regarding different activities, building types, elements or materials; their potential impact, i.e. emission reduction potential, at building level; as well as their potential diffusion, i.e. potential market share, by 2030, 2040 and 2050, considering low, medium or high ability for implementation – depending on our estimates of Member States' differentiated capacity for implementing strategies today and in the future (as established in Report D2.1). In the CPOL/A scenario, this estimated Member State capacity is overwritten to reflect full implementation of current policies. In this modelling, CPOL/A is achieved through "high" diffusion across all Member States for basically all "improve" strategies. CPOL/A also assumes a very fast and strong increase of refurbishment rates, which in practice represents substantial challenges for EU policy and industry.

The additional policy scenario APOL requires model runs with similarly high diffusion assumption as set out under CPOL/A and requires an even faster response and short-term action for reducing both operational as well as embodied carbon emissions of EU buildings and construction, despite similarly high refurbishment activity.

In addition to the optimistic current policy scenario CPOL/A we thus investigate a conservative current policy scenario CPOL/B, based on the diffusion rates and capacity of Member States established in the earlier evidence synthesis and stakeholder consultation.

3.3.2.2 Conservative current policy scenario (CPOL/B)

In addition to the optimistic current policy scenario CPOL/A we investigated a conservative current policy scenario CPOL/B, based on estimates of the likely diffusion rates and capacity of Member States, as established in the earlier evidence synthesis and stakeholder consultation (Report D2.1). CPOL/B is hence based on our estimates of Member State capacity in terms of potential diffusion levels and building stock activity rates (such as refurbishment rates).

Figure 24 shows that CPOL/B results in an increase of refurbishment activity close to the levels in CPOL/A, albeit with a lot less steep increase and a peak only in 2040. Thus, considering the renovation peak to occur 10 years after the 2030 peak required to meet CPOL/A.

Furthermore, the carbon reduction and removal strategies (CRRS) applied in CPOL/B are the same as in CPOL/A although limited to the diffusion rates per Member State as determined in the evidence synthesis. To achieve higher outcomes than CPOL/B, the capacity of Member State for implementing CRR strategies will have to be higher than what the latest evidence suggests (Report D2.1).

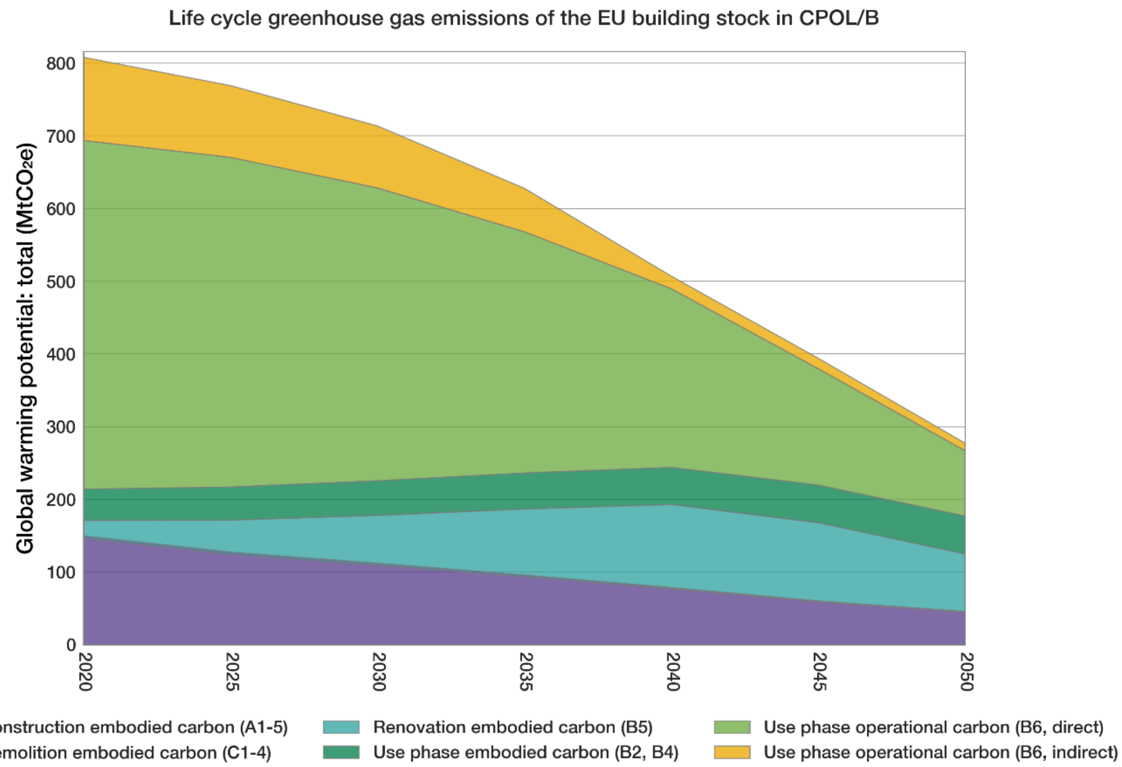

Figure 24: Conservative current policy scenario (CPOL/B) whole life cycle emissions trajectory 2020-2050 by life cycle activity.

The results of CPOL/B, presented in Figure 24, indicate that when considering the ability of Member States to implement the different CRRS as determined, the resulting emission trajectory is substantially higher and considerably deviates from the targets set out in current EU policies.

This can be understood as an indication of the need for advanced efforts to support Member States in delivering higher implementation rates, i.e. higher diffusion, of the 'improve' strategies, especially where current assessments of MS ability for implementation are judged to be 'low' or 'medium'.

An overall increase of Member State capacity for implementing CRRS can be achieved in three ways: 1) those MS where low or medium capacity has been determined are enabled to achieve high diffusion rates in respective markets; 2) MS with high diffusion potentials are further increasing their diffusion rates to compensate shortfall in MS with low or medium capacities; 3) all MS are performing higher than anticipated albeit to different degrees, together achieving implementation of required refurbishments and market shares for improved materials and low carbon alternatives.

Figure 25 further details the trajectory for whole life cycle embodied carbon emissions of EU buildings from 2020 to 2050 under a CPOL/B scenario. Similar as for a CPOL/A scenario, it shows the interim increase of embodied carbon emissions invested for refurbishment (B5) of the existing building stock, which show a steep increase and peak by 2040 at levels about three times the baseline and remaining at high levels until 2050. At the same time, production embodied carbon emissions (A1-3) as well as related emissions from transport to site (A4) and construction and installation (A5) show a continuous decline due to substantial improvements of material production as well as reduction in new construction rates. The decline is however less steep than in a CPOL/A scenario. Embodied emissions arising for existing building use (B2: maintenance; B4: replacement) reduce over time, mostly due to the implemented improvements of new material production. Emissions arising from end-of life processes (C1: deconstruction/demolition; C2: waste transport; C3: waste processing; C4: waste disposal) remain marginal throughout the modelling period.

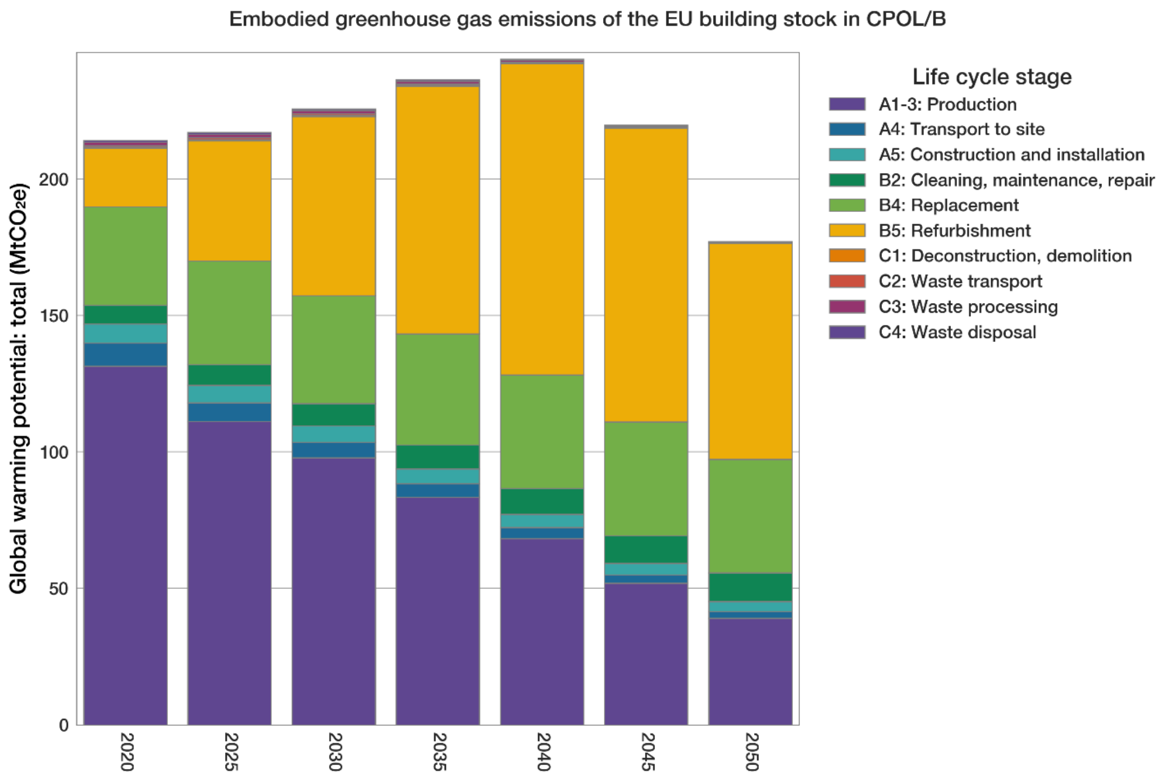

Figure 25: CPOL/B breakdown of embodied carbon emissions ($MtCO_2e$) by building life cycle stage (EN15978) for future EU building stock development (2020-2050).

3.3.3 Exploratory scenario ALL/HIGH: Maximum diffusion of all strategies in all MS.

A breakdown of the whole life cycle embodied carbon emissions of EU buildings from 2020 to 2050 under the theoretical ALL/HIGH scenario is shown in Figure 26.

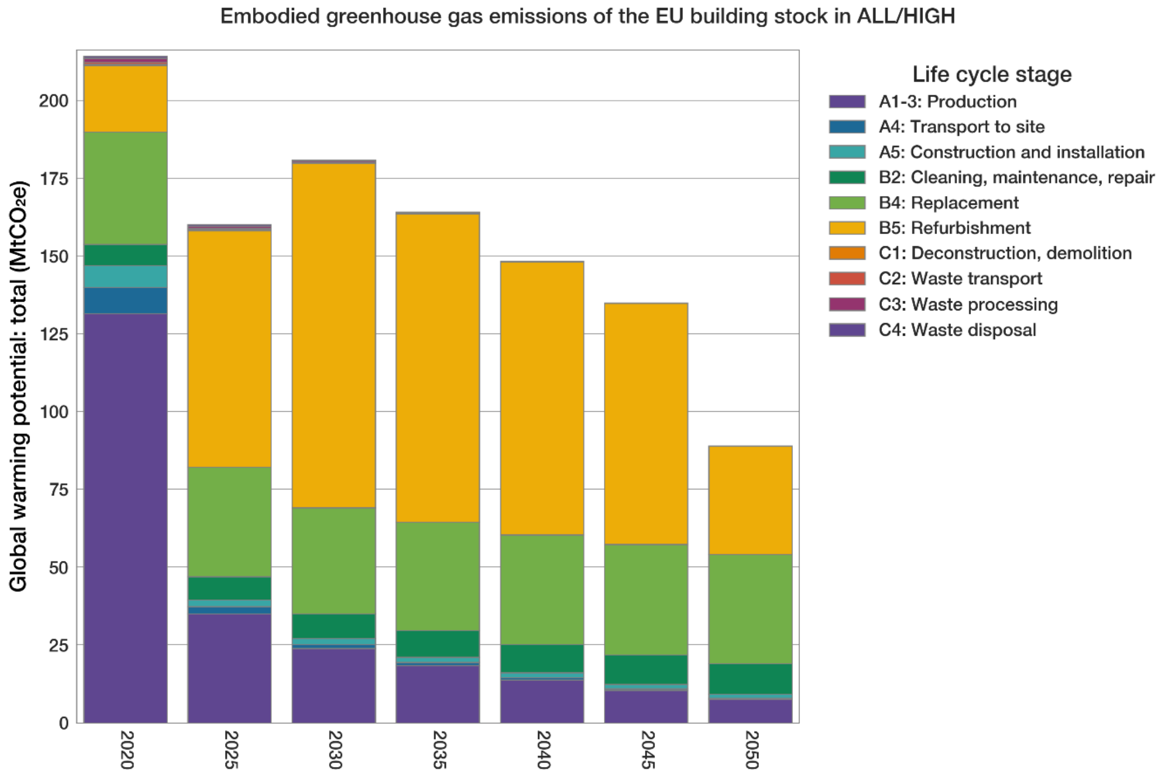

Figure 26: ALL/HIGH scenario: breakdown of embodied carbon emissions (MtCO$_2$e) by building life cycle stage (EN15978) for future EU building stock development (2020-2050).

In this extreme scenario a drastic reduction of the embodied carbon due to production of materials (A1-A3) is noticed, as well as related emissions from transport to site (A4) and construction and installation (A5). This can be explained by the combined effect of reduced material use, increased use of bio-based materials, increased use of CDR solutions, reduced carbon emissions of conventional materials and reduced transport and construction emissions; all assumed to be implemented in all Member States at high diffusion level. Similar as for the CPOL/A and CPOL/B scenarios, it shows the interim increase of embodied carbon emissions invested for refurbishment (B5) of the existing building stock, which shows a very steep increase and peak by 2030 (same year as in CPOL/A), and remaining at high levels until 2045. Embodied emissions arising for existing building use (B2: maintenance; B4: replacement) reduce over time also in this scenario, mostly due to the implemented improvements of new material production. Emissions arising from end-of life processes (C1: deconstruction/demolition; C2: waste transport; C3: waste processing; C4: waste disposal) remain marginal throughout the modelling period.

3.3.4 BAU complemented with Avoid/Shift/Improve strategies individually

To gain insight in the various carbon reduction and removal strategies (CRRS) defined, a comparison has been made of these various strategies (i.e. avoid, shift, improve) on top of the BAU scenario. The additional reduction in emissions compared to BAU are presented in Table 5. The ‘Avoid’ scenario focuses on reduced need for materials and energy via circularity and sufficiency measures, as well as lifestyle changes. The results indicate an additional reduction of annual emissions in 2050 of 20%. The 'Shift' scenario represents a shift towards alternative low-carbon, bio-based construction materials and renewable energy and proves to result in an additional reduction of annual emissions in 2050 of 27%. The 'Improve' scenario focuses on improving the conventional construction materials and energy use and reveals to enable an additional reduction of annual emissions in 2050 of 26%. Notably, looking at the reduction of cumulative emissions (2020-2050) from either of these strategy combinations suggests a different outcome. The highest cumulative emission reductions, 14% compared to BAU, are achieved via the 'Avoid' scenario. Whereas the 'Shift' and 'Improve' scenarios deliver 12% and 6% reduction of cumulative emissions, respectively.

Table 5: Additional reduction of emissions (annual/cumulative) via ASI strategies compared to BAU.

Additional reduction of emissions compared to BAU scenario	Cumulative emissions 2020-2050	Annual emissions in 2050
Avoid	14%	20%
Shift	12%	27%
Improve	6%	26%

4. DISCUSSION

4.1 Validation

For results validation, we compare the results of the SLiCE-PULSE models with the results of the MESSAGEix-Buildings model. We focus here on both residential and non-residential buildings and compare key results at Member State level, including floor area, and construction and operational emissions.

The total floor area of residential and non-residential buildings shows strong alignment between the two models in 2020 (Figure 28, 29), which was expected since both models rely on the same characterization of the existing building stocks (see section 2.4). Results for 2050 in the BAU scenario also demonstrate close agreement, further validating the projections and assumptions used in both models. In general, the differences between the two models are minor, with discrepancies remaining below 10%. These differences can be attributed primarily to variations in base year assumptions: the main model (SLiCE-PULSE) uses 2019 as the base year, while the validation model (MESSAGEix-Buildings) is based on 2020.

