Cost-effective building stock decarbonization and seismic resilience: Incorporating EPBD implementation in renovation plans and passports.

WP 2 – D2.2

Building Stock Modelling

January 2026

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Grant Agreement No. 101167626
LIFE-2023-CET

Project acronym:	LIFE23-CET-GreenRenoV8
Project full title:	Cost-effective building stock decarbonization and seismic resilience: Incorporating EPBD implementation in renovation plans and passports
Start of the project:	1 October 2024
Duration:	36 months
Project coordinator:	INSTITUT JOZEF STEFAN (JSI)
Deliverable title:	Building Stock Modelling
Deliverable n°:	D2.2
Version n°:	Draft Version 2
Nature of the deliverable:	R — Document, report
Dissemination level:	SEN — Sensitive
Deliverable leader:	Technische Universität Graz (TUG)
Submission date:	15 January 2025

Deliverable status:

Version	Date	Beneficiary	Status and Authors
1	28 December 2025	Giovanna Cassavia	TUG
2	15 January 2025	Giovanna Cassavia	TUG

Disclaimer

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This report builds upon ongoing research from TU Graz, specifically the development of the PULSE-EU model, which was tested and applied in the EU-WLC project[1]. Specific parts of this report draw from TU Graz publications[2], as well as ongoing work from IEA EBC Annex 89[3] and related unpublished background reports.

[1] Ramboll et al., *Analysis of Life-Cycle Greenhouse Gas Emissions of EU Buildings and Construction*, https://c.ramboll.com/life-cycle-emissions-of-eu-building-and-construction [accessed 14 Dec 2025].

[2] Alaux et al. (2025a); Alaux et al. (n.d.); Alaux et al. (2024b)

[3] IEA EBC Annex 89, *Ways to implement net-zero whole life carbon outcomes for the built environment*, https://annex89.iea-ebc.org/ [accessed 14 Dec 2025].

Co-funded by the European Union

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Glossary

Abbrevation	Description
BSMs	Building Stock Models
BSO	Building Stock Observatory
CES	Cost-effectiveness studies
CRRS	Carbon reduction and removal strategies
EC	European Commission
EPBD	Energy Performance of Buildings Directive
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCIs	Life Cycle Inventories
pBSMs	Prospective Building Stock Models
PULSE	Prospective Upscaling of Life cycle Scenarios and Emissions

Executive Summary

The GreenRenov8 project supports the development of national building renovation roadmaps for a carbon-neutral and resilient EU building stock, adopting integrated building renovation strategies in seismic-prone regions that extend beyond thermal upgrades to include seismic resilience. Understanding the impacts of renovation activities is advanced through exploring operational emissions reduction and parallelly considering the effects on related embodied emissions. These advances are supported by detailed building stock modelling analyses carried out in the GreenRenov8 project. Describing the methodological foundations for developing and applying these building stock analyses form the core subject of this report.

Building upon the state-of-the-art PULSE-EU model (Prospective Upscaling of Life cycle Scenarios and Emissions), the GreenRenov8 project further details existing building archetypes and generates new renovation scenarios for four pilot countries (AT, GR, IT, SI) and a region (Flanders, BE). Respective renovation scenarios include thermal improvements in different depths while also accounting for seismic safety reinforcements. Methodological foundations delineated in this report provide the basis for the development of tailored GreenRenov8 renovation archetypes, detailed in Deliverable 2.1 “Sustainable renovation-supporting building archetypes” and renovation scenarios that will be specified in the forthcoming Deliverable 3.3 – “Renovation scenarios and impact assessment metrics.” Outcomes from the modelling exercise will serve as input and be explored across various GreenRenoV8 tasks and deliverables.

GreenRenov8 archetypes are regionalised according to climatic and seismic characteristics, enabling more precise calculation of energy performance and identification of tailored seismic safety measures. Energy consumption is calculated via detailed pre- and post-renovation demand profiles, yielding more in-depth building stock-level impact assessments. Macro socio-economic contexts inform diverse scenario narratives for future building stock development up to 2050, with emphasis on renovation efforts and their time-related impacts across pilot regions. The findings offer policy makers valuable insights coming from detailed building stock modelling analyses, with strong potential for EU-wide upscaling.

Key outputs:

- Advances prospective building stock modelling framework: Builds on PULSE-EU model with bottom-up, archetype-based analysis of building stocks, incorporating multiple detailed renovation scenarios, along with construction and demolition activities for comprehensive emissions assessment.
- Refines archetypes: Integrates region-specific climate and seismic conditions, plus detailed thermal upgrades (light/medium/deep) and seismic reinforcements for pilot regions (Austria, Greece, Italy, Slovenia, Flanders).
- EPBD-aligned renovation scenarios: Targets 55% primary energy reduction in 43% worst-performing residential buildings with tailored national pathways.
- Whole-life carbon projections: Enables nuanced stock-level assessments of operational/embodied emissions, calibrated with current data and macroeconomic factors up to 2050.
- Supports policy KPIs: Derives EPBD metrics like stock segmentation, energy/GHG estimates, renovation pathways, GWP thresholds, and progress monitoring for national plans.

1| Background

The European Union increasingly recognises that decarbonisation of the building stock relies on the transformation of existing buildings rather than only improving new construction. Around 75% of EU buildings have poor energy performance, approximately 35% are more than 50 years old, and the annual renovation rate is close to 1%, which is insufficient to deliver a climate-neutral building stock by mid-century (Official Journal of the European Union, 2024). In parallel, a large share of European buildings is located in regions with significant seismic hazard and was constructed without modern seismic design, creating combined energy and structural vulnerabilities with potentially severe social, economic and environmental consequences.

In response, the recast Energy Performance of Buildings Directive (European Union, 2024) establishes a framework for a highly energy-efficient, zero-emission building stock by 2050, requiring each Member State to prepare National Building Renovation Plans that define trajectories and intermediate targets for 2030, 2040 and 2050, with a strong focus on upgrading the worst-performing buildings and reducing average primary energy use. These developments underline the need for integrated renovation strategies that jointly address energy performance and structural safety; failing to combine energy and seismic upgrading in hazard-prone regions risks losing efficient and cost-effective opportunities for deep, long-term reduction of emissions and risks.

At the same time, mitigation strategies for the buildings and construction sector are being developed worldwide, ranging from requirements to calculate and limit life-cycle greenhouse gas emissions at the level of individual buildings to the formulation of national decarbonisation pathways for entire building stocks (Alaux et al., 2026). To underpin such policies, detailed models of national building stocks and their future evolution are indispensable, as they link technical options and renovation dynamics to long-term emission trajectories and carbon-budget compatibility (KU Leuven et al., n.d.).

Existing building stock models (BSMs) largely reflect the EU policy objective of improving energy efficiency in the building stock, but few monitor the environmental impacts associated with energy end uses, while also accounting for variations in climatic conditions and the energy mix. Likewise, only a limited number of studies examine the environmental consequences of future new construction and renovation activities (Röck et al., 2021). These considerations are critical to support EU building stock development in line with environmental targets. The state-of-the-art PULSE EU (Prospective Upscaling of Life Cycle Scenarios and Emissions) model significantly advances this area and serves as a modelling base for the GreenRenoV8 project. In GreenRenoV8, building renovation is further assessed through the development of detailed renovation strategies and scenarios tailored to EPBD requirements. In order to assess benefits of combined efforts, the project links improvements in energy performance and seismic resilience within building renovation scenarios customized to specific regional conditions.

1.1 Prospective Building Stock Models (pBSMs)

Building stock models (BSMs) are tools used to systematically represent and analyse a wide range of buildings within a defined area. In these models, diverse characteristics of building are aggregated, capturing information on building types, construction periods, materials, technical installations, and energy performance at scales ranging from individual buildings to entire countries (Alaux et al., 2025c). Drawing on methods from industrial ecology—such as material flow analysis—alongside building energy simulation and environmental assessment, these models can estimate both operational and embodied emissions, including direct and indirect impacts, across locations and over time (Alaux et al., n.d.).

