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

Integrated seismic and energy renovation of buildings

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Foreword

Mariya Gabriel

Commissioner for Innovation, Research, Culture, Education and Youth

Buildings are fundamental for the achievement of strategic European and international goals for climate neutrality and disaster resilience. Energy efficiency, seismic safety, life-cycle thinking, circularity and affordability feature within the key principles for building renovation towards 2030 and 2050.

Eight out of ten buildings in Europe were constructed before 1990. These buildings are structurally weaker and not energy efficient, as requirements were lower some decades ago. Seismic, climatic and socioeconomic conditions, and building characteristics vary significantly across the EU. This makes it very difficult for authorities and practitioners to develop renovation plans at regional, national or EU level, and to select the most appropriate renovation technologies and assessment methodologies.

The European Commission's Joint Research Centre collaborated with a group of experts to develop a European Parliament pilot project that provides state-of-the-art scientific evidence and best practices for the integrated seismic and energy renovation of buildings. Integrated renovation of existing buildings and urban spaces is more advantageous than separate improvements because it saves more lives and further reduces costs, the use of materials and the production of waste over the life-cycle of a building.

The pilot project produced technical guidelines, data and user-friendly impact evaluation tools, based on the analysis of the European building stock, renovation technologies, assessment methodologies and scenarios for renovation. The recommendations of the pilot project can directly feed into renovation plans that are tailored to local needs, leave no one behind and create jobs in the construction ecosystem.

I trust that the rich output of the pilot project will enable policy makers, practitioners and researchers to make the best out of building renovation plans and create a future-proof built environment for millions of Europeans.

Acknowledgements

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More than 20 experts have contributed with their work to the pilot project and the material presented in this science-for-policy report. Comments and suggestions were also provided by Artur Pinto. The aforementioned contributions are gratefully acknowledged.

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Abstract

Our buildings are ageing, posing an urgent need for renovation to achieve multidimensional European and international goals. Integrated renovation of buildings provides a unique opportunity to create a safe, sustainable and inclusive built environment, as it lies at the nexus between European policies on disaster resilience, energy efficiency, circularity and social cohesion. The pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' promotes this holistic view of renovation, provides scientific support to building renovation policies in the EU and encourages their further development. This science-for-policy report summarises the main outcomes of the pilot project. Existing seismic, energy and combined/integrated renovation technologies were reviewed. A simplified method for assessing the benefit of combined renovation was proposed and applied to representative buildings. An integrated framework was developed for regional impact analysis. Seismic risk, energy performance and socioeconomic aspects were assessed throughout Europe to identify priority regions and investigate renovation scenarios. Integrated renovation can save lives, energy and investments while reducing the environmental burden. Policy makers, EU, national and regional authorities together with practitioners and the public are the beneficiaries of this project.

Executive summary

The pilot project ‘Integrated techniques for the seismic strengthening and energy efficiency of existing buildings’ (or REEBUILD) provides scientific support to building renovation policies in the EU by promoting a holistic point of view on the topic. This science-for-policy report summarises main outcomes of the pilot project with regard to (*i*) assessments of seismic and energy renovation technologies from a life cycle perspective, (*ii*) reviews of combined renovation solutions considering available technologies and recent scientific developments, (*iii*) available methodologies for evaluating the benefit of combined renovation of buildings and a proposal for a simplified methodology, and (*iv*) the development and implementation of an integrated framework for regional impact assessments considering seismic risk, energy performance and socioeconomic aspects, along with the impact of renovation scenarios. Apart from policy makers, EU/national/regional authorities and practitioners are the beneficiaries of the project. Dissemination and outreach are supported by the ‘Building renovation makerspace’ platform[1] and by science-for-policy and technical reports (Annex A).

Policy context

Renovation of buildings provides a unique opportunity to create a safe, sustainable and resilient built environment. The European Green Deal calls for a Renovation Wave, supported by the New European Bauhaus to create sustainable, inclusive and beautiful living spaces. The Energy Performance of Buildings Directive, besides reducing greenhouse gas and carbon emissions, addresses seismic risk to new and existing buildings. Accelerating building renovation is a key parameter to achieve the ambitious energy saving and greenhouse gas reduction targets, set by the European Climate Law for a climate neutral Europe by 2050. The New Circular Economy Action Plan promotes life cycle thinking and circular economy principles in the construction sector. Seismic risk mitigation and disaster prevention are put forward by the Union Civil Protection Mechanism, the EU disaster resilience goals and the Action Plan on the Sendai Framework. Integrated renovation lies at the nexus between the above policies as it allows to encompass energy efficiency measures and circularity principles, while ensuring the seismic safety of buildings to protect lives and renovation investments.

Key conclusions

A review of policy measures across Member States provides best practices to facilitate further implementation of integrated renovation and shape action plans at the EU, national and regional level.

The classification of seismic and energy renovation technologies considering life cycle thinking criteria, cost and compatibility with different building types provides useful guidance at the preliminary stages of renovation design. Such rankings allow practitioners to identify cost-efficient and sustainable solutions.

[1] https://buildings-renovation-makerspace.jrc.ec.europa.eu.

The comparative evaluation of different technologies for integrated renovation identifies appropriate renovation technologies for specific projects. Indicative information on their sustainability, disruptiveness, performance and cost is provided, which is useful for building project practitioners but also regional impact analysts.

The proposed method for evaluating the benefit of combined renovation translates the seismic, energy and environmental performance of a building into cost from a life cycle perspective without employing complex analysis. Therefore, it provides a user-friendly tool for designers and practitioners, whereas results in economic terms facilitate a common understanding of benefit among different stakeholders.

The integrated framework for regional prioritisation and impact analysis highlights the regions and building classes where each type of renovation is most suitable, evaluating the benefit of renovation scenarios in terms of saving lives, cost and energy consumption, while considering socioeconomic vulnerability. It can be employed by EU, national and regional authorities to intensify building renovation efforts, explore financing schemes, allocate funding and strengthen the regulatory framework.

Main findings

The diversity of seismic, climatic, socioeconomic and building characteristics across regions and construction eras together with a multitude of available renovation technologies and methodologies challenges the selection of suitable renovation strategies. Comprehensive studies are required for a surge in renovation rates.

A catalogue of seismic renovation technologies is provided. Their classification considering life cycle thinking highlights exoskeleton systems for both masonry and reinforced concrete buildings as promising solutions.

A catalogue of energy renovation technologies was compiled. Ranking of technologies identifies insulation of walls and roofs as highly attractive energy renovation solutions, due to cost efficiency and low generated waste.

Exoskeletons, upgrading or replacement of the existing envelope, and interventions on horizontal elements constitute efficient schemes for combined renovation. Further research is required as many relevant technologies are at a conceptual stage, while only a few have been tested and validated.

A simplified method for evaluating the benefit of combined seismic and energy renovation from a life cycle perspective was proposed as an effective means to communicate results to different stakeholders and facilitate decision-making.

An integrated framework for regional prioritisation and impact analysis was proposed to inform bespoke renovation plans at a regional, national or European scale. Approximately 10 % of the energy consumption and cost, 61 % of fatalities, and 49 % of repair cost derive from 100 regions in south-eastern Europe.

Integrated seismic and energy renovation is more beneficial than separate interventions. It saves more lives, reduces the renovation cost and generated waste, while exhibiting significant cost savings. In 100 priority regions, seismic, energy, and integrated renovation can save 78, 708, and 742 million euro a year, respectively.

Further action is needed to promote future-proof renovation through research, regulatory framework, financial instruments and awareness campaigns.

Related and future JRC work

JRC activities that preceded the pilot project include, among others, analytical and experimental investigations of innovative seismic and energy retrofitting solutions (iRESIST+),[2] and design approaches for safe and sustainable construction (SAFESUST). JRC will continue fostering holistic approaches of renovation in support of the EU policies. The development of guidance for projects to align with the New European Bauhaus principles is currently underway.

Quick guide

Seismic risk involves the estimation of the probability and magnitude of undesirable consequences from potential future earthquakes by combining exposure (buildings, population), hazard and vulnerability. **Energy performance** refers to the capability of a building class to provide a desired living comfort to occupants as a function of climatic conditions and building energy attributes. **Socioeconomic vulnerability** measures socioeconomic development, smart, sustainable, and inclusive growth, and social progress. The **renovation impact** reflects the benefit derived from a renovation scenario, along with its significance (e.g. affected building stock, population) and economic feasibility.

2 https://joint-research-centre.ec.europa.eu/scientific-activities-z/iresist-home_en.

1. Introduction

Our buildings are ageing, posing an urgent need for renovation to achieve multidimensional European and international goals. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. 40 % of the buildings in the European Union (EU) are located in seismic prone regions and were built without modern seismic design considerations. During the last decades, earthquakes caused severe human and economic losses in Member States with moderate and high seismic risk, such as Bulgaria, Croatia, Greece and Italy (Figure 1). Attention should be drawn also 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 (Figure 2). The highest amount of energy use in old buildings derives from the operational stage of their life (e.g. heating, cooling), resulting in high energy bills and significant carbon emissions with detrimental effects on climate change.

