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REEBUILD Integrated Techniques for the Seismic Strengthening and Energy Efficiency of Existing Buildings

Assessment methodologies for the combined seismic and energy retrofit of existing buildings

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REEBUILD

Integrated Techniques for the Seismic Strengthening & Energy Efficiency of Existing Buildings

Assessment methodologies for the combined seismic and energy retrofit of existing buildings

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Foreword

Our buildings are ageing, posing an urgent need for renovation to align with the goals of multidimensional European and international policies. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. It is worth noting that 40 % of the European Union (EU) building stock is located in seismic prone regions and was built without modern seismic design considerations. Apart from Member States with moderate and high seismic risk, such as Greece and Italy exhibiting a severe impact (i.e. fatalities, injuries, and economic losses) from earthquakes during the last decades, attention should be drawn to regions with lower risk, e.g. in France and Spain. At the same time, buildings stand out as one of the most energy consuming sectors, therefore having a negative environmental impact. In fact, buildings are responsible for 40 % of EU energy consumption and 36 % of the EU total carbon dioxide (CO_2) emissions, whereas 75 % of the EU existing building stock is considered energy inefficient. The highest amount of energy use in buildings derives from the operational stage of their life time (e.g. heating, cooling), resulting in a significant source of carbon emissions with detrimental effects on climate change.

Notwithstanding this negative impact, the building sector provides a unique opportunity to create, through risk-proofed renovation, a safe, sustainable, and resilient built environment which promotes wellbeing and economic growth, and ensures that EU energy and climate targets are met. In this context, the European Parliament entrusted the European Commission's Joint Research Centre with the two-year pilot project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" or REEBUILD.

REEBUILD aims to define technical solutions that can reduce seismic vulnerability and increase energy efficiency of existing buildings, at the same time and in the least invasive way. Thereby, increased earthquake resilience and limited environmental impact of buildings is sought by protecting life, economy and the environment. The project has the following key-objectives:

- Define the tools and guidelines to reduce, all at once, vulnerability and energy inefficiency of buildings.
- Stimulate the use of integrated solutions.
- Create awareness about the topic in the aim of prevention.
- Increase resilience of the built environment to seismic hazard and climate change.

The geographical scope of the project covers EU seismic prone regions. However, all EU citizens are potential beneficiaries of the project since it can easily be extended to all EU regions considering the ageing of existing buildings and other hazards, including extreme climatic events.

In a policy context, REEBUILD provides scientific advice to support the development of an action plan, which shall supplement existing European Union policies and initiatives in the field of buildings' renovation. Crucially, the European Green Deal (COM(2019) 640) emphasises the need for a Renovation Wave (COM(2020) 662), supported by the New European Bauhaus (1) (COM(2021) 573) to create sustainable, inclusive and beautiful living spaces. The plans to put the European Green Deal into effect further contribute to the economic recovery following the COVID-19 pandemic. In the Energy Performance of Buildings Directive (EPBD) (Directive 2018/844) and the recent proposal for its revision (Proposal COM(2021) 802), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM(2020) 98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (Commission SWD 2016/205) encourages investment in disaster risk reduction, integrating "Build Back Better" principles for a more resilient built environment. The European Framework for Action on Cultural Heritage (Commission SWD 2019), emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development (2) (UN, Resolution 2015/A/Res/70/1) and the Sustainable Development Goal (SDG) 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

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(1) New European Bauhaus, https://europa.eu/new-european-bauhaus/index_en

(2) Sustainable Development Goals (SDG) Policy Mapping tool, https://knowsdgs.jrc.ec.europa.eu/intro-policy-mapping

Integrated retrofitting of existing buildings can be seen as a nexus between policies improving the disaster resilience of the EU, encouraging the energy renovation of buildings, promoting circularity within the building sector, and protecting cultural heritage.

Several activities were foreseen to achieve the REEBUILD objectives. EU buildings requiring upgrading were identified, and existing seismic and energy retrofit technologies were assessed in a life-cycle perspective. Combined retrofit solutions were explored based on available technologies and recent scientific developments in the field. A simplified method for the assessment of the combined upgrading was proposed and applied to case studies of representative building typologies retrofitted with the identified solutions. Seismic risk and energy performance of buildings along with socioeconomic aspects were assessed at regional level throughout Europe. Such regional assessments were used to identify appropriate intervention scenarios based on their regional impact and highlight the regions where interventions are of higher priority. National, regional and local authorities, industrial associations and expert communities were involved in enquiries and discussions of relevant implementing measures (legislation, incentives, guidance and standards), technologies and methodologies for the combined upgrading of existing buildings. Dissemination and outreach is further supported by reports, a web platform and public communication material. REEBUILD activities were organised in five main actions:

1. Overview and classification of technologies for seismic strengthening and energy upgrading of existing buildings.
2. Analysis of technologies for combined upgrading of existing buildings.
3. Methodologies for assessing the combined effect of upgrading.
4. Regional impact assessment and contributions to an action plan.
5. Stakeholders’ engagement.

This report provides a synopsis of the main results carried out within Action 3, briefly introducing a simplified combined assessment method for seismic and energy retrofit of the existing buildings based on a multi-performance, Life Cycle Thinking (LCT) approach. An existing standard assessment method and the proposed simplified one are also applied to four case studies representative of European residential and non-residential buildings needing combined seismic and energy retrofit. This JRC science for policy report has to be considered as a summary of its corresponding detailed JRC technical report prepared by Romano et al. (2023).

Acknowledgements

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Abstract

The renovation of the EU existing built environment to make it more energy-efficient and less carbon intensive over its entire life cycle, as emphasised by the Renovation Wave strategy within the European Green Deal, assumes a key-role to meet the ambitious goal of a climate-neutral society and economy by 2050. However, the European existing building stock, mainly located in the EU seismic-prone regions, also suffers from seismic vulnerability leading to detrimental social, economic, and environmental impacts in case of an earthquake. Hence, it is essential to boost integrated renovation interventions aimed at simultaneously enhancing the seismic and energy performances of buildings to effectively achieve a safe, resilient and sustainable building sector.

This report introduces a simplified method for the assessment of the combined seismic and energy retrofit of existing buildings, along with their environmental performance, in a life-cycle perspective by achieving a global assessment result in economic terms. The development of a user-friendly method, which exploits a simplified common language (i.e. monetary units), to assess the potential improvements achieved in a combined renovation project is essential to ease and speed up the knowledge of benefits that different stakeholders e.g. owners, industry, policy makers, etc., can gain by combining seismic safety and energy efficiency retrofit technologies, thus overcoming renovation barriers, such as intervention cost, execution time, inhabitants' relocation, institutional and administrative issues. The proposed simplified assessment method considers the Sustainable Structural Design (SSD) methodology (developed in the framework of the JRC activity SAFESUST) as point of reference for its introduction. Both methods are applied to four case studies referring to EU representative residential and non-residential building typologies needing combined seismic and energy retrofit, demonstrating the renovation benefits in economic terms.

Executive summary

The EU existing building stock, considering both residential and non-residential segments, accounts for 25 billion square meters of built-up area (BPIE, 2011), of which 20 billion erected before 1990, thus representing an ageing built environment compliant neither with the recent energy efficiency regulations, nor with modern seismic design code requirements (i.e. Eurocodes). The achievement of an energy-efficient built environment by boosting renovation solutions for obsolete buildings is a high-priority issue for Europe, as it represents not only an effective key to meet the EU ambitious energy and climate targets by 2050, but it can also generate economic and social benefits, fulfilling the sustainable development principles. At the same time, these ageing buildings need to satisfy structural safety and reliability requirements both in ordinary and exceptional conditions (e.g. in case of seismic events), to prevent both extensive structural and non-structural damages along with consequent considerable economic losses, fatalities, and environmental impacts. Hence, a successful and cost-effective building renovation solution should not be exclusively energy/environmental goal-oriented, but it should deal with integrated seismic and energy retrofit interventions to achieve a safe and sustainable built environment over time.

The pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD, financed by the European Union under decision C/2019/3874-final of 28 May 2019, was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life-cycle perspective. In this context, a fundamental step to facilitate the integrated seismic and energy renovation of buildings deals with the development of an adequate assessment methodology aimed at evaluating the enhanced performances of the retrofitted buildings in an effective and streamlined way. The proposed assessment methodology aims to provide the corresponding results in a simplified language, such as economic terms and/or payback time, which allows different stakeholders to easily recognise the importance and benefits of implementing such a renovation strategy.

Policy context

The integrated seismic and energy upgrading of existing buildings supports and creates a nexus among several EU policy goals related to green transition, industrial strategy, disaster risk reduction, and protection of cultural heritage, according to the scope of REEBUILD project.

The European Green Deal (COM(2019) 640) emphasises the need for a Renovation Wave of buildings (COM(2020) 662), supported by the establishment of the New European Bauhaus initiative (COM(2021) 573) to bring the European Green Deal closer to people's minds and homes. Within this policy framework devoted to the ecological transition, the energy renovation of buildings is envisaged as a fundamental step to be also enforced at legislative level by the proposal of the revision of the 2018 Energy Performance of Buildings Directive (Directive 2018/844, Proposal COM(2021) 802) outlining measures Member States should take to at least double the annual energy renovation rate of buildings by 2030 and foster deep renovations.

Building renovation also supplements the EU industrial strategy through the principles of the New Circular Economy Action Plan (COM(2020) 98), one of the main blocks of the European Green Deal, stimulating a resource efficiency and LCT approach for several sectors to achieve a climate-neutral society by 2050, as legally enshrined by the European Climate Law (Regulation 2021/1119). As for the construction and building sector, the promotion of circularity principles throughout the life-cycle of buildings is emphasised by considering measures to improve the durability and adaptability of built assets, thus reducing both pressure on natural resources and construction and demolition waste generation. The revision of the Construction Products Regulation (Regulation (EU) 305/2011) is also foreseen as one of the deliverables of the action plan in order to address the sustainability performance of construction products.

The holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to the importance of disaster prevention measures and integration of risk reduction and cohesion policies. Furthermore, the Acton Plan on the Sendai Framework for Disaster Risk Reduction 2015-2030 (Commission SWD 2016/205) promotes EU and national investments for disaster risk reduction and supports the development of a holistic disaster risk management by integrating the 'Build Back Better' objective to strengthen resilience of built environment.

Furthermore, integrated seismic and energy retrofit technologies help to preserve cultural heritage sites according to the European Framework for Action on Cultural Heritage (Commission SWD 2019), which emphasises the need to safeguard the EU built heritage against natural disasters and climate change.

Key conclusions

The study consists of two main interconnected parts: (i) development of a simplified combined assessment method, and (ii) application of both a standard and the proposed simplified combined assessment methods to four selected case studies.

In the context of the first part of the study, the following key conclusions are achieved:

- Current assessment methodologies for the seismic and energy retrofit of existing buildings are still based on independent renovation strategies leading to business dead-end upgrading solutions over time. Hence, the need to develop quantitative multi-performance methods based on a LCT-approach is of paramount importance with research efforts towards holistic approaches.
- A fundamental step to facilitate the combined/integrated seismic and energy renovation of buildings deals with the development of adequate assessment methodologies aimed at evaluating the enhanced performances of the retrofitted buildings in an effective and streamlined way, providing the corresponding results in a simplified language, such as economic terms, which allows different stakeholders to easily recognise the importance of implementing such a renovation strategy.
- The proposed simplified combined assessment method assesses the seismic, energy, and environmental performances of the combined renovation in equivalent costs in a life cycle perspective, without requiring complex analyses.

In the context of the second part of the study, the following key conclusion is carried out:

- The four selected case studies differ each other in terms of various factors, including geometric and structural features (e.g. structural system, construction technologies, etc.), building use, seismic hazard and climatic zone parameters, seismic and energy retrofit technologies employed, to cover a wide range of the most spread and representative EU existing buildings. However, a common target of the employment of a standard (i.e. SSD methodology) and the simplified combined assessment methods refers to the evaluation of the seismic and energy performances of the four case studies after a combined retrofit intervention. Besides assessing the integrated retrofit benefits, the applications of the two methodologies serve as a comparison key of their feasibility and ease of use.

Main findings

Main findings of the study concern both the analysis of the methodologies for the assessment of the combined upgrading of existing buildings leading to the proposal of a simplified combined assessment method and the case studies selection along with the application of a standard and the proposed simplified combined assessment methods.

The use of fully quantitative integrated life-cycle based approaches was found to be the most appropriate way to carry out a combined assessment of the seismic and energy upgrading of existing buildings with the SSD methodology resulting noteworthy to introduce a simplified combined assessment method.

The **proposed simplified combined assessment method** satisfies a set of requirements identified and classified according to three main levels: (i) general principles, related to both sustainable development principles and LCT in the construction sector, (ii) technological characteristics, devoted to guarantee an effective technological integration of energy and seismic retrofit technologies, and (iii) engineering computation requirements, aimed at addressing the computational stage of the novel assessment method and its related outcomes while avoiding complex analyses.

The **framework** of the **proposed simplified combined assessment method** consists of four main steps: Step 1 – Input information, Step 2 – Selection of technologies, Step 3 – Integrated design and evaluation, and Step 4 – Optimised solution. Step 3 represents the computational core of the method aimed at assessing the seismic, energy, and environmental performances of the retrofitted building in terms of equivalent costs at three different time of the life cycle: initial time, extended lifetime, end of life time. The final economic result expresses the variation of the equivalent Total Life Cycle Cost over the lifetime of the building, and it can be represented by a cost vs time curve. The total initial cost is the sum of the equivalent costs of seismic and energy retrofit interventions, and the equivalent CO_2 costs for manufacturing the retrofit materials. As for the extended lifetime stage, the three performances are assessed on a yearly basis, expressed in economic terms and combined into a global 'Integrated Retrofitting Performance Parameter' (IRPP). The IRPP is defined as the sum of expected annual seismic losses, expected annual costs related to energy consumption, and equivalent CO_2 costs due to both seismic damage and energy consumption. The difference in IRPP before and after the retrofit (ΔIRPP) represents the total extended lifetime cost, which includes the economic savings due to retrofit and the opportunity to consider fiscal incentives. The total end-of-life cost is the sum of the equivalent cost for dismantling seismic and energy retrofit measures and the cost associated with the environmental impact of dismantling and recycle/reuse of retrofit materials/components. One of main key simplification of the proposed method refers to the performance assessment at the extended lifetime stage. Indeed, it consists in directly using generalised performance results obtained from simulation procedures for representative building classes and compatible retrofit technologies, although further research to enrich this catalogue is needed. Furthermore, the possibility to analyse the final outcomes of the assessment procedure by means of a total life cycle cost vs time curve simplifies the decision-making process. It is possible to directly know the initial investment, the corresponding payback time, as well as the effective economic savings during the whole residual lifetime of the building after its retrofit. Moreover, the potential increase or reduction of these savings at the end-of-life of the building can be also indicated due to the potential recycle and reuse of materials and/or components of the retrofit technologies used.