BSMs can also explore how different policy or design choices—such as changes in renovation intensity, expanded deployment of renewable energy, alternative material selections, or revised demolition and reuse practices—shape long-term greenhouse gas (GHG) emission trajectories (Röck et al., 2021). BSMs are capable of integrating prospective scenarios that offer clear outlooks on the future development of building-related actions by mid-century and beyond. By doing so, prospective building stock models (pBSMs) can support policymakers on the evaluation the impact of a wide range of design and retrofit strategies at the building stock level (Dong et al., 2023). These evaluations enable the implementation of evidence-driven climate strategies and benchmarks for building related activities. By providing clarifications on the mitigation potential of building-related actions, pBSMs advance the alignment with the Paris Agreement and national policy objectives, support the formulation of NDC targets, and ensure national decarbonization pathways remain consistent with available carbon budgets (Alaux et al., 2025b).

Prospective building stock models typically pursue complementary goals. According to Alaux et al. (n.d.), scientific research employing pBSMs generally address the following:

1. Quantify life cycle GHG emissions and impacts from building stocks:
   - Provide science-based evidence on the origin of environmental impacts across building stocks.
   - Offer data disaggregated by building typology (via modelled archetypes) and by the split between embodied and operational impacts.
   - Establish a transparent understanding of the current and future emissions profile to inform targeted policy design.
2. Identify emission hotspots and clarify origins:
   - Pinpoint which components of the stock drive overall emissions, including operational energy use, material production, construction, and end-of-life processes.
   - Extend system boundaries beyond direct building emissions to address intersectoral burden shifting (e.g., reducing operational emissions while increasing embodied emissions).
   - Provide foundation for life cycle GHG reduction.
3. Apply scenario-based modelling to develop and evaluate the mitigation potential of strategies such as:
   - Higher renovation rates.
   - Improved thermal performance.
   - Energy grid decarbonization.
   - Use of less carbon-intensive materials
   - Reuse of components and recycling materials.

- Policy design across building codes, standards, and incentive programs.

4. Assess climate goal compliance

   - Compare prospective impacts of scenarios with top-down trajectories, goals, benchmarks for different indicators to determine which strategies are essential to meet science-based thresholds and policy targets.
   - Guide national building stock decarbonization pathways according to national carbon budgets.
   - Support long-range planning for renewable energy implementation and climate adaptation.

Building stock models can operate at multiple scales, from micro-scale representations of individual buildings, through meso-scale aggregations such as neighbourhoods and cities, up to macro-scale analyses covering entire countries or even continents. As the spatial scale increases, data granularity decreases, but policy relevance and the need to demonstrate compliance with climate goals grow correspondingly; implementing these models in policymaking is therefore both the most challenging and the most critical step, and it effectively defines the starting point for developing such models in the first place.

The following Figure 1 illustrates how data granularity, modelling challenges, policy relevance, and compliance with carbon budgets evolve across different spatial scales in building stock models. At the micro scale, the focus is on individual buildings, complexes, or portfolios, where the limited scope enables highly detailed data and low model complexity, allowing most influencing building characteristics to be explicitly represented but with relatively modest relevance for policymaking. Moving to the meso-scale of neighbourhoods and cities, the number of buildings grows substantially, forcing a reduction in data granularity for computational and interpretability reasons and increasing the challenge of deciding which aspects can still be modelled in a meaningful way. At the macro scale, encompassing entire countries or even continents, data are most aggregated, yet this is where policy relevance and the need to demonstrate alignment with carbon budgets are greatest.

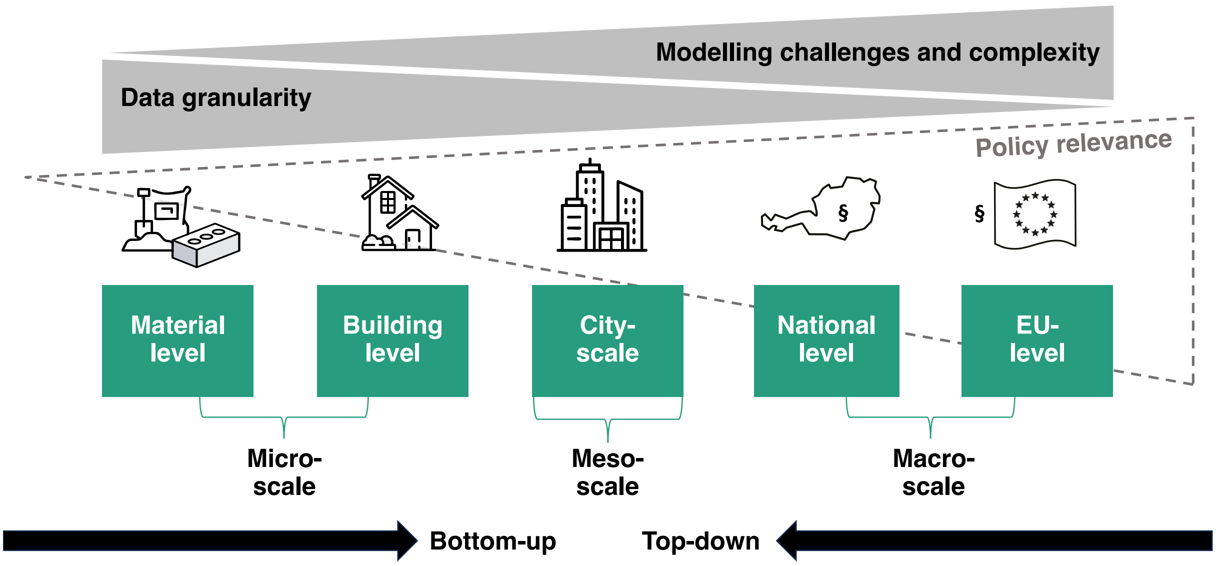

Figure 1: The different building stock scales defined by their data granularity, modelling challenges and complexity and policy relevance and compliance with carbon budgets. In Caballero-Güereca et al.,n.d. adapted from Allacker et al., 2019.

The development of pBSMs consider complementary approaches when it comes to data aggregation. Bottom-up approaches construct pBSMs from individual building characteristics upward, aggregating detailed energy and material inventories, spatial configurations, and renovation dynamics into stock-level projections. These models simulate specific scenarios—such as varied renovation rates, material choices, or decarbonization strategies—to generate building-archetype-specific pathways and emission trajectories. Their strength lies in transparency, flexibility and granularity: they reveal which mitigation levers (thermal upgrades, material substitution, grid decarbonization) have the potential to deliver the greatest emission reductions.

Top-down approaches employ industry-wide metrics, historical data, and aggregate benchmarks—such as national energy demand statistics, material consumption figures, floor area totals, or building counts—as external reference points. Rather than simulating individual buildings, they work backward from societal-level targets (populational growth, carbon budgets, climate goals, Paris Agreement commitments) to define emission trajectories and policy thresholds.