The requalification of buildings for energy efficiency should address structural and earthquake safety. Renovation of existing buildings and urban spaces represents an opportunity to upgrade their structural and energy performance (ECTP, 2019; Chatzidakis et al., 2020). Increased renovation rate and depth, and seismic resistant construction are key actions towards zero-emission, efficient and resilient buildings (GlobalABC/IEA/UNEP, 2020). Seismic risk mitigation is a sound financial investment that reduces property loss, deaths and casualties, disruption of services, and costs for sheltering, search and rescue after a disaster (Multi-Hazard Mitigation Council, 2019). Integrated investments on energy efficiency and structural strengthening of public and private buildings make technical, financial and social sense (The World Bank, 2021).

Renovation of buildings provides a unique opportunity to create a safe, sustainable and resilient built environment. The European Green Deal (COM 2019/640) calls for a Renovation Wave (COM 2020/662), supported by the New European Bauhaus (COM 2021/573) to create sustainable, inclusive and beautiful living spaces. Ensuring seismic safety is part of the Green Deal key principle for high health and environmental standards. Building renovation contributes to the economic recovery following the COVID-19 pandemic. Saving energy is an action of the REPowerEU plan (COM 2022/230) to achieve higher energy efficiency. In the Energy Performance of Buildings Directive (Directive 2018/844) and the proposal for its revision (COM 2021/802), besides reducing

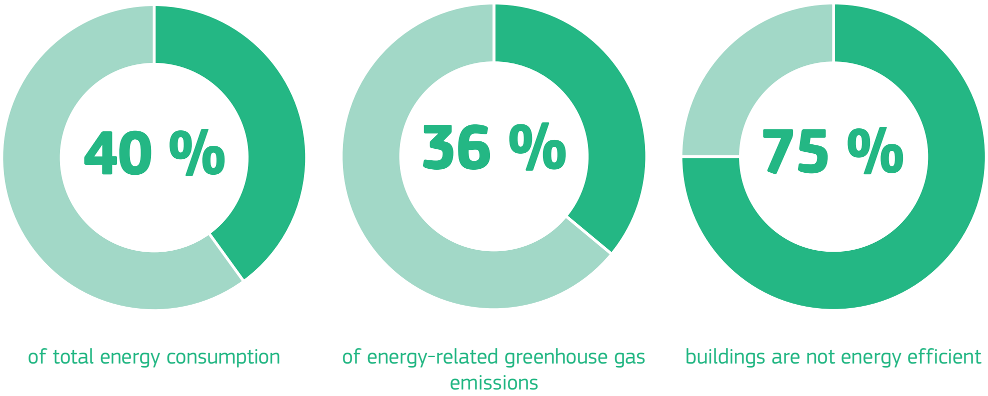
Figure 1. Seismic risk in the European Union.

of EU Solidarity Fund assistance granted in 2002-2019

earthquake addressed in 17 national risk assessments

Source: Overview of natural and man-made disaster risks the European Union may face (SWD 2020/330).

Figure 2. Energy efficiency of the European building stock.



Source: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives (COM 2020/662).

greenhouse gas and carbon emissions, addressing seismic risk to new and existing buildings is encouraged. The Cities Mission (COM 2021/609) puts research and innovation into a new role to achieve climate neutrality, including in buildings. The European Climate Law (Regulation 2021/1119) sets a legally binding target of a climate neutral Europe by 2050. The Circular Economy Action Plan (COM 2020/98) stresses clean and circular economy principles for construction, and addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The holistic renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention and the integration of risk reduction and cohesion policies. Improving risk assessment, anticipation and disaster risk management planning, and increasing risk awareness are among the EU disaster resilience goals (COM 2023/61). Likewise, the Action Plan on the Sendai Framework (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 (SWD 2019) emphasises the need to safeguard cultural heritage against natural disasters. The above contribute to the 2030 Agenda for Sustainable Development (Resolution 2015/A/Res/70/1) and the Sustainable Development Goal 11 for inclusive, safe, resilient and sustainable cities. In this context, the European Parliament entrusted the European Commission's Joint Research Centre with the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD.

The pilot project on integrated renovation of buildings defines technical solutions to reduce seismic vulnerability and increase energy efficiency, 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 pilot project has the following key objectives:

— Define tools and guidelines to reduce, all at once, vulnerability and energy inefficiency of buildings

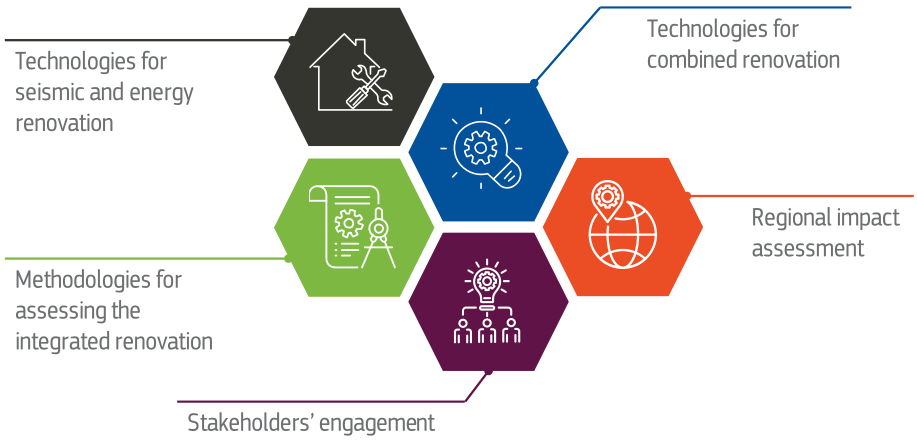
— Stimulate the use of integrated solutions

— Create awareness about the topic in the aim of prevention

— Increase resilience of the built environment to seismic hazard and climate change.

This report summarises the output of the pilot project. Five actions were foreseen to achieve the project objectives (Figure 3). Existing seismic and energy renovation technologies were assessed in a life cycle perspective (Chapter 2). Combined renovation solutions were explored based on available technologies and recent scientific developments (Chapter 3). A simplified method for assessing the benefit of combined renovation was proposed and applied to representative buildings (Chapter 4). By employing an

Figure 3. Pilot project actions.



Source: JRC.

integrated framework, seismic risk, energy performance and socioeconomic aspects were assessed throughout Europe to identify regions where interventions are of higher priority and investigate renovation scenarios (Chapter 5). National, regional and local authorities, industrial associations and expert communities were involved in enquiries and discussions of relevant policy measures, technologies and methodologies for the combined renovation of buildings. Dissemination and outreach are further supported by a web platform, reports (Annex A) and public communication material.

2. Technologies for seismic and energy renovation of buildings

The number and diversity of the EU buildings make a large-scale modernisation based on combined seismic and energy renovation complex. The analysis of the EU building typologies which could benefit from combined renovation facilitate the selection of suitable renovation strategies and technologies, useful for practitioners and local authorities. Technologies for seismic and energy renovation are explored to assess their applicability mainly in terms of compatibility, cost and disruption time, as well as ease the decision-making process in the preliminary phase of renovation.

2.1. Overview

A simplified analysis to identify EU building typologies that could benefit from combined seismic and energy renovation was carried out, with a focus on the Italian building stock.

Technologies for seismic renovation were reviewed and classified both qualitatively by life cycle thinking-based criteria, and quantitatively through a cost analysis to define average cost ranges of common renovation technologies for masonry and reinforced concrete (RC) buildings.

Technologies for energy renovation were reviewed, qualitatively classified by a set of indicators, and ranked using a multi-criteria decision-making analysis.

2.2. Target building typologies for combined renovation

The analysis of the EU existing buildings most needing combined seismic and energy renovation is crucial to facilitate the selection of suitable renovation strategies. This investigation was carried out according to a three-step approach (Romano et al., 2023a, b), focusing on the residential building stock as it represents the most widespread building segment in the EU.

The first step deals with an overview of the main characteristics of the EU residential building stock. The distribution of dwellings in EU residential buildings by year of construction, building type (i.e. one, two, three-dwelling buildings or buildings with more than three dwellings), and size based on useful floor space[3] were analysed according to the EU 2011 Population and Housing Census database[4]. Nearly 80 % of EU dwellings were built before 1990 and more than 20 % before 1945. Hence, the majority of the EU existing dwellings do not comply with modern seismic design requirements (i.e. Eurocodes), or with recent EU energy efficiency provisions, as set in the Energy Performance of Buildings Directive (Directive 2018/844). The highest share of dwellings (i.e. more than 50 %) is located in multi-family houses including at least three dwellings per building, followed by 40 % of dwellings in single-family houses. Both single- and multi-family houses need to be considered for the EU building stock modernisation. Estonia, Latvia, Spain and Italy are the EU countries exhibiting the highest number of dwellings in multi-family houses, whereas Ireland includes the highest share of dwellings in single-family houses, followed by Belgium and the Netherlands. The highest share of dwellings in most of the EU Member States was found to have a useful floor area into the range 50–120 m^2. According to data retrieved by the ENTRANZE tool[5], the EU single-family houses generally possess a higher average useful floor area per dwelling than multi-family houses with a mean value equal to 100 m^2 and 68 m^2 for single- and multi-family houses, respectively. The distribution of the EU building stock by construction material was also investigated, according to data collected by the NERA project[6] (Ozcebe et al., 2014). The major share of the EU building stock consists of masonry structures, although RC buildings are predominant in some countries, such as Cyprus, Greece and Portugal.