Reinforced concrete (RC) and masonry buildings represent the predominant construction technologies in the EU-27, mainly spread as RC framed structures and rubble and brick stones constructions. Based on this outcome and on the most common envelope components of the EU building stock, four case studies were selected in Italy, since this country was found to include all seismic hazard-climate scenarios identified by a six-column matrix defined by two macro-seismic hazard areas and three climate zones. The selected buildings result into the following case studies:

- **Case study 1** is a three-storey RC residential building with cast-in-place RC beam and hollow clay block roofs and floors, and hollow brick infill walls, erected in 1967 in Toscolano Maderno (Brescia province). The retrofit solution consists of steel exoskeletons, external expanded polystyrene cladding, and heating system replacement.
- **Case study 2** is a three-storey residential brick masonry building with pitched timber roof, and cast-in-place RC beam and hollow clay block floors, erected in Dalmine (Bergamo province) in 1955. The building was retrofitted with prefabricated steel shear walls, and the application of roof insulation, new heating system and windows.
- **Case study 3** is the three-storey RC primary school 'Pietro Santini' in Loro Piceno built in 1965 with cast-in-place RC beam and hollow clay block roofs and floors, and hollow brick infill walls. Its integrated retrofit solution consists of an exoskeleton of concentric steel x-braced frames and a double-skin envelope.
- **Case study 4** is a four-storey cultural monumental rubble masonry building dating back to the early XX century with pitched timber roof, and steel beam and hollow clay flat block floors, hosting the city hall of Barisciano. Various local strengthening interventions to provide a box-like behaviour of the structure, and the replacement of both the heating system and windows were considered.

The **application of the SSD methodology** demonstrated that combined/integrated retrofit interventions provided an effective seismic and energy improvement in all four buildings in terms of total cost, (i.e. the sum of energy, environmental, and structural costs represented by the global assessment parameter according to the Step IV of the SSD methodology). Specifically, total cost reductions of approximately 42 %, 41 %, 31 %, and 47 % for the case study 1, 2, 3, and 4 were achieved, respectively, compared to the non-retrofitted buildings.

The **application of the proposed simplified combined assessment method** led to the assessment of the energy, seismic and environmental performances of the retrofitted building at three different time of the life cycle: initial time, extended lifetime stage, and end-of-life time in terms of equivalent costs. The ΔIRPP, calculated for the four case studies, confirmed the economic savings found by applying the SSD methodology, although with a moderate result discrepancy. Specifically, cost reductions between the pre-and post-retrofit scenarios result equal to 71 %, 55 %, 61 %, and 39 % for the case study 1, 2, 3, and 4, respectively, with the highest discrepancy of results between the SSD method and the proposed simplified one referring to the case study 1 and 3. Furthermore, the payback time for the four case studies, considering a service life of 50 years, resulted equal to approximately 16, 17, 18, and 20 years, respectively.

Related and future JRC work

JRC activities on the methodologies for assessing the combined effect of upgrading complementary to REEBUILD project refer to the previous work carried out within the SAFEty and SUSTainability (**SAFESUST**) project, aimed at defining a holistic approach to optimise at the same time safety and sustainability of the built environment (Caverzan et al., 2018). One the most significant contributions of SAFESUST concerns the development of the Sustainable Structural Design (SSD) methodology, aimed at defining a holistic approach to optimise at the same time safety and sustainability of new and existing buildings (Romano et al., 2014, Lamperti Tornaghi et al., 2018). The SSD methodology includes the energy and environmental performance into the structural one by combining the results into a global assessment parameter in monetary units. It has been considered as point of reference for a simplified combined assessment method introduced within REEBUILD project. Another relevant contribution regards the outcomes of the SAFESUST workshop (Caverzan et al., 2016) based on multi-disciplinary discussions on the needs to overcome sectoral retrofit of buildings. One of its key conclusions highlights that the adoption of the SAFESUST approach represents an opportunity to address building renovation in an integrated way, fostering safety and resilience of cities and communities, which is in line with REEBUILD purposes. Further developments within SAFESUST activities regards the extension of the SSD methodology to urban/regional/national level as a decision-making tool for assessing the best way to allocate intervention resources (Caruso et al., 2017) or the possibility to apply the SSD methodology for a broader structural assessment, not limited to seismic actions (Iuorio and Negro, 2020).

In the perspective of a broader vision of a sustainable, beautiful and inclusive built environment in line with the three dimensions of the New European Bauhaus (NEB) initiative, JRC has recently initiated to conduct a **Preparatory Action 'NEB Knowledge Management Platform'** in the context of the NEB Lab project on a labelling strategy (3) to develop a self-assessment tool allowing interested parties to align with the NEB dimensions while designing, implementing or assessing NEB transformation projects (e.g. buildings, living spaces). This on-going activity results complementary to REEBUILD project since it expands the combined seismic and energy assessment of buildings to a multitude of aspects related to environment, economy, functionality, beauty, context, etc. to assess the overall performance of a project in a holistic way.

Further JRC activities related to REEBUILD project with regard to the analysis of technologies for the combined upgrading of existing buildings refer to previous and on-going work within the **iRESIST+** (4) project devoted to explore innovative integrated seismic and energy retrofitting solutions for existing buildings (Bournas, 2018, Pohoryles et al., 2020, Pohoryles and Bournas, 2021).

Quick guide

This report aims to introduce a simplified method to assess the combined seismic and energy retrofit of the EU building stock in a life-cycle perspective, along with its application to representative EU buildings to provide a user-friendly tool aimed at tangibly demonstrating the benefits gained by an integrated seismic and energy renovation. Section 1 provides a general introduction on the need for an integrated seismic and energy retrofit of existing buildings. Section 2, after briefly presenting a review of the assessment methodologies for the combined upgrading, introduces a simplified method for the assessment of the combined seismic and energy retrofit of existing buildings based on a LCT approach. Section 3 focuses on the selection of four case studies, indicative of EU representative residential and non-residential buildings needing combined seismic and energy upgrading, to which both a standard and the proposed combined assessment methods are applied. Final remarks and conclusions of the study are summarised in Section 4.

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(3) NEB Lab: Labelling Strategy, https://new-european-bauhaus.europa.eu/get-inspired/inspiring-projects-and-ideas/neb-lab-labelling-strategy_end

(4) iRESIST+ project, https://joint-research-centre.ec.europa.eu/iresist-home_en

1 Introduction

The most consolidated concept of sustainable development as the *"development that meets the needs of the present, without compromising the ability of future generations to meet their own needs"* (Bruntdland, 1987), date back to three decades ago. This concept has led to the most accepted definition of sustainable development as the interaction of three main pillars - Environment, Economy, and Society - also known as the triple bottom line (TBL) of sustainable development (Elkington, 1997). However, the exponential population growth and the increase of global energy consumption with its related CO_2 emissions, as well as the intensification of natural disasters with their consequent fatalities, and economic losses, represent unsustainable trends still affecting the Planet. Before reaching an irreversible condition, an urgent change of direction is needed in several industrial sectors with the construction and building one playing a key-role due to its huge impacts produced on each dimension of sustainable development. As for the environmental dimension, buildings are responsible for 40 % of the total EU energy consumption and 36 % of greenhouse gas (GHG) emissions (COM(2020) 662). Moreover, construction and demolition waste represents one third of the total waste produced in the EU (EC, 2016), thus exerting a huge ecological pressure. As for the economic dimension, the construction sector began recovering from the effects of the economic crisis due to the Covid-19 pandemic by generating 11 % of the EU Gross Domestic Product (GDP) in 2021, accounting for an increase in investment for all segments of construction activity (i.e. new residential building, building renovation, non-residential construction) (FIEC, 2022). As for the social dimension, people spend long time inside buildings, so safety, comfort, and healthy indoor environment have to be guaranteed.

The challenge to renew and plan cities and human settlements in a safe, inclusive and resilient way satisfying the sustainable urban development and management is one of the United Nations Sustainable Development Goals (UN SDGs) (UN, Resolution 2015/A/Res/70/1). In line with the international actions, the achievement of a sustainable building sector is recognised as a fundamental goal at European level in order to meet the climate-neutrality by 2050, as emphasised by the European Green Deal (COM(2019) 640) and later enshrined as a legally binding target with the European Climate Law (Regulation 1119/2021). A particular focus on the existing building stock is needed, since 85-95 % of buildings that exist today will still be standing in 2050 (COM(2020) 662). Hence, the existing building stock is vital for the transition to climate neutrality, although the current annual energy renovation rate is equal only to 1 %, further reduced to 0.2 % for deep renovations. The Renovation Wave strategy (COM(2020) 662) stresses the need to at least double the renovation rate of buildings by 2030 and to foster deep renovations, also included into the proposal for the EPBD revision (Proposal COM(2021) 802), to meet the goal of this crucial green transition. Furthermore, the recent Russian war against Ukraine makes this challenge even more urgent calling for increased energy efficiency and savings for an accelerated transition towards renewable energy sources, as at the heart of the REPowerEU plan (COM(2022) 230). However, any action aimed at achieving exclusively the enhancement of the energy performance of existing buildings without simultaneously addressing structural safety could be a business dead-end, mainly in seismic prone regions. Indeed, the European existing building stock accounts for 25 billion square meters of built-up area (BPIE, 2011), of which 20 billion erected before 1990, thus representing ageing built environment not compliant with modern EU seismic design code requirements, e.g. Eurocodes (5). In case of an earthquake the damage due to an inadequate seismic performance of buildings may yield considerably high economic, environmental, and social impacts, as demonstrated by recent earthquakes (e.g. 1999 Athens, 2009 L'Aquila, 2012 Emilia Romagna, 2016 Central Italy), also leading to a high likelihood of the loss of energy retrofit interventions, if any (Marini et al., 2014).

This picture significantly alerts towards the need of an integrated seismic and energy renovation of existing buildings, considering that uncoupled approaches are ineffective in fostering a sustainable transformation of the EU existing building stock (Marini et al., 2014, Belleri and Marini, 2016, Passoni et al., 2021). Conversely, renovation strategies aimed at enhancing simultaneously both the seismic and energy performances of an existing building result into long-term incisive solutions when implementing a design for life-cycle approach. Design for life-cycle means to make decisions related to structural, environmental/energy, and economic requirements in the design phase of a retrofit intervention that will affect the entire life-cycle of a building, becoming a tool to ensure an adequate degree of reliability, reduce costs, increase occupants' comfort and safety and protect the Planet, also implementing circularity principles (COM(2020) 98). However, different barriers still impede an effective integrated renovation of existing buildings (BPIE, 2011, La Greca and Margani, 2018) to improve all at once their potential deficiencies in a life cycle perspective with the final aim to foster safety and resilience of built environment. The main obstacles includes economic barriers (e.g. high cost of retrofit intervention, insufficient fiscal incentives and/or subsides), technical obstacles (e.g. ineffective

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(5) Eurocodes, https://eurocodes.jrc.ec.europa.eu/

conventional retrofit technologies), building functionality barriers (e.g. disruption time, occupants' relocation, etc.). Furthermore, institutional and administrative barriers, mainly regarding potential regulatory and planning issues, as well as information and cultural barriers may slowdown renovation interventions.

In the above context, the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life-cycle perspective. The need of a simplified assessment method aimed at evaluating the combined seismic and energy retrofit of existing buildings is a priority-issue to provide an effective tool aimed at easily evaluate the benefits gained by a combined upgrading in the view of the urgent action for a large-scale renovation of the EU building stock. Furthermore, the proposed tool needs to provide results easily comprehensible by a broad group of stakeholders with different expertise, such as owners, policy makers, local administrations, thus leading to a common language that underlines the importance of implementing such a renovation strategy to overcome some renovation barriers.

This report aims to introduce a simplified integrated method to assess the combined seismic and energy retrofit of the EU building stock in a life-cycle perspective, along with its application to representative EU buildings to provide a user-friendly tool aimed at tangibly demonstrating the benefits gained by an integrated seismic and energy renovation. Following this introduction, Section 2 presents a synopsis of the existing retrofit strategies providing a state-of-the-art to introduce a simplified combined assessment method based on a LCT approach. A set of requirements and the framework of the proposed method, consisting of four main steps, are briefly presented with a particular focus on the third step representing the computational core of the method and enabling the assessment of the seismic, energy and environmental performances into equivalent costs in a life cycle perspective. Section 3 focuses on the identification of four case studies, indicative of EU representative residential and non-residential buildings needing combined seismic and energy retrofit. A selected standard (i.e. SSD methodology) and the proposed simplified combined assessment methods are applied to the four case studies in order to assess their seismic, energy, and environmental performances before and after the retrofit. Finally, Section 4 summarises the final remarks and conclusions of the study. It is worth noting that this report aims to expose the study in a simplified way, mainly useful for policy makers, whereas a comprehensive presentation of the outcomes above including both technical and computational details can be found in the related JRC technical report prepared by Romano et al. (2023).

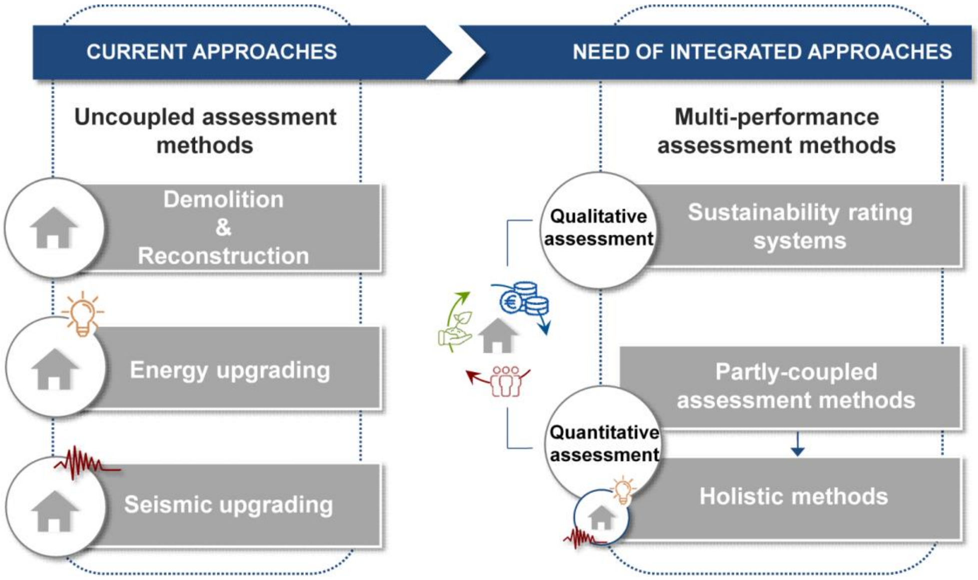
2 A simplified method for the combined assessment of seismic and energy upgrading of existing buildings

A brief review of the existing methodologies for the combined assessment of seismic and energy upgrading of existing buildings is first presented (Section 2.1), serving as a state-of-the-art to propose a simplified combined assessment method (Section 2.2 and Section 2.3). The reader is recommended to refer to the related JRC technical report (Romano et al., 2023) for an in-depth overview of the reviewed methods and tools, as well as for a comprehensive presentation of the proposed simplified combined assessment method, also including technical and computational details.

