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Life cycle environmental and cost modelling to support the development of national renovation roadmaps

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Abstract. In the context of the European Green Deal, achieving a climate-neutral building stock by 2050 has become a key objective. The 2024-revision of the Energy Performance of Buildings Directive (EPBD) highlights this goal by requiring EU Member States to transform their long-term renovation strategies into practical National Renovation Plans. The LIFE project GreenRenoV8 supports the practical implementation of the EPBD by developing a scalable, cost-effective methodology for deep, sustainable building renovation. By combining the environmental performance with the economic implications (both investment and life cycle cost), the project aims to identify the most cost-effective renovation strategies. GreenRenoV8 focuses on five EU Member States: Austria, Belgium (Flanders region), Greece, Italy and Slovenia. A stock modelling approach is used, starting with the identification of representative building archetypes per country. For each archetype, specific renovation strategies are developed and their life cycle environmental impact, investment cost and life cycle cost are assessed. The results are extrapolated to the national level to determine the most cost-effective measures and to prioritize these. The modelling moreover incorporates seismic resilience where required. This paper describes the approach taken within the GreenRenoV8 project to support evidence-based renovation planning that maximizes environmental impact reduction and cost-effectiveness across the EU.

Keywords: Sustainable renovation, Carbon-neutral buildings, Building stock modelling, Life cycle assessment (LCA), Life cycle costing (LCC)

1. Introduction

The Paris Agreement of 2015 established a global framework to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C, avoiding dangerous climate change [1]. The European Union launched, in response to the Paris Agreement, an international commitment in 2019, the European Green Deal. This deal aims at making Europe carbon-neutral by 2050 and integrates climate, energy, building policy and transport in a unified framework for decarbonization. [2]

One of the key aspects of the European Green Deal, is the decarbonization of the building stock. The construction sector accounts for 37% of global greenhouse gas (GHG) emissions, 37% of global energy-related carbon dioxide emissions [3], 30% of global final energy use and almost 40% of the total EU's waste generation [4]. In response, the revised Energy Performance of Buildings Directive (EPBD EU/2024/1275) supports the increase in renovation rate and mandates that Member States translate their long-term renovation strategies into practical National Renovation Plans [5]. The 2024 EPBD revision promotes prioritizing the worst-performing buildings and supports step-by-step renovation planning.

The LIFE project, GreenRenoV8, directly supports the revisions made in the EPBD by developing cost-effective and scalable approaches to building renovation. GreenRenoV8 targets five EU Member States: Austria, Belgium (Flanders region), Greece, Italy and Slovenia to integrate energy efficiency, seismic resilience and environmental sustainability into a comprehensive framework. It directly supports the goal of the revised EPBD and the EU Renovation Wave Strategy, aiming to double the average annual renovation rate by 2030.

2. Objectives and underlying concept

The overall objective of GreenRenoV8 is to improve the practical implementation of national carbon reduction roadmaps through analysing sustainable renovation strategies that incorporate energy efficiency, seismic considerations and whole-life carbon targets. By addressing these strategic and technical aspects of renovation, the project ensures alignment with the EPBD goals and ensures replication across other EU Member States.

Energy renovations have long been the main focus of European building policy, particularly under the EPBD. However, addressing energy performance alone is not sufficient to ensure a future proof building stock. Large parts of EU's existing building stock are located in regions where seismic activity is present. It is estimated that around 50% of EU's surface area is susceptible to earthquakes. Seismic activity has resulted in more than 36000 fatalities and displaced 1.4 million individuals in the past 50 years. [6] This dual challenge, energy efficiency and seismic resilience, calls for renovation strategies that maximize both energy upgrades and structural safety. GreenRenoV8 addresses this need by developing a methodology for integrated planning that combines these priorities. To ensure financial viability and long-term cost-effectiveness, the project also includes a life cycle costing analysis of renovation strategies. By incorporating seismic assessment and life cycle costing into the same framework used for energy performance analysis, the project ensures that renovations enhance energy efficiency, seismic resilience and economic sustainability across the buildings lifespan.

The project is carried out by a multidisciplinary consortium of research institutions, universities, policy makers and other stakeholder.