The second step focuses on mapping the EU territory into seismic hazard zones and climatic zones. Maps of low, moderate and high seismic hazard zones were considered, depending on specific ranges of peak ground acceleration, obtained from the European Seismic Hazard Model 2020 (ESHM20) (Danciu et al., 2021). The heating degree days (i.e. variable calculated from outside air temperature measurements to estimate the heating energy demand of buildings), were used to define EU climatic zones. Specifically, six climatic zones were defined based on the related 2019 average annual data at EU member state level (Eurostat, 2020a).

The third step concerns the identification of EU priority countries exhibiting the most severe seismic–climatic combinations. A simplified score-based approach relying on peak ground acceleration, heating and cooling degree day data by EU country was considered. Bulgaria, Croatia, Greece, Italy and Romania were selected as representative countries characterised by moderate-to-high seismic hazard and considerable climatic requirements, along with Germany, chosen as a country indicative of low-to-moderate seismic hazard. Regions representative of various seismic-climatic scenarios in each of the six identified priority countries were selected. Ad-hoc analyses combining building age, year of implementation of moderate seismic design code and year

[3] Useful floor space (or useful floor area) indicates the dwelling floor area measured inside the external walls.

[4] European Statistical System – Census Hub, https://ec.europa.eu/CensusHub2.

[5] Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe (ENTRANZE) project (2009–2012), https://www.entranze.eu/, and dedicated tool, https://www.entranze.eu/tools/interactive-data-tool.

[6] Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation (NERA) project (2010-2014), https://cordis.europa.eu/project/id/262330.

of implementation of first energy efficiency regulations, as well as construction material were carried out for the different regions within the selected countries. Main results underline that at least 60–70 % of the existing building stock (including both masonry and RC buildings) in the examined regions of the selected countries were built with no or low seismic design and energy efficiency requirements.

Italian building typologies were further investigated due to their variability in terms of construction technologies, structural details, and envelope components. The residential building stock in Italy represents the highest share of buildings, which mainly consists of masonry (i.e. 57 %) and RC (i.e. 30 %) buildings (Istat, 2011). According to their distribution by year of construction, more than 90 % and 55 % of Italian masonry and RC residential buildings were constructed without seismic provisions, respectively. Furthermore, 88 % of the Italian masonry and RC buildings do not comply with modern energy performance requirements since a stringent code on energy efficiency of buildings was first issued in Italy in 1991 (Law 10/1991). The combination of various seismic–climatic scenarios in Italy pointed out that nearly 20 % and 15 % of masonry and RC buildings, respectively, are located in high seismic hazard zones with severe climatic requirements. The identification of Italian masonry and RC building typologies to be renovated relied on specific seismic and energy driven investigations (Romano et al, 2023a, b). According to data retrieved from survey forms for post-earthquake damage and safety assessment of buildings (Baggio et al., 2007) with reference to the 2012 Emilia earthquake (Dolce and Di Bucci, 2014), two masonry building typologies were identified as most vulnerable to earthquake damage. The two typologies are characterised by the absence of connections among masonry walls and floors and they mainly vary by period of construction (i.e. pre-1945 and pre-1971), total floor area (i.e. 300–400 m^2 and 400–450 m^2), and horizontal structural elements (i.e. timber floors and RC floors). They also exhibit an inadequate energy performance, since the thermal properties of the envelope components, based on data retrieved by the TABULA[7] database, do not comply with the current Italian regulation on energy efficiency of buildings (Ministerial Decree, 2015). Research studies on seismic vulnerability assessment of residential RC buildings (Masi and Vona, 2012; Masi et al., 2015) were reviewed. RC frame structures designed without seismic requirements were found to be the most widespread RC structural typology in Italy. Two RC frame typologies most needing seismic renovation were identified based on the period of construction: (*i*) pre-1971 and (*ii*) post-1971, mainly varying in mechanical properties of materials (i.e. concrete and steel). The two typologies were differentiated between small and large floor area, as well as among two-, four-, and eight-storey buildings. Masonry infills play a crucial role in the seismic performance of RC frame structures, thus various configurations of infill walls were considered. Both pre-1971 and post-1971 RC building typologies exhibited the highest seismic vulnerability in case of absence of infills at the ground floor (i.e. pilotis). Infill walls significantly affect also the energy performance of frame structures, thus their construction evolution from ’40s to ’90s was investigated (Manfredi and Masi, 2018). A poor thermal performance of the infill walls used during the period 1950–1990 was pointed out, not compliant with the current Italian regulations on energy efficiency of buildings (Ministerial Decree, 2015).

2.3. Seismic renovation technologies

Technologies for seismic renovation of buildings can be classified into global and local ones. Global solutions involve the structural system as a whole, while local ones operate on individual structural elements. Common seismic renovation technologies at both global and local level were reviewed in Romano et al. (2023b), whereas a brief overview is provided herein.

[7] Typology Approach for Building Stock Energy Assessment (TABULA) project (2009-2012), https://episcope.eu/iee-project/tabula/, and dedicated web-based tool, https://webtool.building-typology.eu/.

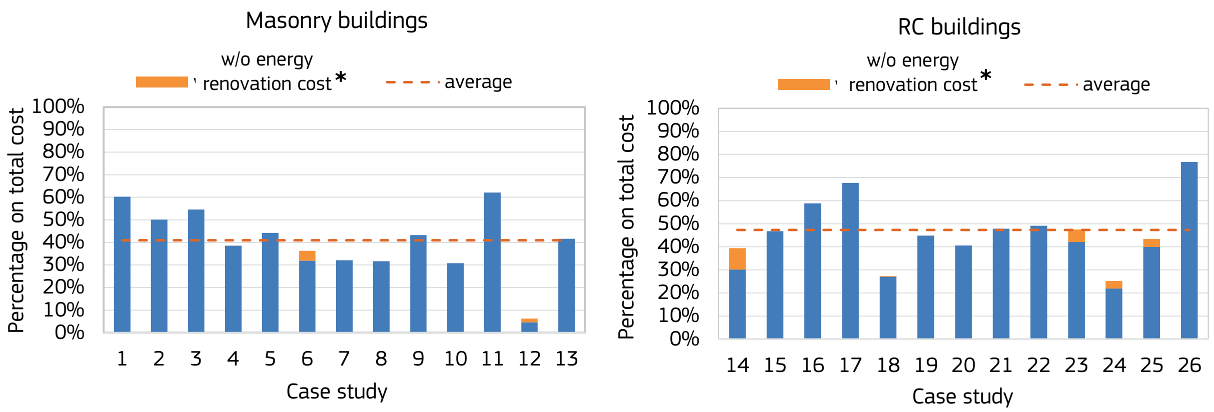
Global renovation technologies common to different building typologies aim to either reduce the seismic demand or enhance the seismic capacity of a building. Solutions that reduce the seismic demand include seismic isolation (Warn and Ryan, 2012) and additional damping (Costantinou et al., 1998). Enhancing the seismic capacity refers to the provision of new seismic-resistant systems, including RC infills, rocking wall systems, shear wall exoskeletons (e.g. RC walls, steel bracing systems, steel wall panels), and shell exoskeletons, (e.g. steel diagrid system, Labò et al., 2020; cross-laminated timber (CLT) panels, Zanni et al., 2021).

Local renovation technologies were investigated by building typology. Local solutions for RC buildings refer to beam, column, and beam-to-column joint strengthening to enhance their ductility and strength. These improvements can be achieved by means of various technologies, such as RC, steel, or high-performance fibre RC jacketing, fibre reinforced polymers wrapping, steel plates (e.g. Karayannis et al., 2008; Yen and Chien, 2010; Martinola et al., 2010). Local interventions for unreinforced masonry buildings include solutions which aim to enhance the in-plane and out-of-plane mechanical behaviour of masonry walls (Salvalaggio and Valluzzi, 2022), typically made of stone or clay brick units bonded via mortar. The improvement of masonry quality and continuity of masonry leaves (e.g. by applying grout injection, repointing of walls, reconstruction of wall portions) need to be ensured before proceeding with other seismic renovation solutions. Conventional local renovation technologies refer to the use of structural coatings by applying a thin mortar or concrete layer reinforced by high strength fibres to enhance the tensile strength of walls. All these solutions need to be coupled with further renovation technologies (e.g. floor/roof diaphragm, perimeter ties) to avoid out-of-plane failure mechanisms (e.g. overturning of external masonry walls), thus ensuring a box-like behaviour of the building (D'Ayala and Speranza, 2003), and exploiting the in-plane capacity of masonry walls.