2.1 Background: state-of-the-art review of assessment methodologies for the combined upgrading

A synopsis of the current state of retrofit strategies for existing buildings to enhance their seismic and energy performances is provided in Figure 1.

Figure 1. Seismic and energy retrofit strategies for existing buildings



Independent retrofit strategies, mainly focused on either seismic or energy retrofit, are still the most common approaches for building renovation (when the demolition and reconstruction alternative can be discarded), only partly avoiding some detrimental impacts on the TBL of sustainable development (e.g. exploitation of raw materials, demolition and reconstruction waste, high costs, occupants' relocation). These retrofit strategies can be referred to as 'sector-specific methods', based on uncoupled assessment methods, aimed at evaluating either the seismic or the energy/environmental performance of an existing building before and after the retrofit intervention. It is evident that an ineffective building renovation is achieved in case of a single-performance retrofit because the investigated building remains either unsafe or energy consuming, depending on the adopted strategy. Unsustainable solutions over time are envisaged in this direction with consequent huge life-cycle environmental, economic, and social burdens.

In the perspective of a sustainable and resilient built environment, the importance of considering multi-performance design/assessment methodologies has arisen in the last decades due to the awareness that a radical change of direction was essential by considering a building as a multi-performance whole (COST Action C25, 2011, Landolfo et al., 2011) with different potential deficiencies, as underlined by recent studies aimed at emphasising the need for an integrated retrofit (Belleri and Marini, 2016, Passoni et al., 2021). The first action in this direction dates back to the '90s with the development of sustainability rating systems in various EU and non-EU countries to rapidly provide potential investors, clients, and other stakeholders with an indication of the sustainability level of a specific building by mean of a sustainability certification. However, these tools provide a qualitative assessment based on indicators of different weight, mainly including only environmental aspects, thus usually denoted as Green Building Rating Systems. This drawback makes the sustainability rating systems quite limited in terms of multi-performance assessment. Furthermore, the majority of these certification schemes is based on local versions, which are strongly dependent on regional characteristics of the area where a specific tool was developed, thus lacking of homogeneity, which leads to some inherent issues related to the difficult comparability of results. Since the last decade the importance of introducing quantitative methods aimed at assessing different building performances has led the scientific community to develop integrated life-cycle based approaches. The difficult challenge to combine a number of different performances in a life cycle perspective have led to the initial research effort of developing partly-coupled assessment methods towards holistic methods, as reviewed in Passoni et al. (2021, 2022).

In this context the existing assessment methods and tools for seismic and energy upgrading of existing buildings can be grouped in two key-streams: (i) sector-specific assessment methods, and (ii) multi-performance assessment methods. The former includes methods and tools devoted to the independent quantitative assessment of seismic and energy/environmental performances of existing buildings. The latter refers to qualitative and quantitative integrated assessment methods. Although the sector-specific methods refer to single-performance assessment procedures, their analysis is essential since they are usually implemented in the development of combined/integrated methods. Both key-streams lead to a total group of four main categories of assessment methodologies, briefly presented in the following according to the two key-streams grouping.

2.1.1 Sector-specific assessment methods

The **first category** of assessment methods refers to seismic performance assessment methods and tools. This category includes **seismic loss estimation methods** at both building and regional level, focused on a performance-based approach, known as Performance-Based Earthquake Engineering (PBEE) approach, in which the expected losses (e.g. economic losses due to downtime, repair costs, etc.) become a key-parameter to quantify and compare the seismic performance of a building during its service life. These methods, which started to be developed during '90s, are generally based on a probabilistic four-step quantitative assessment consisting of (i) hazard analysis, (ii) structural analysis, (iii) damage analysis, and (iv) loss analysis. As for the building-specific seismic loss estimation methodologies, the PBEE methodology developed by the Pacific Earthquake Engineering Research Center (PEER), i.e. PEER-PBEE, is recognised as one of the most robust procedure based on a fully probabilistic framework to assess the so-called 3D's decision variables, namely Deaths (loss of life), Dollars (economic losses), and Downtime (temporary loss of use of the facility), useful for the stakeholders' decision-making process (Cornell and Krawinkler, 2000, Porter, 2003). However, this methodology is particular complex, thus several research efforts were carried out over time to develop procedures more accessible to engineering practice, such as the FEMA P-58 methodology (FEMA P-58, 2018). The latter was subjected to various developments leading to its implementation in a dedicated tool and introducing approaches to add indirect losses in terms of probable environmental impacts due to repair for seismic-induced damages. Proposals to further simplify the PEER-PBEE approach, by replacing the fully probabilistic formulation by simple equivalent piecewise summations, were also introduced by Contini et al., (2008) and Negro and Mola (2017). In the context of a broader view of the existing PEER-PBEE simplified approaches, it is worth mentioning the recent Italian guidelines for the seismic risk assessment of constructions based on the calculation of the expected annual losses (Ministerial Decree 28/02/2017, Ministerial Decree 09/01/2020). These guidelines define the general principles and the technical rules to effectively exploit tax deductions, currently up to 110 % (Decree Law 34/2020, Law 234/2021), for seismic strengthening interventions on private buildings (i.e. the so-called 'Sisma Bonus' mechanism) in Italy. This mechanism can also be combined with retrofit interventions to improve the energy efficiency of existing buildings (i.e. the so-called 'Eco Bonus' mechanism). The combination of the two mechanisms represents a tangible example on the activation of fiscal incentives by national governments to foster the integrated renovation of the built environment at large-scale by overcoming economic barriers. The regional loss assessment methods aim to quantify losses for a large number of buildings within a specific geographic area. One of the most significant research outcomes within this group of methods is represented by the development of a geographic information system (GIS)-based regional loss estimation methodology in USA, called Hazards US (Hazus) Loss Estimation and implemented in a dedicated tool. This methodology estimates potential physical damage, economic and social losses from natural hazards (by following an approach similar to the PEER-PBEE methodology) in order to provide state, local, and territorial government officials with a decision supporting tool to develop plans and strategies for natural hazards risk reduction and to prepare for emergency response and recovery.

The first category of examined methods also includes methods and tools for **seismic vulnerability and resilience assessment**. It is worth noting that the concept of resilience has only recently been applicable to the engineering field (Kammouh et al., 2017) and, specifically, to the earthquake engineering introducing the time dimension to cover the post-event recovery phase (Tsionis, 2014). Seismic resilience assessment could become a significant tool for decision makers to evaluate retrofit alternatives for existing buildings, preferring the one with the lowest recovery period, i.e. downtime (Carofilis Gallo et al., 2022). A number of resilience-rating systems, aimed at assessing the post-disaster functionality beyond the loss assessment have been developed in the last decade with the Resilience-based Earthquake Design Initiative (REDi^{TM}) (Almufti and Wilford, 2014) resulting into one of the most robust tools.

The **second category** of assessment methods and tools includes the Life Cycle Assessment (LCA) methodology, along with a streamlined LCA procedure, namely the Life Cycle Energy Assessment (LCEA) to quantitatively assess the environmental impacts and the energy consumption of buildings during their entire life cycle, respectively.

The four-step framework of the **LCA methodology**, addressed by the recently reviewed ISO 14040-44:2006 standards (ISO, 2020a, b), allows the quantitative evaluation of the ecological impacts of products and services throughout their entire life cycle according to the *cradle-to–grave* (i.e. from raw material extraction to end-of-life) approach. After defining the goal and scope (Step 1) of a LCA study, the Life Cycle Inventory (LCI) analysis (Step 2) is carried out by quantifying inputs (resources) and outputs (emissions, wastes) for each phase of the life cycle of the assessed product or process, followed by the Life Cycle Impact Assessment (LCIA) (Step 3), which translates the LCI results into measurable impacts by classifying and characterising them within impact categories (e.g. Global Warming Potential (GWP), acidification potential, etc.) or damage categories (e.g. damage to human health, ecosystems, etc.) to finally proceed with the interpretation (Step 4) of the LCIA results. It is worth noting that the LCI step can be quite challenging due to the lack of data for a specific product under study, thus in the last three decades several international, national or regional, industry, and consultants' LCI databases have been developed and implemented into LCA software tools. Similarly, impact results are strongly dependent on the impact assessment method used in the LCIA step; thus various methods including problem-oriented (results related to impact categories), damage-oriented (results related to damage categories), and single issue-oriented (results related to a single point of view) methods have been developed and implemented in different LCA tools. The LCA methodology, which started to be developed during '60s-'70s (Udo de Haes and Heijungs, 2007), is widely used in a multitude of industrial sectors, such as food and agriculture industry, chemical industry, textile industry, etc., to investigate the interaction of their own products with the environment (Toniolo et al., 2021). This growing interest is mainly due to the scientific consensus in the recognised capability of the LCA to assess the environmental impacts of products and processes with the aim of overcoming the current concerns of resources depletion, unsustainable production of waste, and high consumption of energy. The construction sector also represents one of the most fertile grounds for LCA studies due to its huge pressure exerted on the environment, mainly in terms of GHG emissions and energy consumption (COM(2020) 662). The impetus to the direct application of the LCA to the building sector has significantly increased in the first decade of the 21th century, as reviewed by Ortiz et al. (2009), Singh et al. (2011), Buyle et al. (2013), and it is still fervid, with important milestones reached at both policy and legislative level to date. One of the most significant achievements in this direction refers to the European standardisation process in the field of sustainable constructions related to the environmental performance assessment at both building and product level based on LCA to define a common evaluation language for building designers, as briefly reviewed in Romano et al. (2020). To this end, the standardisation of the life cycle of a building into four main modules was also introduced (EN 15978: 2011): (i) the production and construction stages (Module A), (ii) the use stage (Module B), (iii) the end-of-life stage (Module C), and (iv) the benefits and loads beyond the system boundary (Module D). The application of the LCA methodology within the construction sector can be carried out at three different levels increasing with the complexity of the system to be investigated, namely (i) construction product, (ii) building component, and (iii) building as a whole. The application of the LCA to construction products provides core Product Category Rules for developing Type III environmental declarations of construction products – a particular type of LCA referred to as Environmental Product Declarations (EPDs). Conversely, LCA applied to an entire building is a more demanding task due to a series of issues, including long lifespan, the assessment of local impacts depending on building site, the LCA data collection, potential impacts on occupants' well-being, and occupants' behaviour during the use phase of the building (Cabeza et al., 2014, Chau et al., 2015). In the last two decades different LCA tools have been developed and they can be grouped into two main groups: (i) generic LCA tools, devoted to product assessment and/or comparison, and (ii) building-specific LCA tools, aimed at the whole building design decision. Two of the most used and robust tools within the first group are GaBi and SimaPro, which provide complete transparency processes during all the life cycle stages of a product assessment and are fully integrated with the latest science-based LCI databases, such as Ecoinvent, and consistent problem-, damage-, and single issue-oriented LCIA methods. The second group of LCA tools includes tools developed to analyse the environmental performance of a building as a whole throughout its entire life cycle by considering both stand-alone softwares (e.g. ATHENA) or plugs-in in the perspective of the growing integration of Building Information Modeling and LCA (e.g. One-click LCA).

The **LCEA methodology** is a simplified version of the LCA methodology to assess the energy inputs to a building at each stage of its life cycle (Adalberth, 1997a, Fay et al., 2000, Ramesh et al., 2010) with the aim to facilitate the decision-making process concerning the energy efficiency of buildings, rather than to replace a broader environmental assessment method (i.e. LCA methodology), thus considering energy as the sole measure of potential environmental impacts. The interest towards the LCEA methodology is mainly due to the awareness that buildings consume energy directly or indirectly in all phases of their life cycle. Specifically, the energy consumed directly and indirectly through various products and processes used in design, initial construction, life cycle maintenance/renovation, and final demolition of a building is indicated as embodied energy. Energy required during the operational stage of a building to maintain its indoor comfort conditions through different processes, such as heating and cooling, hot water use, and powering appliances, is defined as operational energy. The traditional assumption related to the life cycle energy distribution in buildings considers the operational energy as the major share, accounting for 80-90 % of the total life cycle energy use, whereas the embodied energy constitutes only a little segment equal to 10-20 % (Adalberth, 1997b, Ramesh et al., 2010), thus the latter is typically considered in second instance or neglected into the energy assessment. However, in the last decades these figures have been re-evaluated by acknowledging the importance of the embodied energy relative proportion into the estimation of total life cycle energy use of buildings. The growing demand for the building operational energy reduction to tackle the climate change mitigation can lead to embodied energy increases for both new (Stephan, 2013, Crawford, 2014) and retrofitted buildings (Beccali et al., 2013, Vilches et al., 2017, Shadram et al., 2020). The LCEA results into a simplification of the four stages of the LCA framework, with the LCIA step extensively simplified since a unique impact category, i.e. energy use, is considered. The system boundaries for performing a LCEA analysis include the energy use of the following three phases of the building life cycle: (i) production phase, including building materials manufacture and transport, construction, and maintenance/renovation of the building, (ii) use phase, and (iii) demolition phase, thus leading to the estimation of three main energy contributors, namely embodied energy, operation energy, and demolition energy. Focusing on the operational energy computation, it can be quantified by using three major approaches, namely (i) energy bills method, (ii) national statistics-based method, and (iii) Building Energy Simulation (BES) methods, as reviewed in Chau et al. (2015) and Omrany et al. (2020, 2021). The BES methods were found to be the most applied approach to compute the operational energy in LCEA studies on conventional and energy-efficient residential buildings in the last two decades (Omrany et al., 2021). To this end, several BES tools, typically consisting of an engine software and a Graphical User Interface (GUI), have been developed in the last six decades to facilitate and automate demanding calculation processes or model highly complex systems to carry out dynamic energy analyses with an increasing interest in their development acquired after the 1973 energy crisis. Some of the most used and robust dynamic BES tools are EnergyPlus (Crawley et al., 2001) (with DesignBuildier currently recognised as the most comprehensive GUI for Energy-Plus), ESP-r (Clarke, 1977), and TRNSYS (Van der Veken et al., 2004).