3. Methodology

GreenRenoV8 follows a multi-tiered methodological framework that supports the transition towards a carbon neutral building stock. The methodology incorporates technical, environmental and economic dimensions in four main methodological parts as visualized in figure 1: 1) business-as-usual (BAU) modelling and assessment, 2) scenario modelling and evaluation, 3) financing the transition and 4) support the transition to a climate-neutral, seismic resilient building stock.

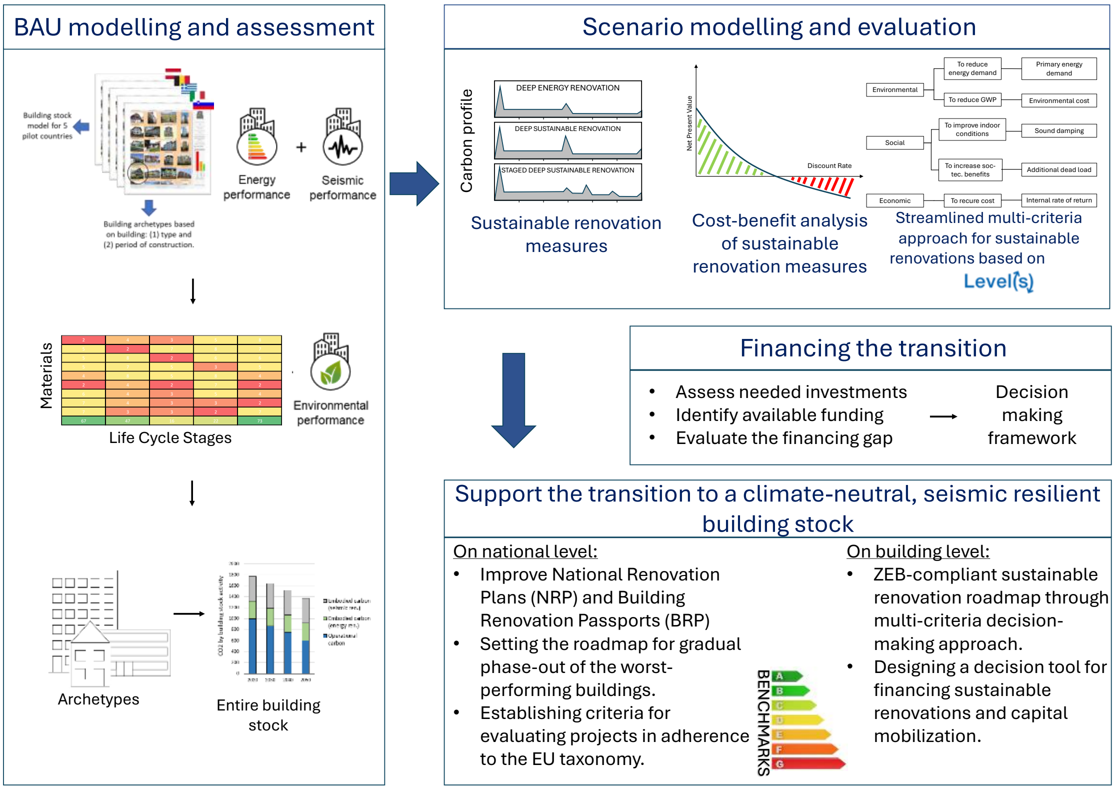

Figure 1. Overall methodology applied in the LIFE GreenRenoV8 project, highlighting four main methodological parts.

3.1 Business as usual modelling and assessment

At the basis of the GreenRenoV8 methodology lies the systematic assessment and classification of the existing building stock in the five pilot countries. This foundational step establishes the basis for all future modelling, calculations and policy evaluation. The process used to define building archetypes is illustrated in Figure 2. Each national building stock is represented by 30 archetypes. The archetypes are selected based on a number of criteria, including building type, construction period, share of the constructed area in the entire stock and geometry. For each archetype, a comprehensive set of parameters is defined which are necessary for conducting life cycle assessment of environmental performance indicators, particularly Global Warming Potential (GWP). These 30 archetypes are derived departing from the archetypes defined in the study 'Analysis of life-cycle greenhouse gas emissions of EU buildings and construction' for DG GROW, further referred to as DG GROW study [7].