The identified technologies were qualitatively classified by life cycle thinking criteria. These criteria refer to different environmental, economic, social, and technical aspects of renovation over the building life cycle, such as holistic/integrated renovation compatibility, occupants' disruption, replacement of wall/roof finishes, the possibility to use repairable and demountable technologies, potential to recycle/re-use, initial economic investment, life cycle cost, etc. Relevant technologies were rated by assigning scores to the selected criteria (Romano et al., 2023b). In the case of global renovation technologies, steel bracing systems and external shell exoskeleton (i.e. steel diagrid system and CLT panel) solutions were found to be particularly effective from a life cycle perspective. These outcomes were mainly due to the full compatibility with holistic renovation solutions, minimum disruption of occupants, short on-site works duration thanks to the use of prefabricated elements, high level of recycle/re-use, extensive use of easily demountable components, low life cycle cost. However, the CLT solution showed marginally lower scores than steel diagrid systems in a few criteria. It was found to be less compatible with incremental renovation, less repairable and requiring a slightly higher initial economic investment. However, it was evaluated as a very promising technology for holistic renovation encompassing structural, energy and architectural restyling (e.g. Labò et al., 2021) in line with the New European Bauhaus values (COM 2021/573). All the investigated local renovation technologies for RC buildings presented various drawbacks from a life cycle perspective, including the need to relocate occupants, the necessity to replace finishes, and the inability to re-use/recycle materials and components. The latter disadvantage is overcome in the case of steel jacketing for RC beams or columns, and steel plates for joints, which is easy to demount. In the case of masonry buildings, all examined local renovation technologies resulted in similar ratings of life cycle thinking criteria. The majority of technologies were found to be barely compatible with a holistic renovation. Moreover, they necessitate a quite long duration of works and relocation of occupants, and their components can be difficultly reused or dismantled. However, these technologies require little maintenance, and have moderate initial cost and potentially low life cycle cost.

The identified technologies were quantitatively classified through a two-stage cost analysis. The first stage dealt with the investigation of 26 actual seismic renovation projects of RC and masonry residential and public buildings located in northern Italy. The investigated projects implement some of the most common seismic renovation technologies for masonry buildings (e.g. improvement of masonry quality, structural coatings, perimeter ties, roof/floor diaphragm, and foundation system strengthening) and RC buildings (e.g. beam-to-column joint strengthening, exoskeleton, roof/floor diaphragm). Project documents were examined to calculate a breakdown of the total construction cost for the renovation activities. Cost was subdivided into six categories, namely preliminary works, structural intervention, energy intervention, finishes, construction site management, other expenses (including contingencies, technical expenses, vat, etc.). Each cost category was expressed as a percentage on the total construction cost with the structural intervention being the highest in the majority of investigated projects. The average cost ratios of the structural intervention were found to be equal to 41 % and 48 % of the total construction cost in masonry and RC buildings, respectively (Figure 4). Finishes and preliminary works were also found to be expensive, unless the intervention is carried out from outside. The second stage concerned the estimation of average unit-cost range of selected seismic renovation technologies for masonry and RC buildings, using the previous cost breakdowns, construction cost books with reference to the Italian market, and interviews with design professionals, experienced estimators, and construction companies. The provided costs should serve as a supporting tool in the preliminary phase of the renovation design to facilitate decision-making. Indeed, the average cost ranges are intended to be used to develop budget estimates, enable project financing and authorisation. They may serve as a valuable aid for the pre-screening of eligible renovation strategies, compliant with budget restriction, and for comparative assessment of renovation alternatives. Specific building geometries were considered, and assumptions were made, thus cost fluctuations can occur for different cases. The following renovation technologies were considered for masonry buildings: improvement of masonry quality, strengthening of masonry walls with structural coatings, introduction of new seismic-resistant systems made of shear walls (either inside or outside of the building), floor/roof diaphragms and perimeter ties, and strengthening of vaults. The highest average unit-cost ranges refer to new RC or steel-braced shear walls outside of the buildings with isolated footings (i.e. 510–880

Figure 4. Structural renovation cost as percentage of the total renovation cost for the investigated masonry and RC buildings.



* The structural renovation cost is also given as a percentage of the total renovation cost without including the energy renovation cost.

Source: Data from Romano et al. (2023b).

€/m^2 or 530–910 €/m^2 of shear wall vertical surface, respectively), mainly due to the cost of new foundations. Strengthening of vaults also resulted into quite high average unit-cost ranges. For example, renovation with ultra-high tensile steel strength strips and mortar layer costs 350–415 €/m^2 (of vault plane area), and renovation with fibre reinforced cementitious matrix coatings costs 365–420 €/m^2 (of vault plane area). The following technologies were investigated for RC buildings: strengthening of beams and columns with high-performance fibre RC jacketing, additional shear walls (either inside or outside the building), seismic isolation, and strengthening of floors. The highest average unit-cost ranges refer to seismic isolation (i.e. 2500–3000 €/m^2), followed by shear walls (i.e. same results as in masonry buildings).

2.4. Energy renovation technologies

Technologies for energy renovation of buildings are usually categorised as active or passive, depending on their applicability to energy systems (e.g. heating, cooling) or building envelopes, respectively. A total number of 20 passive energy efficiency technologies were classified by envelope component (Romano et al., 2023b): (*i*) wall (insulation technologies, ventilated façades, green walls), (*ii*) floor and roof (insulation technologies, green and cool roofs), (*iii*) window (replacement, films, and weather-stripping), and (*iv*) door (replacement, and weather-stripping). Generally, the investigated technologies aim to improve thermal insulation of walls (Barreira and de Freitas, 2013), floors and roofs, reduce air infiltration through windows and doors (Younes et al., 2012), and control solar gains (e.g. Pereira et al., 2022). Modern technologies, such as green walls, or green and cool roofs, provide also benefits in global warming reduction and in mitigating the urban heat island effects beyond enhancing the thermal performance of buildings (Santamouris, 2011; Berardi et al., 2014; Susca et al, 2022).

The compatibility of the investigated technologies with the EU building stock was assessed. The EU Member States exhibiting high and moderate seismic hazard according to the ESHM20 were first selected (the whole group of these countries is referred to as ‘target region’ hereafter). The building stock in the target region was investigated through the Hotmaps[8] and TABULA projects by focusing on different aspects: building use (i.e. residential, and non-residential buildings), building age, construction and thermal characteristics. Residential buildings were further classified in single-family houses, terrace houses, multi-family houses and apartment buildings. Construction and thermal performance criteria were considered to estimate the residential and non-residential building shares to which the identified energy efficiency technologies could be applied (i.e. construction compatibility) with different levels of thermal performance compatibility, i.e. low, medium, high. Thermal performance compatibility levels indicate qualitatively the thermal performance improvement a technology may provide to the examined building stock. The implementation of wall and floor insulation technologies, as well as internal insulation of roofs and cool roofs fully satisfies construction compatibility with the residential building stock in the target region, exhibiting different levels of thermal performance compatibility. Similar considerations were also pointed out for window and door replacement and weather-stripping, and window films.
For instance, the external thermal insulation composite system (ETICS) for walls exhibits a high, medium, and low thermal performance compatibility with 12 %, 80 %, and 8 % of apartment buildings, respectively. The same results were found for single family houses. ETICS resulted in high, medium, and low thermal performance compatibility with 10 %, 58 %, and 32 % of multi-family houses, respectively. Some technologies were found to be incompatible in terms of construction criteria with a specific share of the building stock in the target region. In this case no thermal performance compatibility level was also considered. For instance, external insulation of flat roofs was found to be incompatible in terms of construction (and hence thermal performance) with 5 % of the

[8] Hotmaps project, https://www.hotmaps-project.eu/.

apartment buildings, while it was found to have a low, medium and high level of thermal performance compatibility with 7 %, 71 % and 17 % of the apartment buildings, respectively. The insulation of external wall air chambers was evaluated as the less compatible technology with the highest share of apartment buildings, multi- and single-family houses, as this solution can be implemented only in cavity walls. The investigated energy efficiency technologies were ranked to assess the impact of reduced energy each technology may have on the whole building stock in the target region. The ranking score was based on both the number of buildings and the energy consumed before renovation, along with the implementation probability of each energy efficiency technology. Specifically, high, medium, low, and no compatibility levels were converted into implementation probability values equal to 75 %, 50 %, 25 %, and 0 %, respectively). Focusing on technologies that resulted in full construction compatibility with the building stock, ranking results pointed out that the highest impact is achieved by external insulation technologies for walls, followed by floor insulation, door replacement and door/window weather stripping, as well as internal insulation and cool roofs.

Eleven energy efficiency technologies were ranked based on their attractiveness for integrated renovation of residential buildings in the target region. The technologies were first analysed according to a set of indicators including unit cost of implementation, unit energy saved, unit cost-effectiveness, disruption time, life-span, and generated waste. A multi-criteria decision-making analysis was carried out through the Analytic Hierarchy Process (Saaty, 1980). The unit cost of implementation and unit energy saving indicators were assumed as highly important, while life-span and generated waste as modestly important. Ranking results are reported in Table 1. Insulation of external wall air chambers, internal insulation of roofs, and internal insulation of external walls are highly attractive energy renovation technologies due to their low cost, high performance and low generated waste. However, the applicability of the insulation of external wall air chambers was found to be compatible with a low share of buildings. Replacement and weather stripping of doors/windows revealed a medium

Table 1. Ranking of 11 selected energy efficiency technologies.