2.1.2 Multi-performance assessment methods

The **third category** of assessment methods groups EU and non-EU **sustainability rating systems** based on indicators of different weight, thus essentially providing a qualitative assessment. The era of these tools started in '90s with the development of the 'Building Research Establishment Environmental Assessment Method (BREEAM)' rating system in the United Kingdom (Reed et al., 2009). It was followed by a multitude of rating systems worldwide with a growth rate that became exponentially in few years, mainly during the period 1995-2010 (Haapio and Viitaniemi, 2008, Bernardi et al., 2017). These tools generally address only the environmental dimension of sustainability, neglecting or marginally reflecting economic and social aspects. Hence, it is not surprising that the majority of investigated sustainability rating schemes include energy efficiency and CO_2 emission indicators as highly relevant, but a seismic safety indicator is only implemented in a couple of them with a low weight, such as 'Deutsche Gesellschaft für Nachhaltiges Bauen' (DGNB) (DGNB, 2020) at European level or 'Comprehensive Assessment System for Built Environment Efficiency' (CASBEE) at non-European level with reference to new buildings. A significant effort to overcome the extensive heterogeneity of the existing sustainability rating systems was carried out at European level by developing a new tool, denoted as Level(s) at the JRC- Seville. Level(s) is a voluntary reporting framework to improve the sustainability of buildings, based on a common system of macro-objectives and core indicators (Dodd e al., 2021). The latter enables users to measure carbon, materials, water, health, comfort and climate change impacts throughout the entire life cycle of a building to provide different project actors (e.g. designers, clients, policy makers) with a common language to assess, compare, optimise, and report the sustainability of buildings. One of the novel aspect of Level(s) refers to its capacity to provide both qualitative and simplified quantitative assessments, depending on the stage of the building's life-cycle a stakeholder wants to assess. Hence, it can be considered as a hybrid tool integrating peculiarities of both rating systems and quantitative assessment methods in a life-cycle perspective.

Fully quantitative integrated methods need to be considered for a proper combined seismic and energy retrofit assessment of existing buildings. The **fourth category** of assessment methods refers to the methodologies developed in the last years devoted to **quantitative integrated life-cycle based approaches**, towards the development of holistic methods. The challenge to combine different performances of a building led to the initial research effort of developing *partly-coupled assessment methods*, aimed at combining building performances in pair. Some outcomes in this direction refer to the integration of environmental requirements and safety targets (Menna et al., 2013, Wei et al., 2016, Lamperti Tornaghi et al., 2018), the combination of economic and social impacts as consequences of various seismic retrofit options (Calvi, 2013), or the assessment of seismic risk on the economic management of energy retrofit processes (Mauro et al., 2017). Focusing on methods coupling seismic and energy performance assessment, a recent review can be found in Menna et al. (2022). A significant development in this direction refers to the procedure developed by Calvi et al. (2016) introducing the Green and Resilient Indicator based on two parameters, namely the energy and the seismic expected annual losses to compare different retrofit strategies through a cost-benefit analysis. One of most promising methodologies to carry out an integrated retrofit assessment refers to the Sustainable Structural Design (SSD) methodology (Lamperti Tornaghi et al., 2018), which was developed at the JRC - Ispra within the SAFEty and SUSTainability (SAFESUST) project. The SSD methodology aims at defining a holistic approach to optimise at the same time safety and sustainability of new and existing buildings by including energy and environmental performance assessment in structural design/retrofit in a life-cycle perspective in order to obtain a global assessment parameter in economic terms (i.e. cost) for facilitating the decision-making process. The SSD methodology consists of four main steps, as follows:

- *STEP I - Energy performance assessment*, aimed at estimating the operational energy of a building (in terms of electricity and heating consumptions) during its use-phase.
- *STEP II - Life Cycle Assessment (LCA)*, aimed at assessing the environmental performance of a building focusing on the GWP evaluation in terms of equivalent CO_2 emissions during its entire life-cycle.
- *STEP III - Structural performance assessment*, which refers to the application of the four-step simplified Performance-Based Assessment (s-PBA) (Negro and Mola, 2017), based on the consolidated PBEE-PEER methodology, aimed at assessing the expected annual economic losses due to repair interventions after seismic-induced damages and/or downtime costs. Specifically, the following steps are considered: (i) definition of limit states (i.e. low, heavy, severe structural damage, and collapse/replacement of the building) and corresponding interstorey drift ratios, (ii) performing standard nonlinear static analysis to estimate the peak ground acceleration (PGA) values to attain the inter-storey drift ratio values defined in the step (i), (iii) estimation of the return periods and probabilities of exceedance in 50 years (i.e. service life for ordinary structures) of the seismic actions associated with the PGA values obtained from the step (ii) (i.e. for each limit state), and (iv) loss analysis to calculate the expected losses based on the repair costs at each limit state.
- *STEP IV – Combination in economic terms,* aimed at combining the outcomes of the three previous steps (expressed in different measure units) into a global assessment parameter in monetary units. Energy consumptions and environmental impacts results are first converted into costs by means of unitary electricity/natural gas and unitary carbon prices, respectively. The obtained energy and environmental costs are combined with structural safety cost, thus providing a final monetary result.

A significant advantage of the SSD methodology is the capacity to offer a common language (i.e. monetary units) to all the design process operators (e.g. owners, engineers, LCA experts, etc.), policy makers and other stakeholders to allow them to understand the benefits of an integrated new building or renovation design regardless their expertise in a specific scientific area.

Based on the synopsis above, multi-performance assessment methodologies based on fully quantitative approaches (i.e. fourth category of reviewed methods) are the most appropriate methods to be pursued for the assessment of the combined effect of seismic and energy upgrading of existing buildings in a life-cycle perspective. Specifically, the SSD methodology is considered as point of reference to develop a simplified combined assessment method. The requirements and the framework of the proposed method are briefly introduced in the following.

2.2 Overview of suitable requirements for a simplified combined assessment method

The first step for the development of a simplified combined assessment method deals with the identification of a set of suitable requirements. These requirements encompass different action levels, which can be classified according to three main categories: (i) Level 1: General principles, (ii) Level 2: Technological characteristics, and (iii) Level 3: Engineering computation, briefly introduced in the following.

2.2.1 Level 1 – General principles

The first category of requirements - **Level 1: General Principles** - includes three main requirements, mainly related to both the TBL principles of sustainable development and the LCT approach in construction sector, to which correspond specific outcomes, as follows:

- **Sustainability principles** - General requirements of the proposed simplified combined assessment method should take into account both the sustainability goals in the construction sector and the recent EU policies related to the Renovation Wave of existing buildings (COM(2020) 622), also supported by the New European Bauhaus movement (COM(2021) 573), in the framework of the European Green Deal (COM(2019) 640) priority. Hence, the UN SDGs of the 2030 Agenda for the Sustainable Development and the ambitious targets of 2050 EU long-term Strategy need to be satisfied. As for the UN SDGs, attention needs to be paid mainly on the SDG 11 for achieving cities and human settlements inclusive, safe, resilient and sustainable. Emphasis is also drawn on the ambitious energy and GHG emission targets for achieving a decarbonised and climate neutral Europe by 2050, legally enshrined by the European Climate Law (Regulation (EU) 2021/1119), along with the revised intermediate GHG targets by 2030 to be implemented via the 'Fit for 55' legislative package (COM(2021) 550). The potential outcomes associated with these general requirements refer to the importance of considering sustainable retrofit solutions able to ensure environmental/energy efficiency, cost-effectiveness, and safety in a holistic way, thus leading to the need of developing integrated retrofit design and/or assessment methodologies, as recently reviewed in Passoni et al. (2021).
- **Available legislation** - The requirements of the simplified combined assessment method should comply with the EU legislative context in terms of energy and seismic retrofit. The EPBD and the Energy Efficiency Directive (EED), both amended in 2018 (Directive 2018/844), are the main regulatory drivers for energy upgrading, along with the recent proposal for the EPBD revision (Proposal COM(2021) 802). The latter represents an essential element of the Renovation Wave strategy to reflect higher ambitious and pressing needs in climate and social action, with specific measures to increase the rate of renovation of buildings in each EU member state towards building decarbonisation. The EPBD revision proposal also suggests to strengthen the 'long-term renovation strategies (LTRS)' framework towards 'national building renovation plans', which should include national targets, an outline of the investment needs for their implementation and an overview of policies and measures to foster more transparency, better implementation and monitoring procedures compared to the LTRS. The Decision on a Union Civil Protection Mechanism (Decision (EU) 2019/420) could guide in mitigating natural and man-made disaster effects, whereas national and regional legislation should be considered for seismic retrofit design in line with the European structural design codes, i.e. Eurocodes. The potential outcomes related to this requirement deal with the need to guarantee minimum performance targets for the seismic (e.g. targets related to the structural safety, containment of seismic damages to structural and non-structural components) and energy (e.g. reduction of yearly energy consumption per square meter of building) retrofit. The parameter related to the energy retrofit allows professionals and/or stakeholders involved in the retrofit intervention to also quantify the environmental emissions of a selected energy source indirectly.
- **Life-cycle performances** - An effective sustainable renovation of an existing building should consider the assessment of both TBL-related and structural performances over the 'upgraded' service life of the examined building in order to obtain more reliable results by means of a life-cycle analysis approach to be considered at the retrofit design stage. The potential outcomes corresponding to this requirement refer to the assessment of the environmental/energy efficiency, cost-effectiveness, and safety of a renovated building during its entire extended life cycle – from the retrofit design stage to the end–of-life of the building. Indeed, a LCT-based approach - from cradle-to-grave - leads to the minimisation of the potential environmental and economic negative impacts, while maximising the energy and seismic performances of the investigated existing building during each stage of its life-cycle. Hence, in the pre-use stage it is essential to consider the use of sustainable and eco-efficient materials for the potential retrofit technologies, while reducing transportation, and construction energy burdens. In the use-phase,

the energy consumption and CO_2 emission-related impacts need to be minimised along with costs, while ensuring safety both in ordinary and exceptional conditions (e.g. earthquake). At the end-of-life stage, a sustainable waste management should be envisaged by fostering the Design for Deconstruction concept, which facilitates the re-use of components and the material recycling, leading to environmental and economic benefits.

2.2.2 Level 2 - Technological characteristics

The second category of requirements - **Level 2: Technological characteristics** - identifies the following three requirements, which are essentially devoted to guarantee an effective technological integration of energy and seismic retrofit measures, leading to specific outcomes, as follows:

- **Compatibility and feasibility** – This requirement aims at maximising the efficiency of combined/integrated seismic and energy retrofit technologies by avoiding a potential physical-functional incompatibility before the retrofit design phase. A ‘pre-screening’ stage of combined/integrated energy-seismic technologies should be considered in order to ensure technological effectiveness, feasibility, economic viability and fulfilment of stakeholders’ constraints. The potential outcomes corresponding to this requirement refer to the elaboration of an interference matrix taking into account the mechanical and physical characteristics of the potential combined/integrated retrofit technologies along with additional assessment criteria depending on different constraints related to initial economic resources, building functionality, dimensional scale and extent of the building to be retrofitted.
- **Cost evaluations** - A cost-optimal combined retrofit assessment needs to be carried out through a life-cycle costing analysis. It allows stakeholders to know, during the retrofit design stage, the real economic investment by assessing not only the initial costs of energy and seismic retrofit interventions, but also the expected repair costs in case of damages due to earthquakes (i.e. economic losses) and the annual costs for energy consumption, as well as the end-of-life costs. The potential outcomes related to this requirement consider the economic efficiency of a combined/integrated retrofit intervention based on its seismic, energy, and environmental performances in terms of equivalent cost. The use of a life cycle economic metric allows the combined/integrated retrofit solutions to be related to the payback time of the investments, as specific tool to assess their economic efficiency, thus providing a simple language to make the combined/integrated renovation strategy viable.
- **Incremental implementation** – This requirement deals with the possibility of spreading the retrofit intervention and costs depending on time and investment constraints by adopting an incremental retrofit strategy. This strategy, which was introduced in USA for seismic retrofit interventions (FEMA P-420, 2009), foresees a series of discrete actions to be implemented over an extended lifetime of the building to be renovated. Each step ensures an incremental performance improvement, expressing a percentage of the overall structural performance enhancement achieved by a single-stage retrofit intervention, with a low initial cost and a minimum functional disruption of the building. The outcome of this requirement refers to the possibility of considering an incremental retrofit strategy to achieve incremental performance targets by implementing combined/integrated retrofit over time depending on time, and/or economic constraints. This approach could be needed in some cases (e.g. school and/or office buildings) to guarantee the continuity of building functionality.

2.2.3 Level 3 - Engineering computation

The third category of requirements – **Level 3: Engineering computation** – includes four requirements aimed at addressing the computational stage of the novel simplified combined assessment method and its related outcomes, while streamlining complex analyses, as follows:

1. **Site-dependent parameters –** This requirement refers to the building site characterisation, which becomes a fundamental pre-requisite for the method implementation. Indeed, the seismic hazard and climatic zone of a specific building location affect the ‘intensity’ of the combined/integrated retrofit in achieving the pre-defined sustainability performance targets (i.e. adequate structural/seismic and energy performances). The outcomes of this requirement are related to the identification of two key site-dependent parameters: (i) the expected PGA indicating the seismic hazard level of a specific location, and (ii) the Heating Degree Days (HDD), defined as a weather-based index designed to quantify the energy demand needed to heat a building, identifying the climatic zone of a specific location.
2. **Combined performance evaluation** – The results of the energy/environmental and structural assessments are expressed in different units of measure, thus a suitable ‘conversion’ method is needed to combine

them into an equivalent parameter, essential to evaluate the effectiveness of combined retrofit solutions. The outcome of this requirement refers to a proper way to combine the performance results into a single global parameter. An effective approach in this direction consists in converting seismic, energy, and environmental performance results into monetary units to obtain a final result in terms of equivalent cost, as proposed in the SSD methodology. The use of a common language allows different stakeholders to easily compare alternative retrofit scenarios in order to select the most suitable one.

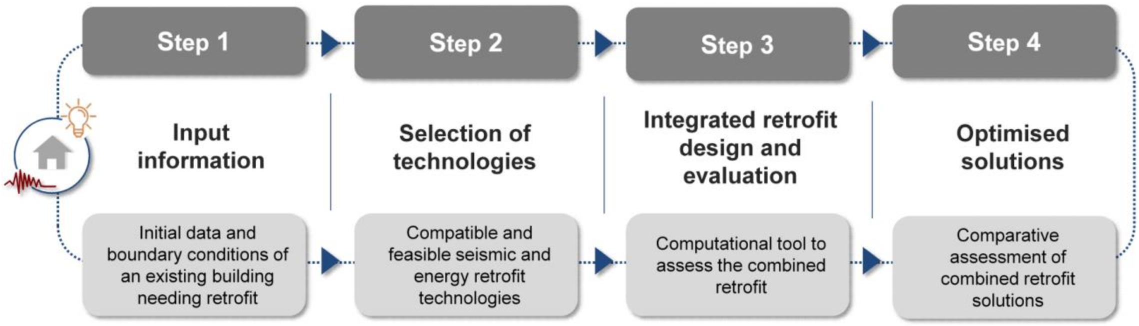
3 **Dimensional scale of the application** – The proposed simplified method should ensure its application at urban, regional and national level to support the territorial administrations in addressing EU policy goals related to the renovation of buildings from small to big areas, e.g. from districts and cities to regions and whole countries. The outcome of this requirement refers to the classification of building stock in group types to define representative building classes (RBCs). The results of the combined assessment related to different RBCs can lead to define urban, regional, and national selection criteria for the application of integrated retrofit technologies based on specific seismic-energy performance targets.