In a complementary way, bottom-up modelling explores the mitigation potential of specific operational (building retrofits, heating efficiency codes) and embodied (material efficiency, low-carbon product standards) strategies, while top-down constraints (remaining carbon budget, 2050 zero-emission targets) define the boundaries within which these strategies must operate. This dual framing ensures policies are both potentially technically feasible (bottom-up) and climatically necessary (top-down). Bottom-up and top-down approaches together enable stakeholders to systematically evaluate alternative decarbonization pathways against policy-relevant trends, identifying the most effective strategies for emissions reduction. Stakeholders commonly making use of pBSMs include (Hong et al., 2025):

- **Governments:** Development and evaluation of policies regarding buildings (renovations, energy savings, etc.) and prioritization of recourse allocation
- **Urban planners:** Assessment of energy and recourse demands for new developments
- **Utilities and Grid Operators:** Forecasting of energy and recourse demands
- **Insurance and Risk Assessment Organizations:** Prediction of building level hazards
- **Technology Developers:** Assessment of impacts of new technologies
- **Investors:** Cost-benefit analysis of construction investments

In summary, prospective building stock models are a powerful instrument for examining a broad spectrum of questions across multiple spatial scales of the building stock. They can offer high policy relevance, but this comes at the cost of substantial data-processing requirements. Figure 2 illustrates possible goals and research questions for developing pBSMs:

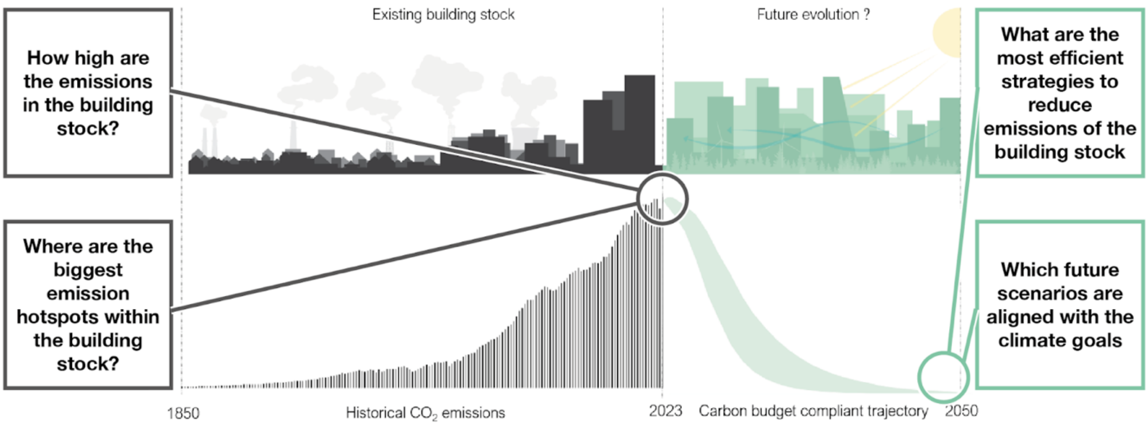

Figure 2: Possible goals and research questions for creating prospective Building Stock Models (Alaux et al., 2025a).

2 | PULSE-EU: pBSM

The PULSE-EU model (Alaux et al., 2026) provides the primary analytical foundation for GreenRenov8 assessments, which focuses on the evaluation of sustainable building renovation pathways along with seismic resilience of the assessed countries in the scope of the project. The following section summarizes the aspects of the base PULSE-EU[4] model most relevant to GreenRenov8. The description in present section is based on the report "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" submitted to the EU Commission (KU Leuven et al., n.d.), which provides detailed information on the PULSE-EU model. PULSE-EU offers an integrated representation of the European building stock, capturing both its current composition and projected developments. to characterize and analyse the EU building stock, the model presents a bottom-up modelling framework using archetype-based representations (Ramon et al., 2025)., where archetypes capture key variables such as different types of use, building geometry, materials, energy performance, and HVAC systems. It quantifies the resulting material, energy, and water demands, as well as the associated emissions, enabling assessments of whole-life carbon impacts and the design of effective policy measures. Figure 3 presents an overview of the PULSE-EU modelling framework.

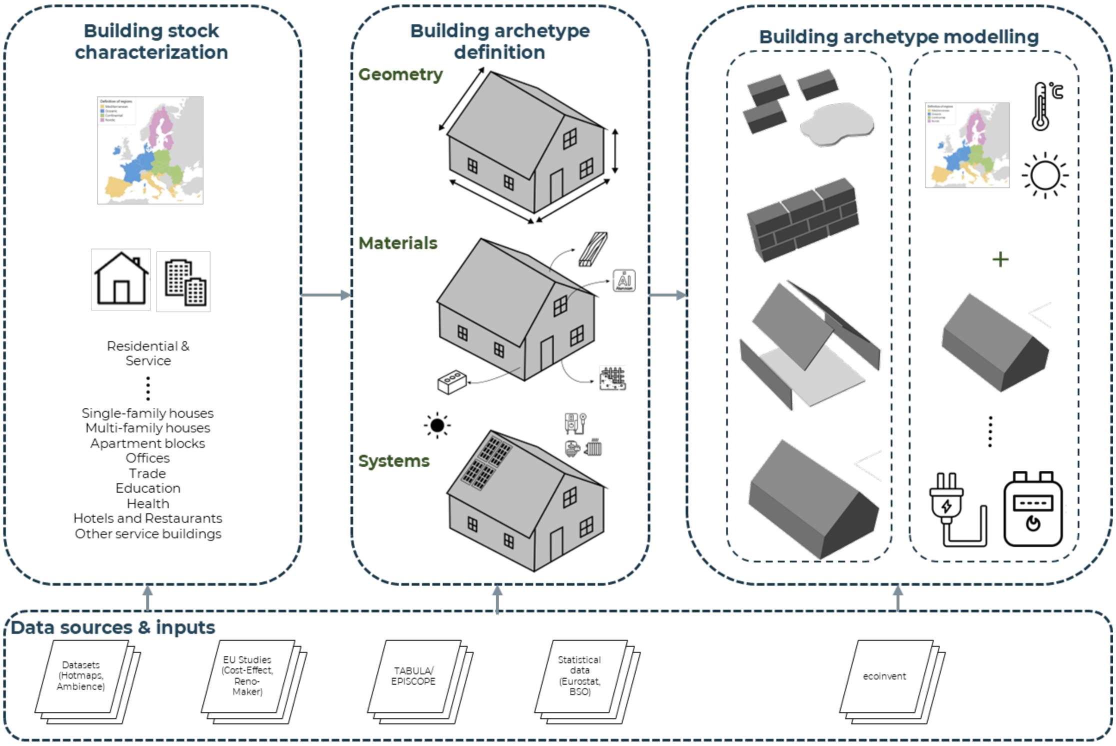

Figure 3: Summary of bottom-up building stock modelling approach: stock characterization, archetype specification (including geometry, materials, and systems), archetype inventory development, and life cycle impact evaluation (KU Leuven et al., n.d.).

[4] *PULSE-EU* [Data set]. GitHub. https://github.com/ITE-NHB/PULSE-EU

Drawing on statistical data from sources such as the Building Stock Observatory[5] and the AmBIENCe project[6], the model differentiates between existing, new, and renovated buildings. Each archetype is evaluated through Life Cycle Assessment using the SLiCE framework (Röck et al., 2024), providing detailed insights into emissions across the building life cycle. This archetype-based structure also underpins scenario simulations that explore the implications of future policy and technological developments.

To construct the building stock model within PULSE-EU, instead of modelling each individual building, representative archetypes serve as placeholders that capture the diversity of the European building stock while enabling macro-scale analysis. These archetypes are virtual representations of groups of buildings sharing similar attributes—such as age, size, construction type, renovation state, installed systems, and usage patterns—and are derived from statistical analysis of official and sector-specific data sources. This approach allows the detailed representation of typical buildings while maintaining computational efficiency and reflecting regional and national building characteristics.