Rank	Envelope component	Energy efficiency technologies	Attractivenes for potential investments
1	Wall	Insulation of wall air chamber	High
2	Roof	Internal insulation	High
3	Wall	Internal insulation by cladding	High
4	Roof	External insulation of flat roofs	High
5	Door Window	Weather stripping	Medium
6	Door Window	Replacement	Medium
7	Door Window	Replacement	Medium
8	Wall	System of façade renovation with cement panels sheathing	Low
9	Roof	External insulation of pitched roofs	Low
10	Wall	Prefabricated units for external wall insulation	Low
11	Wall	External Thermal Insulation Composite System (ETICS)	Low

Source: Romano et al. (2023b).

attractiveness, whereas prefabricated units for external wall insulation or external thermal insulation composite systems ranked low. These solutions are the least preferable options mainly due to their high cost, although their implementation provides the highest reduction of energy.

3. Technologies for combined renovation of buildings

The combined seismic and energy renovation of buildings can be more cost-effective than traditional separate renovation, as shown by economic feasibility studies for moderate to high seismic regions of Europe. To identify the most promising technologies for combined renovation, an overview is provided here for the four main types of interventions: (*i*) exoskeletons; (*ii*) interventions on the existing building envelope; (*iii*) replacement of the existing envelope; and (*iv*) interventions on horizontal elements. The encountered solutions present different levels of technological maturity, ranging from a conceptual stage to technologies already tested and validated experimentally. In all cases, further research is required to develop viable renovation solutions that can be readily applied and provide solutions for accelerating building renovation across the EU. The analysis of presented in the pilot project may be useful for researchers and practitioners working on the development of new technologies.

3.1. Overview

A large proportion of the EU building stock is energy-inefficient and presents structural vulnerabilities due to its old age. An analysis of novel seismic renovation technologies highlights two major categories: the ones that operate at the element level (local measures), and those that act on the structure as a whole (global measures). Naturally, for actual buildings, various techniques can and should be combined, so that an economic strengthening scheme can be designed.

Novel and integrated approaches may lead to better cost-effectiveness and hence promote increases in renovation rates in line with current EU policies. An assessment of the latest developments of materials and technologies for combined renovation is presented, which exhibit different relative effectiveness, environmental impact and market-readiness. While the potential of combined retrofitting approaches is evident, further experimental research and validation still needs to be carried out.

3.2. Novel seismic retrofitting technologies

Due to the poor performance of structures during past earthquakes, the field of seismic upgrading of existing buildings has received great attention both in the academic world and in engineering practice. A detailed analysis of the novel technologies that have been developed for the seismic upgrading of RC, masonry and steel buildings was recently presented (Gkournelos et al., 2021, 2022; Triantafillou et al., 2022), while a brief summary is made herein. Both local and global techniques are discussed and assessed in terms of their strengths and weaknesses.

When a building has an acceptable level of lateral strength and stiffness, the application of local retrofitting measures is selected. Typically, retrofitting solutions involve jacketing of RC beams and columns aiming to increase their flexural and shear strength, as well as members' deformation capacity. Fibre-reinforced polymers (FRP) have been used successfully in many experimental campaigns as well as real-world applications for the seismic upgrading of RC, masonry and steel buildings. To address the poor behaviour of FRP at high temperatures, textile reinforced mortars (TRM) offer a very promising alternative for RC and masonry buildings, as strengthening materials (e.g. Koutas et al., 2019, Cerniauskas et al., 2020).

Global structural upgrading techniques, increasing the capacity and decreasing the demand, were also analysed. The addition of bracing systems (e.g. infill walls and shear walls) yields a significant increase in lateral strength and stiffness of a building. Buckling-restrained braces, replaceable infill panels made of high-performance materials, and isolated infill walls are promising solutions, worth of further detailed investigation. The addition of RC shear walls, either as new elements or by infilling of existing frames, can also be beneficial for the seismic strengthening of RC and steel buildings. Moreover, masonry infills represent a very economical way of increasing lateral strength and stiffness. When strengthened using FRP, TRM or reinforced mortar overlays, they form a reliable lateral load resisting mechanism (e.g. Koutas et al. 2015; Pohoryles and Bournas 2020). Finally, integrated seismic and energy upgrading can be provided in some of the global seismic retrofitting measures (e.g. by combining TRM, exoskeleton systems, RC/masonry infilling with thermal insulation) as it is thoroughly discussed in Section 3.3. To enhance the integrity of masonry structures, a number of retrofitting techniques have been developed with the aim of consolidating the entire structure, improving the stress redistribution capabilities and forcing a box-type behaviour.

Base isolation and passive energy dissipation systems can effectively reduce the seismically induced vibrations on RC, masonry and steel buildings. This family of methods might not always be structurally or economically feasible, however it has the feature of minimally altering the aesthetics and functionality of the structure to be retrofitted. This feature might make such retrofitting methods particularly attractive for the protection of monument-type masonry buildings, where the preservation of the original architectural view is a requirement; or in cases of retrofitting important structures or when vibration control is of outmost importance, such methods can yield extremely good results.

Selecting the appropriate retrofitting solution for a given structure is a multi-parametric problem without a one-fits-all solution. The specific details of the examined structure, the desired level of performance upgrade, the availability of materials, specialised personnel etc., and of course, the overall intervention cost need to be accounted for. Moreover, the design of such retrofitting measures usually calls for advanced simulations. Therefore, it is important that engineers have robust standards and regulatory framework to follow, so that their designs can be reliable.

With the exception of Eurocode EN 1998-3, today we lack design guidance and standards for the design of the seismic retrofitting of buildings with novel technologies. EN 1998-3 covers (only partially) FRPs for the enhancement of the shear capacity of RC columns and walls, for the enhancement of the available ductility at beam or column ends through added confinement, and for the prevention of lap splice failures through increased lap confinement. It is hoped that the upcoming version of the Eurocodes will play some role with respect to that matter. To the best of the authors' knowledge, the upcoming version of EN 1998-3 will include revised models for FRP retrofitting of RC members. Moreover, EN 1998-3 will make also reference to vertical and horizontal steel bars, FRP or other composite strips as a means of strengthening masonry walls, as well as to the possibility of adding bracings, dissipative passive or active devices, without providing specific design guidance. However, other novel techniques do not seem to be covered, despite the fact that research has already advanced substantially. This is a gap that needs to be filled.

Research gaps with regard to seismic upgrading of RC, masonry and steel buildings with novel techniques appear to be generally minor. An emerging field, which will progressively be gaining the attention of the scientific community, is the *integration* of today's novel seismic upgrading techniques with interventions for energy upgrading including advanced materials, and possibly with low cost – yet reliable – systems for smart monitoring.