4 **Simplification** – This requirement aims to develop simplified energy and structural indicators based on output data of retrofit options. The outcome of this requirement deals with the employment of simplified procedures for performance assessment to achieve clear and easily comprehensible results, although they refer to different building performances in terms of seismic losses, energy consumptions, and environmental impacts. The possibility to implement them in a dedicated optimization framework should be also considered to obtain a single global parameter for identifying the most cost-effective and sustainable retrofit solution.

2.3 Framework of the simplified combined assessment method

The proposed simplified combined assessment method can be classified as a holistic method. It aims at satisfying the sustainable development principles by considering the peculiarities of the available seismic and energy retrofit technologies in order to foster the combined renovation of existing buildings through the selection of the most effective solution in terms of structural, energy, environmental, and economic performances throughout the remaining life cycle of the examined building. The framework of the proposed method consists of four interconnected steps (Figure 2), briefly described in the following.

Figure 2. Framework of the proposed simplified combined assessment method



2.3.1 Step 1 – Input information

The first step - *Input information* - aims at collecting the initial data and boundary conditions of an existing building needing renovation. Three categories of input data need to be considered: (i) audit of the examined building in its 'as-built' condition to define minimum Sustainability Performance Targets for the renovation process, (ii) building site characterisation to identify two key site-dependent parameters describing the climatic zone and the seismic hazard level of the building location, and (iii) potential constraints associated to the building boundary conditions in terms of space, time and cost to consider an incremental renovation strategy, if needed. The latter category becomes particularly significant for public buildings, e.g. schools, offices, which commonly have to fulfill a limited time period for their service interruption to ensure the continuity of their activities. Similarly, the inability or an expensive cost to relocate inhabitants of residential buildings could become a renovation barrier, which could be overcome with incremental retrofit interventions, thus avoiding the detrimental risk of a delayed or missed improvement of building performances.

2.3.2 Step 2 - Selection of retrofit technologies

The second step - *Selection of technologies* - deals with the analysis of physical and mechanical characteristics of the seismic (SRT) and energy (ERT) retrofit technologies to identify a set of potential compatible combined/integrated retrofit solutions. Suitable SRTs and ERTs are first evaluated separately by means of specific classification parameters (i.e. performance parameter, affected building component/structural element, building typology, building site characteristics, initial cost, potential environmental impact, disruption time, interaction with other renovation works, and thermal interaction) to be subsequently combined into a matrix of interference. The latter highlights the classification parameters to be carefully assessed to verify the physical-functional compatibility of the preliminary set of selected retrofit technologies. However, an optimal combined/integrated seismic and energy retrofit intervention can be achieved if both the ERT and SRT fulfil additional constraints related to performance requirements, extent of the building, time, and cost, which become criteria for their selection. Hence, a simplified approach for the classification of available SRTs and ERTs, aimed at facilitating the selection of compatible combined retrofit solutions, needs to be based on increasing levels of predefined seismic and energy performance targets, as well as of disruption in terms of extent of the building, time, and cost, as proposed in Menna et al. (2021).

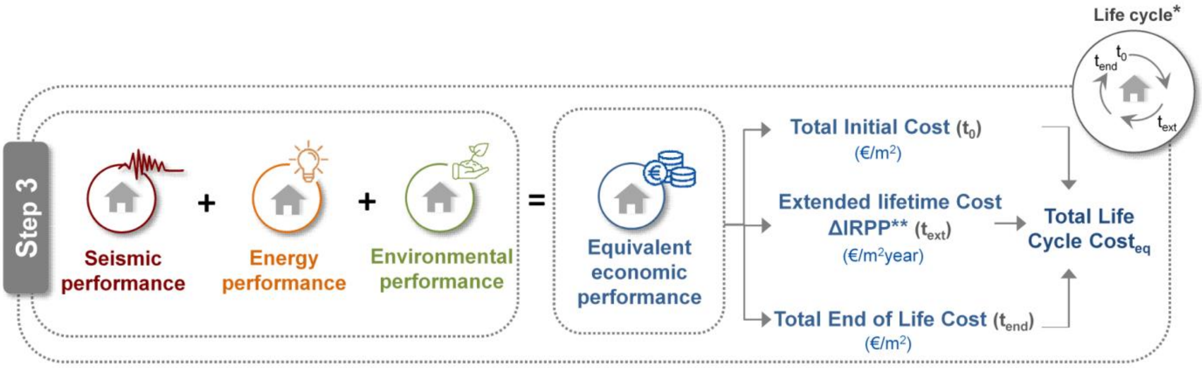
2.3.3 Step 3 – Integrated retrofit design and assessment

The third step - *Integrated retrofit design and evaluation* - represents the computational tool of the proposed simplified combined assessment method aimed at maximising the benefits of a combined renovation by integrating three key points, as it follows:

- **Life-cycle performances**, aimed at assessing the seismic and energy/environmental performances of a retrofitted building within its 'new' service life cycle, consisting of three main stages, namely (i) initial time (t_0), i.e. time of retrofit intervention, (ii) extended lifetime stage (t_{ext}), and (iii) end-of-life time (t_{end}).
- **Generalised performance results**, aimed at providing a simplified tool to group the performance results within the extended lifetime stage into 'seismic and energy generalised performances' results related to representative building classes of the EU existing building stock to which various compatible seismic and energy retrofit technologies are applied.
- **Building global performance**, aimed at providing a global metric, which combines seismic, energy, and environmental outcomes in equivalent monetary terms, namely equivalent costs, thus providing a single measure of the overall improved efficiency of the retrofitted building during its entire life cycle.

Based on the key points above, Step 3 assesses the seismic, energy, and environmental performances of a building subjected to a combined/integrated retrofit in a life cycle perspective, expressed in equivalent costs and combined to obtain a global result in monetary units. The total equivalent economic performance of the retrofitted building, expressed as the equivalent Total Life Cycle Cost (Total Life Cycle $Cost_{eq}$), is obtained by combining three main equivalent total cost contributions associated with the three different stages of its 'upgraded' life cycle, namely (i) initial time (t_0), (ii) extended lifetime (t_{ext}), and (iii) end of life time (t_{end}) and related to the combination of seismic, energy, and environmental performance assessment for each of the above time stage (Figure 3).

Figure 3. Framework of the Step 3 of the proposed simplified combined assessment method



* **Life cycle** → t_0: Initial time (time of retrofit intervention); t_{ext}: Extended lifetime stage; t_{end}: End-of-life time

** **ΔIRPP** → **Annual economic savings** due to retrofit and opportunity to consider **fiscal incentives**

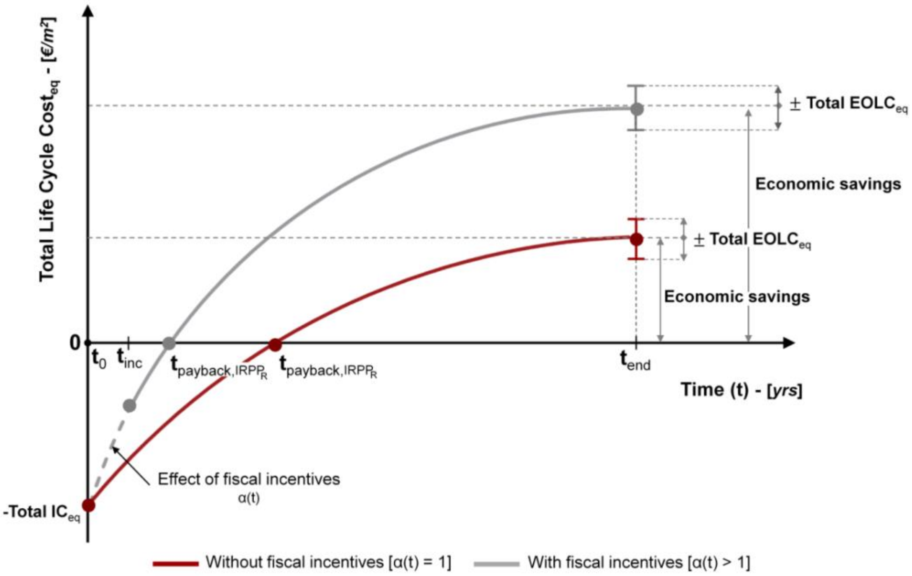
The **total initial cost** (€/m^2) at the **time t_0** is the sum of the equivalent initial costs of seismic and energy retrofit interventions, and the equivalent initial cost of the environmental impact (in terms of CO_2 emissions) for manufacturing the materials adopted in the retrofit intervention.

As for the **extended lifetime stage t_{ext}**, the seismic, energy, and environmental performances are assessed on annual basis, and expressed in economic terms to be combined into a global Integrated Retrofit Performance Parameter (IRPP) (€/m^{2}year). The IRPP is defined as the sum of the expected annual losses due to damages induced by a seismic event, the expected annual costs related to energy consumption, and the expected annual cost due to the environmental impact generated by the expected seismic damage and energy consumption. The difference in IRPP before and after the retrofit (ΔIRPP) represents the **total extended lifetime cost**, which includes the annual economic savings due to retrofit, as well as the opportunity to consider potential fiscal incentives. It is worth noting that the assessment of the seismic performance at the time t_{ext} follows four main steps in order to provide its monetary output in terms of expected annual losses for seismic damage. The first step focuses on grouping the existing building stock into RBCs according to various classification parameters related to (i) structural typology, classified in reinforced concrete, masonry, other, (ii) age of construction, and (iii) geometric details, including number of stories, interstorey height, gross floor area, window to wall ratio. The second step deals with the selection of potential SRTs (compatible with suitable ERTs) to be applied to the investigated RBCs according to classification parameters referring to both the interference matrix and the achievable improved seismic performance. The third step concerns the simulation procedure to assess the seismic performance of the examined building; the analysis (i.e. non-linear static analysis) provides seismic generalised performances (i.e. fragility curves), as a function of different RBCs and selected SRTs, valid for any site depending on the specific PGA value. The fourth step uses the seismic generalised performances to evaluate the expected annual losses associated with the repair interventions of the earthquake-induced damages by adapting the PEER-PBEE methodology. A similar four-step procedure is considered for the assessment of the energy performance at the time t_{ext} in order to provide its monetary output in terms of expected annual costs due to energy consumption. The first step is the same as in the seismic performance assessment, thus providing the same RBCs carried out previously. The second step deals with the selection of potential ERTs (compatible with suitable SRTs) to be applied to the investigated RBCs according to classification parameters referring to both the interference matrix and the achievable improved energy performance. The third step deals with the simulation procedure to assess the energy consumption of the examined building; the analysis (i.e. dynamic energy analysis), which is carried out by means of a user-friendly tool developed and validated by Ascione et al. (2021), provides energy generalised performances (i.e. thermal energy demand vs HDD curve), as a function of different RBCs and selected ERTs, valid for any site depending on the specific HDD value. The fourth step focuses on the assessment of the expected annual cost due to energy consumptions by using the energy generalised performance results, thus converting the thermal energy demand in cost by considering the Eurostat unitary energy price in terms of electricity and natural gas.

The **total end-of-life cost** (€/m^2) at the **time t_{end}** is the sum of the equivalent end-of-life costs for dismantling seismic and energy retrofit technologies and the cost associated with the environmental impact of dismantling and recycle/reuse of retrofit materials/components.

The final economic result expresses the variation of the **Total Life Cycle Cost$_{eq}$ over the lifetime of the building**, and it can be represented by a Cost vs Time curve. Two representative qualitative curves differing for the exclusion or inclusion of potential fiscal incentives are depicted in Figure 4. The red curve (i.e. fiscal incentives excluded) starts at the initial time (t_0) with a negative value of cost corresponding to the total initial cost (Total IC_{eq}), which indicates the initial economic investment for the combined retrofit. Subsequently, the benefits of the combined seismic and energy retrofit intervention (i.e. the reduction of seismic vulnerability, improvement of energy efficiency, and reduction of CO_2-equivalent emissions), expressed by the economic savings in the ΔIPRR term, lead the curve to progress towards the positive quadrant of the graph by crossing the time axis. The crossing point corresponds to the total recovery of the Total IC_{eq} at a specific time, defined as the extended payback time ($t_{payback,IPRR}$). The latter represents the time needed (expressed in years) to equal the initial economic investment for the retrofit. This metric assumes a key value since it can indicate the economic effectiveness of any implemented retrofit intervention; the lower is the $t_{payback,IPRR}$ value, the more cost-effective is the retrofit. Finally, the curve continues to progress into the positive quadrant of the graph, indicating the cumulated annual economic savings, until the end-of-life of the building is reached at the time t_{end}, which corresponds to the end of the service life of a building. Finally, at the time t_{end}, a positive or negative equivalent total cost, corresponding to the total end-of-life cost (Total $EOLC_{eq}$), is associated. In case the potential for reuse/recycle of materials and/or components of seismic and energy retrofit technologies exists leading to the reduction of environmental impacts and consequently reduced costs, expressing economic benefits, the Total $EOLC_{eq}$ is assumed as 'credit' and indicated in the curve as a positive value, which increases the final economic savings. The grey curve (i.e. fiscal incentives included) differs from the red one by a change in the slope, represented by the dashed part in Figure 4, due to a faster recovery of the initial economic investment, with a consequent reduced extended payback time and higher cumulated economic savings. However, the incentives are active for a limited period of time (i.e. $t_0 \le t \le t_{inc}$), after which the curve assumes the same trend of the red one.

Figure 4. Qualitative Total Life Cycle $Cost_{eq}$ vs Time curves (with and w/o fiscal incentives),



Source: JRC, Romano et al. 2023

The representation of the output of the proposed simplified combined assessment method through a graphic format provides a useful tool to facilitate the decision-making process. Indeed, it allows stakeholders to easily compare potential solutions based on separated or combined interventions or different retrofit technologies in a life cycle perspective. Furthermore, it enables to verify the retrofit effectiveness over time by monitoring the payback time among different retrofit strategies, thus reducing or extending this parameter depending on the seismic or energy performance targets to satisfy.