The stock is first characterized and then clustered into standardized categories, typically based on sector (residential, non-residential), building type, and construction period. For the residential sector, which includes all buildings with permanent inhabitants, three primary building types are distinguished: single-family houses, multi-family houses, and apartment blocks. Each of these is represented across eight construction epochs, corresponding to different historical periods defined by characteristic construction methods, material choices, and energy standards. Across all 27 EU Member States, this results in 648 unique residential building type-age combinations. Figure 4 illustrates the baseline building types considered in PULSE-EU:

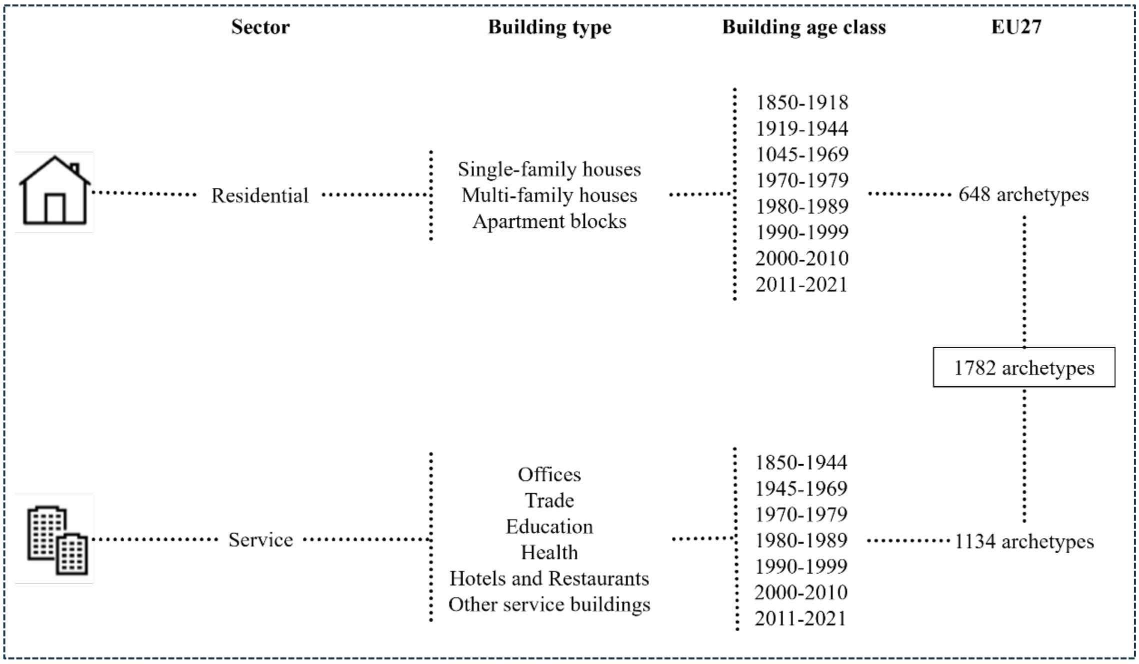

Figure 4: Composition of the PULSE-EU building stock building types split into sectors, building types and building age classes (KU Leuven et al., n.d.)

[5] European Commission (2020), *EU Building Stock Observatory*, https://building-stock-observatory.energy.ec.europa.eu/database/

[6] AmBIENCe project, *Actively Managed Buildings with Energy Performance Contracting*, **https://www.ambience-project.eu/** [accessed 04 Jan 2026]

Non-residential buildings—comprising offices, trade, education, health, hotels and restaurants, and other service buildings—are represented with lower granularity due to their smaller share of the total stock. Each non-residential type is subdivided into seven construction epochs, resulting in 1134 building type-age combinations across the EU. Together, the residential and non-residential archetypes form a set of 1782 unique baseline building types. Construction variants, including differences in heating systems, further refine the archetypes.

Archetypes are defined to represent both existing and newly constructed buildings, with older archetypes captured either in their original condition or as renovated variants. New-build archetypes are derived from recent baseline types and adapted to current performance requirements, while variants reflecting a transition toward bio-based materials are included where applicable. For future scenario analysis, both renovation and new-build archetypes are modified to represent expected design practices and the implementation of carbon reduction and removal strategies.

To complement the characterization of the historic building stock new building archetypes and refurbishment archetypes were included. The new construction archetypes are more granular with additional information about energy standards and more construction types. The refurbishment archetypes are tied to the existing buildings, since they represent an existing building with an augmentation to its envelope or heating system and thus energy performance.

To describe each building archetype a total of 157 attributes are used holding three main categories of information: 1) building geometry and occupational properties; 2) building materialization and 3) HVAC system related properties. Table 1 summarizes the main groups of archetype characteristics:

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)

The attribute data collection process was carried out in three main steps. First, relevant information was extracted from primary sources. Second, the collected data were recalculated, where required, to align with the defined construction periods. This step revealed existing data gaps, which were subsequently addressed using secondary sources. To ensure transparency and assess data quality, each dataset entry is accompanied by a brief description specifying its origin together with any applied calculations or assumptions.

A detailed review of building element attribute data was also conducted, as information obtained from primary and secondary sources may not always be fully reliable or representative. This review drew on national datasets and expert judgement. A detailed description of sources and specifications of attributes is available in Section 2.2 on the report “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” submitted to the EU Comission (KU Leuven et al., n.d.).

2.1 Refurbishment archetypes

The refurbishment of the existing building stock in PULSE-EU is represented through refurbishment archetypes developed to quantify both operational and embodied emission impacts of renovation activities. These archetypes build on existing building archetypes to assess operational emissions and on new-build archetypes to capture the embodied emissions of components replaced or newly installed. Three renovation classes—light, medium, and deep—are defined according to their expected energy savings and intervention scope (KU Leuven et al., n.d.).

Operational emission reductions are modelled using the performance characteristics of existing building archetypes to assess the renovation effects across different building types, construction periods, and countries. Based on these archetypes, energy performance levels within the building stock are categorized, and renovation options are modelled using the following energy reduction factors:

- Light renovation: energy savings < 30%, reduction factor = 0.25
- Medium renovation: energy savings 30–60%, reduction factor = 0.50
- Deep renovation: energy savings > 60%, reduction factor = 0.75

Associated operational emissions are adjusted accordingly for the baseline year and accounted for under the progressive decarbonization of energy systems (e.g., electricity grid decarbonization) in future scenario years.

Embodied emissions related to renovation activities are modelled as a nested life cycle, capturing both the removal of existing materials and the production, transport, and installation of new materials and systems (LCA product. Summed together, these stages represent the embodied emissions associated with refurbishment interventions. The depth of renovation determines the extent of works, ranging from improving insulation in external walls and roofs to replacing windows and upgrading technical systems with low-carbon, electricity-based technologies such as heat pumps. Where such technologies are integrated, emission factors are adapted to account for the progressive decarbonization of the European electricity mix.

The use of refurbishment archetypes within the building stock model is determined by the combination of renovation rates and depths defined under each future scenario, following the carbon reduction strategies and its specified energy performance targets.

2.2 Archetype LCA modelling

Building life cycle inventories (LCIs) were developed using a set of representative archetypes defined from consolidated datasets (TABULA/EPISCOPE)[7] and expert judgment to capture the diversity of existing building stocks and to address uncertainties. These definitions underwent internal review to enhance robustness and representativeness. The archetypes were then modelled in detail to support whole-life carbon assessment using life cycle assessment (LCA) using the MMG-SLiCE (Röck et al., 2024) data model, which enables consistent assessment across archetypes.

LCIs follow a modular life cycle framework aligned with European standards (EN 15804 + A2 and EN 15978). The modelling applies a hierarchical decomposition approach—from building to element to component to material. This structured modelling approach enabled fine-grained analysis of environmental hotspots, providing insights

[7] TABULA (Loga et al., 2016). WebTool available at: https://webtool.building-typology.eu

into the timing of emissions by life cycle stage and over time, as well as the contribution of materials across multiple scales (building, element, and work section).

MMG-SLiCE uses life cycle assessment methods in line with the current European LCA standards EN 15804+A2 and EN 15978. For that purpose, it utilises the generic LCI data from Ecoinvent 3.6. Here European market data is used for material production data and national data is used for end-uses like electricity or gas used in heating. The main environmental impact assessed is the GHG emissions and carbon removals. These are modelled as GWP-fossil, GWP-biogenic and GWP-luluc (land use and land use changes). Scenario assumptions are defined for transport and end-of-life phases in accordance with EN 15978, specifically modules A4, C1–C4, and C2. The operational energy use modelled in MMG-SLICE includes the space heating, space cooling, domestic hot water, and ventilation.