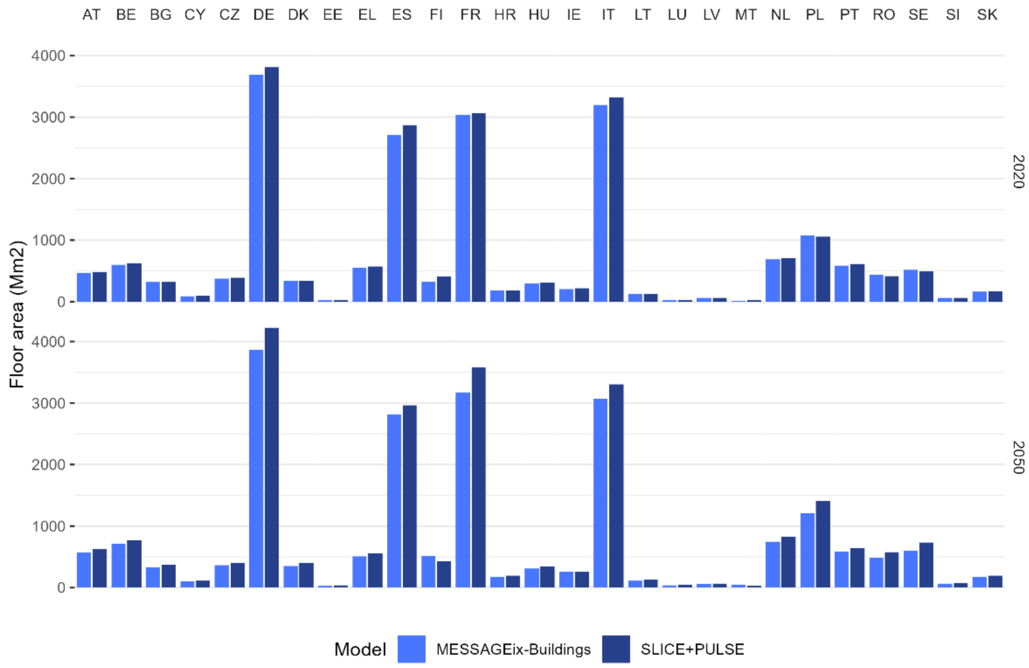

Figure 28: Comparison of total residential floor area from SLICE-PULSE and MESSAGEix-Buildings at Member State level in the BAU scenario in 2020 and 2050.

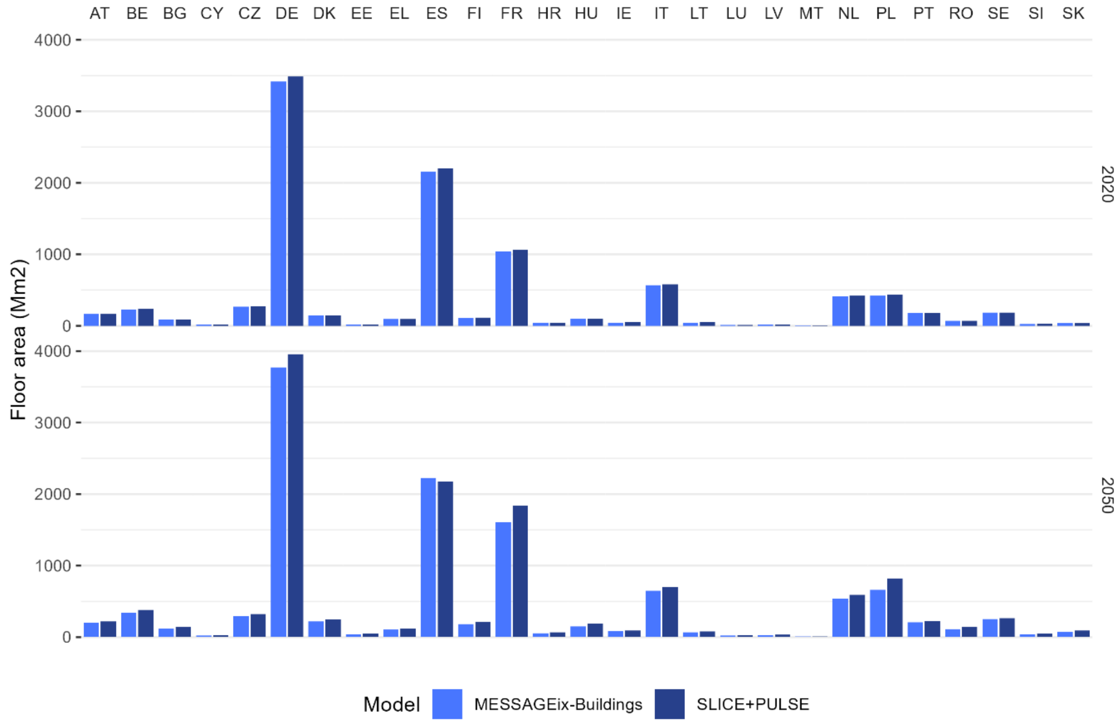

Figure 29: Comparison of total non-residential floor area from SLICE-PULSE and MESSAGEix-Buildings at Member State level in the BAU scenario in 2020 and 2050.

We compare the GHG emissions for building construction and operation between the two models at both the Member State and EU levels. At the Member State level, the results show good agreement between the two models in the BAU Scenario (Figure 2930, 31). The main difference lies in the embodied emissions, where estimates from MESSAGEix-Buildings are slightly lower than those from SLiCE-PULSE. This discrepancy arises primarily from differences in the treatment of material types and emission factors. SLiCE-PULSE incorporates a broader range of material types, including insulation materials that are not accounted for in MESSAGEix-Buildings, and employs component-based, country-specific emission factors. In contrast, MESSAGEix-Buildings adopts a more streamlined approach, focusing on manufacturing emissions that reflect average EU-level technologies.

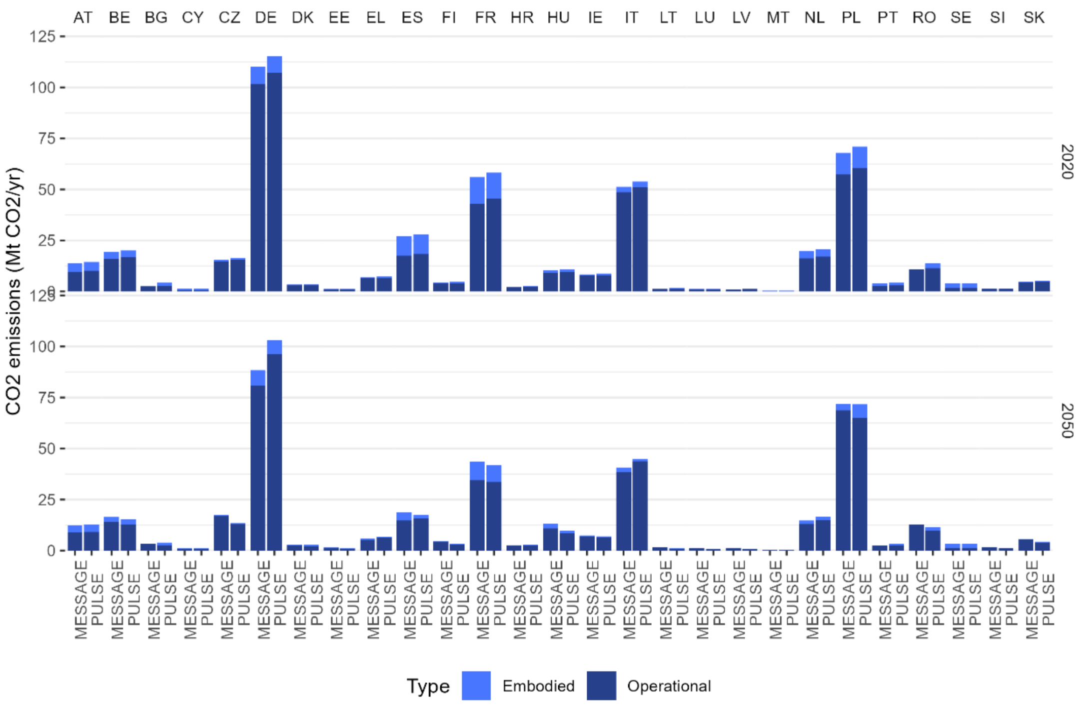

Figure 30: Comparison of residential emissions from SLICE-PULSE (PULSE) and MESSAGEix-Buildings (MESSAGE) at Member State level in the BAU scenario in 2020 and 2050.

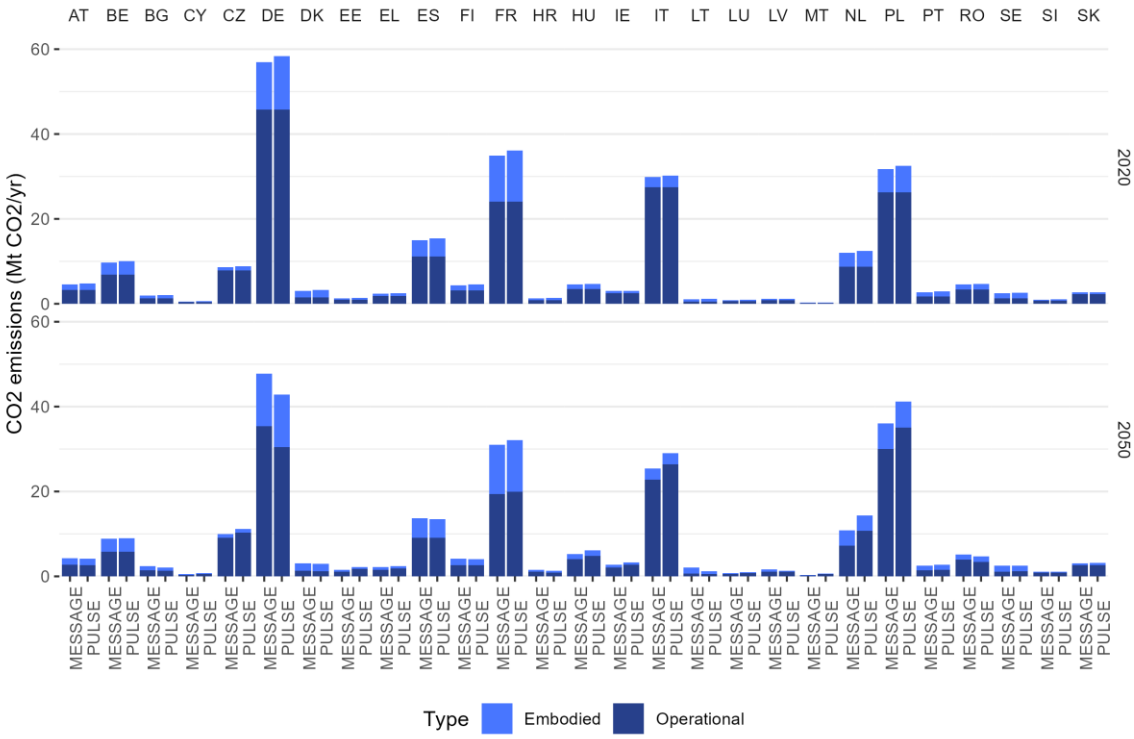

Figure 31: Comparison of non-residential emissions from SLICE-PULSE (PULSE) and MESSAGEix-Buildings (MESSAGE) at Member State level in the BAU scenario in 2020 and 2050.

At the EU level, we compare the emission results over time for three scenarios: BAU, CPOL/A, and CPOL/A+ALL (Figure 32). Overall, there is good alignment between the two models. However, it is worth noting that in 2050, SLiCE-PULSE shows a stronger reduction in emissions compared to MESSAGEix-Buildings in the CPOL/A and CPOL/A+ALL scenarios relative to the BAU scenario (Table 6). This difference is mainly because some strategies, such as vacancy reduction (Avoid) and bio-based insulation (Shift), are not captured in MESSAGEix-Buildings. Despite these methodological differences, the overall alignment between the two models demonstrates their robustness in estimating life cycle GHG emissions at various scales.

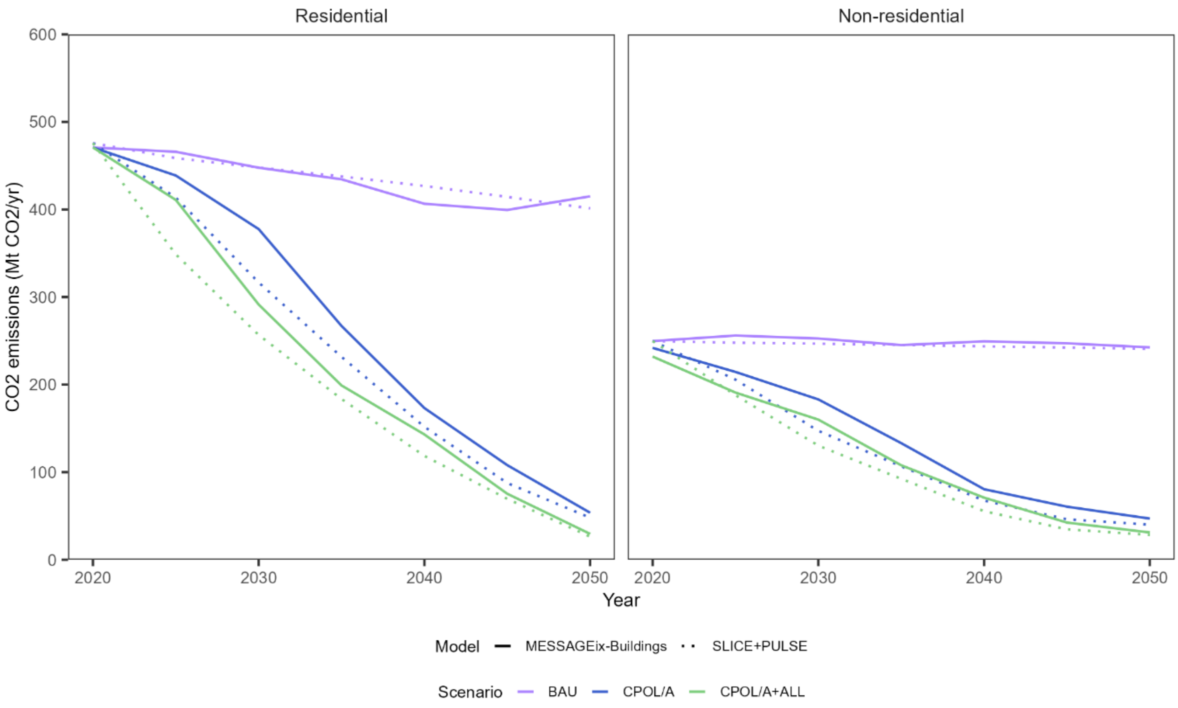

Figure 32: Comparison of residential (left) and non-residential (right) emissions timeseries from SLiCE-PULSE (dotted lines) and MESSAGEix-Buildings (solid lines) at EU level for three selected scenarios.

Table 6: Annual emissions outcomes in SLiCE-PULSE and MESSAGEix-Buildings under CPOL/A and CPOL/A + ALL compared to BAU.

Scenarios	Annual emissions in 2050			
	SLiCE-PULSE		MESSAGEix-Buildings	
	Residential	Non-residential	Residential	Non-residential
BAU	100%	100%	100%	100%
CPOL/A	12% (-88%)	17% (-83%)	13% (-87%)	19% (-81%)
CPOL/A + ALL	7% (-93%)	12% (-88%)	17% (-93%)	13% (-87%)

4.2 Limitations

Building archetypes

In this study, the building stock is modelled using a set of representative archetypes, each using one a single geometry. However, in reality there is a wide variety of building geometries with different element ratios, which may affect the results. Additionally, this study utilized generic background data based on Ecoinvent 3.6, released in 2019, hence representing production systems from a few years ago. Future updates to more recent background data are expected to improve the accuracy of baseline emissions, particularly for energy and electricity-related emissions, and to a lesser extent, for material-related emissions.

Building stock, scenarios and strategies

All CRR strategies are based on a theoretical assessment from scientific literature and/or industry sources. Archetype-based strategies are mostly modelled with carbon reduction percentages found in the literature. A main limitation from this modelling method is that the reduction in carbon emissions is always compared to current technology. There is no adaptation of this factor in future years. Similarly, as recycling and reuse are modelled as archetype-related strategies, there is a potential mismatch between the annual inflows and outflows of materials and the diffusion assumed for these strategies. Future work could further integrate them in a more robust prospective life cycle assessment framework, like performed in the original building stock model in Austria (PULSE-AT). For stock-related strategies, further empirical evidence is required, for example regarding sufficiency strategies, to improve modelling of unexpected dynamics such as rebound effects, and other implications. For example, reducing per capita space demand also has resilience implications, for which other aspects might be considered. An increase of ceiling height could be necessary to reduce overheating while increasing spatial quality and construction adaptability. Similar considerations can be made for vacancy, and considering the typology or location of the vacant buildings in more detail could change the results of the analysis.

Carbon removals

The analysis of biogenic carbon storage via **bio-based materials** carried out was based on the currently valid standards and guidelines in life cycle assessment, i.e., the '-1/+1 method. On the one hand, the storage and the emission of biogenic carbon in the LCA approach were considered using the GWP-bio indicator. In the LCA analysis, the Ecoinvent records used, have determined the system boundary, i.e. considered with the cut-off approach. In addition, the biogenic carbon stored in bio-based materials was quantified based on the material flows in the models. In doing so, we also followed the normative requirements in order to visualize the flows of biogenic carbon through the life cycle of the modelled archetypes. This analysis was also based on the building inventories of the modelled archetypes. Therefore, the system boundaries for this this analysis were the building archetypes and the materials used in the archetypes themselves.