2.3.4 Step 4 – Optimised solutions

The fourth and last step - *Optimised solutions* – focuses on a comparative assessment of different combined retrofit solutions to identify the most effective one. The assessment consists in comparing the results of the total equivalent economic performance, i.e. the Total Life Cycle $Cost_{eq}$ vs time, of the various solutions carried out according to the Step 3 of the proposed simplified combined method.

3 Case studies

Four case studies, representative of the EU residential and non-residential buildings needing combined retrofit, are first identified (Section 3.1) to subsequently apply both a selected standard method (i.e. SSD methodology) (Section 3.2) and the proposed simplified combined assessment method (Section 3.3). The reader is recommended to refer to the corresponding JRC technical report (Romano et al., 2023) for an in-depth analysis of the case studies selection, and for a detailed presentation of the application of the assessment methodologies (i.e. the SSD methodology and the proposed simplified method) to the four case studies.

3.1 Case studies selection

The selection of four case studies follows a three-step approach: (i) identification of case study categories, (ii) identification of case study location, and (iii) identification of four representative buildings (case studies).

The **first step** deals with a detailed analysis of the construction technologies in terms of construction material (i.e. RC, masonry, timber, other) along with the investigation of the structural systems, and building envelope components (i.e. both vertical – walls, and horizontal components – floors and roofs) of the EU existing residential building stock to identify four suitable **categories of case studies**. Results, based on both quantitative data by national statistical institutes (where available) and qualitative data retrieved by TABULA WebTool (6) and NERA project (7) (Ozcebe et al., 2014), point out that RC and masonry buildings represent the predominant construction technologies in the EU-27, mainly spread as RC framed structures, and rubble stones or brick masonry constructions. The analysis of the most common envelope components of the EU residential building stock has been carried out according to data retrieved by TABULA WebTool. Although the results of the investigations above refer to residential buildings, a wider extent of building use needs to be considered by also including a public building and a cultural/monumental building, beyond two residential buildings, due to the high exposure of public buildings and the importance of preserving the value of historical buildings. Specifically, the following four categories of case studies were considered (Figure 5): (i) a cultural monumental rubble masonry building with pitched timber roof, and steel beam and hollow clay flat block floors, (ii) a residential brick masonry building with pitched timber roof, and cast-in-place RC beam and hollow clay block floors, (iii) a residential RC building, and (iv) a public RC building, both with cast-in-place RC beam and hollow clay block roofs and floors, and hollow brick infill walls. However, the roof is pitched for the residential building and flat for the public one.

The **second step** defines a seismic-climate hazard matrix to identify the **location of case studies** to be representative of all possible European seismic hazard-climate scenarios. Specifically, the average value of the PGA range defining a moderate seismic hazard zone (i.e. 0.1g ≤ PGA ≤ 0.25g) in the European Seismic Hazard Model 2020 (Danciu et al., 2021) was considered to identify two macro-seismic hazard areas, namely low-to-moderate (L–M) (PGA < 0.175g) and moderate-to-high (M-H) (PGA ≥ 0.175g). Based on the EU 2019 HDD average annual data for each EU Member State (Eurostat, 2020a), and on their variation by province/municipalities (i.e. NUTS-3 regions level) (Eurostat, 2020b), three climatic zones were defined, namely Climatic zone A (HDD < 2200), Climatic zone B (2200 ≤ HDD < 3500), and Climatic zone C (HDD ≥ 3500). The combination of the outcomes above results into a six-column matrix identifying regions with different levels of seismic hazard and climatic conditions (Figure 6). Two categories of case studies need to be located in moderate-to-high seismic hazard zones to be representative of the countries in southern Europe. The other two categories of case studies need to be located in low-to-moderate seismic hazard zones, thus being distinctive of the countries in northern and central Europe. As for the climatic zones, all the three possible options are considered due to the large variability of the European climatic conditions. Thus, the climatic zones characterised by low (A) and intermediate (B) levels of HDD, typically corresponding to the weather conditions of the southern Europe countries, have been associated to the M-H seismic hazard zones. The climatic zones with intermediate (B) and high (C) levels of HDD, commonly characterising the central and northern Europe countries have been associated to the L-M seismic hazard zones. Hence, four representative

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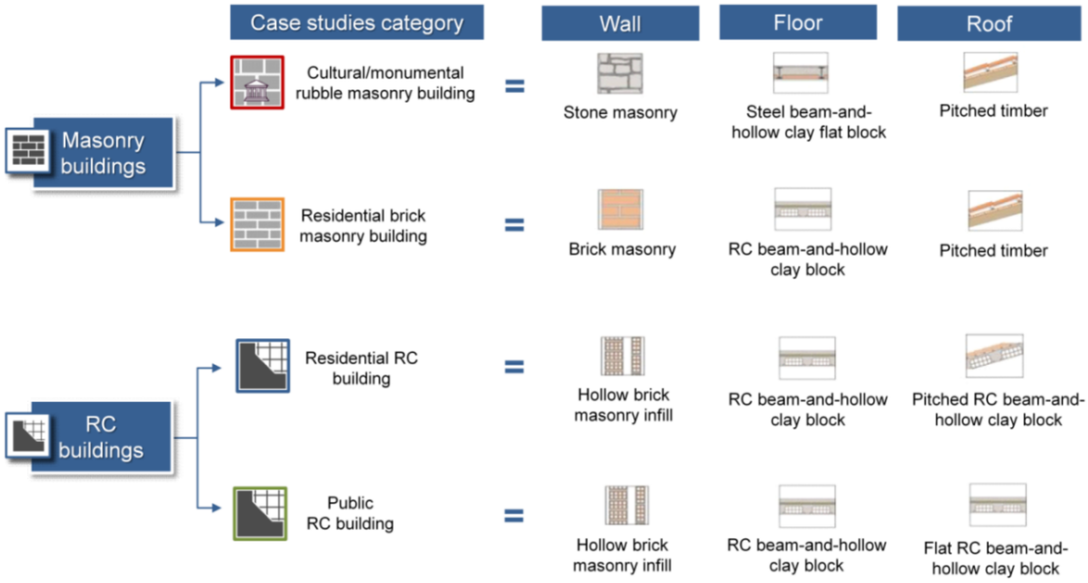
(6) The 2009-2012 Intelligent Energy European project 'Typology Approach for Building Stock Energy Assessment' (TABULA) (https://episcope.eu/iee-project/tabula/) has led to the development of a series of databases of the national building typologies representing the residential building stock of 21 European countries, implemented into a dedicated web-based tool, named *TABULA WebTool* (https://webtool.building-typology.eu/).

(7) The 2010-2014 'Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation' (NERA) project (https://cordis.europa.eu/project/id/262330) has led to a series of deliverables (https://www.orfeus-eu.org/other/projects/nera/) to achieve an improvement and a long-term impact in the assessment and reduction of the vulnerability of constructions and citizens to earthquakes.

seismic-climatic scenarios have been obtained in the matrix and they correspond to the selected locations of the four case studies. Italy is identified as the most suitable country for locating the case studies, as it includes all four selected seismic-climatic scenarios of the matrix.

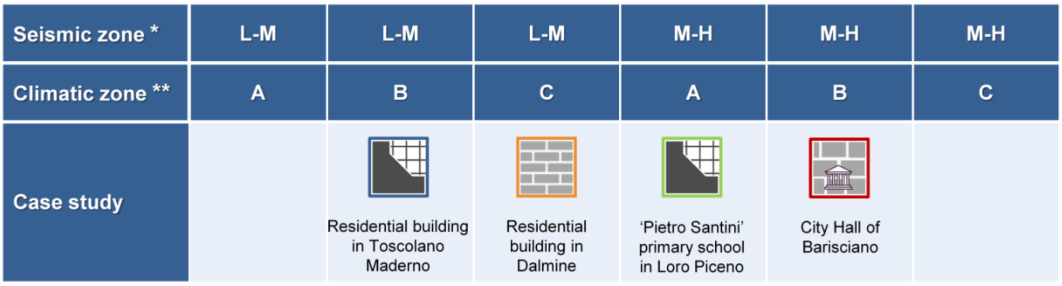
Figure 5. Case studies categories



Source: JRC, Romano et al. 2023

The **third step** refers to the combination of the two previous steps leading to the **selection of four representative buildings** needing combined seismic and energy retrofit in Italy, based on both categories and location of case studies (Figure 6). **Case study 1** is a three-storey residential RC building erected in 1967 in Toscolano Maderno (Brescia province), retrofitted with steel exoskeletons, external expanded polystyrene cladding, and heating system replacement. **Case study 2** is a three-storey residential brick masonry building constructed in 1955 in Dalmine (Bergamo province), retrofitted with prefabricated steel shear walls, and the application of roof insulation, new heating system and windows. **Case study 3** is the three-storey 'Santini' RC primary school in Loro Piceno (Macerata province), erected in 1965, and retrofitted with an exoskeleton of concentric steel x-braced frames and a double-skin envelope. **Case study 4** is a four-storey rubble masonry building dating back to the early 20th century and hosting the city hall of Barisciano (L'Aquila province). Various local strengthening interventions to provide a box-like behaviour of the structure, and the replacement of both the heating system and windows were considered. Further details on the general features of the four buildings in terms of geometry layout, structural typology, and building envelope components, as well as on seismic and energy retrofit interventions can be found in the related JRC technical report (Romano et al., 2023).

Figure 6. Case studies location and selected buildings



Seismic zone *	**L-M**	**L-M**	**L-M**	**M-H**	**M-H**	**M-H**
Climatic zone **	**A**	**B**	**C**	**A**	**B**	**C**
Case study		Residential building in Toscolano Maderno	Residential building in Dalmine	'Pietro Santini' primary school in Loro Piceno	City Hall of Barisciano	

* **L-M**: Low-to-Moderate (PGA < 0.175g); **M-H**: Moderate-to-High (PGA ≥ 0.175g)

** **A** (HDD < 2200); **B** (2200 ≤ HDD ≤ 3500); **C** (HDD > 3500)

Source: JRC, Romano et al. 2023

3.2 Application of SSD methodology to the four case studies

The four case studies are first analysed by means of a standard combined assessment methodology to be subsequently compared with the application of the proposed simplified one. The SSD methodology (Section 2.1.2) was selected to fulfil this scope, since it is an effective integrated multi-performance design/retrofit assessment method to quantitatively evaluate the structural, energy, and environmental performances of buildings in a life cycle perspective by providing a unique global assessment parameter in economic terms. Furthermore, the SSD methodology can serve for different assessment alternatives, such as the comparison of different structural systems for a new building, the comparison of two retrofit solutions or the alternative of retrofit vs demolition and reconstruction for an existing building. In this study, the SSD methodology is devoted to the comparison of each of the four selected case studies in their 'as-built' (i.e. pre-retrofit) and post-retrofit scenarios to indicate the performance enhancement due to the combined retrofit intervention. It is worth noting that the application of a standard combined assessment methodology to the four case studies, beyond demonstrating the benefit of the retrofit solution, mainly aims to evaluate the feasibility and ease of use of the chosen method, as a cornerstone to subsequently apply the proposed simplified combined assessment method.

The four main steps of the SSD methodology were applied to the four case studies before and after the combined seismic and energy retrofit. The **STEP I - Energy performance assessment** focuses on the calculation of the energy needed during the operational phase of the examined building, thus dynamic energy analyses were carried out by means of DesignBuilder tool, which uses EnergyPlus as a BES engine, to quantify the annual electricity and heating consumptions of the building (expressed in kWh/m^{2}year) for both pre- and post-retrofit scenarios. The **STEP II – Life Cycle Assessment** deals with the employment of the LCA methodology by means of the SimaPro software to assess the GWP in terms of equivalent CO_2 emissions (expressed in tCO_2eq) of structural and non-structural components of the building related to the production stage (i.e. Module A1 to A3) of the standardised building life cycle – from cradle-to-gate. The **STEP III - Structural performance assessment** employs the four steps of the s-PBA methodology (Negro and Mola, 2017) to assess the expected losses due to seismic damages related to four different limit states of the structure, defined as (i) low damage, (ii) heavy damage, (iii) severe structural damage, and (iv) near collapse in both pre- and post-retrofit scenarios. The expected losses (expressed in €) are based on the corresponding costs for repairing the damaged structural and non-structural components of the examined building at each limit state. The **STEP IV – Global assessment parameter in economic terms** enables the combination of energy, environmental, and structural performance results (obtained by the three previous steps in different measure units) into a global result in monetary units for an effective comparison of the examined buildings between their pre- and post-retrofit scenarios. Specifically, the energy consumption results carried out in STEP I were converted into cost by means of the 2019 Eurostat unitary electricity and natural gas prices in Italy. Similarly, the environmental impacts carried out in STEP II were converted into cost by mean of the unitary carbon price. A brief excursus concerning the most significant developments to date within the carbon market needs to be introduced to identify the unitary carbon price. Different types of policies and measures defining the carbon pricing have been adopted in the last two decades to internalise the external cost of climate change (Romano et al., 2014, The World Bank, 2021), mainly distinguished in direct (e.g. carbon tax, emission trading system) and indirect (e.g. fossil fuel taxes) mechanisms (The World Bank, 2021). At European level, the cap-and-trade European Union Emission Trading System (EU-ETS) (8) represents the EU's cornerstone strategy to tackle climate change, firstly established in 2005 to anticipate the 2008-2012 Kyoto Protocol target (UN, 1997), and it is currently at its fourth trading phase (2021-2030). Consequently, the EU-ETS has been selected as the most effective instrument to identify the unitary carbon price (expressed as €/tCO_2eq) for the SSD methodology. Based on the main features of a cap-and-trade system, the EU ETS sets an upper limit, i.e. the cap, on the total amount of GHG emissions that businesses covered by the system (i.e. energy-intensive industries and the power generation sector) can emit each year. Furthermore, a fixed number of emission permits (equivalent to the cap), called EU emission allowances (EUAs), are issued. EUAs are allocated for free or auctioned out according to specific criteria and they can be sold or additional EUAs can be bought. One EUA represents the right to emit one tonne of CO_2-equivalent, thus becoming the currency of the emission trading. Carbon price is hence determined by the supply and demand of EUAs. Large fluctuations of the carbon price occurred within the various trading periods of the EU ETS with a downward trend until 2017. A price surge was finally achieved in 2018 with the highest registered EUA price stood at about 25 €/tCO_2eq in September 2018 (COM(2020) 740). This radically different trend finds its main reasons in the EU market design reforms, such as the entry in force of the revised EU ETS directive (Directive 2018/410), the EU ETS revision for the fourth trading phase, and the EU decision on a Market Stability Reserve (Decision 2015/1814).