For each of the 30 archetypes, various energy performance levels occur in the stock, depending on whether or not the building already underwent an energetic renovation. The 30 archetypes are hence further differentiated in various energy performance levels. Different structural build-ups are also considered depending on the seismic zone in which the archetype is located. To illustrate the outcome of this approach, the results for Slovenia are shown in figure 3 and 4.

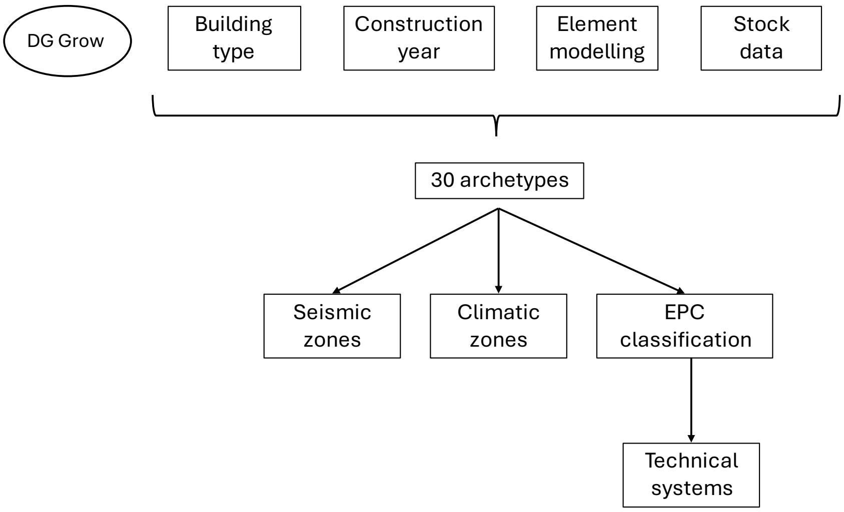

Figure 2. Process to define 30 national archetype.

Archetypes				Seismic					Climate
Number	Archetype			Seismic Zone	Building Structural Type			Seismic vulnerability	Climate zone
[number]	[text]	[text]	[text]	[text]	[text]	[text]	[text]	[text]	Share %
No. Archetype	Building type	Building age class	Archetype ID	Seismic Hazard	General Building Structural Type	Specific Structural system	Specific Structural Type	Seismic vulnerability of construction type	Continental zone
1	Single family houses	0-1920	SI-SFH-0-1920-EXB	High	Load-bearing masonry	Stone masonry walls	SM-2	High	100,00%
2	Single family houses	1921-1965	SI-SFH-1921-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-2	Moderate	100,00%
3	Single family houses	1966-1981	SI-SFH-1966-1981-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
4	Single family houses	1982-2008	SI-SFH-1982-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-4	Very Low	100,00%
5	Single family houses	2009-NOW	SI-SFH-2009-NOW-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-4	Very Low	100,00%
6	Multifamily houses	0-1965	SI-MFH-0-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
7	Multifamily houses	1966-1981	SI-MFH-1966-1981-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-2	Moderate	100,00%
8	Multifamily houses	1966-1981	SI-MFH-1966-1981-EXB	High	Reinforced concrete frame	RC shear walls	SWC-1	Moderate	100,00%
9	Multifamily houses	1982-2008	SI-MFH-1982-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
10	Multifamily houses	1982-2008	SI-MFH-1982-2008-EXB	High	Reinforced concrete frame	RC shear walls	SWC-2	Low	100,00%
11	Multifamily houses	2009-NOW	SI-MFH-2009-NOW-EXB	High	Reinforced concrete frame	RC shear walls	SWC-2	Very Low	100,00%
12	Multifamily houses	0-1965	SI-HRE-0-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
13	Multifamily houses	1966-2008	SI-HRE-1966-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
14	Public office buildings	0-1965	SI-OFF-0-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
15	Public office buildings	1966-1981	SI-OFF-1966-1981-EXB	High	Reinforced concrete frame	RC moment-resistant frames	MRCF-3	Low	100,00%
16	Public office buildings	1982-2008	SI-OFF-1982-2008-EXB	High	Reinforced concrete frame	RC shear walls	SWC-2	Low	100,00%
17	Retails stores	0-1945	SI-SHO-0-1945-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
18	Retails stores	1946-2008	SI-SHO-1946-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
19	Educational buildings	0-1920	SI-EDU-0-1920-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
20	Educational buildings	1921-1965	SI-EDU-1921-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-2	Moderate	100,00%
21	Educational buildings	1966-1981	SI-EDU-1966-1981-EXB	High	Reinforced concrete frame	RC shear walls	SWC-2	Low	100,00%
22	Educational buildings	1982-2008	SI-EDU-1982-2008-EXB	High	Reinforced concrete frame	RC shear walls	SWC-2	Low	100,00%
23	Educational buildings	0-1965	SI-CUS-0-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
24	Educational buildings	1966-1981	SI-CUS-1966-1981-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
25	Educational buildings	1982-2008	SI-CUS-1982-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
26	Healthcare buildings	0-1965	SI-HEA-0-1965-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-1	High	100,00%
27	Healthcare buildings	1966-1981	SI-HEA-1966-1981-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-2	Moderate	100,00%
28	Healthcare buildings	1982-2008	SI-HEA-1982-2008-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-3	Low	100,00%
29	Public office buildings	2009-NOW	SI-OTB-2009-NOW-EXB	High	Load-bearing masonry	Burnt clay brick masonry	BM-4	Very Low	100,00%
30	Public office buildings	2009-NOW	SI-OTC-2009-NOW-EXB	High	Reinforced concrete frame	RC moment-resistant frames	MRCF-4	Very Low	100,00%