The system boundaries in both approaches were set based on the modelled background data and the requirements of the relevant normative specifications. An expanded analysis or a system boundary extension to consider effects in natural sink systems was not possible in this study. Given the latest scientific discussions, the authors consider this a limitation of the present study. It is noted that the '1/+1 method' used in the study appears to be no longer compliant with the evidence emerging in the last two years on the so-called carbon opportunity costs of using biogenic materials For example, the study by Peng et al. 2023 shows that the unrealized carbon storage in forests associated with the use of wood in products is significantly greater than the GHG emissions substitution benefits that prevail when wood is used in product systems[69],[70]. This observation appears consistent with national studies from individual European countries [71], [72], [73], [74],[75].

From this point of view, no final statement can be made based on the present study about using bio-based materials to store atmospheric carbon. A comprehensive assessment for the optimal carbon storage requires a holistic view of biogenic material flows, starting from the carbon sink effect of natural systems. A combined view of land use models with building stock models is required to get a more comprehensive picture of the usage of bio-based materials in the construction sector. Future research needs to establish such interdisciplinary approaches in order to involve the latest evidence in this area of research.

The analysis of the carbonation of **mineral materials** in this report was also based on relevant normative specifications. It should be noted that more complex models of carbon removal via carbonation have been published in the literature, which are based on the physical and chemical properties of the mineral materials and more comprehensively on Fick's second law of diffusion [76], [77]. This study did not implement such a comprehensive and detailed model to consider carbonation, due to the aggregated data nature of the modelling of average building archetypes and average materials involved. It can be noted that the requirements based on the standards, which have been followed herein, build upon and simplify these physical diffusion models, which allowed the application in this study. Future studies could go advance such assessments by implementing such physical carbonation models. The authors wish to note this point as a limitation for the mineral carbonation assessment conducted in this study.

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4.3 Contextualization

4.3.1 Comparison with WLC roadmap study (WLCR)

One relevant reference for comparing the results of the present modelling is the study "Supporting the development of a roadmap for the reduction of whole life carbon of buildings", contracted by the European Commission's DG ENV. The modelling deployed in this WLCR study in many ways is a predecessor of the current modelling approach. The original WLCR study was the first study modelling the EU building stock from a whole life cycle perspective, with various limitations, e.g. regarding the final calibration of (operational) carbon emission results. The present modelling and study advances on several aspects, improving the modelling and providing considerably more robust quantification of whole life carbon emissions at across the EU, with results calibrated according to relevant reference data on operational emissions of EU buildings. The present study is the latest recommended reference for EU policy and research related to the whole life cycle emissions of buildings and building stocks across the Union. In the following, further considerations are offered.

Building archetype level

The current study's outcomes on the archetype level show significant differences compared to the WLCR study. In that study, the EU building stock was represented by 60 building archetypes (distinguishing four EU regions), whereas the present analysis increased the number to 6466 archetypes (making a distinction and modelling individual archetypes for each EU Member State). The modelling approach and latest data sources are discussed in Section 2.1 and 2.2. Consequently, a higher variation in building types, their respective geometries, materializations, and HVAC systems has been considered in this study, leading to a larger variety of WLC results, with better representation for individual Member States and building types. Overall, trends and conclusions from building level results are consistent across the former WLCR study and the current modelling.

Building stock level

Table 7: Comparison of building stock level WLC baseline results with WLCR study

Baseline year (2020)	GROW D4.1		WLCR D7	
	MtCO2e	Share	MtCO2e	Share
Whole life carbon (WLC)	808	1,00	1360	1,00
Embodied Carbon (EC)	214	0,27	285	0,21
Operational Carbon (OC)	594	0,73	1075	0,79

Comparing results for the baseline year between the WLCR study and the present one show different results regarding WLC emissions, as shown in Table 7. Embodied carbon emissions have slightly reduced, from 285 to 214 MtCO2eq. They now account for 27% of WLC emissions, compared to 21% in the WLCR study. This is due to multiple reasons: (i) The WLCR study was the first of its kind for Europe, with specific limitations, which can explain why results were more granular. For example, building archetypes were modelled for four regions, three building typologies and generic LCA background datasets. In this study, we now have building archetypes for each EU Member State and for nine typologies. The LCA background data used was also updated and regionalised, which typically leads to lower carbon emissions; (ii) While the upscaling in the WLCR study was performed with average construction and demolition rates for the EU, country specific dynamics are now modelled individually, based on different parameters, such as population or age of the building stock. Construction and demolition rates are thus modelled individually for each Member State.

The upscaling of operational carbon emissions was also thoroughly revised. In the WLCR study, the operational carbon emissions calculated at the archetype level were upscaled without modification or calibration step. We now refined the analysis and noticed considerable differences between operational carbon emissions reported in the EEA or BSO and the upscaled data from the WLCR study. This is the reason why we now calibrate the upscaled operational carbon emissions to fit the ones reported in the BSO, as explained in the methodology section. Note that, as we do not include appliances in our modelling scope, the resulting emissions are lower than the ones reported in the BSO (only heating, cooling and ventilation are included in our upscaled results). This now provides a more robust assessment of operational carbon emissions and consistency with reported statistics.

4.3.2 Comparison with EU 2040 climate target

A relevant recent reference to compare the results of this study is the European Commission's assessment for a 2040 climate target for the EU, presented in February 2024[78]. In the following, the technical reports of the impact assessment (IA) underlying these targets, including some of its authors inside the Commission, have been consulted to compare the future emission trajectories, as much as possible. Table 8 presents a comparison of the WLC emission under APOL scenarios (A/B) in 2040 with the EU 2040 IA estimates.

Table 8: Comparison of WLC emissions of APOL (A/B) in 2040 with EU 2040 IA results.

Results in 2040	GROW D4.1 (APOL/A)	GROW D4.1 (APOL/B)	CLIMA 2040 (S2/S3)
	MtCO2e	MtCO2e	MtCO2e
Whole life carbon (WLC)	87	140	-
Embodied Carbon (EC)	80	80	100/200 (S3/S2)
Operational Carbon (OC)	7	60	50
New construction (A1-A3)	18	18	-
Replacement (B4)	48	48	-
Renovation (B5)	7	7	-

It is important to note that the 2040 IA utilizes a top-down, sector-based modelling approach aimed at capturing future emissions trajectories for the whole EU economy, with buildings and construction being subsectors in a larger model with limited detail at lower scale levels. In contrast, the present study uses a bottom-up, whole life cycle modelling approach focused on representing emissions of EU buildings and construction across EU Members states, considering different types of buildings and detailed modelling of building life cycle stages. Furthermore, the targets expressed in the CLIMA

[78] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

2040 study are based on a reference year 1990 (as is common in EU policy), whereas the present study expresses reduction rates compared to the 2020 baseline established in this study, as there are no numbers of corresponding scope for prior reference years.

The closest comparison to operational carbon emissions (OC) in the 2040 IA is Figure 48, "building CO emissions by sector", which shows around 50Mt in 2040 and 0 in 2050 for direct emissions (i.e. not considering the indirect, upstream emissions from electricity generation, but electricity is considered to be essentially decarbonised by 2040). In that sense, the results of the present study are higher than the 2040 IA estimates.

For New construction (A1-A3) embodied emissions, the closest comparison is Figure 55 "CO2 emissions from industrial sector". The underlying numbers include also products that go into other activities than construction, but construction remains the main user of cement and a large user of other emission intensive materials, such as steel, bricks, glass, etc. We can observe a large variation in 2040 IA results depending on the selected scenario - 200Mt in S2 and 100Mt in S3. In any case, the construction and renovation embodied emissions seem to be under 200Mt in 2040 according to the IA estimates. For 2050, the IA estimates show around 20-30Mt of emissions from all of industry, which is less than what is calculated in the present study for construction and renovation. The building and construction specific modelling presented in this study, therefore seems to not fully align with the anticipated decarbonisation of the energy and industry sectors under the 2040 IA 90% reduction scenario.

5. CONCLUSIONS

This study presents a detailed, bottom-up life cycle assessment of GHG emissions from the EU buildings and construction sector, forming part of a European Commission DG GROW Preparatory Action "Analysis of life cycle greenhouse gas emissions of EU buildings and construction". It models future emissions trajectories under multiple scenarios, evaluating the effectiveness of diverse carbon reduction and removal (CRR) strategies across the whole life cycle at the level of archetype buildings as well as national building stocks. The results offer a robust analytical foundation to inform EU policy development toward climate neutrality by 2050.

Under a business-as-usual (BAU) scenario, whole life cycle GHG emissions of the sector decline marginally—from 808 $MtCO_2e$ in 2020 to 751 $MtCO_2e$ in 2050—equating to only a 7% reduction. This underscores that without significant additional action, current trends will fall far short of supporting the EU's climate targets and that significant systemic interventions are required.

By contrast, ambitious implementation of CRR strategies involving accelerated and comprehensive strategy deployment can deliver deep decarbonization of the building stock:

- The explorative ALL/HIGH scenario, representing maximal implementation of all identified CRR strategies, achieves an 83% reduction compared to the 2020 baseline, reaching 136 $MtCO_2e$ by 2050.
- The optimistic additional policy scenario (APOL/A) shows the deepest reduction (89% 2020) to 87 $MtCO_2e$, while the optimistic current policy scenario (CPOL/A) achieves an 80% reduction to 158 $MtCO_2e$.
- The conservative policy scenario (CPOL/B), accounting for differentiated Member State capacities, results in a 66% reduction (to 278 $MtCO_2e$).

The analysis highlights several key conclusions:

- Policy Differentiation: Decarbonization pathways and starting points vary considerably across EU Member States, underlining the need for differentiated and adaptive policy frameworks that reflect national capacities and contexts.
- Strategic Leverage Points: The most effective decarbonization pathways combine rapid increases in renovation rates, decarbonization of construction material production, greater uptake of low-carbon material alternatives, and improved intensity of building use (sufficiency strategies).
- Role of Sufficiency: Sufficiency-oriented 'avoid' strategies, which focus on reducing the demand for new construction and optimizing existing floor space use, emerge as critical components for achieving deep emissions reductions within realistic scaling limits of technological solutions.
- Modelling Advances: The study advances the state of knowledge through the development of new building archetypes, improved modelling of life cycle impacts and CRR strategies, and enhanced validation through cross-model comparisons.

Crucially, these findings underscore the importance of tailored national approaches, as baseline emissions, renovation capacity, and strategy applicability vary significantly across the EU27. Policies must therefore be adaptive and equitable, recognizing diverse starting points while ensuring that aggregate EU targets are met.

These estimates are derived using an advanced modelling framework that integrates:

- New Member State-specific building archetypes covering nine residential and non-residential subtypes.
- Life cycle inventories and impact assessment via the MMG-SLiCE model, consistent with EN 15978 and EN 15804+A2.
- EU-wide upscaling using the PULSE-EU stock model, an evolution of the national PULSE-AT model.
- Validation through MESSAGEix-Buildings and STURM stock turnover modelling.

From a policy perspective, this study provides:

- Quantitative evidence on the scale of ambition required to meet EU climate targets.
- Insight into which CRR strategies yield the greatest emissions reductions, and under what conditions.
- A foundation for assessing policy gaps and identifying priority interventions for future regulatory frameworks, including enhanced integration of whole life carbon metrics in building codes, renovation strategies, and materials regulation.

This analysis offers valuable insights for EU policymakers and stakeholders in the building and construction sector. It identifies promising areas for climate action and highlights where current policies may need to be strengthened or extended to achieve climate neutrality goals. Ultimately, the study confirms that radical reductions in whole life cycle GHG emissions from EU buildings are technically feasible and essential for the EU's fair contribution to global decarbonization efforts.

Appendix 1:
SUPPLEMENTARY INFORMATION

6. SI: FIGURES AND DATA TABLES

Figures and related data tables are available via the authors upon reasonable request.

7. SI: METHODS AND MATERIALS

7.1.1 Overview of attributes collected for building archetype characterization

7.1.1.1 Building geometry and occupation

AMBIENCE_REFERENCE BUILDING USEFUL FLOOR AREA [M2]

Definition: "Useful floor area of a reference building is an average of useful floor areas defined for TABULA reference buildings" (Ambience, 2021). The useful floor area is expressed in m^2.

Methodology: This data is not available in Hotmaps but in Ambience only. As we have seen, Ambience does not have the same period ranges as Hotmaps for building stock classification, but rather larger or smaller periods of time are considered depending on the country. Hence the necessity to adapt the data to the periods given in the file that are, mostly, constructed on Hotmaps classification. As for useful floor area, it is necessary to calculate the weighted average of the useful floor area covered by the period of years given by Ambience to obtain the useful floor area included in a specific period.

AMBIENCE_REFERENCE BUILDING GROUND FLOOR AREA [M2]

Definition: Area of the reference building's floor in contact with the ground, expressed in m^2.

Methodology: This data is not available in Hotmaps but in Ambience only. As we have seen, Ambience does not have the same period ranges as Hotmaps for building stock classification, but rather larger or smaller periods of time are considered depending on the country. Hence the necessity to adapt the data to the periods given in the file that are, mostly, constructed on Hotmaps classification. As for ground floor area, it is necessary to calculate the weighted average of the ground floor area covered by the period of years given by Ambience to obtain the ground floor area included in a specific period.

AMBIENCE_REFERENCE BUILDING WALL AREA [M2]

Definition: Total wall area of the reference building, expressed in m^2.

Methodology: This data is not available in Hotmaps but in Ambience only. As we have seen, Ambience does not have the same period ranges as Hotmaps for building stock classification, but rather larger or smaller periods of time are considered depending on the country. Hence the necessity to adapt the data to the periods given in the file that are, mostly, constructed on Hotmaps classification. As for wall area, it is necessary to calculate the weighted average of the wall area covered by the period of years given by Ambience to obtain the wall area included in a specific period.

AMBIENCE_REFERENCE BUILDING WINDOW AREA [M2]

Definition: Total window area of the reference building (not included in wall area) and expressed in m^2.

Methodology: This data is not available in Hotmaps but in Ambience only. As we have seen, Ambience does not have the same period ranges as Hotmaps for building stock classification, but rather larger or smaller periods of time are considered depending on the country. Hence the necessity to adapt the data to the periods given in the file that are, mostly, constructed on Hotmaps classification. As for window area, it is necessary to calculate the weighted average of the window area covered by the period of years given by Ambience to obtain the window area included in a specific period.

AMBIENCE_REFERENCE BUILDING ROOF AREA [M2]

Definition: The total roof area of the reference building, expressed in m^2.

Methodology: This data is not available in Hotmaps but in Ambience only. As we have seen, Ambience does not have the same period ranges as Hotmaps for building stock classification, but rather larger or smaller periods of time are considered depending on the country. Hence the necessity to adapt the data to the periods given in the file that are, mostly, constructed on Hotmaps classification. As for roof area, it is necessary to calculate the weighted average of the roof area covered by the period of years given by Ambience to obtain the window area included in a specific period.

CES_REFERENCE BUILDING GROSS FLOOR AREA [M2]

Definition: The total floor area contained within the building measured to the external face of the external walls.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING GROSS VOLUME [M3]

Definition:Total volume contained within the building measured to the external faces of the external walls, roof, and underground floor.

Methodology:As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING SHAPE FACTOR (ENVELOPE AREA/GROSS VOLUME) [N]

Definition: The ratio between the reference building envelope area and its volume.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_NUMBER OF REFERENCE BUILDING STOREYS (ABOVE GROUND) [N]

Definition: Number of storeys above ground in the reference building.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_NUMBER OF REFERENCE BUILDING STOREYS (BELOW GROUND) [N]

Definition: The number of storeys below ground in the reference building.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING INTERPLANE HEIGHT [M]

Definition: The height of the reference building interplane expressed in m.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING ROOF TYPE IN TERMS OF GEOMETRY

Definition: Indicates whether the roof is flat or pitched.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING HEIGHT (HIGHEST POINT RIDGE OF THE ROOF IF PITCHED ROOF) [M]

Definition: Total height of the building measured from ground level to the highest point of the reference building, and up to the ridge of the roof if pitched.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING ENVELOPE AREA (FACADES+ROOF) [M2]

Definition: The total amount of envelope area including all the facades and the roof.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING RATIO OF WINDOW AREA/EXTERNAL WALL AREA [N]

Definition: The ratio between the amount of window area and the external wall area.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_REFERENCE BUILDING BOUNDARY CONDITION (NB OF FACES TOUCHING ANOTHER BUILDING) [N]

Definition: Building geometry boundary condition as the number of faces that are touching another building, interpreted as: 0 = detached; 1 = semidetached; 2+ = terraced.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

CES_NUMBER OF USERS [N]

Definition: Number of capita in a single dwelling.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

EUROSTAT_SURFACE AREA PER PERSON [M2/CAPITA]

Definition: Ratio between the total covered area constructed per number of the people.