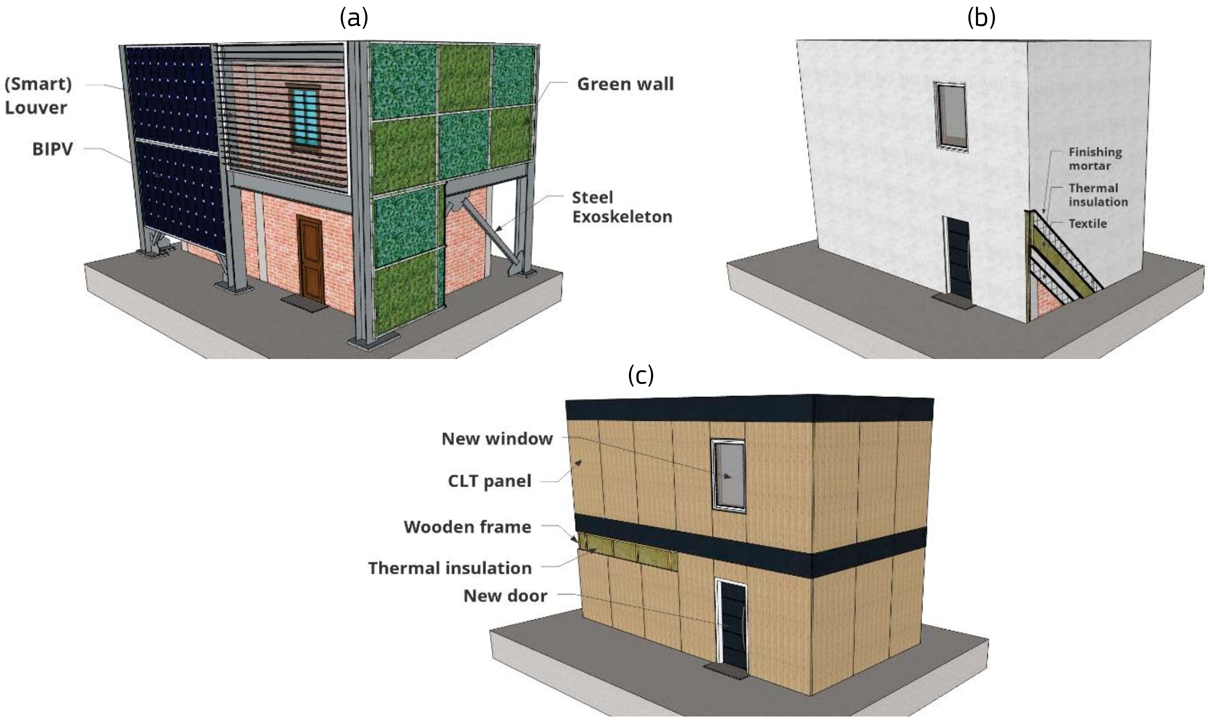
3.3. Combined renovation technologies

The renovation of buildings has typically focussed on improving their energy efficiency. For buildings that are vulnerable to structural damage or collapse, for instance due to an earthquake, investments into energy renovation alone may be ineffective and potentially lost. This was in fact observed after recent earthquakes (Belleri and Marini, 2016), leading to research into integrated seismic and energy renovation (Bournas, 2018a, b). From a life cycle perspective, the combination with seismic renovation can preserve the structural integrity over a prolongued period and reduce repair works associated to damage. Integrated retrofitting was also shown to be more cost-effective compared to energy renovation alone, particularly in regions of moderate to high seismic hazard (Calvi et al., 2016; Bournas, 2018a; Gkournelos et al., 2019; Pohoryles et al., 2020; Gkatzogias et al. 2022b). In terms of materials and technologies currently under development, four main directions can be identified in the scientific literature: (*i*) integrated exoskeleton solutions; (*ii*) integrated interventions on the existing building envelope; (*iii*) replacement of the existing envelope with better performing materials; and (*iv*) interventions on horizontal elements, such as roof and floor slabs. A summary of the developments in these directions is offered here, while more comprehensive technical information and detailed references can be found in (Pohoryles et al., 2022a, b).

Integrated exoskeletons are external structures that are connected to existing buildings to improve their structural safety and reduce energy consumption. Examples of such external structures range from simple structural braces combined with solar shading, to material-efficient diagonal steel grids or frames supporting different kinds of thermal panels (e.g. building integrated photovoltaics or BIPV, green facades or shading), as shown in Figure 5a. Integrated solutions also include the use of thermal insulation integrated with auxiliary reinforced concrete frames or walls.

Given that the external envelope is the main source of energy losses in older buildings, many renovations focus on reducing the thermal transmittance of exterior walls through insulation. Such interventions on the existing envelope can be integrated with seismic strengthening solutions for external walls, as shown by research on composite materials, prefabricated panels, or the use of structural window frames. The combination of composite materials (such as textile-reinforced mortars, or TRM) with thermal insulation (Figure 5b) appears to be the most market-ready approach, given that significant experimental validation studies have already been carried out on masonry (e.g. Triantafillou et al., 2017; Gkournelos et al., 2020) and RC structures (e.g. Baek et al., 2022). The application of such solution is currently investigated for a full-scale building at the

Figure 5. Examples of combined and integrated retrofitting solutions: (a) exoskeletons, (b) textile reinforced mortars and (c) timber panels with thermal insulation.



Source: JRC.

JRC's ELSA laboratory within the iRESIST+ project[9] (Pohoryles and Bournas, 2021).

To reduce on-site construction time and increase modularity, prefabricated integrated retrofit panels are also explored. For instance, a system combining textile-based cement panels with capillary tube systems for active heating and cooling has been investigated in the framework of an international research collaboration[10] between the JRC and KOCED CMI[11] (Baek et al., 2022). Other approaches with prefabricated panels include the use of bio-based materials, such as CLT panels (Figure 5c), currently being tested on individual RC frames (Smiroldo et al., 2023) and on a full-scale building at the JRC[12]. Finally, an additional approach for integrated retrofitting of existing walls, is the use of structural window frames to increase their stiffness, while also improving the thermal properties of the glazing surfaces (e.g. double- or triple-glazing).

When improving the building envelope is not feasible, e.g. due to degradation of existing materials, it can be possible to replace external brick walls with stronger or more flexible materials that also provide better thermal insulation. Experimental testing of different modern brick solutions has already proven that a safer seismic behaviour can be achieved either through stiffening of the building or through reducing the interactions between external walls and the existing building frame; the latter may be combined with the installation of CLT panels too. Bricks made from sustainable materials or bricks filled with thermal insulation can reduce the environmental impact of the building.

9 https://joint-research-centre.ec.europa.eu/scientific-activities-z/iresist-home_en.

10 https://joint-research-centre.ec.europa.eu/scientific-activities-z/iresist-home/ongoing-projects/koced-partnership_en.

11 Korea Construction Engineering Development Collaboratory Management Institute.

12 https://joint-research-centre.ec.europa.eu/scientific-activities-z/iresist-home/ongoing-projects/noticeeub_en.

Finally, renovating existing floors and roofs is often required in older buildings to ensure structural integrity and reduce thermal losses. Renovation solutions on horizontal elements can be considered to have a high potential for integration, however, to date, only few have been proposed or conceptualised. Examples include thin-folded shells combined with a ventilating layer to improve existing wooden roofs, but also the use of timber panels combined with thermal insulation for replacing older floors in existing buildings.

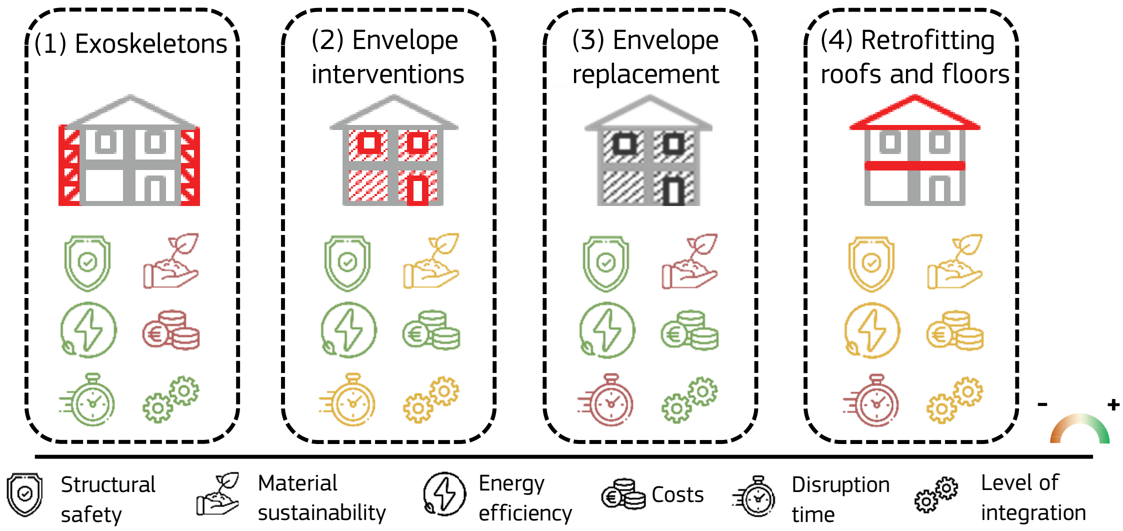
Altogether, despite the relatively limited amount of research that has been conducted on technologies for integrated structural and energy retrofitting, important findings and insights have already been made. The potential of such solutions will be further evaluated with increasing experimental research and validation through use on existing buildings.

3.4. Evaluation of technologies for combined renovation

To give an overview of the current state of development of technologies for combined or integrated renovation, a brief assessment of their effectiveness, environmental impact, costs, disruptiveness and level of integration is presented in Figure 6. The effectiveness of the renovation is evaluated from reported values of improvements in energy efficiency and structural capacity. The costs and environmental impact[13] of the proposed technologies was instead evaluated for a typical mid-rise building (Pohoryles et al., 2022a). The disruptiveness of an intervention represents the duration of the intervention, associated business downtime and potential relocation of residents. Finally, the level of integration considers if the seismic and the energy upgrading can be achieved through a single element (integrated) or two elements working in parallel (combined).

An important consideration with exoskeletons is the need for an additional foundation system, which means their execution is not always feasible (e.g. in densely built-up urban areas) and typically is more costly than other renovation options. The type of materials (reinforced concrete or steel) used for exoskeletons, also mean they are typically less sustainable than other solutions. Due to the additional external structure, the appearance of the building is changed significantly. This may be prohibitive, e.g. for cultural heritage buildings, but can also provide an architectural and aesthetic upgrade, in line with the

Figure 6. Evaluation of four different avenues for combined seismic and energy retrofitting.



[13] Only the embodied carbon (cradle-to-gate) of the materials is considered, i.e. excluding the embodied carbon of transportation and retrofit construction.

approach of the New European Bauhaus (COM 2021/573).

Interventions improving the existing envelope of an existing building can also be considered to improve not only the energy efficiency and structural performance, but also the external appearance of the building. The disruptiveness of such interventions is significantly lower, particularly when considering prefabricated solutions. The associated reduced labour time also keeps the costs of these interventions low if works can be carried out from the outside of the building. Depending on the materials used, a low environmental impact can be achieved (e.g. by using bio-based materials such as timber) and little construction waste is generated.

In the case of envelope replacement, similar improvements in seismic safety and energy efficiency can be achieved as in the previous case, but construction works are significantly more invasive and disruptive. The environmental impact is also important, as large amounts of non-recyclable waste are typically generated. Integrated renovation of roofs and floors alone is less effective in improving the seismic and energy performance of an existing building. Hence, such interventions would normally be combined with interventions on exterior walls. The works associated with floor and roof strengthening or replacement are significant and affect building occupancy for prolonged periods of time, increasing costs and disruptiveness.