Figure 3. Definition of seismic and climate zones for the 30 Slovenian archetypes.

Archetypes		Energy performance classes								
Number	Archetype ID	A1	A2	B1	B2	C	D	E	F	G
[number]		Share %	Share %	Share %	Share %	Share %	Share %	Share %	Share %	Share %
1	SI-SFH-0-1920-EXB	0%	0%	0%	3%	4%	11%	12%	16%	54%
2	SI-SFH-1921-1965-EXB	0%	0%	0%	1%	5%	13%	18%	21%	42%
3	SI-SFH-1966-1981-EXB	0%	0%	0%	1%	7%	24%	23%	22%	23%
4	SI-SFH-1982-2008-EXB	0%	1%	1%	4%	9%	35%	24%	16%	10%
5	SI-SFH-2009-NOW-EXB	2%	3%	7%	7%	42%	24%	9%	4%	2%
6	SI-MFH-0-1965-EXB	0%	0%	4%	6%	17%	28%	20%	17%	8%
7	SI-MFH-1966-1981-EXB	0%	1%	2%	6%	19%	38%	19%	9%	6%
8	SI-MFH-1966-1981-EXB	0%	1%	2%	6%	19%	38%	19%	9%	6%
9	SI-MFH-1982-2008-EXB	0%	1%	4%	8%	33%	39%	9%	4%	2%
10	SI-MFH-1982-2008-EXB	0%	1%	4%	8%	33%	39%	9%	4%	2%
11	SI-MFH-2009-NOW-EXB	1%	4%	11%	18%	46%	18%	2%	0%	0%
12	SI-HRE-0-1965-EXB	0%	0%	0%	1%	7%	12%	19%	26%	35%
13	SI-HRE-1966-2008-EXB	0%	0%	1%	6%	22%	39%	19%	6%	7%
14	SI-OFF-0-1965-EXB	0%	0%	0%	0%	4%	14%	25%	26%	31%
15	SI-OFF-1966-1981-EXB	0%	0%	0%	1%	12%	26%	28%	18%	15%
16	SI-OFF-1982-2008-EXB	0%	0%	3%	6%	20%	29%	22%	13%	7%
17	SI-SHO-0-1945-EXB	0%	0%	0%	0%	12%	16%	25%	28%	19%
18	SI-SHO-1946-2008-EXB	0%	0%	0%	3%	13%	32%	21%	18%	13%
19	SI-EDU-0-1920-EXB	0%	0%	0%	0%	0%	12%	27%	38%	23%
20	SI-EDU-1921-1965-EXB	0%	0%	0%	2%	6%	19%	31%	24%	18%
21	SI-EDU-1966-1981-EXB	0%	0%	0%	4%	16%	21%	26%	21%	12%
22	SI-EDU-1982-2008-EXB	0%	5%	10%	17%	29%	28%	6%	3%	2%
23	SI-CUS-0-1965-EXB	0%	0%	0%	0%	1%	20%	22%	26%	31%
24	SI-CUS-1966-1981-EXB	0%	0%	0%	1%	6%	25%	34%	20%	14%
25	SI-CUS-1982-2008-EXB	0%	0%	0%	12%	19%	26%	25%	8%	10%
26	SI-HEA-0-1965-EXB	0%	0%	0%	0%	4%	16%	23%	32%	25%
27	SI-HEA-1966-1981-EXB	0%	0%	0%	2%	9%	17%	26%	25%	21%
28	SI-HEA-1982-2008-EXB	0%	0%	0%	19%	14%	31%	18%	4%	14%
29	SI-OTB-2009-NOW-EXB	2%	8%	22%	23%	45%	0%	0%	0%	0%
30	SI-OTC-2009-NOW-EXB	5%	12%	19%	19%	45%	0%	0%	0%	0%