Methodology: Eurostat

7.1.1.2 Building element characteristics

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL

Definition: Type of the floor material used in the reference building. This attribute contains information about floor material, and the percentage of material employed to constructing the floor.

Methodology: This attribute describes both the material of the reference building's floor and the percentage of material involved in the reference building's floor construction. The attribute is organized as follows: in a single column it is necessary to specify the percentage of type of material involved in the floor's construction. Each column corresponds to a type of material and the percentage of material involved in the construction of the floor is exclusively given by Hotmaps. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

HOTMAPS_REFERENCE BUILDING FLOOR CONSTRUCTION METHODOLOGY

Definition: Specifies the construction methodology used for the floor, depending on the material involved in the construction process.

Methodology: The attribute is organized as follows: in a single column, choose the material involved in the reference building floor's construction. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

CES_REFERENCE BUILDING TYPE OF INTERMEDIATE FLOOR

Definition: Describes the material used and the thickness of the intermediate floor.

Methodology: No data is available for any country in the cost-effectiveness study.

CES_REFERENCE BUILDING TYPE OF UNDERGROUND FLOOR

Definition: Describes the material used and the thickness of the underground floor.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL THICKNESS 1

Definition: The thickness of the structural element included in the reference building's floor, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the dates between 1970 and 1979 do not have a precise correspondence with Ambience dates, which give us the range between 1961 and 1975 with 0,49m of thickness and the range between 1976 and 1990 with 1,27m of thickness.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL THERMAL CONDUCTIVITY 1 [W/M/K]

Definition: Thermal conductivity of the reference building floor's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the date between 1990 and 1999 do not have a precise correspondence with Ambience dates, which give us the range between 1976 and 1990 with 1,5 W/m/k and the range between 1991 and 2005 with 1,32 W/m/k.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL DENSITY 1 [KG/M³]

Definition: The density of the reference building floor's structural material, expressed in kg/m3.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL 1

Definition: Material used for the insulation element of the reference building's floor.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL THICKNESS 1 [M]

Definition: The thickness of the structural element included in the reference building's floor, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL THERMAL CONDUCTIVITY 1 [W/MK]

Definition: Thermal conductivity of the reference building floor's structural material, expressed in W/m/K.

Methodology:

Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the dates between 1945 and 1969 do not have a precise correspondence with Ambience dates, which give us the range between 1946 and 1960 with 0,047 W/m/k of thermal conductivity and the range between 1961 and 1975 with 0,051W/m/k of thermal conductivity.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL DENSITY 1 [KG/M³].

Definition: The density of the reference building floor's structural material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR U-VALUE 1 [W/M²/K]

Definition: U-value of the reference building's floor, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which type of windows glazing type dominates in that range of years.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL THICKNESS 2

Definition: The thickness of the structural element included in the reference building's floor, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the dates between 1970 and 1979 do not have a precise correspondence with Ambience dates, which give us the range between 1961 and 1975 with 0,49m of thickness and the range between 1976 and 1990 with 1,27m of thickness.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL THERMAL CONDUCTIVITY 2 [W/M/K]

Definition: Thermal conductivity of the reference building floor's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the date between 1990 and 1999 do not have a precise correspondence with Ambience dates, which give us the range between 1976 and 1990 with 1,5 W/m/k and the range between 1991 and 2005 with 1,32 W/m/k.

AMBIENCE_REFERENCE BUILDING FLOOR MATERIAL DENSITY 2 [KG/M³]

Definition: The density of the reference building floor's structural material, expressed in kg/m3.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL 2

Definition: Material used for the insulation element of the reference building's floor.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL THICKNESS 2 [M]

Definition: The thickness of the structural element included in the reference building's floor, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL THERMAL CONDUCTIVITY 2 [W/MK]

Definition: Thermal conductivity of the reference building floor's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. In detail, the dates between 1945 and 1969 do not have a precise correspondence with Ambience dates, which give us the range between 1946 and 1960 with 0,047 W/m/k of thermal conductivity and the range between 1961 and 1975 with 0,051W/m/k of thermal conductivity.

AMBIENCE_REFERENCE BUILDING FLOOR INSULATION MATERIAL DENSITY 2 [KG/M³].

Definition: The density of the reference building floor's structural material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING FLOOR U-VALUE 2 [W/M²/K]

Definition: U-value of the reference building's floor, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which type of windows glazing type dominates in that range of years.

CES_REFERENCE BUILDING GROUND FLOOR U-VALUE [W/M²/K]

Definition: U-value of the reference building's ground floor, expressed in W/m2 /K.

Methodology: As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

AMBIENCE_REFERENCE BUILDING WINDOW MATERIAL

Definition: Material used for the frame element of the reference building's window.

Methodology: This attribute describes both the material of the reference building's window frame and the percentage of material involved in the reference building's window construction. The attribute is organized as follow: in a single column it is necessary to specify the percentage of type of material involved in the window's construction. Each column corresponds to a type of material and the percentage of material involved in the construction of the window is exclusively given by Hotmaps. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

AMBIENCE_REFERENCE BUILDING WINDOW GLAZING TYPE 1

Definition: Glazing of the window used in the reference building.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which type of windows glazing type dominates in that range of years.

AMBIENCE_REFERENCE BUILDING WINDOW COATED 1

Definition: The existence of the low-E layer in the reference building's window, expressed as Coated/Non-coated.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which element dominates between no coated and coated in that range of years.

AMBIENCE_REFERENCE BUILDING WINDOW FILLING GAS 1

Definition: Gas used for filling the window panels, if applicable, expressed as Argon/No gas. This means that in the case of gas-filled windows only argon-filled windows are used to model the reference buildings.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check if in that range of years used the filling gas.

AMBIENCE_REFERENCE BUILDING WINDOW U-VALUE 1 [W/M²/K]

Definition: U-value of the reference building's window, expressed in W/m2/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from comparison between Hotmaps and Tabula.

AMBIENCE_REFERENCE BUILDING WINDOW GLAZING TYPE 2

Definition: Glazing of the window used in the reference building.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which type of windows glazing type dominates in that range of years.

AMBIENCE_REFERENCE BUILDING WINDOW COATED 2

Definition: The existence of the low-E layer in the reference building's window, expressed as Coated/Non-coated.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check which element dominates between no coated and coated in that range of years.

AMBIENCE_REFERENCE BUILDING WINDOW FILLING GAS 2

Definition: Gas used for filling the window panels, if applicable, expressed as Argon/No gas. This means that in the case of gas-filled windows only argon-filled windows are used to model the reference buildings.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, it is necessary to check if in that range of years used the filling gas.

AMBIENCE_REFERENCE BUILDING WINDOW U-VALUE 2 [W/M²/K]

Definition: U-value of the reference building's window, expressed in W/m2/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from comparison between Hotmaps and Tabula.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL

Definition: Material used for the structural element of the reference building's wall.

Methodology: This attribute describes both the material of the reference building's wall and the percentage of material involved in the reference building's wall construction. The attribute is organized as follow: in a single column it is necessary to specify the percentage of type of material involved in the wall's construction. Each column corresponds to a type of material and the percentage of material involved in the construction of the wall is exclusively given by Hotmaps. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

HOTMAPS_REFERENCE BUILDING WALL CONSTRUCTION METHODOLOGY

Definition: Specifies the construction methodology used for the wall, depending on the material involved in the construction process.

Methodology: The attribute is organized as follow: in a single column, choose the material involved in the reference building wall's construction. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

CES_REFERENCE BUILDING TYPE OF INTERNAL/PARTITION WALLS

Definition: Describes the material used and the thickness of the internal/partition walls.

Methodology: No data is available for any country in the cost-effectiveness study.

CES_AMOUNT OF SUB-SYSTEM WALL [M2]

Definition: Describes the material used and the thickness of the sub-system walls.

Methodology:As we have seen, any information coming from the cost-effectiveness study must be treated on a case-by-case basis depending on the data available for each country and depending on the archetype described. This implies that it is necessary to proceed in 2 steps to get the data right. Firstly, check the available archetypes and see if they match the archetypes of our classification. Secondly, check if the data is available and proceed to its transformation to retrieve the information in our classification.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL THICKNESS 1 (M)

Definition: The thickness of the insulation element included in the reference building's wall, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL THERMAL CONDUCTIVITY 1 [W/M/K]

Definition: Thermal conductivity of the reference building wall's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL DENSITY 1 [KG/M^3]

Definition: The density of the reference building wall's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL 1

Definition: Material used for the insulation element of the reference building's wall.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL THICKNESS 1 [M]

Definition: Thickness of the insulation element included in the reference building's wall, expressed in meters.

Methodology: No data is available for Italy in Ambience.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL THERMAL CONDUCTIVITY 1 [W/M/K]

Definition: Thermal conductivity of the reference building wall's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL DENSITY 1 [KG/M^3]

Definition: The density of the reference building wall's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL U-VALUE 1 [W/M²/K]

Definition: U-value of the reference building's wall, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from a comparison between Hotmaps and Tabula.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL THICKNESS 2 (M)

Definition: The thickness of the insulation element included in the reference building's wall, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL THERMAL CONDUCTIVITY 2[W/M/K]

Definition: Thermal conductivity of the reference building wall's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

AMBIENCE_REFERENCE BUILDING WALL MATERIAL DENSITY 2 [KG/M³]

Definition: The density of the reference building wall's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL 2

Definition: Material used for the insulation element of the reference building's wall.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL THICKNESS 2 [M]

Definition: Thickness of the insulation element included in the reference building's wall, expressed in meters.

Methodology: No data is available for Italy in Ambience.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL THERMAL conductivity 2 [W/m/K]

Definition: Thermal conductivity of the reference building wall's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL INSULATION MATERIAL DENSITY 2 [KG/M³]

Definition: The density of the reference building wall's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING WALL U-VALUE 2 [W/M²/K]

Definition: U-value of the reference building's wall, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from a comparison between Hotmaps and Tabula.

HOTMAPS_REFERENCE BUILDING ROOF MATERIAL

Definition: Material used for the structural element of the reference building's roof.

Methodology: This attribute describes both the material of the reference building's roof and the percentage of material involved in the reference building's roof construction. The attribute is organized as follow: in a single column it is necessary to specify the percentage of type of material involved in the roof's construction. Each column corresponds to a type of material and the percentage of material involved in the construction of the roof is exclusively given by Hotmaps. In this case the information given by Hotmaps, even for the attributes included "before 1945" and "after 2010" is applied to the whole period of the study (from 1850 to 2021).

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL THICKNESS 1 [M]

Definition: The thickness of the structural element included in the reference building's roof, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL THERMAL CONDUCTIVITY 1 [W/M/K]

Definition: Thermal conductivity of the reference building roof's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL DENSITY 1 [KG/M³]

Definition: The thermal conductivity of the reference building roof's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL 1

Definition: The thickness of the insulation element included in the reference building's roof, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL THICKNESS 1 [M]

Definition: The thickness of the insulation element included in the reference building's roof, expressed in meters.

Methodology: No data is available for Italy in Ambience.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL THERMAL CONDUCTIVITY 1 [W/M/K]

Definition: Thermal conductivity of the reference building roof's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL DENSITY 1 [KG/M³]

Definition: The density of the reference building roof's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

HOTMAPS-AMBIENCE_REFERENCE BUILDING ROOF U-VALUE 1 [W/M²/K]

Definition: U-value of the reference building's roof, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL THICKNESS 2 [M]

Definition: The thickness of the structural element included in the reference building's roof, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL THERMAL CONDUCTIVITY 2 [W/M/K]

Definition: Thermal conductivity of the reference building roof's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF MATERIAL DENSITY 2 [KG/M³

Definition: The thermal conductivity of the reference building roof's structural material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL 2

Definition: The thickness of the insulation element included in the reference building's roof, expressed in meters.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL THICKNESS 2 [M]

Definition: The thickness of the insulation element included in the reference building's roof, expressed in meters.

Methodology: No data is available for Italy in Ambience.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL THERMAL CONDUCTIVITY 2 [W/M/K]

Definition: Thermal conductivity of the reference building roof's insulation material, expressed in W/m/K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience. To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

AMBIENCE_REFERENCE BUILDING ROOF INSULATION MATERIAL DENSITY 2 [KG/M^3]

Definition: The density of the reference building roof's insulation material, expressed in kg/m3 .

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, firstly, we check the available data and see if they match with our range years. On the contrary, to retrieve the data, we make a weighted average between the years.

HOTMAPS-AMBIENCE_REFERENCE BUILDING ROOF U-VALUE 2 [W/M^2/K]

Definition: U-value of the reference building's roof, expressed in W/m2 /K.

Methodology: Data included between 1850 and 2021 correspond to data available in Ambience.

To retrieve the information, we checked data available from both Ambience and Hotmaps, and we chose to use data from Ambience because they should be more complete as they are derived from a comparison between Hotmaps and Tabula.

7.1.1.3 HVAC systems

CES_SPECIFIC TYPE AND SCOPE OF BIPV (BUILDING INTEGRATED PV) [M^2] AND [KWPEAK]

Definition: Specifies the type and the performance of the BIPV if present on the reference building.

Methodology: Data for this attribute is available for France and Netherlands but only for restricted archetypes, consequently the data can't be properly retrieved for the whole EU building stock.

AMBIENCE_HEATING SYSTEM 1 TECHNOLOGY

Definition: Specifies the nature of the first heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 1 DIMENSIONS

Definition: Specifies the nature of the first heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 1 FUEL USED

Definition: Specifies the nature of the fuel of the first heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 1 FUEL EFFICIENCY [%]

Definition: Specifies the nature of the fuel of the first heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 1 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the prevalence of the first heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 2 TECHNOLOGY

Definition: Specifies the nature of the second heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 2 DIMENSIONS

Definition: Specifies the dimensions of the second heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 2 FUEL USED

Definition: Specifies the nature of the fuel of the second heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 2 FUEL EFFICIENCY [%]

Definition: Specifies the efficiency of the second heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 2 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the prevalence of the second heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_Heating system 3 technology

Definition: Specifies the nature of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

MBIENCE_HEATING SYSTEM 3 DIMENSIONS

Definition: Specifies the dimensions of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 3 FUEL USED

Definition: Specifies the nature of the fuel of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 3 FUEL EFFICIENCY [%]

Definition: Specifies the nature of the fuel of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_HEATING SYSTEM 3 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the prevalence of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 1 TECHNOLOGY

Definition: Specifies the prevalence of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 1 DIMENSIONS

Definition: Specifies the prevalence of the third heating system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 1 FUEL USED

Definition: Specifies the nature of the fuel of the first DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 1 FUEL EFFICIENCY [%]

Definition: Specifies the efficiency of the first DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 1 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the efficiency of the first DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 2 TECHNOLOGY

Definition: Specifies the nature of the second DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 2 DIMENSIONS

Definition: Specifies the dimensions of the second DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 2 FUEL USED

Definition: Specifies the nature of the fuel of the second DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 2 FUEL EFFICIENCY [%]

Definition: Specifies the nature of the fuel of the second DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 2 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the prevalence of the second DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 3 TECHNOLOGY

Definition: Specifies the nature of the third DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 3 DIMENSIONS

Definition: Specifies the dimensions of the third DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 3 FUEL USED

Definition: Specifies the nature of the fuel of the third DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_DHW 3 FUEL EFFICIENCY [%]

Definition: Specifies the efficiency of the third DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

DHW 3 PREVALENCE ON BUILDING STOCK [%]

Definition: Specifies the prevalence of the third DHW system used in the reference building.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_COOLING SYSTEM PRESENCE ON BUILDING STOCK [%]

Definition: Specifies the percentage of the reference building that is being cooled.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

AMBIENCE_COOLING PRESENCE

Definition: Specifies whether the reference building possesses a cooling system.

Methodology: The information is retrieved as it is from Ambience as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors.

HOTMAPS_SPACE COOLING SYSTEM TECHNOLOGY.

Definition: Specifies the nature of the cooling system used in the reference building.

Methodology: The information is retrieved as it is from Hotmaps as the data is sufficiently repetitive and exhaustive for all the periods concerned (1850-2021). This applies to both the residential and service sectors. In this case the information is very generic as the data is indicated is always "Most widespread technology". Please note that this information is not given for non-residentials buildings.

7.1.2 Additional information on the upscaling methods from PULSE-EU

Table 9. Scale and shape parameters of the Weibull function per country and typology.