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(8) EU Emission Trading System (EU ETS), https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

The carbon price signal remained strong, levelling at an average of almost 25 €/tCO$_2$eq until the end of 2020. The fourth trading phase initiated with an increasing trend of prices passing from more than 30 €/tCO$_2$eq at the beginning of 2021 to about 60 €/tCO$_2$eq after six months (COM(2021) 962), further increasing at the beginning of 2022 with a record of 96 €/tCO$_2$eq in February 2022 (ESMA, 2022). High prices are fundamentally a sign that the market is pricing in the cost of transition to a greener economy and they are needed to provide the right incentives to meet the stringent EU climate-neutrality goal by 2050 (CPCL, 2017). Various accredited exchange markets related to different international organisations provide historical and current data on the carbon price for the EU-ETS, such as the World Bank, and the International Carbon Action Partnership. At European level, the European Energy Exchange (EEX) (9), in Leipzig (Germany), awarded the leading role as the EU common platform for EUAs auctioning. Hence, the EEX is selected to identify the carbon price by considering the EUA spot price equal to 76.50 €/tCO$_2$eq (specific date of observation: 24th March 2022).

Computational and technical details of the results related to each step of the SSD methodology for the four case studies considering both pre- and post-retrofit scenarios are provided in Romano et al. (2023), to which the reader is recommended to refer for a comprehensive overview of all energy, environmental and structural analyses, while a synthesis of results related to the STEP IV expressing the energy, environmental, and structural performances in economic terms to carry out the global assessment parameter are provided in Table 1.

Table 1. SSD methodology – Energy, environmental, and structural performance results in economic terms (STEP IV) for case study 1, 2, 3 and 4.

Results in economic terms	Case study 1		Case study 2		Case study 3		Case study 4	
	Pre-retrofit Scenario	Post-retrofit Scenario	Pre-retrofit Scenario	Post-retrofit Scenario	Pre-retrofit Scenario	Post-retrofit Scenario	Pre-retrofit Scenario	Post-retrofit Scenario
STEP I Energy cost [k€]	630. 8	486.3	1174.8	739.9	1055.6	762.2	1378.7	684.3
STEP II Environmental cost [k€]	9.7	18.5	7.4	14.4	19.9	32.8	12.7	21.2
STEP III Structural cost (Expected loss) [k€]	234.0	3.5	102.7	2.5	87.8	6.8	85.9	76.9
STEP IV Global assessment parameter [k€]	874.5	508.3	1284.8	756.8	1163.4	801.9	1477.3	782.4

Data source: Romano et al., 2023.

In both pre- and post-retrofit scenarios the energy performance exhibits the highest cost incidence on the total economic result (i.e. the sum of energy, environmental, and structural costs represented by the global assessment parameter) for all four case studies. In the pre-retrofit scenarios, the energy cost is followed in order by the seismic and environmental performance ones. Conversely, in the post-retrofit scenarios the environmental impacts have a cost incidence higher than the seismic performance one (except for the case study 4), also demonstrating the importance of considering an adequate unitary carbon price towards the EU decarbonisation path, as occurred in the two last years, to achieve an effective multi-performance analysis.

Retrofit interventions provided an effective seismic and energy improvement in all four buildings, as demonstrated by the performance results in economic terms (Table 1). Specifically, the reduction of the energy consumptions due to the energy retrofit interventions for the case studies 1, 2, 3, and 4 leads to a

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(9) European Energy Exchange (EEX), https://www.eex.com/en/markets/environmentals

corresponding cost reduction compared to the non-retrofitted buildings equal to 23 %, 37 %, 28 %, and 50 %, respectively. Similarly, the seismic retrofit interventions enable a reduction of the expected losses due to seismic damages for the case studies 1, 2, 3, and 4 equal to approximately 98 %, 95 %, 92 %, and 10 %, respectively. Although the energy and seismic retrofit technologies lead to an increase of the environmental costs for all the four case studies compared to the non-retrofitted buildings, since the LCA only refers to the production phase of the life cycle of the examined buildings, a total cost reduction taking into account the sum of the energy, environmental and seismic performances of the case studies 1, 2, 3, and 4, expressed through the global assessment parameter, was achieved for all four case studies. Specifically, total cost reductions of approximately 42 %, 41 %, 31 %, and 47 % (compared to non-retrofitted buildings) were achieved for the case studies 1, 2, 3, and 4, respectively.

Beyond drawing the above necessary attention on the combined seismic and energy retrofit benefits to achieve a safe, sustainable and resilient built environment, the role of carbon price addressing the environmental performance in economic terms in the SSD methodology also assumes a particular importance at policy level in the light of the recent ambitious goals for the EU green transition, although some significant advancements for a more stable trend of an high price have been already achieved in the last years reaching an all-time high of 100 €/tCO$_2$eq in February 2023. Since the release of the 'Fit for 55' policy package, five legislative proposals were adopted by the European Parliament and the Council in April 2023 ([10]). These reforms define a milestone for the EU ETS, and for carbon pricing more broadly. Indeed, some changes such as the reduction of EUAs and the removal of free allowances to meet the ambitious 'Fit for 55' goals, as well as the expansion of the EU ETS to cover new sectors from 2027 (or 2028), i.e. buildings, road transport and additional sectors (mainly small industry), the update of the Market Stability Reserve, amongst others, are expected to increase the EU carbon prices in the coming years and create strong price signals to drive emissions down (Oxera, 2022, IETA, 2023). In this context, the analysis of the EUA price through the end of this decade and beyond becomes an essential policy–driver to meet the decarbonisation targets. Specifically, according to the 2023 International Emissions Trading Association (IETA) survey the average EU ETS carbon price is expected to be 84.40 €/tCO$_2$eq and 100 €/tCO$_2$eq during the periods 2023-2025 and 2026-2030, respectively (IETA, 2023). Although the above mentioned survey results on the carbon price projections were more cautious than the ones carried out within the IETA surveys of the previous two years, the long-term trend of rising prices remains. A similar trend is also confirmed by carbon market forecasts carried out by various organisations and research institutes in 2022 indicating an increase of the EUA spot price for the next years: the Independent Commodity Intelligence Service (ICIS) and the Potsdam Institute for Climate Impact (PIK), among others, estimated an EU carbon price rise ranging from 90 €/tCO$_2$eq to 129 €/tCO$_2$eq by 2030, respectively (Oxera, 2022, Pahle et al., 2022). It is worth noting that the PIK forecast for the carbon price by 2030 at EU level (i.e. 129 €/tCO$_2$eq) is in line with the 2021 Organisation for Economic Co-operation and Development (OECD) analysis, which underlined the need for an average carbon price equal to 120 €/tCO$_2$eq globally by 2030 to decarbonise by this mid-century (i.e. 2050) in order to limit the global temperature increase to 1.5°C, as called for in the Paris Agreement (OECD, 2021). However, according to the more recent 2023 IETA survey, an even higher value of the average global carbon price equal to 145 €/tCO$_2$eq is needed by 2030 to meet the 1.5°C goal worldwide. In this context, it is interesting to perform a simplified sensitivity analysis to investigate the effects of the estimated increases of carbon price on the environmental cost of the examined case studies to have a forecast picture of their expected multi-performance assessments for both pre- and post-retrofit scenarios by the end of this decade. If the EUA spot price equal to 76.50 €/tCO$_2$eq is assumed as a base case, a corresponding percentage increase of this initial value equal to 10.3 %, 30.7 %, 68.6 %, and 89.5 % is achieved by considering the following forecast average carbon prices during the period 2023-2030: 84.40 €/tCO$_2$eq (2023-2025), 100 €/tCO$_2$eq (2026-2030), 129 €/tCO$_2$eq (2030) at EU level, and 145 €/tCO$_2$eq (2030) at global level, respectively (according to the projection analyses above). Consequently, the environmental cost based on the base case EUA spot price (i.e. environmental cost indicated in Table 1) will increase of the same above mentioned percentage variances in all four case studies. As example, results of the expected environmental cost related to the case study 1 for both pre- and post-retrofit scenarios are depicted in Figure 7. It is worth noting that in case the global average carbon price is considered, the expected environmental cost in 2030 is nearly double the corresponding result referring to the base case in 2022. The increase of the environmental cost obviously leads to an increase of the global assessment parameter (compared to the corresponding result referring to the base case in 2022, as reported in Table 1) with a consequent change of the cost incidences (in %) of the energy, environmental, and structural performances on the total economic result (i.e. global assessment parameter results) in both pre- and post-retrofit scenarios (Annex 1 – Table 1). Specifically, the environmental cost exhibits the major difference of the cost incidence (in

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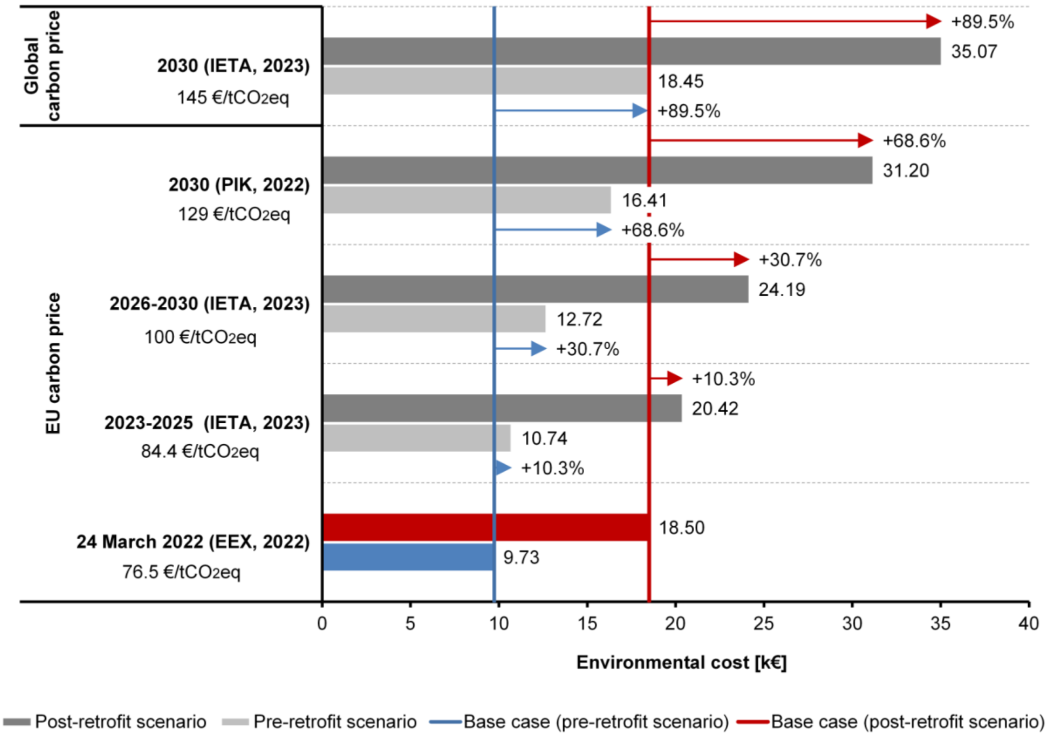
([10]) Council of the EU, Press release, 25 April 2023, https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/fit-for-55-council-adopts-key-pieces-of-legislation-delivering-on-2030-climate-targets/

%) on the global assessment parameter ranging from 1.2 % to 2.1 % (pre-retrofit scenario) and from 4.0 % to 6.7 % (post-retrofit scenario) for the period 2023-2030 compared to the 1.1 % and 3.6 % cost incidence, respectively, related to the base case in 2022.

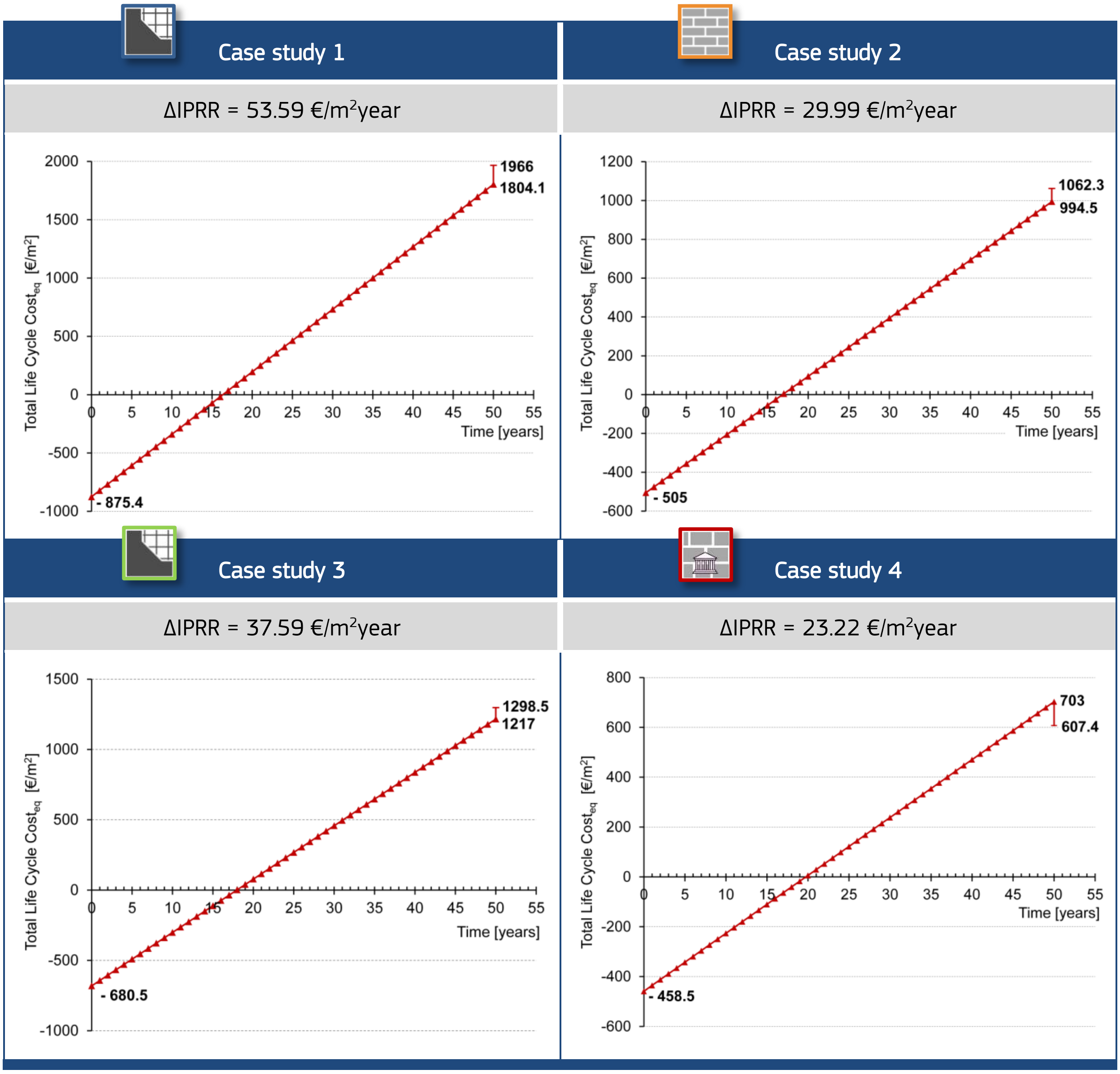
Figure 7. Sensitivity analysis indicating the environmental cost of the case study 1 based on different unitary carbon price forecasts between 2023-2030



3.3 Application of the proposed simplified assessment method to the four case studies

The **proposed simplified combined assessment method** (Section 2.3) is applied to the four case studies to demonstrate the advantages of implementing a user-friendly assessment tool that can be easily used by practitioners without requiring complex calculations. The data collection related to the Step 1 and the selection of seismic and energy retrofit technologies related to the Step 2 were previously identified to carry out the application of the SSD methodology. Hence, the focus for the application of the proposed simplified method draws on the Step 3 since it represents the computational step to assess the seismic, energy, and environmental performances of a building needing combined retrofit at three stages of its ‘ upgraded’ life cycle: (i) initial time (t_0), (ii) extended lifetime stage (t_{ext}), and (iii) end-of-life time (t_{end}). These results, expressed in equivalent costs, provide the equivalent economic performance assessment corresponding to the estimation of the three total cost contributions corresponding to each of three time stages above to finally build the equivalent Total Life Cycle Cost vs Time curves, expressing the final economic result for the four case studies (Figure 8). Computational details of the results related to seismic, energy, and environmental performances at each stage of the ‘upgraded’ life cycle of the four case studies are provided in Romano et al. (2023).