Figure 4. Variation in the level of energy performance of each of the 30 Slovenian archetypes.

The archetypes are evaluated by modelling the environmental impact, associated with the archetypes, across multiple life cycle stages, providing insights into the distribution of embodied and operational impacts. Based on the archetypes and collected data on the existing building stock, a business-as-usual (BAU) baseline is established. The aim is to understand the current national GHG emissions and removals associated with buildings. This baseline assumes a continuation of current renovation rates, construction practices and demolition patterns in each pilot country till 2050. These results are then scaled up to model the entire building stock in each of the five Member States. This is performed by multiplying each archetype by the total floor area of the building stock, based on current and projected rates of construction, renovation and demolition. These projections are calibrated to each country's National Energy and Climate Plan (NECP), ensuring accurate assessment of scenarios developed in the next tasks.

Combining the results from the BAU assessment with the scaling model, provides a quantitative reference of the baseline GHG emissions for the whole building stock. This reference defines the starting point for the scenario analysis.

3.2 Scenario modelling and evaluation

The second part of the GreenRenoV8 methodology focuses on scenario modelling and evaluation, to identify renovation strategies that are technically, environmentally, socially and economically viable. Before these renovation scenarios can be defined, benchmarks for Minimum Energy Performance Standards (MEPS) and Zero Emission Buildings (ZEB) are developed in line with the 2024 EPBD revision. These benchmarks help guide phased reduction of the worst-performing buildings, focussing on maximizing decarbonization potential, minimizing energy poverty and improving broader social benefits. Following the definition of these benchmarks, renovation

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measures are defined that meet the MEPS. These measures are defined at archetype level. For each building archetype, three levels of energy renovation are defined: light-medium-deep. Similarly each archetypes is divided across defined seismic and climatic regions. This allows for region-specific analysis of renovation strategies. Seismic strengthening measures are only considered in the case of deep renovation, where structural interventions are both technically feasible and economically justified. For each of these renovation measure, the embodied impact and reduced operational impact are assessed. Life cycle costing methods are furthermore used to calculate the investment cost, reduction in operational energy cost, other operational costs and end-of-life costs of these renovation measures. The various life cycle costs are discounted to present values to calculate the sum of the present values of costs at different moments in time. This life cycle cost enables the comparison of different measures. Building cost data are gathered from existing cost databases, such as ASPEN for Belgium and energy cost data are gathered from national statistics. To estimate the cost-effectiveness of the renovation measure, the difference in life cycle cost before and after renovation is calculated and compared to the investment cost.

Through scenario modelling, the impact of various renovation rates are investigated. Regional renovation scenarios are then formulated and evaluated in the five Member States. The scenarios differ in terms of renovation depth, timing, seismic upgrades and other considerations. To evaluate these national and regional renovation measures, a holistic analytical framework is established. A set of key metrics, including potential loss of life, economic implications linked to seismic repair, energy consumption related to heating and socio-economic indicators are used to assess the effectiveness of various renovation options. The overarching aim of this framework is to provide quantitative insights on the effects of specific renovation strategies, all within the overarching goal of achieving climate neutrality and enhancing resilience by the year 2050. To select the most suitable renovation strategy for a given building archetype, a Multi-Criteria Decision-Making (MCDM) methodology is developed. The MCDM takes into account social, environmental and economic indicators from the EU Level(s) framework. The methodology helps to achieve an optimal balance between reducing seismic vulnerability, enhancing energy efficiency and the need for replacement construction.