Country	Typology	Pre-war	Post-war
AT	Residential	(0.9, 220)	(4, 2130)
	EDU		(3, 80)
	HEA		
	HOR		
	OFF		
	OTH		(3.5, 120)
	TRA		(2.5, 90)
BE	ALL	(2.95, 132.76)	(2, 105)
BG		(2.5, 133.51)	(2.5, 80)
CY		(2.95, 140.08)	(2.95, 156.89)
CZ		(2.5, 135.25)	(2.5, 157.79)
DE		(2.95, 140.08)	(2.95, 156.89)
DK		(2.95, 134.48)	(2.5, 157.79)
EE		(2.5, 133.51)	(2.95, 156.89)
EL		(2.95, 78.45)	(2.95, 156.89)
ES		(2.95, 132.76)	(2.5, 157.79)
FI		(2.95, 132.76)	(2.95, 156.89)
FR		(2.95, 140.08)	(2.95, 156.89)
HR		(2.5, 133.51)	(2.95, 156.89)
HU		(2.5, 140.88)	(2.95, 156.89)
IE		(2.95, 132.76)	(2.5, 157.79)

IT		(2.95, 132.76)	(2.5, 157.79)
LT		(2.5, 133.51)	(2.95, 156.89)
LU		(2.95, 132.76)	(2.95, 156.89)
LV		(2.5, 133.51)	(2.5, 157.79)
MT		(2.95, 132.76)	(2.95, 156.89)
NL		(2.95, 134.48)	(2.5, 157.79)
PL		(2.5, 133.51)	(2.95, 156.89)

Table 10. Distribution of renovation across construction periods.

Typology	1850-1918	1919-1944	1945-1969	1970-1979	1980-1989	1990-1999	2000-2010
SFH	0,24	0,17	0,08	0,25	0,08	0,1	0,08
MFH	0,2	0,07	0,07	0,24	0,18	0,18	0,06
ABL	0,08	0,05	0,05	0,34	0,17	0,2	0,11
OFF	0,32	0,32	0,37	0,14	0,05	0,07	0,05
TRA	0,32	0,32	0,37	0,14	0,05	0,07	0,05
EDU	0,11	0,11	0,37	0,17	0,17	0,11	0,07
HEA	0,11	0,11	0,37	0,17	0,17	0,11	0,07
HOR	0,22	0,22	0,27	0,13	0,13	0,11	0,14
OTH	0,32	0,32	0,37	0,14	0,05	0,07	0,05

Table 11. Relative increase in average living area per person in 2050 versus 2020 (as used in BAU).

Member State	Relative increase in m^2/cap (%)
AT	34,0
BE	33,0
BG	52,0
CY	4,0

CZ	3,0
DE	13,0
DK	2,9
EE	42,0
EL	12,0
ES	0,5
FI	100,0
FR	3,1
HR	32,0
HU	27,0
IE	1,0
IT	0,5
LT	32,0
LU	33,0
LV	41,0
MT	100,0
NL	10,0
PL	51,0
PT	21,0
RO	81,0
SE	0,5
SI	17,0
SK	23,0
EU27	**15,0**

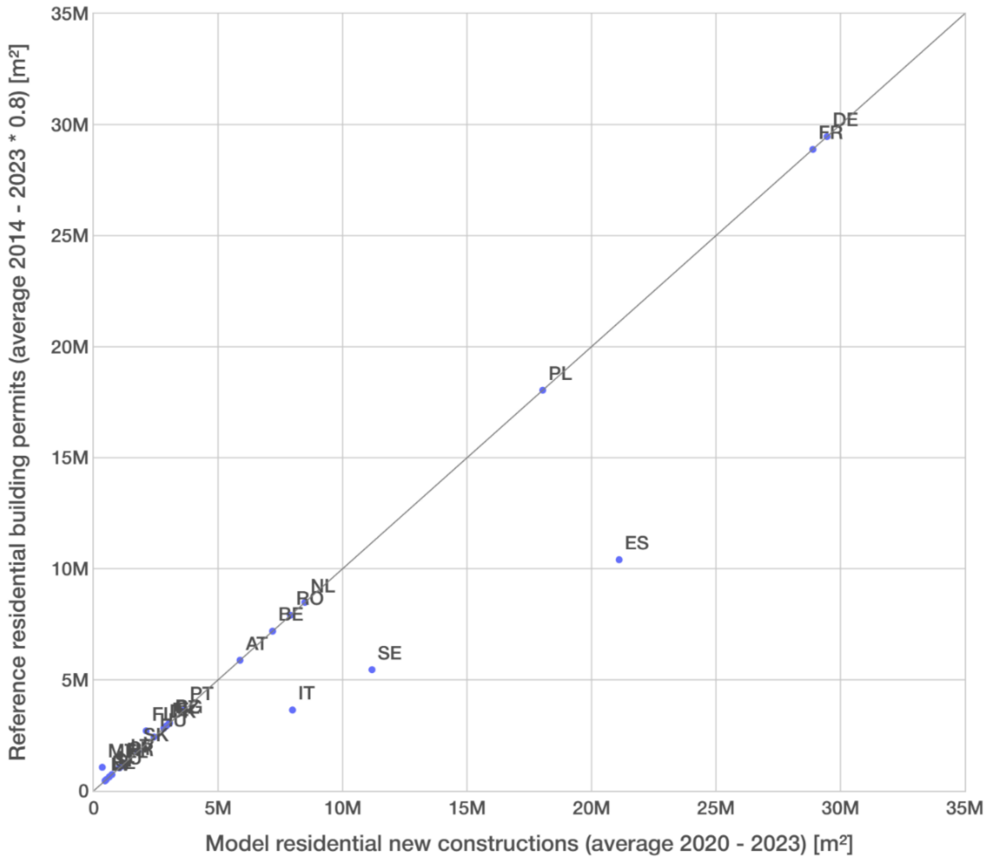

Figure 27. Comparison of the useful floor area built in the model with the reference values from the building permits.

Table 12. Reference values (from the BSO and EUcalc), original value (from SLiCE input data) and calibrated value (from PULSE) for operational carbon emissions (B6).

Member State	Reference value	Original value	Calibrated value
Austria	13.3	41.6	13.3
Belgium	23.8	66.9	23.8
Bulgaria	4.0	21.4	4.0
Croatia	3.2	6.2	3.2
Cyprus	1.1	4.1	1.1
Czechia	23.3	57.3	23.3
Denmark	4.6	8.1	4.6
Estonia	2.0	3.2	2.0

Finland	7.1	55.9	7.2
France	69.3	272.4	69.3
Germany	152.9	511.5	152.9
Greece	8.6	37.5	8.6
Hungary	12.9	23.3	12.9
Ireland	10.5	16.9	10.5
Italy	78.5	208.7	78.6
Latvia	2.1	4.1	2.1
Lithuania	1.8	10.6	1.8
Luxembourg	1.7	3.4	1.7
Malta	0.4	0.6	0.4
Netherlands	25.7	63.9	25.8
Poland	86.6	98.2	86.6
Portugal	4.6	32.9	4.6
Romania	14.7	66.9	14.7
Slovakia	6.8	18.2	6.8
Slovenia	2.0	2.7	2.0
Spain	29.5	246.0	29.5
Sweden	3.0	40.7	3.0
EU27	**594.0**	**1 922.8**	**594.0**

7.1.3 Details on scenario modelling and strategies implementation

First in deliverable D1.2 Report on the most promising carbon reduction and removal strategies (CRRS), and then in a follow-up journal publication[79], eleven (CRRS) were identified, further specified in more than thirty specific measures and classified across life-cycle stages, as well as the

[79] Alaux, N., Marton, C., Steinmann, J., Maierhofer, D., Mastrucci, A., Petrou, D., Potrč Obrecht, T., Ramon, D., le Den, X., Allacker, K., Passer, A., & Röck, M. (2024b). Whole-life greenhouse gas emission reduction and removal strategies for buildings: Impacts and diffusion potentials across EU Member States. Journal of Environmental Management, 370, 122915. https://doi.org/10.1016/J.JENVMAN.2024.122915

avoid-shift-improve (ASI) framework. For example, the strategy "Increase circular material use" is further specified in three measures: "Reuse of building components and materials", "Use of materials with high recycled content" and "Design for disassembly". This was based on the existing literature and stakeholders' consultations. Within this work, these strategies were translated into relevant model parameters and assumptions for the **future diffusion** of each measure was also collected, for three decades (2030, 2040, 2050) and three ambition levels (low, medium, high). This leads, for each measure, for nine data points for their future diffusion. An example is provided in Table 13 in the case of the measure "Optimise the use of space in buildings". The relevant modelling parameter is the average living area, and these diffusion assumptions represent possible reductions in the average living area compared to the BAU. Additionally, the **impact on reducing carbon emissions** of each measure was also quantified (at the building or material level) as part of this desk research. All of this data constitutes the basis for the projection of future scenarios. They were thoroughly discussed during the stakeholders' workshop which was held in November and, when necessary, adapted.

Table 13. Future diffusion assumptions for the strategy "Optimise the use of space in buildings". These percentages refer to the reduction in average living area compared to the BAU.

	2030	2040	2050
Low	3%	5%	10%
Medium	5%	10%	20%
High	10%	20%	30%

The implementation of the strategies in the model depend if their influence is on the building archetypes or on the building stock, as can be seen in Table 14.

- **Archetype-related strategies** are strategies that do not directly influence the building stock activities, but might influence the emissions from the archetypes, such as for example changes in the production of materials. The impact (understood as reduction in carbon emissions) of these strategies is taken from the literature (e.g. strategy 5 can reduce carbon emissions by 70%), then multiplied by the diffusion assumptions and used to adjust the SLiCE archetype results. For example, if concrete can reduce its emissions by 70% and the diffusion of this strategy is 30% for a specific country, then the archetype emissions results are multiplied by (1-0.7)*0.3. These reductions are then applied to the archetypes in a preprocessing step, before they are used for multiplication with the building stock activities. If multiple strategies affect the same material, the reductions in carbon emissions are multiplied with each other.
- **Stock-related strategies** are strategies that do directly influence the building stock activities, meaning that they have the ability to change the number of constructions, renovations or demolitions (such as for instance vacancy reduction). These strategies are directly implemented in the PULSE-EU model using the diffusion assumptions. Their impact on the carbon emissions are not taken from the literature but are calculated directly by the model. The stock-related strategies are:
    - **1.1 Optimise the use of space in buildings** is reducing the living area per person in residential buildings by a percentage compared to the BAU scenario and therefore reduces the need for new constructions.

- **2.1 Extend building lifetime through renovation and repurposing.** The number of demolitions is reduced by a percentage. These buildings get a deep refurbishment instead of being demolished.
- **2.2 Reduce vacancy.** A percentage of empty dwellings get a deep refurbishment and then are considered used instead of vacant. This reduces the need for new constructions.
- **4.1, 4.2 Full/hybrid timber buildings.** A share of conventional new buildings is instead constructed as the corresponding full or hybrid timber buildings archetypes provided in the SLiCE emissions data.
- **9.1 - 9.3 Renovation rate (light, medium and deep refurbishments).** A defined rate of the building stock is renovated with light, medium or deep refurbishment packages.
- **9.4, 9.5 Share of new nearly zero emission buildings (NZEB).** A percentage of new constructions are built as NZEB buildings using the corresponding SLiCE archetypes.

- For strategies marked "not explicitly in scope" in Table 14, expert review of potential impact as well as effort for modelling determined to not to explicitly model these due to the following reasoning:
  - Due to similarities between measures 1.1 and 1.2 in the modelling parameters that are influenced, the reduction of living area that is applied in the modelling is expected to be influenced by both 1.1 and 1.2. As such, these measures are merged together and only 1.1 is explicitly modelled. 1.2 is indirectly included in this modelling.
  - Measures 2.3 and 8.3 were found in the literature not to have potential to reduce carbon emissions by 2050, but rather in the second lifetimes of the buildings, which would occur farther in the future. Due to this fact, they are not explicitly modelled (the benefits would occur after 2050 and would not be visible).
  - Measures 7.1 and 10.2 are out of the scope of the SLiCE modelling and could therefore not be included.
  - Measure 10.3 is indirectly addressed through measure 10.1 and therefore also not explicitly modelled.
  - As extensively described in the deliverable D1.2 Report on the most promising carbon reduction and removal strategies, measures 11.1, 11.2 and 11.3 are remaining data gaps concerning diffusion, Member State capacity and carbon reduction potential. Despite additional desk research and discussion with stakeholders, we did not find more plausible data. We therefore did not explicitly model them. The carbon removal potential is now addressed through the use of bio-based materials and carbonation of cement-based materials.

Table 14. Implementation of the CRRS.

Number	Strategy	Measure	Implementation
1.1	Reduce the per capita space demand	Optimise the use of space in buildings	Stock

1.2		Redesigning buildings for a denser use	Not explicitly in scope
2.1	Prioritize better use, renovation and repair over demolition and new construction	Extend building lifetime through renovation and repurposing	Stock
2.2		Reduce vacancy	Stock
2.3		Design for flexibility and adaptability	Not explicitly in scope
3.1	Optimize the use of materials	Optimize the use of materials in structural design	Archetypes
3.2		Offsite construction	Archetypes
4.1	Increase the use of bio-based materials	Full timber buildings	Stock
4.2		Hybrid timber buildings	Stock
4.3		Bio-based insulation	Archetypes
5.1	Reduce emissions from traditionally high-impact construction materials	Material substitution	Archetypes
5.2		Production of materials via the use of renewable/low-carbon energy	Archetypes
5.3		Production of materials via carbon capture, utilization and storage during manufacturing	Archetypes
6.1	Reduce emissions from the transport of construction materials	Use of locally sourced materials	Archetypes
6.2		Use of alternative fuels in transportation	Archetypes
7.1	Reduce emissions at construction sites	Use of alternative fuels in construction machinery	Not explicitly in scope
7.2		Machine use optimization	Archetypes
8.1	Increase of circular material use	Reuse of existing building components and materials	Archetypes
8.2		Use of materials with high recycled material content	Archetypes
8.3		Design for disassembly	Not explicitly in scope
9.1	Reduce operational greenhouse gas emissions	Renovation rate residential (light refurbishment)	Stock

9.2		Renovation rate residential (medium refurbishment)	Stock
9.3		Renovation rate residential (deep refurbishment)	Stock
9.4		Renovation rate non-residential (light refurbishment)	Stock
9.5		Renovation rate non-residential (medium refurbishment)	Stock
9.6		Renovation rate non-residential (deep refurbishment)	Stock
9.7		Share of new NZEB buildings (education and health sector)	Stock
9.8		Share of new NZEB buildings (all other buildings)	Stock
9.9		Renewable electricity	Archetypes
9.10		Renewable energy in district heating	Archetypes
9.11		Reduce temperature setpoints	Archetypes
10.1	Reduce construction and demolition waste	On-site waste material sorting and separation	Archetypes
10.2		Reduce construction packaging	Not explicitly in scope
10.3		End-of-life and waste audits	Not explicitly in scope
11.1	Implement dedicated carbon dioxide removal solutions	Green roofs and/or green façades	Not explicitly in scope
11.2		Using biochar	Not explicitly in scope
11.3		Direct air capture	Not explicitly in scope

In deliverable D1.2 Report on the most promising carbon reduction and removal strategies, a **capacity** for implementing each of the ten CRRS (in terms of low, medium or high capacity) was defined for each Member State and each decade, from 2020 to 2050. This was performed via a qualitative analysis of suitability criteria and indicators for each CRRS. These capacities are then directly linked to the diffusion assumptions for each CRRS. For example, Austria has a medium capacity of implementing strategy 1 in 2030, which means that its reduction in average living area would be 6% in 2030 (see Table 5). Notably, the implementation level refers to the diffusion conditions defined for each strategy, which differ depending on the expected year. In other words, just because the same number of countries exhibit a low, medium or high implementation rate for a given strategy in both 2030 and 2040 does not suggest that the situation will not evolve. Since the low implementation in 2030 differs from that in 2040, the implementation of that strategy can still evolve.

Linking each Member State capacity for every year to the diffusion assumptions for each CRRS leads to one possible value per year, CRRS and MS. This one scenario indicates what future carbon emissions would be if every Member State would implement each CRRS to their expected capacity. However, the ambition of each Member State to implement these strategies might differ. They could be lower or higher than their capacity. To allow for a more flexible approach to scenario modelling, we allow for **scaling** the diffusion of the strategies. For example, if a strategy is scaled by 50%, it means that the Member State applies this strategy to 50% of their capacity. A 100% scaling would give the one scenario in which each Member State applies the strategies to their expected capacity. When the scaling is higher than 100%, such as 150%, then the countries that have a low or medium capacity increase their ambition by 50%, but it cannot be higher than the high diffusion levels (which can be the maximum technical diffusion and would therefore not make sense).