Figure 8. Simplified combined assessment method - Representative Total Life Cycle Cost$_{eq}$ vs Time curves for case study 1, 2, 3 and 4



Specifically, the curves in Figure 8 show the initial costs for the combined interventions (total initial cost at time t_0), the recovery of the investment over time up to the payback time (i.e. curves crossing the time axis) and the cumulated economic savings considering a service life profile of the retrofitted buildings equal to 50 years (total extended lifetime cost within the time t_{ext}), and the potential credits achievable at the end of life stage due to the recycle/reuse of materials/components (total end-of-life cost at the time t_{end}). It is worth noting that the recycle and reuse of materials and components do not enable the achievement of potential credits only for the case study 4, thus reducing the final value of economic savings at the end-of-life time. The ΔIRPP values of the four case studies indicate the annual economic savings due to the combined retrofit, and consequently confirm the effectiveness of retrofit interventions, as also demonstrated by applying the SSD methodology. Specifically, cost reductions between the pre-and post-retrofit scenarios result equal to 71 %, 55 %, 61 %, and 39 % for case study 1, 2, 3, and 4, respectively. Furthermore, the payback time for the four case studies, considering a service life of 50 years, resulted equal to approximately 16, 17, 18, and 20 years, respectively. These results can be reduced, if fiscal incentives are considered (e.g. Sisma Bonus and Eco Bonus mechanisms in Italy).

Beyond the retrofit benefits, it is worth focusing on some advantages in the use of the proposed combined assessment method in a simplified way compared to the standard method. The proposed simplified method allows users to take into account the mechanical interactions of different potential seismic and energy retrofit technologies to select the most effective one by easily comparing the results of the seismic, energy, and environmental performances of a retrofitted building. Indeed, they are expressed in monetary terms facilitating their understanding and the corresponding benefits of an integrated retrofit to different stakeholders. Another key simplification refers to the assessment of the IRPP (i.e. sum of the annual expected seismic losses, expected cost due to energy consumption, and expected environmental cost due to seismic damage and energy consumption at the extended lifetime stage) before and after the retrofit. Indeed, the simplicity of the method in calculating the expected annual seismic losses and costs related to energy consumption at the extended lifetime stage was ensured by using generalised seismic (i.e. fragility curve) and energy (i.e. thermal energy demand vs HDD curve) performance results. They are based on simulation procedures (i.e. nonlinear static and energy dynamic analyses, respectively) for the combination of different representative building classes and retrofit technologies. Further research is needed to enrich the catalogue of generalised seismic and energy performance curves and extend the application of the proposed simplified combined assessment method to a larger number of representative building classes in Europe. Finally, the possibility to analyse the final outcomes of the assessment procedure by means of a total life cycle cost$_{eq}$ vs time curve simplifies the decision-making process, since it is possible to directly know the initial investment, the corresponding payback time, as well as the effective economic savings during the whole residual lifetime of the building after its retrofit. Moreover, the potential increase or reduction of these savings at the end-of-life of the building are also indicated due to the potential recycle and reuse of materials and/or components of the retrofit technologies used.

4 Conclusions

The need of a simplified assessment method aimed at evaluating the combined seismic and energy retrofit of ageing existing buildings is a priority-issue to provide an effective tool aimed at easily achieving the benefits gained by a combined upgrading in the view of the urgent action for a large-scale renovation of the EU building stock in line with the Renovation Wave strategy and the European Green Deal to also meet the climate-neutrality by 2050.

The brief **review of the existing assessment methods and tools** for the combined seismic and energy upgrading of buildings led to their classification in two key streams: (i) sector specific methods, and (ii) multi-performance assessment methods. The first key stream includes methods and tools devoted to the independent quantitative assessment of seismic and energy/environmental performances of existing buildings, which are still the current preferred building renovation strategies. The second key stream refers to qualitative and quantitative integrated assessment methods. Qualitative methods include sustainability rating systems based on indicators of different weight (mainly related to the environmental aspects of buildings), whereas quantitative methods indicate the recent research efforts dealing with integrated life-cycle based approaches towards the development of holistic methods. The category of quantitative methods results into the most appropriate one to carry out a combined assessment of the seismic and energy upgrading of existing buildings with the SSD methodology resulting noteworthy to introduce a simplified combined assessment method.

The **proposed simplified combined assessment method** has to satisfy a set of **requirements** identified and classified according to three main levels: (i) general principles, related to both sustainable development principles and LCT in the construction sector; (ii) technological characteristics, devoted to guarantee an effective technological integration of energy and seismic retrofit technologies; and (iii) engineering computation requirements, aimed at addressing the computational stage of the novel assessment method and its related outcomes, while avoiding complex analyses. Based on these requirements, the **framework** of the proposed method consists of four main steps. The first step - *Input information* - aims at collecting the initial data and boundary conditions of an existing building needing retrofit. The second step - *Selection of technologies* – deals with the analysis of the physical and mechanical characteristics of the seismic and energy retrofit technologies to identify a set of potential compatible retrofit technologies. The third step - *Integrated retrofit design and evaluation* - represents the computational tool to assess the seismic, energy, and environmental performances, expressed in equivalent costs, of the combined retrofit in a life cycle perspective. The total equivalent economic performance of a retrofitted building is obtained by combining three main cost contributions associated with three different stages of its life cycle, i.e. initial time (time of the retrofit intervention), extended lifetime, and end-of-life time. The final economic result expresses the variation of the equivalent Total Life Cycle Cost over the lifetime of the building, and it can be represented by a cost vs time curve. The fourth step - *Optimised solutions* – focuses on a comparative assessment of different combined retrofit solutions to identify the most effective one.

Finally, **four case studies** representative of EU residential and non-residential buildings needing combined retrofit were identified to apply both a selected standard (i.e. SSD methodology) and the proposed simplified combined assessment methods. RC and masonry buildings represent the predominant construction technologies in the EU-27, mainly spread as RC framed structures and rubble and brick stones constructions. Specifically, the following four **categories of case studies** were considered: (i) a cultural monumental rubble masonry building with pitched timber roof, and steel beam and hollow clay flat block floors, (ii) a residential brick masonry building with pitched timber roof, and cast-in-place RC beam and hollow clay block floors, (iii) a residential RC building, and (iv) a public RC building, both with cast-in-place RC beam and hollow clay block roofs and floors, and hollow brick infill walls. However, the roof is pitched for the residential building and flat for the public one. A six column seismic-climatic hazard matrix to identify potential **locations of case studies** was developed by combining two macro-seismic hazard areas (based on the average values of PGA available from ESHM20) with three climatic zones (based on 2019 Eurostat HDD annual data). Four representative buildings needing combined retrofit were selected in Italy, as this country includes all possible scenarios of the matrix. **Case study 1** is a residential RC building in Toscolano Maderno, retrofitted with steel exoskeletons, external expanded polystyrene cladding, and heating system replacement. **Case study 2** is a residential brick masonry building in Dalmine, retrofitted with prefabricated steel shear walls, and the application of roof insulation, new heating system and windows. **Case study 3** is the Santini RC primary school, retrofitted with an exoskeleton of concentric steel x-braced frames and a double-skin envelope. **Case study 4** is a rubble masonry building hosting the city hall of Barisciano. Various local strengthening interventions and the replacement of the heating system and windows were considered.

The **SSD methodology** was applied to the four case studies. Retrofit interventions provided an effective seismic and energy improvement in all four buildings in terms of total cost (i.e. the sum of energy, environmental, and structural costs expressed by the global assessment parameter in the fourth step of the SSD methodology). Specifically, total cost reductions of approximately 42 %, 41 %, 31 %, and 47 % for the case study 1, 2, 3, and 4 were achieved, respectively (compared to the non-retrofitted buildings). Focusing on various carbon price forecasts during the period 2023-2030, a continuous increase of the environmental cost is expected with a significant result projected by 2030 (i.e. nearly double of corresponding environmental cost carried out by using the 24 March 2022 EUA spot price by the EEX), if a global carbon price equal to 145 €/tCO$_2$eq is considered. Subsequently, the **proposed simplified combined assessment method** was applied to the four case studies. The estimation of the three total cost contributions corresponding to the initial time, the extended lifetime, and end-of-life time was carried out to build the equivalent total life cycle cost vs time curves indicating the total equivalent economic performance of the retrofitted buildings. The annual economic savings due to retrofit interventions expressed by mean of the ΔIRPP values indicate cost reductions between the pre- and post-retrofit scenarios equal to 71 %, 55 %, 61 % and 39 % for case study 1, 2, 3, and 4, thus confirming the benefits of a combined/integrated retrofit, as carried out by the SSD methodology. Furthermore, the payback time for the four case studies, considering a service life of 50 years, resulted equal to approximately 16, 17, 18, and 20 years, respectively. The simplicity of the method in calculating the expected annual seismic losses and costs related to energy consumption at the extended lifetime stage was ensured by using generalised seismic (i.e. fragility curve) and energy (i.e. thermal energy demand vs HDD curve) performance results. They are based on simulation procedures (i.e. nonlinear static and energy dynamic analyses, respectively) for the combination of different representative building classes and retrofit technologies.

The combination of many different data within the quantitative assessment methods for an integrated retrofit of existing buildings remains an ambitious challenge. Hence, within the proposed simplified assessment method further research is needed to enrich the catalogue of generalised seismic and energy performance curves and extend the application of the proposed simplified method to a larger number of representative building classes in Europe.

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List of abbreviations and definitions

BES	Building energy simulation
CO_2	Carbon dioxide
EED	Energy Efficiency Directive
EEX	European Energy Exchange
$EOLC_{eq}$	End-of-Life cost
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
ERT	Energy retrofit technology
EU	European Union
EU-ETS	European Union Emission Trading System
EUA	EU emission allowance
FEMA	Federal Emergency Management Agency
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic information system
GUI	Graphical User Interface
GWP	Global Warming Potential
HDD	Heating Degree Days
JRC	Joint Research Centre
IC_{eq}	Initial cost
ICIS	Independent Commodity Intelligence Service
IETA	International Emissions Trading Association
IRPP	Integrated Retrofitting Performance Parameter (i.e. sum of expected seismic losses, expected cost due to energy consumption, and expected cost of environmental impacts due to seismic damage and energy consumption)
L-M	Low-to-moderate
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LTRS	Long-term renovation strategies
M-H	Moderate-to-high
NEB	New European Bauhaus
NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation’
NUTS	Nomenclature of territorial units for statistics
OECD	Organisation for Economic Co-operation and Development
PBEE	Performance-based Earthquake Engineering methodology
PEER	Pacific Earthquake Engineering Research Center

PGA	Peak ground acceleration
PIK	Potsdam Institute for Climate Impact (Potsdam-Institut für Klimafolgenforschung, in German)
RBC	Representative building class
RC	Reinforced concrete
SDG	Sustainable Development Goal of the 2030 Agenda for sustainable development
s-PBA	simplified Performance-Based Assessment
SRT	Seismic retrofit technology
SSD	Sustainable Structural Design
TABULA	Typology Approach for BUiLding Stock Energy Assessment
TBL	Triple Bottom Line of sustainable development – Planet, People, and Profit
UN	United Nations
t_0	Initial time (i.e. time of the retrofit intervention)
t_{ext}	Extended lifetime stage
t_{end}	End-of-life time
ΔIRPP	Difference in IPRR before and after retrofit intervention

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Annex 1

Annex 1 – Table 1. Cost incidences (in %) of the energy, environmental, and structural performances on the total economic result (i.e. global assessment parameter) in both pre- and post-retrofit scenarios for the case study 1 (SSD methodology), based on carbon price forecasts during 2023-2030.

Unitary carbon price	EU carbon price								Global carbon price	
	Base case		Forecasts							
	24 March 2022 (EEX, 2022) **76.5** €/tCO_2eq		**2023-2025** (IETA,2023) **84.4** €/tCO_2eq		**2026-2030** (IETA, 2023) **100** €/tCO_2eq		**2030** (PIK, 2022) **129** €/tCO_2eq		**2030** (IETA, 2023) **145** €/tCO_2eq	
Pre-retrofit scenario										
STEP I Energy cost [k€]	630.8	72.1%	630.8	72.0%	630.8	71.9%	630.8	71.6%	630.8	71.4%
STEP II Environmental cost [k€]	9.7	1.1%	10.74	1.2%	12.72	1.4%	16.4	1.8%	18.4	2.1%
STEP III Structural cost [k€]	234	26.8%	234	26.7%	234.00	26.7%	234.0	26.6%	234.0	26.5%
STEP IV Global assessment parameter [k€]	874.5	100%	875.5	100%	877.5	100%	881.2	100%	883.2	100%
Post-retrofit scenario										
STEP I Energy cost [k€]	486.3	95.7%	486.3	95.3%	486.3	94.6%	486.3	93.3%	486.3	92.7%
STEP II Environmental cost [k€]	18.5	3.6%	20.4	4.0%	24.1	4.7%	31.2	6.0%	35.1	6.7%
STEP III Structural cost [k€]	3.5	0.7%	3.5	0.7%	3.5	0.7%	3.5	0.6%	3.5	0.7%
STEP IV Global assessment parameter [k€]	508.3	100%	510.2	100%	513.9	100%	521.0	100%	524.8	100%

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