2.3 Upscaling

The upscaling from archetype modelling to the building stock model is illustrated in *Figure 5*. The process begins with the EU-27 Building Stock Dataset, which provides the foundational input data, including the characterization of building archetypes—covering geometry, energy consumption, and other attributes—as well as the composition of the 2020 stock, such as the number of buildings, total floor area, and typological distribution (se. These data enable a detailed representation of the existing building stock, forming the basis for subsequent modelling steps. At the building scale, archetype modelling is performed using the SLiCE framework. Each representative archetype undergoes detailed LCA to quantify whole-life carbon emissions, material flows, and energy use. The resulting emission profiles serve as inputs for PULSE-EU, which scales these detailed building-level results to the entire building stock.

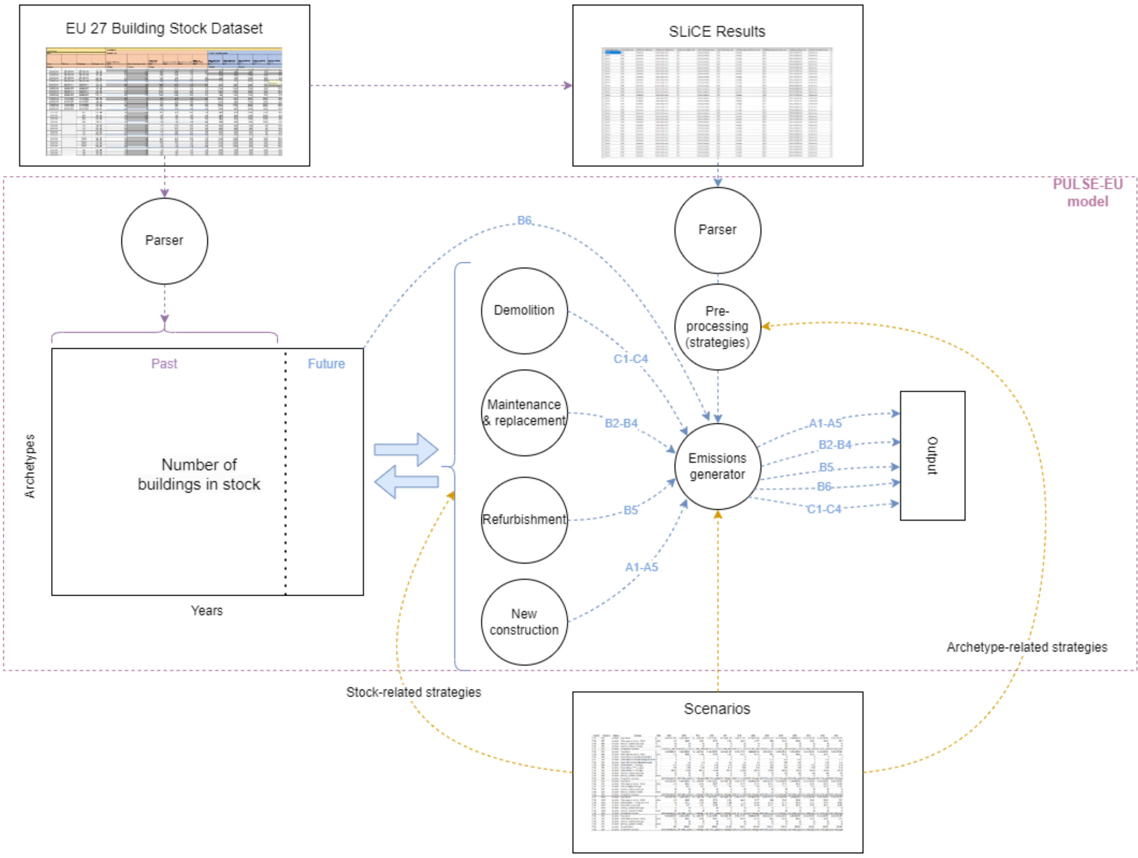

Figure 5: Overview of the PULSE-EU building stock modelling framework (KU Leuven et al., n.d.).

Within this framework, the PULSE-EU model integrates the SLiCE-derived emission data with stock composition data to project future building stock developments from 2020 to 2050. It models key stock dynamics—such as demolition, renovation, new construction, maintenance, and replacement—and links these activities to corresponding carbon emission intensities. This integrated approach enables the representation of both current stock conditions and long-term transitions in response to evolving construction practices and policy measures.

National building archetypes are defined to reflect the composition of existing buildings and anticipated changes due to refurbishment and new construction across Member States. At the macro scale, PULSE-EU aggregates and projects the life cycle impacts from these archetypes to national and EU-wide levels, allowing robust analysis of system-level trajectories for material demand and greenhouse gas emissions.

Both the stock activities and emissions projections are influenced by Carbon Reduction and Removal Strategies (CRRS) Scenario exploration within PULSE-EU investigates alternative development pathways for the European building sector, evaluating how different CRRS strategies affect whole-life carbon emissions across the building life cycle. The resulting projections provide disaggregated outcomes for future scenarios by building type and typology, expressed per square metre of floor area and per capita at both national and EU-wide scales. These results are made accessible through an interactive data visualization and scenario exploration tool (Röck et al., 2025), enabling further comparison and analysis of the potential trajectories towards a decarbonized European building stock.

2.4 Carbon reduction and removal strategies

To achieve climate neutrality targets, A wide range of strategies is needed to support the transition of building and construction across all EU Member States, building types, and material inputs (Alaux, et al., 2024a). The different measures and scenario parameters are grouped into three distinct carbon reduction and removal strategies. The different strategies describe how the carbon is reduced or removed. They are made up of avoid, shift and improve, with each including several measures (KU Leuven et al., n.d.):

AVOID

- **Increase repair and renovation:** Through the improvement and preservation of existing structures and spaces the demand for new materials is avoided. In addition to the reduction of emissions, this measure also relates to the retention of cultural and historic values already present in the building stock.
- **Increase material efficiency:** Using optimized construction techniques, additional material demand can be avoided.
- **Reduce construction waste:** Through more efficient construction techniques the quantity of construction and demolition waste can be reduced, thus avoiding additional material demands.
- **Reduce space per capita:** By reducing the per person space demand, the already existing stock can house more persons, thus avoiding new constructions.

SHIFT

- **Increase circularity and reuse:** Through improvements in recycling and reuse, and thus the shifting from new materials to reused materials, the demand of new materials can be reduced.
- **Increase bio-based solutions:** Through the shift from fossil-based solutions to bio-based solutions (i.e. insulation) the carbon intensity of constructions can be reduced.
- **Increase carbon dioxide removal:** Through additional carbon dioxide removal (CDR) strategies, not yet included in other strategies, existing CO_2 can be removed from the atmosphere.

IMPROVE

- **Reduce operational energy:** Through improved insulation or improvements to windows the demand for operational energy can be reduced.
- **Improve conventional materials:** Through improvement of conventional materials, their carbon intensity can be reduced.
- **Reduce transport emissions:** Through local sourcing and the usage of low-carbon transportation, the transport related emissions can be improved.
- **Reduce construction process:** Through improved efficiencies during the construction process, emissions can be reduced.