7.1.4 Building stock composition (2019)

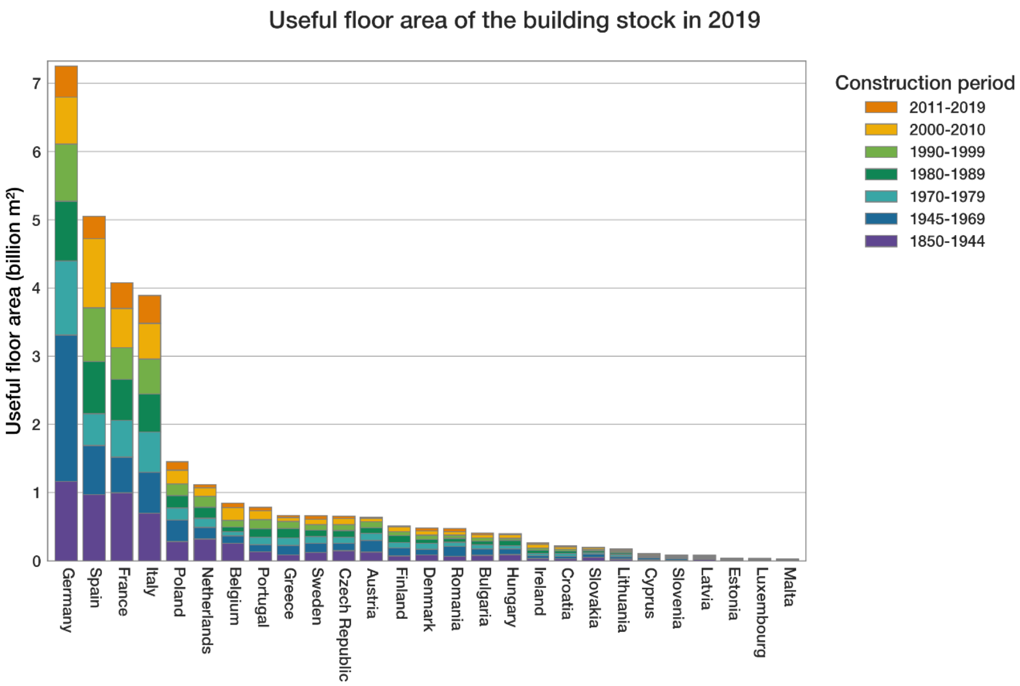

Figure 28: Building stock composition input (2019) by construction period per Member State, expressed as billion m² useful floor area, as determined from statistical data.

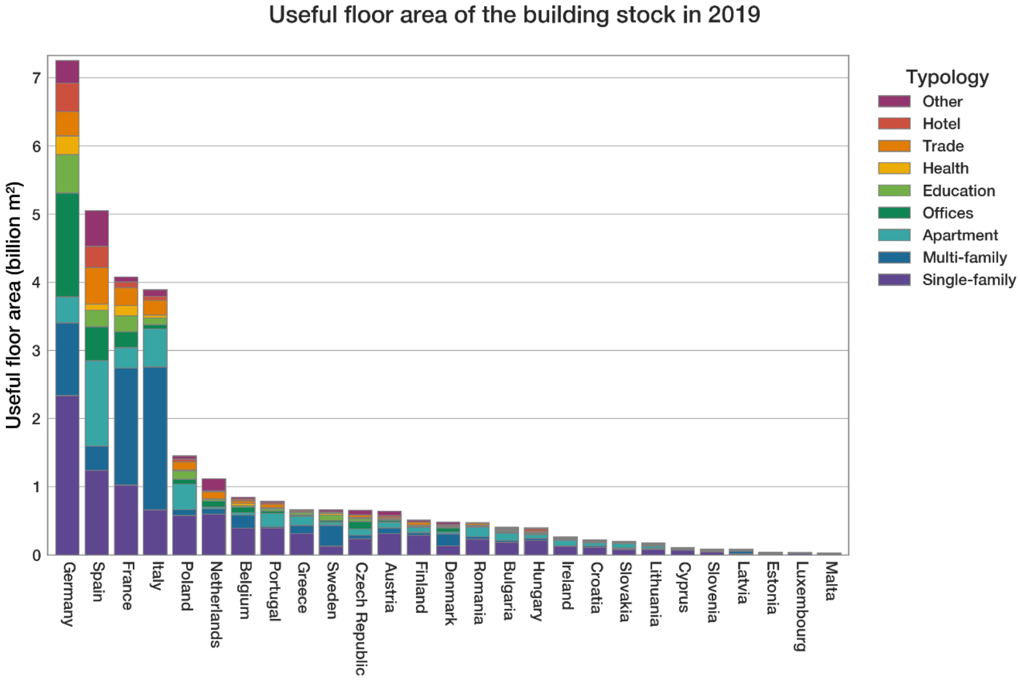

Figure 29: Building stock composition input (2019) by building typology per Member State, expressed as billion m² useful floor area, as determined from statistical data.

7.1.5 Scenario modelling: Activity rates

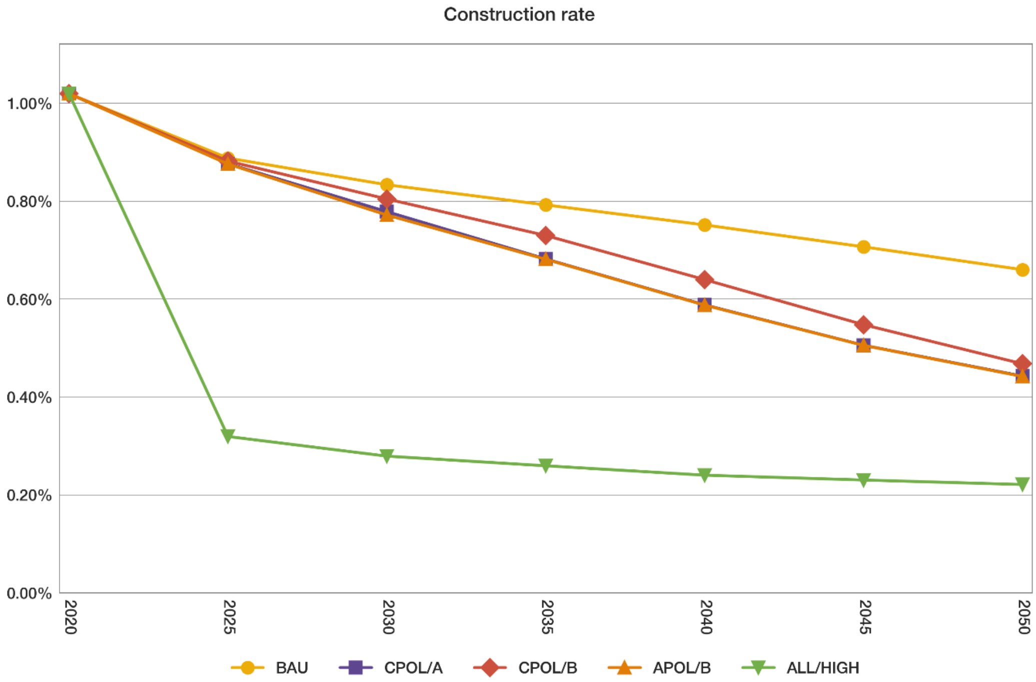

Figure 30: Construction rates (2020-2050), expressed in percentage of useful floor area, as modelled for the pre-defined scenarios (business-as-usual (BAU), optimistic currently policy (CPOL/A); conservative current policy scenario (CPOL/B); additional policy scenario (APOL); and all strategies high (ALL/High))

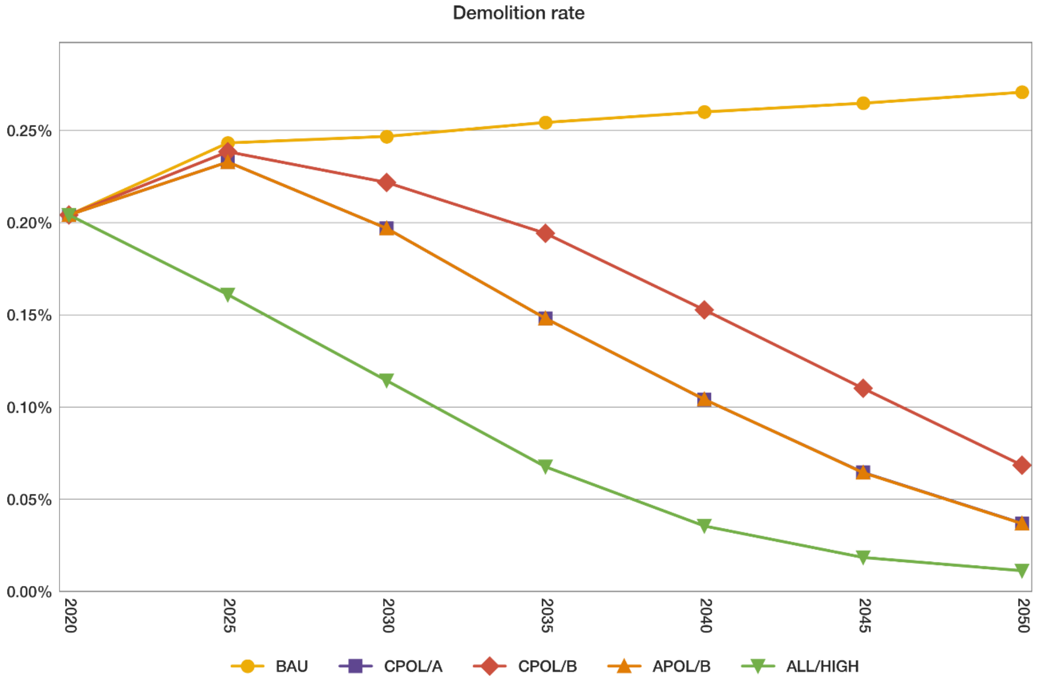

Figure 31: Demolition rates (2020-2050), expressed in percentage of useful floor area, as modelled for the pre-defined scenarios.

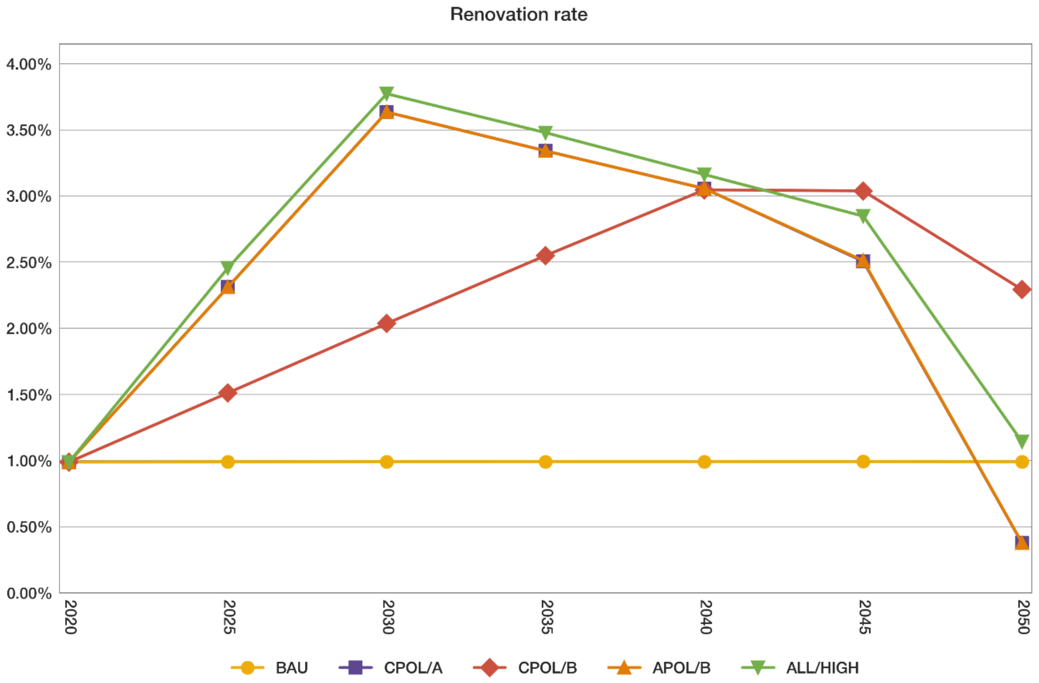

Figure 32: Refurbishment rates (2020-2050), expressed in percentage of useful floor area, as modelled for the pre-defined scenarios.

7.1.6 Additional information on carbon removal quantification

To quantify biogenic carbon dioxide storage via bio-based products applied on archetype level, the biogenic carbon values were calculated applying the requirements of EN 16449:2014-03[80] according to following formula:

$$CDR_{bio} = \frac{44}{12} \cdot c_f \cdot \frac{\varrho_\omega \cdot V_\omega}{1 + \frac{\omega}{100}} \cdot VP$$

Where:

- CDR_{bio} is the biogenic CO2 sequestered in the bio-based materials in $kgCO_2$,
- 44/12 is the ratio of atomic mass between CO_2 and C,
- c_f is the carbon content of the bio-based material in a dry state in %,
- ω the moisture content of the bio-based material in %,
- ϱ_ω is the density of the bio-based material at this moisture content in kg/m^3,
- V_ω is the volume of the solid wood product at this moisture content in m^3,
- VP is the share of bio-based material in the overall product in %.

The information on carbon content and moisture content required for this calculation was taken from ecoinvent data[81]. In addition, the carbon factors given in the National Inventory Reports in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[82] for various wood semi-finished products were used for the materials. In Table 15 below, the biogenic carbon factors CDR factors, minima and maxima values, as well as the resulting averages for the biogenic materials available in all EU SLiCE datasets are listed for the quantification of carbon removals.

Table 15: Stored biogenic CO2 within bio-based materials. MIN and MAX values based on ecoinvent records and IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 12 Harvested Wood Products. AVG values resulting from MAX and MIN values.

Biogenic Materials - Techflow Names MMG obtained from the SLiCE Datasets	Material Categories	Biogenic CDR factors for carbon storage - Before Use (A)		
		MIN	MAX	AVG
		kgCO2 / kg product in SLiCE		
Straw, stand-alone production [RER]| production | Alloc Rec, U	other	-1,439	-1,604	-1,521
Linoleum tile, 2,5 mm thick [RER]| production	other	-1,424	-1,497	-1,460
Hempcrete blocks, excl. mortar	other	-0,314	-0,376	-0,345
Hemp insulation [RER]| production	other	-1,742	-2,090	-1,916
Cork slab {RER}| production | Alloc Rec, U	other	-1,980	-2,061	-2,020
Sawnwood, softwood, dried (u=10%), planed {Europe without Switzerland}| sawnwood production, softwood, dried (u=10%), planed | Cut-off, U	Sawn wood	-1,647	-1,866	-1,756
Hardwood, (untreated) parquet [BE]| production, MIX	Sawn wood	-1,647	-1,833	-1,740
Sawnwood, hardwood, dried (u=10%), planed {RER}| production | Alloc Rec, U	Sawn wood	-1,647	-1,833	-1,740
Cross-laminated timber [RER]| cross-laminated timber production | Cut-off, U	Sawn wood	-1,479	-1,866	-1,672
Wood cladding, softwood {RoW}| wood cladding production, softwood | Cut-off, U	Sawn wood	-1,575	-1,866	-1,720
Laminated timber element, transversally prestressed, for outdoor use {RER}| laminated timber element production, for outdoor use | Cut-off, U	Sawn wood	-1,552	-1,866	-1,709
Plywood, for indoor use {RER}| production | Alloc Rec, U	Wood-based panels	-1,403	-1,806	-1,605

[80] CEN 2014. EN 16449:2014-03 Wood and wood-based products – Calculation of the biogenic carbon content of wood and conversion to carbon dioxide

[81] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230

[82] Rüter, S., Matthews, R. W., Lundblad, M., Sato, A., & Hassan, R. A. (2019). Chapter 12: harvested wood products 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC: Geneva, Switzerland, 49.