4. Methodologies for assessing the benefit of combined renovation

All actors need to know the benefits of integrated seismic and energy renovation of buildings. Employing user-friendly assessment methods may overcome economic, technical and administrative barriers.

Building renovation typically improves either the energy or the seismic performance of buildings, resulting in energy inefficient or earthquake-vulnerable buildings. This may yield environmental burden, economic loss and fatalities over time. A simplified method is introduced to assess the benefits of combined renovation from a life cycle perspective.

Designers and practitioners can translate seismic, energy and environmental performances into equivalent costs without complex analyses. Different stakeholders, e.g. owners, investors, policy makers, can grasp the combined renovation improvement thanks to performance results being expressed in economic terms.

4.1. Overview

Methodologies for assessing the benefit of seismic and energy renovation were reviewed, serving as a reference to develop a simplified assessment method based on life cycle thinking.

A four-step method was developed to assess the seismic, energy, and environmental performance of renovated buildings in equivalent costs from a life cycle perspective without employing complex analyses.

Four case studies, indicative of EU residential and public masonry and RC buildings, were identified to apply both an existing method for assessing the effect of combined renovation (i.e. the Sustainable Structural Design or SSD methodology) and the proposed simplified one.

4.2. Review of methods for assessing the effect of combined renovation

Existing methods to assess performance enhancements of a building due to seismic and energy renovation can be grouped in two main classes: (*i*) sector-specific, and (*ii*) multi-performance. Sector-specific methods, based on uncoupled quantitative assessment of either the seismic or the energy/ environmental performance of buildings, are still the most common approaches in building renovation. The need for a radical change in considering a building as a multi-performance product with different potential deficiencies arose in the last decade, emphasising the importance of developing integrated renovation approaches. Multi-performance methods refer to both qualitative and quantitative integrated assessment methods. Sector-specific and multi-performance methods were reviewed in Romano et al. (2023c, d), whereas a brief synopsis is provided herein.

Sector-specific methods for the seismic performance assessment of a building include seismic loss estimation and seismic resilience assessment methods. Seismic loss estimation methods often apply the Performance-Based Earthquake Engineering (PBEE) approach, which relies on a fully probabilistic context consisting of hazard, structural, damage and loss analysis. The seismic performance of a building is assessed in terms of expected losses (e.g. repair costs, downtime, casualties), which are key-parameters for stakeholders' decision-making. Based on the PBEE methodology developed by the Pacific Earthquake Engineering Research Center (Cornell and Krawinkler, 2000; Porter, 2003), procedures more accessible to engineering practice were introduced (e.g. FEMA, 2018), along with proposals to further simplify its fully probabilistic formulation (e.g. Negro and Mola, 2017). Additional simplified approaches in this direction are the recent Italian guidelines on seismic risk assessment of constructions based on expected annual losses (Ministerial Decree 58/2017), enabling stakeholders to exploit the national fiscal incentive mechanism for seismic renovation (i.e. Sisma Bonus), also combined with the energy renovation one (i.e. Eco Bonus). Seismic resilience assessment aims to evaluate the post-disaster functionality of buildings beyond loss assessment. Although recently introduced, such an assessment can become a significant tool for decision makers to compare building renovation alternatives, preferring for instance the one with the lowest recovery period (Carofilis Gallo et al., 2022). Resilience-rating systems of buildings were developed, such as the Resilience-based Earthquake Design Initiative (Almufti et al., 2014).

Sector-specific methods for the environmental and energy performance assessment of a building refer to Life Cycle Assessment (LCA) and Life Cycle Energy Assessment (LCEA) methodologies. The LCA methodology quantitatively assesses the environmental impacts of products and services throughout their entire life cycle (ISO, 2020a, b). The construction sector provides fertile ground for LCA studies carried out at three different levels: (*i*) construction product, (*ii*) building component, and (*iii*) entire building (Ortiz et al., 2009; Buyle et al., 2013), although the latter is a challenging task due to the long lifespan of buildings and the required LCA data (Chau et al., 2015). Consensus in the LCA methodology use has led to the development of several generic LCA tools, devoted to product assessment, and building-specific ones, aiming for the whole building design decision process. The LCEA methodology (Fay et al., 2000; Ramesh et al., 2010) is a streamlined LCA procedure used to assess only energy inputs to a building at each stage of its life cycle, leading to the computation of embodied, operational, and demolition energy consumption. The growing interest in the LCEA is driven by the realisation that embodied energy consumption cannot be neglected (Crawford, 2014; Vilches et al., 2017). Furthermore, in the last two decades, building energy simulation (BES) methods are the most used approach to compute the operational energy in LCEA studies (Omrany et al., 2020). Hence, the development of BES tools has been increased to facilitate and automate demanding calculation processes or model highly complex systems for dynamic energy analyses.

Multi-performance methods, based on a qualitative assessment, group

sustainability rating systems which rely on indicators of different weight. Following the release of the Building Research Establishment Environmental Assessment Method in the United Kingdom, a multitude of tools were developed worldwide within a few years (Haapio and Viitaniemi, 2008; Reed et al., 2009; Bernardi et al., 2017). This interest emerged from market needs to rapidly provide different stakeholders with a certification of the sustainability level awarded to a specific building. These systems generally address the environmental dimension of sustainability, without substantially focusing on economic and social aspects. Hence, the majority of sustainability rating schemes include energy efficiency and carbon dioxide (CO_2) emission indicators, but a seismic safety indicator is only implemented in a couple of them with a low weight (e.g. DGNB, 2020). Several systems rely on characteristics of specific geographic areas, thus lacking homogeneity and making comparability of results difficult. The development of a new tool at EU level, called Level(s), represents a significant effort to overcome the heterogeneity of these systems. Level(s) is a voluntary reporting framework to improve the sustainability of buildings, based on a common system of macro-objectives and indicators (Dodd et al., 2021). The tool enables both qualitative and simplified quantitative assessments depending on the life cycle stage of the building under consideration.

Multi-performance methods dealing with fully quantitative integrated life cycle-based approaches indicate the most effective direction to assess the benefits of combined renovation towards the development of holistic methods. The challenge to integrate different performance metrics of a building led to the initial effort of developing methods combining only a couple of building performances, such as environmental requirements and safety targets (Menna et al., 2013; Wei et al., 2016), economic and social impacts as consequences of seismic renovation (Calvi, 2013), or seismic risk on the economic management of energy renovation processes (Mauro et al., 2017). Menna et al. (2022) focused on methods coupling seismic and energy performance assessments. A study by Calvi et al. (2016) introduced the Green and Resilient Indicator based on energy and seismic expected annual losses to compare different renovation strategies through a cost-benefit analysis. A promising methodology for the integrated renovation assessment refers to the SSD methodology (Lamperti Tornaghi et al., 2018) aiming for a holistic approach to optimise at the same time safety and sustainability of buildings. This four-step methodology consists of energy, environmental, and structural performance assessment from a life cycle perspective using different metrics, converted into costs and combined into a unique monetary result. A significant advantage of the SSD methodology is the capacity to offer a common language to all the design process operators (e.g. owners, engineers, architects, investors), facilitating decision-making. The SSD methodology was used as the starting point to develop a simplified assessment method for combined seismic and energy renovation.

4.3. A simplified method to assess the benefits of combined renovation

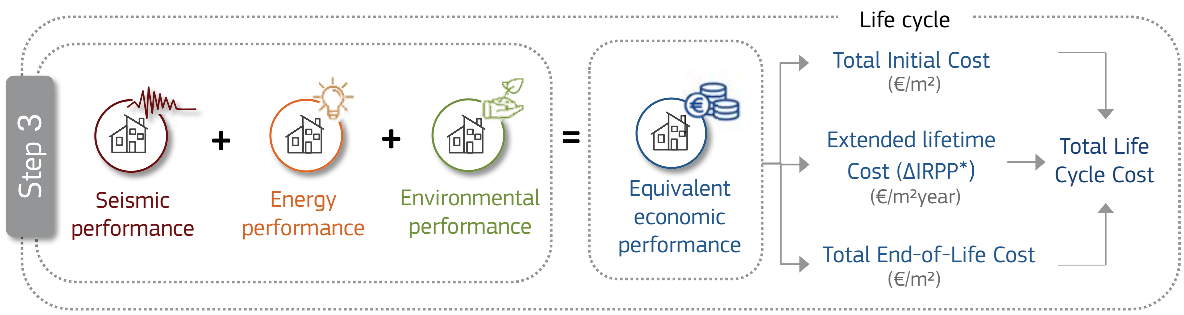
Requirements focussing on general principles, technological characteristics and engineering computation were identified to develop a simplified method for assessing the effects of a combined seismic and energy renovation. General principles consist of sustainable development and life cycle thinking approaches. Requirements related to technological characteristics intend to ensure the complete integration of energy and seismic renovation technologies, also investigating their compatibility for an incremental renovation strategy to overcome potential cost and/or time constraints (e.g. a limited disruption should be guaranteed for public buildings). Engineering computation requirements aim to address the computational stage of the method by employing simplified energy and seismic analyses, and converting the heterogeneous performance results into a single equivalent assessment outcome (e.g. economic output).