2.5 Scenarios modelling

The scenario modelling framework created in PULSE-EU considers different CRRS, the capacity of each Member State 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. An overview of this framework is shown in the following Figure 6:

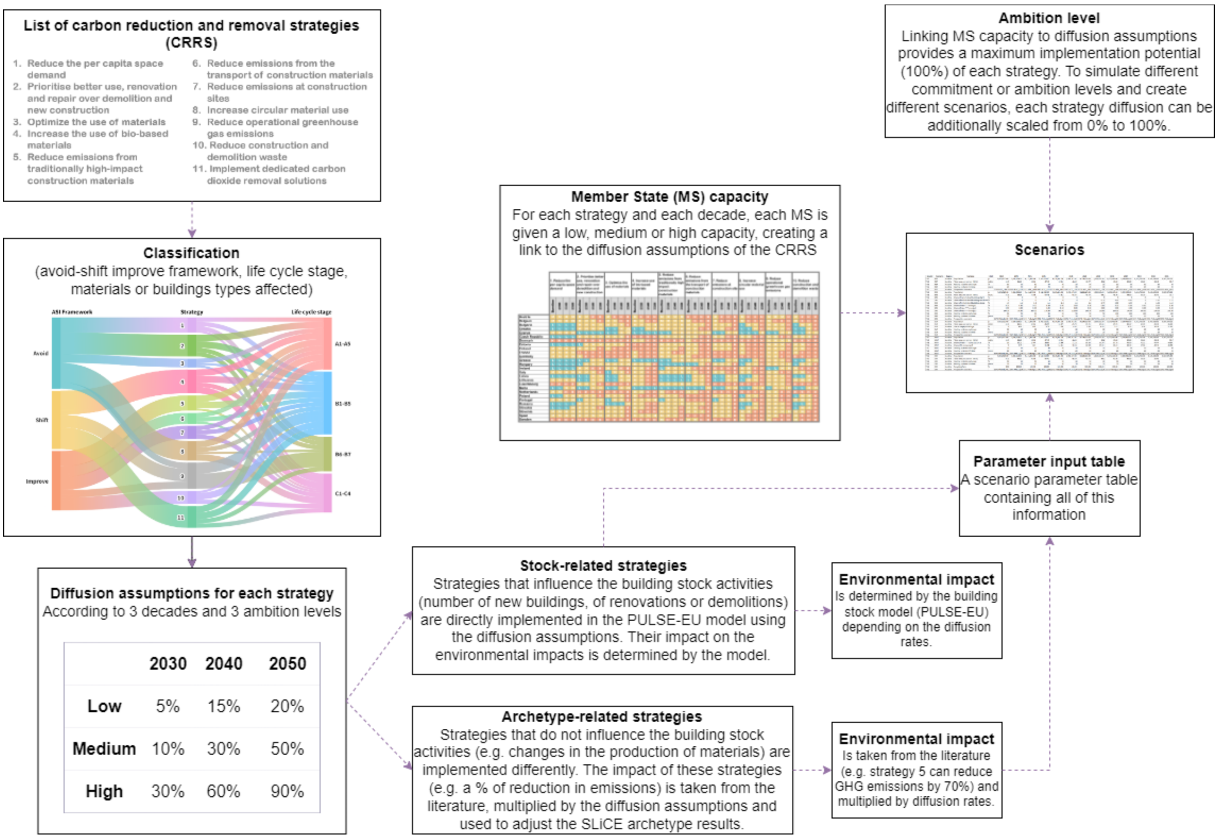

Figure 6: Overview of the PULSE-EU scenario modelling framework (KU Leuven et al., n.d.).

To model the actual policy implementations, the CRRSs are grouped into 4 pre-defined policy scenarios and 2 exploratory scenarios to explore the solutions.

- **CPOL/A - Optimistic current policy scenario:** This pre-defined scenario assumes that all current policies are delivering the planned results in full.
- **CPOL/B – Conservative current policy scenario:** This pre-defined scenario assumes that current policies are implemented, but encounter socio/technical challenges

- **APOL/A – Optimistic additional policy scenario:** This pre-defined scenario assumes additional measures with the goal of reducing the total GHG emissions by 90% until 2040
- **APOL/B – Conservative additional policy scenario:** This pre-defined scenario assumes the implementation of the additional measures, but they encounter socio/technical challenges
- **BAU – Business as usual scenario:** This exploratory scenario is a projection of baseline activities until 2050, with the only dynamic parameter being the population development.
- **ALL/HIGH – High diffusion across all measures:** This exploratory scenario shows the maximum theoretical potential of all combined strategies at their full implementation

2.6 Calibration and validation

The PULSE-EU model was calibrated by aligning its operational emissions in 2020 with reference emissions from the BSO. These differences arise from several factors, including the use of a semi-static energy performance method in the PULSE-EU model, and the varying building layouts and orientations across the building stock. Direct emissions are overtaken as provided but the calibration was not directly applicable, due to the difference in modelling scopes for indirect emissions (PULSE-EU only models 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. The calibration is applied to the model as a factor to reach the reference values. This factor symbolises the difference between the modelled and actual emissions in 2020, which is then further applied to each following year - meaning that the operational carbon emissions of every year are multiplied by the ratio of the calibrated value to the original value

Considering validation, PULSE-EU was validated through a comparison with the MESSAGEix-Buildings modeling framework (Mastrucci et al., 2021). Figure 7 shows a schematical overview of integrated models in both archetype and building stock level in the scope of PULSE-EU, including the validation process:

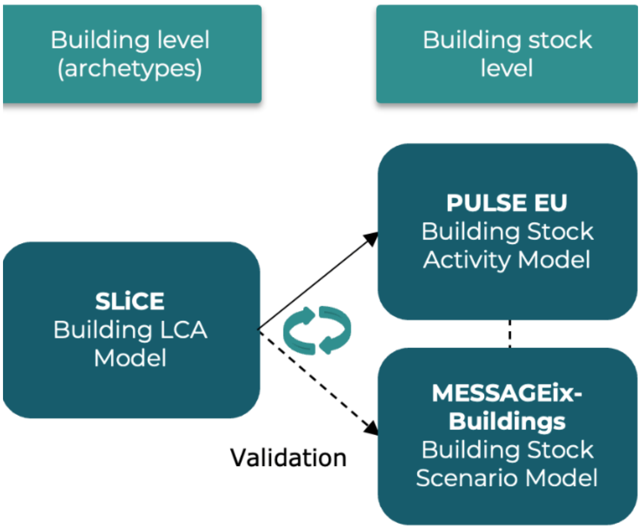

Figure 7: Schematic overview of the integrated modelling framework at both archetype and building stock levels within the scope of PULSE-EU, including the corresponding validation process.

In comparison to the MESSAGEix-Buildings modeling framework, PULSE-EU shows a slightly higher floor area in 2050 than MESSAGEix, in scenarios for both residential and non-residential buildings. The GHG emissions in PULSE-EU are also higher than in MESSAGEix. This difference is mainly due to the assessment of the embodied emissions. PULSE-EU uses different emission factors and material types, including for example insulation materials and thicknesses that are not included in MESSAGEix. Also, MESSAGEix uses emission data that assumes average EU-level technologies, while PULSE-EU uses country-specific emission factors. In a comparison between the emission results over time of the BAU CPOL/A and ALL scenarios, PULSE-EU shows a larger reduction than MESSAGEix, since PULSE-EU accounts for strategies that MESSAGEix does not account for. Despite the difference, both model's alignment shows how robust they are at estimation life cycle GHG emissions at various scales.

2.7 Results

Due to the great number of scenarios and large scope, PULSE-EU has a large amount of outputs. For further outputs the report "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" submitted to the EU Comission (KU Leuven et al., n.d.) should be consulted, here only an insight is shown. In the baseline assessment of 2020 (Figure 8), the top contributing member countries were Germany with ~187 MtCO2e, France with ~110 MtCO2e, Poland with ~109 MtCO2e, Italy with ~92 MtCO2e, and Spain with ~56 MtCO2e, respectively. In all member states, the use phase operational carbon, makes up the largest share of the total emissions.