Fibreboard, soft, without adhesives {CH}| fibreboard production, soft, without adhesives | Cut-off, U	Wood-based panels	-1,563	-1,684	-1,624
Medium density fibreboard {RER}| medium density fibre board production, uncoated | Alloc Rec, U	Wood-based panels	-1,446	-1,565	-1,506
Oriented strand board {RER}| oriented strand board production | Cut-off, U	Wood-based panels	-1,623	-1,696	-1,659
Fibreboard, soft, bitumised [RER]| production | Alloc Rec, U	Wood-based panels	-1,563	-1,611	-1,587
Fibreboard, soft, latex bonded [RER]| production | Alloc Rec, U	Wood-based panels	-1,563	-1,611	-1,587
Fibreboard, hard {RER}| fibreboard production, hard | Cut-off, U	Wood-based panels	-1,559	-1,660	-1,610
Window frame, wood, U=1.5 W/m2K {RER}| window frame production, wood, U=1.5 W/m2K | Cut-off, U	Windows and doors	-1,186	-1,320	-1,253
Door, inner, MDF varnished [RER]| production	Windows and doors	-1,316	-1,425	-1,370

The CDR values for **mineral materials** were also expanded in comparison to Deliverable 2.1 Report with quantitative baseline figures for WLC and carbon removals to include maximum and minimum values. In this case, the maximum and minimum values were calculated on the basis of the information in the relevant standards EN 16757:2022 D[83] and CEN/TR 17310:2019 D[84]. For example, the maximum or minimum were calculated by varying the observed carbonation or the clinker content in the cement based on the standards. The information for the calcination emissions of the mineral bound carbon was taken from the standard CEN/TR 17310:2019 D, Table 16 and converted to the respective cement type depending on the information on the cement type in the updated SLiCE datasets. For clay bricks, TU Graz internal data representing maxima and minima values for the calcination emissions. For the carbonation in the use phase, the standard calculation method based on EN 16757:2022 D was applied. In Deliverable 2.1 Report with quantitative baseline figures for WLC and carbon removals, this formula was still statically assumed on the basis of the study's reference period of 50 years. In Deliverable 4.1 Report with quantitative figures for future scenarios addressing WLC and carbon removals , the mapping of the mineral CDR factors onto the SLiCE datasets was updated so that the residence time of the elements is taken into account, i.e. if an element is installed in year 35, and the reference service life exceeds the reference study period of 50 years, it is accounted that the element is carbonating for 15 years. This gives a more accurate result for the carbonation of the mineral building materials in the use phase. The formula for carbonation in the use phase is shown in the following formula based on EN 16757:2022 D[85].

$$CO_2\, uptake = k \cdot \frac{\sqrt{t}}{1000} \cdot U_{tcc} \cdot C \cdot D_c$$

where:

- CO_2 uptake is the CO2 sequestered via carbonation per m^2 of surface area
- k is the carbonation coefficient in $mm/year^{0.5}$,
- t is the reference study period
- U_{tcc} is the maximum theoretical uptake in $kgCO_2/kg$ cement.
- C is the cement content in kg/m3
- D_c is the degree of carbonation in %

For each of the combinations of mineral material and element location, factors for the degree of carbonation D_c and the carbonation coefficient k were assigned based on EN 16757:2022 D table G.1.

[83] CEN 2022. EN16757:2022 D Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements

[84] CEN 2019. CEN/TR 17310:2019 D Carbonation and CO2 uptake in concrete

[85] CEN 2022. EN16757:2022 D Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements

Based on the methodology in Deliverable 2.1, the carbonation was again converted from m^2 surface area to kg material in SLiCE, whereby a specific surface area of 8 m^2/m^3 was assumed in accordance with CEN/TR 17310:2019 D, Section 6.2[86]. The CO_2 uptake per kg of material was then converted by applying the density of the material.

For end-of-life carbonation, again information from EN 16757:2022 D and CEN/TR 17310:2019 D was used for this report, according to which the carbonation of concrete (and cement rubble) is expected to be a minimum of 5 kgCO$_2$/m^3 of concrete and a maximum of 22 kgCO$_2$/m^3 of concrete[87], [88]. This information was subsequently converted to the respective proportion of cement in a concrete component and also to the cement type according to the SLiCE datasets available.

An overview on the mineral CDR factors applied in D4.1 Report with quantitative figures for future scenarios addressing WLC and carbon removals, including the maximum, minimum and resulting average calcination and carbonation values for before use, use and after use of the mineral materials is presented in following Table 16.

Table 16: CDR-mineral factors for mineral techflow_name_mmg entries in the updated SLICE datasets, including MIN, MAX and resulting AVG observed values. Before_use representing calcination emissions purely from the chemically bound carbon released during production, Use representing the carbonation during use phase for a 50 year time horizon, After_use representing carbonation of crushed mineral materials after demolition

CDR_material_mapping_1	techflow_name_mmg	element_class_generic_name	before_use_MAX	before_use_MIN	before_use_AVG	use_MAX	use_MIN	use_AVG	after_use_MAX	after_use_MIN	after_use_AVG
			kgCO2 / kg product in SLiCE			kgCO2 / kg product in SLiCE			kgCO2 / kg product in SLiCE		
Cement plaster	Base plaster {GLO}| market for base plaster | Cut-off, U	Internal walls	0,097	0,063	0,080	-0,065	-0,057	-0,061	0,000	0,000	0,000
Cement plaster	Base plaster {GLO}| market for base plaster | Cut-off, U	Storey floors	0,097	0,063	0,080	-0,065	-0,057	-0,061	0,000	0,000	0,000
Cement plaster	Base plaster {GLO}| market for base plaster | Cut-off, U	External walls	0,097	0,063	0,080	-0,065	-0,057	-0,061	0,000	0,000	0,000
Cement plaster	Base plaster {GLO}| market for base plaster | Cut-off, U	Roofs	0,097	0,063	0,080	-0,054	-0,047	-0,051	0,000	0,000	0,000
Cement plaster	Primer, unplastered walls, before plastering [RER]| production	External walls	0,097	0,063	0,080	-0,054	-0,047	-0,051	0,000	0,000	0,000
Cement mortar	Cement mortar {CH}| production | Cut-off, U	Storey floors	0,095	0,045	0,070	-0,006	0,000	-0,003	-0,078	-0,010	-0,044
Cement mortar	Cement mortar {CH}| production | Cut-off, U	Substructure	0,095	0,045	0,070	-0,002	0,000	-0,001	-0,078	-0,010	-0,044
Cement mortar	Cement mortar {CH}| production | Cut-off, U	Staircases	0,095	0,045	0,070	-0,006	0,000	-0,003	-0,078	-0,010	-0,044
Cement mortar	Cement mortar {CH}| production | Cut-off, U	External walls	0,095	0,045	0,070	-0,006	0,000	-0,003	-0,078	-0,010	-0,044
Cement mortar	Cement mortar {CH}| production | Cut-off, U	Internal walls	0,095	0,045	0,070	-0,006	0,000	-0,003	-0,078	-0,010	-0,044
Cement mortar	Lime mortar [RER]| production | Alloc Rec, U	External walls	0,366	0,319	0,342	-0,040	0,000	-0,020	-0,308	-0,075	-0,192
Cement mortar	Lime mortar {CH}| lime mortar production | Cut-off, U	Substructure	0,366	0,319	0,342	-0,005	0,000	-0,003	-0,308	-0,075	-0,192
Cement	Cement, Portland {Europe without Switzerland}| cement production, Portland | Cut-off, U	Storey floors	0,475	0,475	0,475	0,000	0,000	0,000	-0,071	-0,018	-0,044

[86] CEN 2019. CEN/TR 17310:2019 D Carbonation and CO2 uptake in concrete

[87] CEN 2022. EN16757:2022 D Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements

[88] CEN 2019. CEN/TR 17310:2019 D Carbonation and CO2 uptake in concrete

Cement	Cement, Portland {Europe without Switzerland}| cement production, Portland | Cut-off, U	Roofs	0,475	0,475	0,475	-0,037	-0,033	-0,035	-0,071	-0,018	-0,044
Cement	Cement, unspecified {Europe without Switzerland}| cement, all types to generic market for cement, unspecified | Cut-off, U	Substructure	0,444	0,444	0,444	-0,019	-0,015	-0,017	-0,065	-0,016	-0,041
Cement	Cement, unspecified {Europe without Switzerland}| cement, all types to generic market for cement, unspecified | Cut-off, U	Storey floors	0,444	0,444	0,444	0,000	0,000	0,000	-0,065	-0,016	-0,041
Clay Brick	Clay brick {RER}| clay brick production | Cut-off, U	Storey floors	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Clay Brick	Clay brick {RER}| clay brick production | Cut-off, U	Roofs	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Clay Brick	Clay brick {RER}| clay brick production | Cut-off, U	External walls	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Clay Brick	Clay brick {RER}| clay brick production | Cut-off, U	Substructure	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Clay Brick	Clay brick {RER}| clay brick production | Cut-off, U	Internal walls	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Clay Brick	Roof tile {RER}| roof tile production | Cut-off, U	Roofs	0,098	0,020	0,059	0,000	0,000	0,000	-0,022	-0,020	-0,021
Concrete	Concrete, normal {CH}| production | Cut-off, U	Substructure	0,050	0,045	0,047	-0,002	-0,002	-0,002	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	Storey floors	0,050	0,045	0,047	-0,005	-0,005	-0,005	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	Technical services	0,050	0,045	0,047	-0,005	-0,005	-0,005	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	Staircases	0,050	0,045	0,047	-0,005	-0,005	-0,005	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	Internal walls	0,050	0,045	0,047	-0,005	-0,005	-0,005	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	Roofs	0,050	0,045	0,047	-0,004	-0,003	-0,004	-0,008	-0,002	-0,005
Concrete	Concrete, normal {CH}| production | Cut-off, U	External walls	0,050	0,045	0,047	-0,010	-0,008	-0,009	-0,008	-0,002	-0,005
Concrete	Poor concrete {CH}| production | Cut-off, U	Roofs	0,032	0,024	0,028	-0,004	-0,003	-0,003	-0,007	-0,002	-0,004
Concrete	Concrete block {DE}| production | Cut-off, U	Internal walls	0,048	0,043	0,046	-0,005	-0,004	-0,005	-0,007	-0,002	-0,004
Concrete	Concrete block {DE}| production | Cut-off, U	External walls	0,048	0,043	0,046	-0,009	-0,008	-0,008	-0,007	-0,002	-0,004

8. SI: RESULTS AND DISCUSSION

8.1.1 Building archetype baseline results

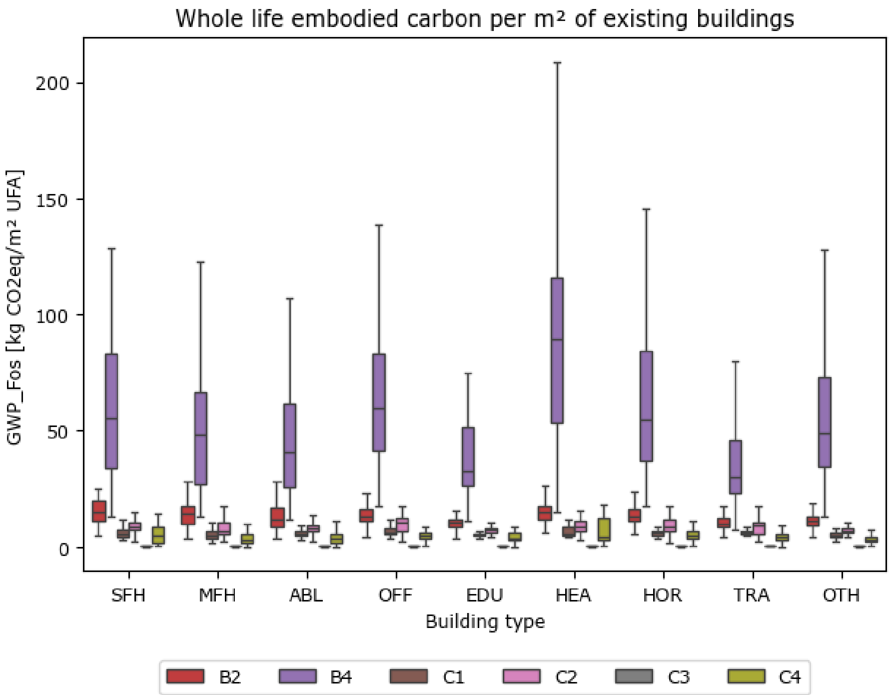

Figure 10: Whole life embodied carbon (GWP Fossil) per m² useful floor area for existing building archetypes grouped per building use type and life cycle stage.

8.1.2 Carbon Dioxide Removal Quantification on Archetype level

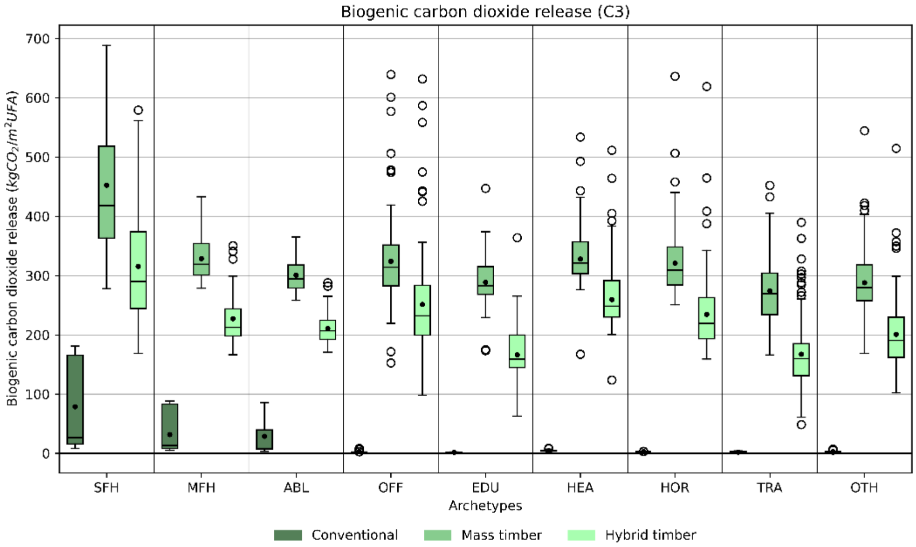

Figure 33: Average end-of-life biogenic carbon dioxide release (C3) of bio-based materials for all NEW archetypes in the 27 Member States, for conventional, mass timber and hybrid timber construction. (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

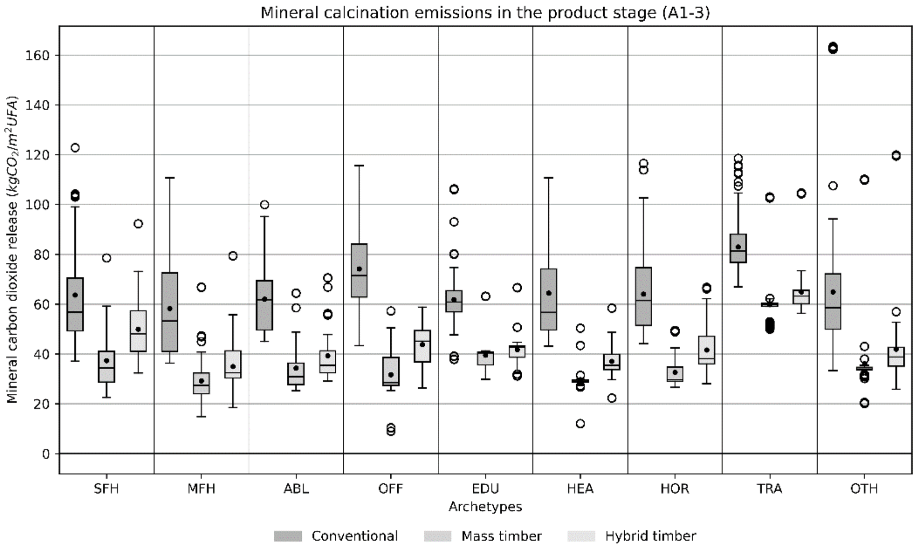

Figure 34: Average product stage calcination emissions (A1-3) of mineral materials for all NEW archetypes in the 27 Member States, for conventional, mass timber and hybrid timber construction. (Single family houses (SFH), Multifamily houses (MFH), Apartment blocks (ABL), Offices (OFF), Education (EDU), Health (HEA), Hotels and Restaurants (HOR), Trade (TRA), Other non-residential buildings (OTH)).

8.1.3 Building stock baseline year (2020)

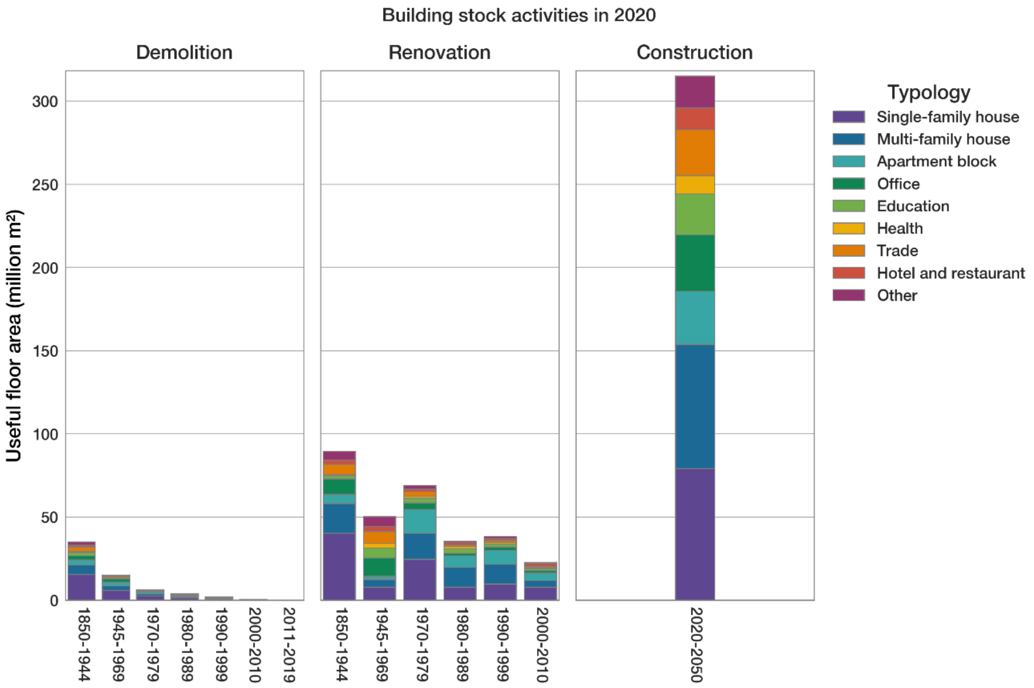

Figure 35: Overview of building stock activity in the baseline year (2020). Showing demolition, refurbishment, as well as new construction activity per construction period and building typology, expressed as million m² useful floor area affected.