In order to support strategic planning, priority regions need to be identified. A scenario-based analysis identifies these regions based on seismic risk, energy saving potential and socio-economic factors.

3.3 Financing the transition

Financing the transition towards a decarbonized building stock requires each Member State to estimate the scale of necessary investments, identify existing funding sources and assess the remaining financial gap. The budget needed to meet the renovation targets is estimated based on the renovation scenarios developed. Once the financial needs are known, the availability of current national funding is evaluated and a market analysis of financial instruments is conducted. In addition, case studies of existing funding models are examined to inform the development of a financing decision-making framework. This framework considers various types of financial instruments, risk and return considerations and implementation settings.

To align renovation financing with the EU Taxonomy, a Sustainable Renovation Taxonomy Protocol (SRTP) is introduced. The protocol establishes a standardized set of evaluation criteria for measuring renovation sustainability, based on operational energy demand and both operational and embodied GHG emissions. This SRTP provides a consistent methodology for assessing renovation projects over their entire life cycle and facilitates alignment with EU-level sustainability classification systems.

3.4 Support the transition to a seismic resilient, climate-neutral building stock

Finally, the outcomes of the previous steps are translated into practical implementation tools, namely National Renovation Plans (NRP) and enhanced Building Renovation Passports (BRP). Stakeholders in each pilot country are consulted through workshops and meetings with public authorities and agencies involved in long-term renovation strategy development. The objective is to discuss country specific implementation measures to enhance seismic safety and energy performance at the national level. The National Renovation Plans are based on minimum energy and seismic performance standards, aligned with the 2024 EPBD recast and national carbon targets. These set minimum performance thresholds and define renovation targets based on energy use, GWP and seismic safety. Additionally, guidelines are defined that include trajectory based planning, supporting phased transition towards carbon-neutral buildings by 2050.

The outcomes and lessons learned are moreover used to improve current BRPs by integrating energy efficiency, seismic safety and long-term renovation planning. A key component is the development of a transnational seismic classification scheme. This scheme allows the implementation of basic seismic information into the BPR without requiring detailed analysis. This ensures consistency and allows applicability across all Member States. Based on this transnational BRP, national versions of the GreenRenoV8 BRP can be developed in the future. A strategy for structured data collection is established to allow the implementation and monitoring of these passports. The strategy suggests the minimal amount of data required for the development of BRP and realistically attainable data. The result is a systematic monitoring framework for sustainable renovation. After establishing the methodology, each pilot country develops three pilot cases of the proposed GreenRenoV8 BRP. The pilot cases include multi-family buildings, public buildings and social housing. The results of these cases help in identifying potential gaps that need to be addressed before practical implementation.

4. Policy implication

GreenRenoV8 delivers practical, scalable tools to support the implementation of the 2024 EPBD recast, impacting national and EU policies. It promotes a holistic renovation approach by integrating energy efficiency, seismic resilience and life cycle assessment. Outputs such as NRP, BRP upgrades and performance benchmarks support policy makers in designing and evaluating renovation strategies. The SRTP further aligns policy and finance, enabling consistent investment evaluation across the EU. Together, these efforts strengthen Member States' capacity to plan, monitor and adapt renovation policies toward the EU's 2050 climate targets.

5. Conclusions and next steps

In summary, by combining archetype development, stock-level modelling, energy benchmarking, economic and seismic assessment, the GreenRenov8 project aims at identifying renovation strategies at building and national level that are sustainable, economically viable and align with national and European policy goals. GreenRenoV8 hence contributes in supporting Member States' transition to a carbon-neutral building stock, combining technical, financial and environmental tools, with policy measures. The project illustrates how deep renovation can address both energy use, seismic risk, and life cycle GHG emissions and searches for the most cost-effective approach. This offers a replicable model for integrated renovation planning. Through its methodology, stakeholder participation and tools, GreenRenoV8 aligns with the core objectives of the updated EPBD and broader EU policies.

As of June 2025, the project focuses on the completion of the national building archetypes and finalizing benchmarks for the Minimum Energy Performance Standards (MEPS). This provides the foundation for the BAU assessment, upscaling and defining the national renovation strategies in the next step of the research project.

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