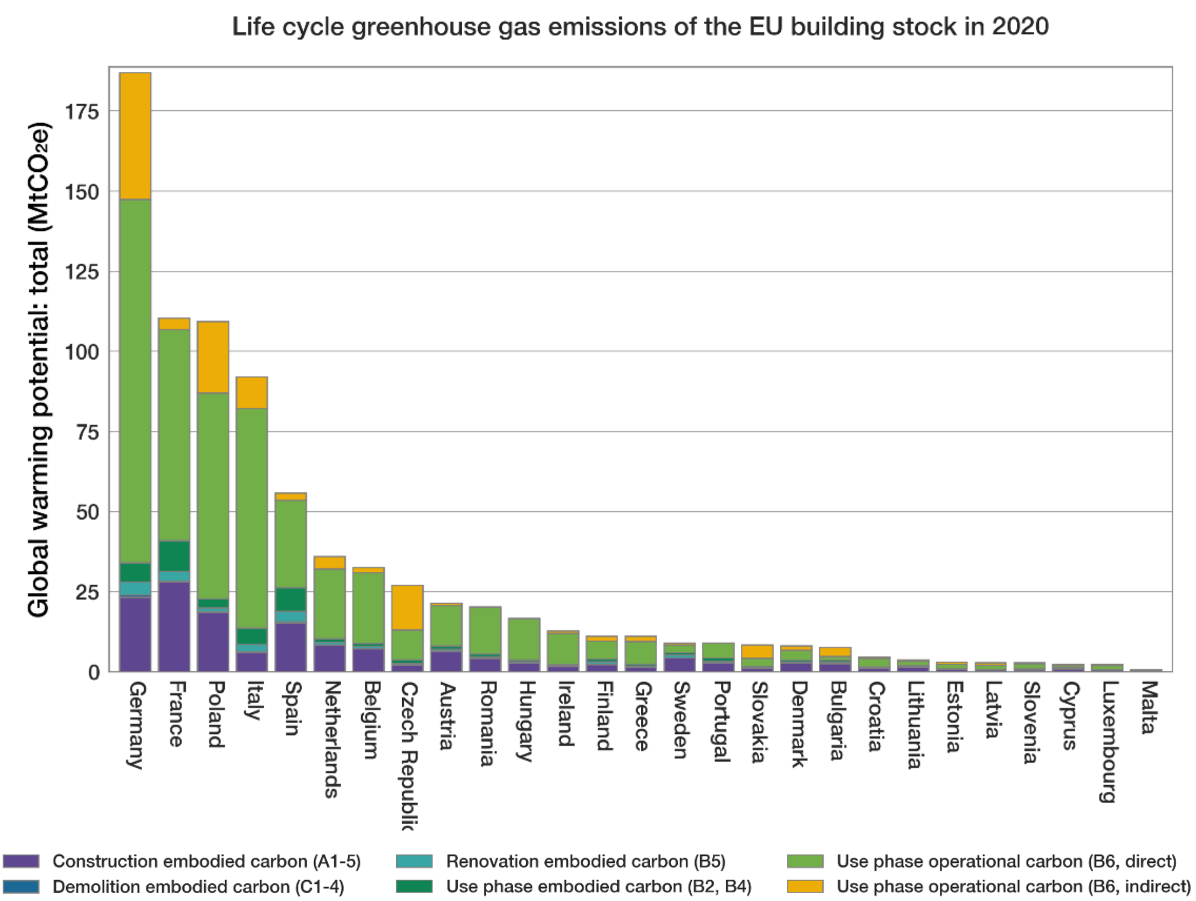

Figure 8: PULSE-EU output for life cycle GHG emissions of the EU building stock in 2020 according to analysis from the PULSE-EU model (KU Leuven et al., n.d.).

Following table 2 summarizes cumulative and annual emissions outcomes from explored scenarios under the PULSE-EU study, taking the Business as usual scenario (BAU) as a comparison base:

Table 2: Cumulative and annual emission outcomes under the BAU scenario, including corresponding reductions achieved in all other researched scenarios (KU Leuven et al., n.d.).

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%)

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. 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. All scenarios are represented in the following Figure 10:

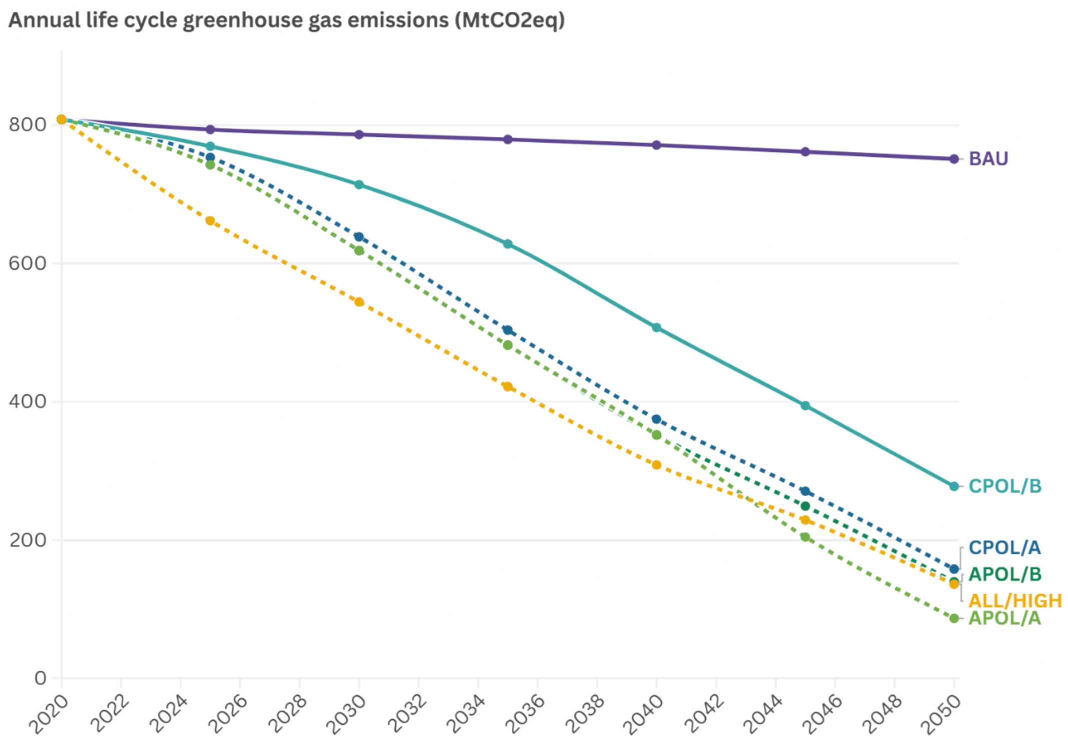

Figure 9: Annual life cycle emissions resulting from modelling the key scenarios. Solid lines = limited by MS capacity; Dashed lines = Diffusion levels beyond established MS capacities (KU Leuven et al., n.d.).

3 | GreenRenov8 scope

3.1 Enhanced pBSM

The overall objective of GreenRenov8 is to advance the practical implementation of national building renovation roadmaps that support the EPBD vision of achieving a decarbonised European building stock by 2050. To this end, the project deepens the understanding of impacts and emissions arising from renovation activities through an in-depth analysis of sustainable renovation efforts in four countries (Austria, Greece, Italy, Slovenia) and one region (Flanders, Belgium). Effective decarbonization of the European building stock demands a comprehensive, data-driven approach; accordingly, GreenRenov8 employs prospective building stock modelling (pBSM). These constitute a bottom-up modelling framework that characterizes and analyses existing building stocks and their future development through archetype-based representations and scenario modelling.