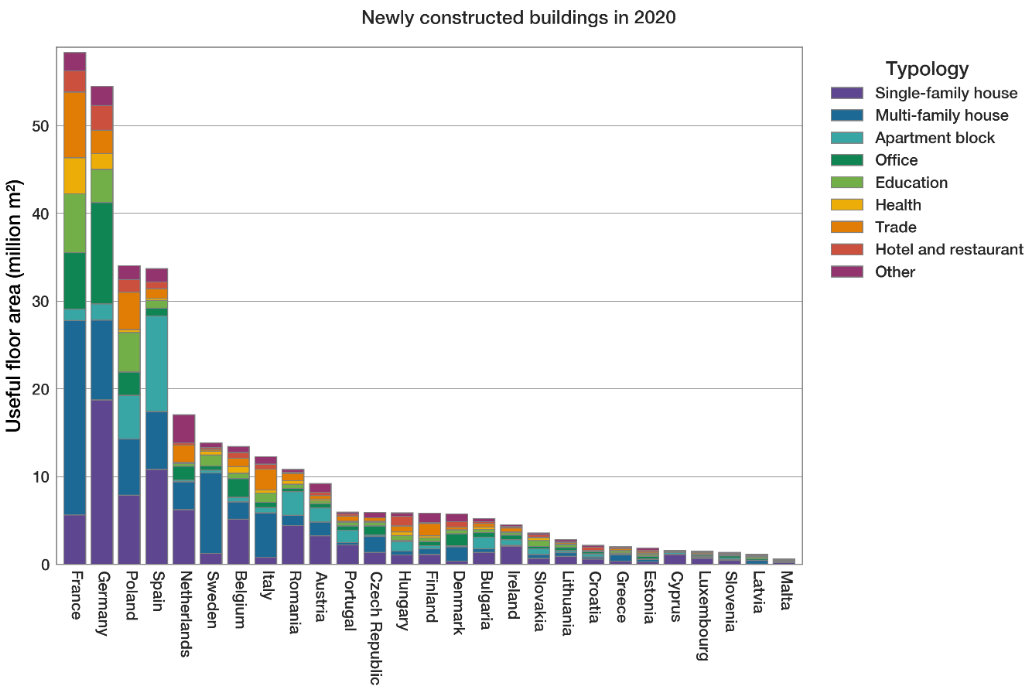

Figure 36: Newly constructed floor area per Member State and building typology in the baseline year 2020, expressed as million m² useful floor area newly constructed.

8.1.4 Scenario results

8.1.4.1 Business-as-usual scenario (BAU)

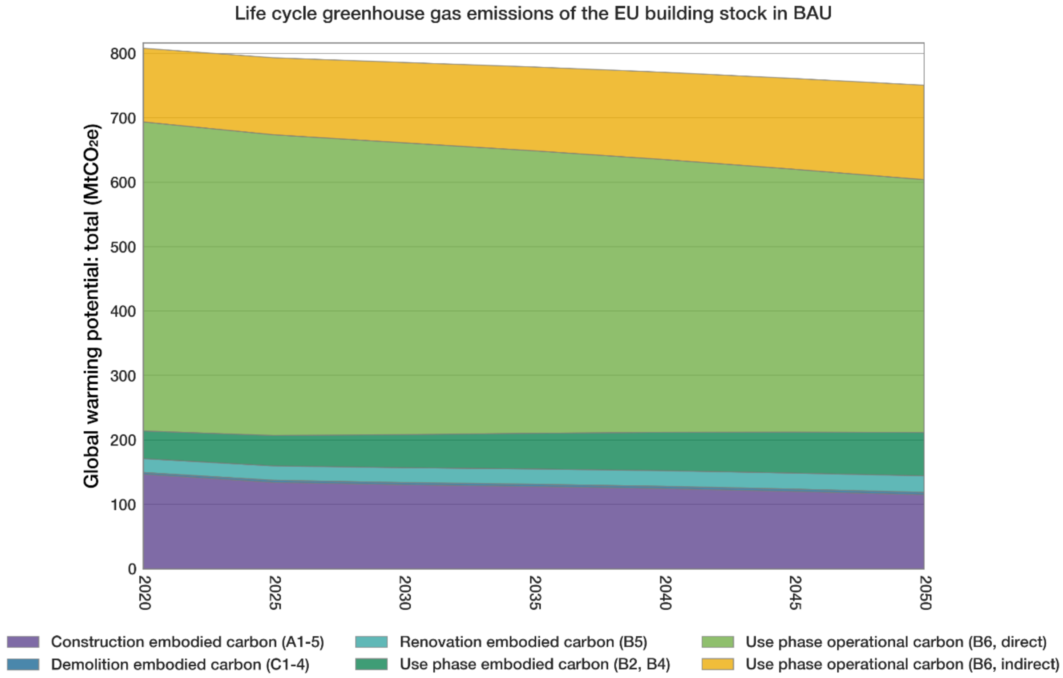

Figure 37: Business-as-usual (BAU) reference scenario results for whole life cycle carbon emissions (MTCO2e) by building stock activity 2020-2050.

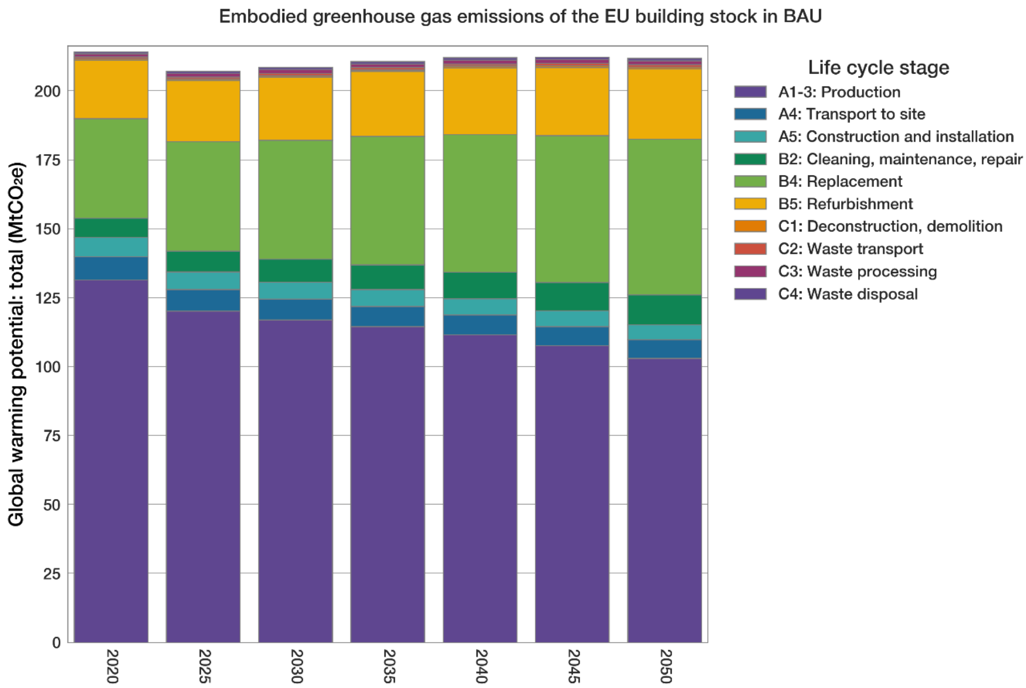

Figure 38: Whole life cycle embodied carbon emissions (MtCO2e) in the BAU reference scenario 2020-2050, with breakdown per life cycle module (acc. EN 15978).

8.1.4.2 Optimistic current policy scenario (CPOL/A): Per-capita emissions by MS

Table 17. Overview of embodied and operational carbon emissions per capita for CPOL/A (in tCO2eq/cap) per Member State.

Member State	Emission type	2020	2030	2040	2050
EU	**Embodied**	**0.48**	**0.56**	**0.45**	**0.22**
	Operational	**1.33**	**0.86**	**0.38**	**0.14**
AT	Embodied	0.92	1.14	0.99	0.38
	Operational	1.50	1.06	0.53	0.16
BE	Embodied	0.76	0.81	0.71	0.26
	Operational	2.07	1.40	0.47	0.14
BG	Embodied	0.52	0.77	0.70	0.27
	Operational	0.58	0.24	0.08	0.05
CY	Embodied	1.46	1.57	1.09	0.36
	Operational	1.24	0.67	0.27	0.10
CZ	Embodied	0.35	0.39	0.32	0.21
	Operational	2.18	0.94	0.43	0.26
DE	Embodied	0.41	0.53	0.43	0.17
	Operational	1.84	1.14	0.56	0.13
DK	Embodied	0.62	0.81	0.65	0.32
	Operational	0.78	0.40	0.17	0.04
EE	Embodied	0.71	0.60	0.52	0.30
	Operational	1.52	0.96	0.38	0.24
EL	Embodied	0.23	0.43	0.36	0.28
	Operational	0.80	0.56	0.29	0.09
ES	Embodied	0.55	0.59	0.43	0.23
	Operational	0.62	0.42	0.19	0.06
FI	Embodied	0.73	1.10	0.95	0.81

	Operational	1.29	0.76	0.32	0.06
FR	Embodied	0.61	0.62	0.47	0.22
	Operational	1.03	0.67	0.25	0.09
HR	Embodied	0.35	0.45	0.39	0.16
	Operational	0.78	0.60	0.30	0.15
HU	Embodied	0.39	0.43	0.38	0.23
	Operational	1.32	1.06	0.52	0.22
IE	Embodied	0.47	0.44	0.34	0.15
	Operational	2.11	1.23	0.44	0.16
IT	Embodied	0.23	0.37	0.29	0.16
	Operational	1.30	0.91	0.44	0.15
LT	Embodied	0.69	0.80	0.72	0.33
	Operational	0.65	0.40	0.19	0.05
LU	Embodied	0.99	0.75	0.53	0.30
	Operational	2.73	1.52	0.40	0.23
LV	Embodied	0.41	0.50	0.46	0.27
	Operational	1.08	0.68	0.32	0.15
MT	Embodied	0.77	0.69	0.50	0.26
	Operational	0.69	0.49	0.24	0.24
NL	Embodied	0.59	0.62	0.47	0.19
	Operational	1.48	0.96	0.42	0.13
PL	Embodied	0.60	0.66	0.57	0.32
	Operational	2.28	1.55	0.64	0.36
PT	Embodied	0.43	0.50	0.40	0.17
	Operational	0.44	0.34	0.16	0.05
RO	Embodied	0.29	0.32	0.29	0.17

	Operational	0.76	0.64	0.35	0.17
SE	Embodied	0.58	0.65	0.57	0.25
	Operational	0.29	0.18	0.08	0.03
SI	Embodied	0.40	0.41	0.36	0.19
	Operational	0.93	0.62	0.30	0.12
SK	Embodied	0.29	0.32	0.27	0.15
	Operational	1.25	0.54	0.20	0.18

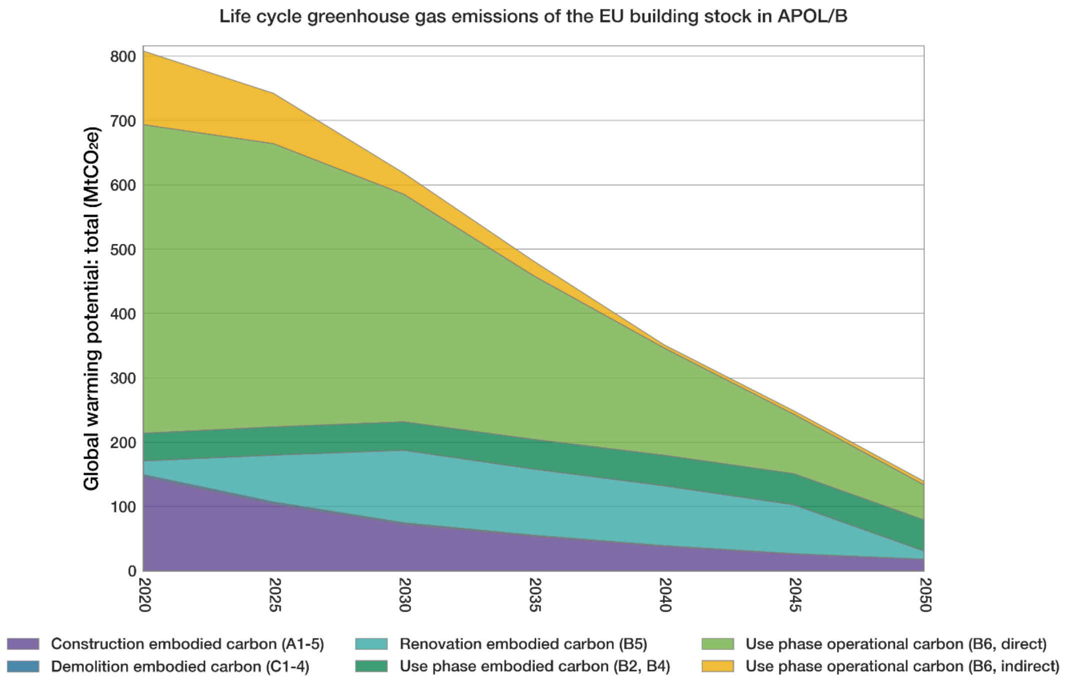

Figure 39: Additional policy (APOL) scenario results for whole life cycle carbon emissions (MTCO2e) by building stock activity 2020-2050.

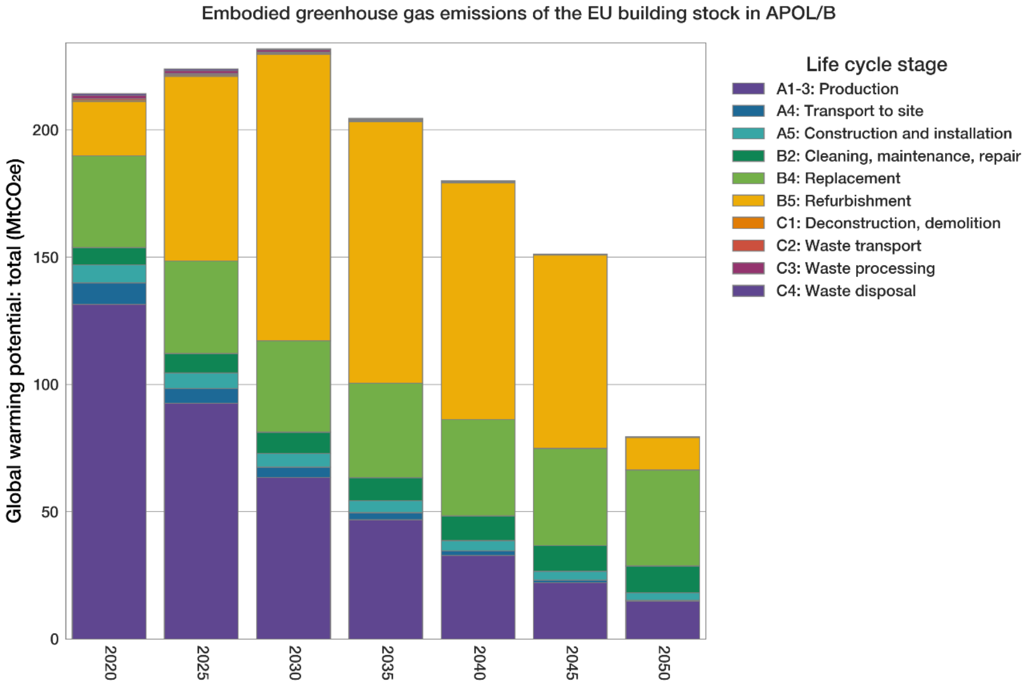

Figure 40: Breakdown of embodied carbon emissions ($MtCO_2e$) by building life cycle stage (EN15978) for future EU building stock development (2020-2050) in the APOL scenario.

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