GreenRenov8 builds on the PULSE-EU (Prospective Upscaling of Life Cycle Scenarios and Emissions) model to explore building renovation scenarios in depth. While the proposed GreenRenov8 pBSM focuses on renovation of the building stock, it also incorporates current and future construction and demolition rates to estimate operational and embodied emissions across all building stock activities. The bottom-up model relies on representative building archetypes, which GreenRenov8 has reviewed and further detailed with a focus on thermal renovation measures and seismic safety reinforcements; this enables robust projections of whole-life carbon impacts from renovations and supports targeted policy interventions. Prior work in GreenRenov8 has advanced archetype modelling by integrating regional climate and seismic conditions for each partner country, thereby creating a common framework for describing and comparing buildings across national and construction contexts.

As delineated in Deliverable 2.1 “Sustainable renovation-supporting building archetypes,” characterizing national building stocks through representative archetypes is now a well-established practice in energy efficiency, structural safety, and environmental impact assessment, as these simplified models capture the key geometric, physical, and functional properties of real buildings while avoiding the need to simulate each structure individually. Archetypes are therefore essential for strategic planning, prioritizing interventions, and aligning regulatory frameworks; increasingly, they are also used to assess environmental impacts, quantify structural risks, and support urban resilience planning, making them central tools for policies concerning the built environment. For more information on the GreenRenov8 archetypes, see Deliverable 2.1 “Sustainable renovation-supporting building archetypes.”

Further advancing pBSMs in the scope of GreenRenov8 work allows for the integration of more detailed, region-specific baseline archetypes for the GreenRenov8 focus areas and introduces new renovation archetypes that can be upscaled to capture renovation impacts at the building-stock level. Based on the EPBD, proposed renovation scenarios shall explore thermal upgrades with different depths (light, medium, and deep), national minimum energy performance requirements and the inclusion of seismic safety reinforcements, enabling a more comprehensive evaluation of potential renovation strategies. Building up on PULSE-EU, in which energy savings from renovation are calculated based on rates of expected energy consumption reduction, GreenRenov8 calculates pre- and post-renovation based on detailed energy demand profiles for each archetype–strategy combination. Together, these enhancements enable more nuanced, stock-level assessments of whole-life carbon impacts of building renovation. They also strengthen stakeholders’ capacity to design National Building Renovation Plans and investment decisions based on evidence-based renovation scenarios.

For explorations carried out within the GreenRenov8 project, key benchmarks taken directly from the revised EPBD serve as the basis for developing renovation scenarios and archetypes. One critical overarching renovation target applied in this study is to achieve a 55% reduction in primary energy demand by renovating the 43% worst-performing residential buildings, as required by the EPBD (European Union, 2024). To account for national differences in regulation, climate, seismic conditions, and socio-economic contexts, each partner explores its own national pathway to meeting this target through tailored renovation strategies according to national regulation and practices. The corresponding renovation archetypes and strategies, for both residential and non-residential buildings, are currently being developed and will be described in detail in upcoming Deliverable 3.3 – "Renovation scenarios and impact assessment metrics."

For future projections of stock-level dynamics, updated macroeconomic framework developments are incorporated into the model and calibrated according to national differences. Parallelly to rates related to building and construction activities (new construction, renovation, demolition), parameters are included to assess indirect effects. These parameters include changes in floor area demand, the decarbonization of space heating and cooling, and broader industry trends. On this basis, macro socio-economic contexts shape scenario narratives for future building stock development up to 2050, with particular emphasis on renovation efforts and their time-dependent impacts in the pilot regions. As the PULSE-EU model simulates developments from 2020 onwards, observed stock changes between 2020 and 2025 are used to calibrate the original model. The resulting analyses provide policymakers with detailed, scenario-based insights on building stock transformation, with strong potential for EU-wide upscaling.

3.2 Potentials

With a specific focus on the EPBD recast, the GreenRenov8 project directly derives assessments of the following topics (among others) from the proposed pBSM, aiming to support their evaluation through the examined pilot countries:

- **Segmentation** of the national building stock **by typology** (single-family houses, apartments, offices, schools, etc.), **age, size, and climate zone** (Article 3(a)).
- **Estimation** of current **primary/final energy consumption**, **operational greenhouse gas emissions**, and, where possible, **embodied GHG emissions**, to be included in the **national database** (Art. 22)
- **Exploration of renovation pathways** to achieve the targets specified in Article 3(b) for 2030, 2040, and 2050, **including required annual renovation rates and energy savings**.
- **Determination** of the **average primary energy consumption** of the entire housing stock and modeling of the **required reduction** (–16% by 2030, –20–22% by 2035).
- Assessment of whole-life cycle (WLC) **global warming potential** (Art. 7 and Annex III) related to renovation activities across evaluated building stocks proving support for the development of policies considering the reduction of WLC emissions.
- **Monitoring** progress based on **KPIs** for **national building renovation plans** (Art. 3, para. 9).
- Support the outlining of **investment needs** for the implementation of national building renovation plans (Art. 37)
- Consideration of **seismic safety upgrades as part of renovation strategies** to quantify their **resilience** benefits alongside the consequent **embodied emissions.**

3.3 Challenges

The GreenRenov8 project establishes an archetype-based framework in which the characteristics of building elements play a crucial role in assessing the environmental impacts of both existing and future building stocks. To this end, the project reviews the most relevant existing building archetypes within the pilot countries, considering materials, performance, and construction technologies. Regional experts contribute by expanding the dataset on constructive and material heterogeneity to verify and, when necessary, adapt information previously compiled in the PULSE-EU project.

Renovation scenarios are developed in alignment with national regulations to examine their outcomes in the context of the EPBD requirements. As building stock modeling demands extensive data input, data availability and collection represent significant challenges that are critical to the development process and should not be underestimated.

While the EPBD sets overarching requirements, it provides flexibility in defining strategies for achieving decarbonisation and other directive targets. Within GreenRenov8, a specific scope is outlined, and multiple scenarios and strategies are evaluated. Nevertheless, limitations related to data availability, modeling tools, and representativeness of archetypes persist. To strengthen robustness and representativeness, consolidated datasets are combined with expert judgment to capture the diversity of existing building stocks and to address uncertainties. All definitions undergo internal review processes to ensure quality and consistency.

4 | Conclusion

The GreenRenov8 project builds upon the analytical foundations established by PULSE-EU to advance the understanding and quantification of renovation impacts across diverse European building stocks. Through its archetype-based and regionalised approach, GreenRenov8 enhances methodological precision in assessing both operational and embodied emissions associated with building renovation. The project expands on the PULSE-EU framework by integrating region-specific climate and seismic conditions, thereby enabling a more detailed depiction of building performance and resilience within national and regional contexts.

A key innovation lies in coupling thermal renovation measures with seismic safety reinforcements, particularly relevant for seismic-prone regions. This integrated strategy not only contributes to achieving EU-wide decarbonisation goals but also addresses structural safety and long-term resilience—core dimensions of a sustainable building stock. The refined modelling approach, based on detailed pre- and post-renovation energy demand profiles, represents a significant advancement over static reduction rate models. It allows for more granular and transparent scenario analyses, closely aligned with anticipated energy performance improvements and embodied carbon reduction trajectories toward 2050 outlined in the EPBD recast.

The results produced in this phase of the project set the foundation for developing comprehensive renovation scenarios in compliance with EPBD requirements. The established methodological framework enables cross-country comparability while accommodating regional specificities in construction practices, materials, and regulatory landscapes. Data gathering and expert validation remain central to ensuring the robustness and representativeness of the model, supporting reliable policy-relevant insights.

Through its detailed building stock analyses and scenario-based evaluations, GreenRenov8aims generates valuable evidence to guide national renovation roadmaps and policy frameworks. By providing whole-life carbon projections and quantifying the combined effects of thermal and seismic upgrades, the project advances the knowledge base for cost-effective, resilient, and low-carbon renovation strategies. The developed archetypes, renovation pathways, and performance indicators lay the groundwork for subsequent project deliverables, reinforcing the GreenRenov8 contribution to achieving a carbon-neutral and seismic resilient European building stock by mid-century.

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Figures

Tables

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