The proposed simplified method consists of four main steps. Step 1 collects input data and boundary conditions of an existing building. Step 2 selects technologies by analysing the physical and mechanical characteristics of seismic and energy renovation technologies to identify a set of potential compatible combined solutions. Step 3 refers to the integrated renovation design and evaluation, which represents the computational step to assess the seismic, energy, and environmental performances of combined renovation from a life cycle perspective to obtain a final result in economic terms. Step 4 addresses optimisation through a comparative assessment of alternative combined renovation solutions to identify the most effective one. Details are provided in Romano et al. (2023c, d).

The computational step represents the core of the proposed simplified method. The seismic, energy and environmental performance of a building, subjected to a combined renovation, are assessed at three different stages of its 'upgraded' life cycle, i.e. initial time (time of renovation intervention), extended lifetime stage, and end-of-life time. Performance results are expressed in equivalent cost, and added into a global result in monetary units leading to three total cost contributions associated with the three different stages of the life cycle (Figure 7). The total initial cost (€/m²) at the initial time is the sum of the equivalent costs of seismic and energy renovation interventions, and the equivalent cost due to environmental impact (in terms of CO_2-equivalent emissions) for manufacturing renovation materials/components. As for the extended lifetime stage, the seismic, energy and environmental performances are assessed on an annual basis, and expressed in economic terms. These are combined into the Integrated Retrofit Performance Parameter (IRPP) (€/m²year). The IRPP is defined as the sum of the expected annual losses due to seismic damages, the expected annual costs due to energy consumption, and the expected annual costs due to environmental impact generated by the expected seismic damage and energy consumption. The difference in IRPP before and after the renovation (ΔIRPP) represents the total extended lifetime cost, which includes the annual economic savings due to renovation, as well as the opportunity to consider potential fiscal incentives. The total end-of-life cost (€/m²) at the end-of-life time is the sum of the equivalent end-of-life cost for dismantling the seismic and energy renovation technologies and the equivalent cost associated with the environmental impact of dismantling and recycling/reusing the renovation materials and components.

The total equivalent economic performance, obtained by combining the three total cost contributions, expresses the variation of the equivalent total life cycle cost over the lifetime of the building, represented by a cost over time curve. A representative qualitative curve (i.e. red curve in Figure 8) starts at the initial time with a negative cost value corresponding to the total initial cost, which indicates the initial economic investment for the combined renovation intervention. Subsequently, the combined renovation, expressed by the annual economic savings (i.e. Δ*IPRR*), starts to demonstrate its benefits leading the curve to cross the time axis. The crossing point corresponds to the total recovery of the total initial cost at a specific time, defined

Figure 7. Simplified method – Step 3.



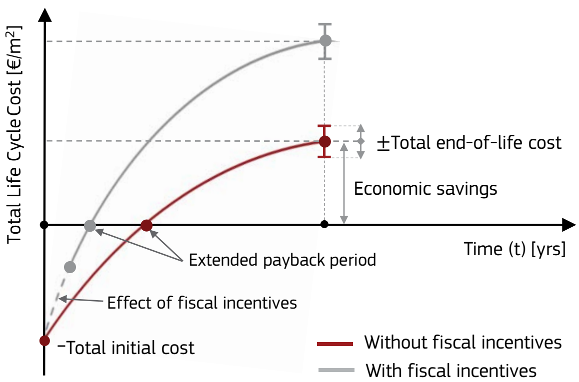
* ΔIRPP → Annual economic savings due to renovation and opportunity to consider fiscal incentives

Source: Romano et al. (2023c, d).

as the extended payback period. The latter represents the time needed (expressed in years) to achieve the return on the initial economic investment for the combined renovation. The extended payback period is a significant parameter indicating the economic effectiveness of any implemented renovation intervention; the lower the payback time, the more cost-effective the renovation. From this point forward, the curve shows the benefits of the combined renovation, indicating the cumulated annual economic savings until the end-of-life of the building. Finally, a positive or negative cost value, corresponding to the total end-of-life cost, is associated to the end-of-life time. If the potential for reuse/ recycle of materials and/or components of seismic and energy renovation technologies exceeds the environmental burdens leading to final environmental benefits, the total end-of-life cost is considered as 'credit'. The latter is indicated in the curve as a positive cost value, which increases the final economic savings. In the case of fiscal incentives, the representative curve (i.e. grey curve in Figure 8) differs from the previous one by a change in the slope due to a faster recovery of the initial economic investment with a consequent reduced extended payback time and higher cumulated economic savings. The incentives are active for a limited period of time, after which the curve assumes the same trend of the red one.

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. Stakeholders can easily compare potential solutions based on combined interventions or different retrofit technologies in a life cycle perspective. Furthermore, it enables the verification of the renovation effectiveness over time by monitoring the payback period among different renovation strategies. The payback period can be reduced or extended depending on the seismic or energy performance targets to be satisfied.

Figure 8. Simplified method – total life cycle cost vs time curve.



Source: Romano et al. (2023c, d).

4.4. Case study: application of methods to assess the effects of combined renovation

Four case studies representative of EU residential and public buildings were identified to assess the benefits of combined renovation. RC and masonry buildings represent the predominant construction typologies in the EU-27, specifically RC frame structures and rubble stone or brick masonry. This outcome along with the analysis of the most common envelope components of the EU building stock led to the identification of the following case studies (Romano et al, 2023c, d): (*i*) a public rubble masonry building with a pitched timber roof, and floors of steel beams and hollow clay flat blocks, (*ii*) a residential brick masonry building with a pitched timber roof and floors of cast-in-place RC beams and hollow clay blocks, (*iii*) a residential RC building, and (*iv*) a public RC building, with a roof and floors of cast-in-place RC beams and hollow clay blocks, and infill walls of hollow bricks. However, the roof is pitched for the residential building and flat for the public one. Potential locations for the case studies resulted from the combination of two macro-seismic hazard areas and three climatic zones. Hazard areas were based on average values of peak ground acceleration, which was obtained from ESHM20 (Danciu et al., 2021). Climatic zones were based on EU 2019 heating degree days average annual data (Eurostat, 2020a, b), leading to a six-column seismic–climatic matrix.

The combination of case studies and different locations enabled the selection of four representative buildings in Italy, as this country includes all possible

scenarios of the seismic-climatic matrix. Case study 1 is a three-storey residential RC building erected in 1967 in Toscolano Maderno (Brescia province), renovated 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), upgraded 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), constructed in 1965, and renovated with an exoskeleton of steel concentric 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.

The SSD methodology was first applied to the four case studies. The methodology (Section 4.2) was applied to the four selected buildings considering both their pre- and post-renovation state. Specifically, during Step 1, results in terms of operational energy consumption derived from dynamic energy analyses were converted into cost using the 2019 Eurostat electricity (Eurostat, 2020c, d) and natural gas (Eurostat, 2020e, f) prices in Italy. Similarly, in Step 2, equivalent CO_2 emissions of structural and non-structural components related to the production stage of their life cycle were converted into cost. Carbon prices for this conversion were based on the cap-and-trade EU Emission Trading System (EU-ETS)[14], which issues EU emission allowances (EUAs), i.e. the currency of the emission trading. The carbon price increased significantly in mid-2021, reaching a value equal to 60 €/tCO_2eq (COM 2021/962), further risen to date. High prices are a fundamental sign that the market is pricing in the cost of transition to a greener economy, and such prices are needed to provide the right incentives to meet the stringent EU climate-neutrality goal by 2050. The European Energy Exchange (EEX)[15] is the EU common platform for EUA auctioning. Hence, the EEX was selected to identify the carbon price by considering the EUA spot price equal to 76.50 €/tCO_2eq (specific date of observation: 24 March 2022). Step 3 resulted in expected losses based on repair costs due to seismic damage. The energy, environmental and structural performance results were subsequently combined into a global result in monetary units, according to Step 4 of the methodology. Results from the four case studies are reported in Table 2. Seismic and energy renovation interventions provided an effective combined improvement in all the studied buildings. Renovation benefits are easily demonstrated by comparing the monetary global assessment parameter accounting for the combination of the energy, environmental and structural costs before and after the renovation. Indeed, total cost reductions (compared to the pre-renovation state) equal to 42 %, 41 %, 31 %, and 47 % were found for the case studies 1, 2, 3, and 4, respectively.

The proposed simplified method was also applied to the four case studies to demonstrate the advantages of implementing a user-friendly assessment tool compared to the existing method. Attention is drawn here to Step 3 of the proposed method to assess the seismic, energy and environmental performance of the four buildings at the three stages of their 'upgraded' life cycle (Section 4.3). These results provide the equivalent total life cycle cost over time curves for the four case studies (Figure 9). The curves show the initial costs for the combined renovations, the recovery of the investment over time up to the extended payback period (i.e. curves crossing the time axis) and the cumulated economic savings considering a remaining economic life of the

[14] The EU-ETS represents the EU's cornerstone strategy to tackle climate change, firstly established in 2005 and currently at its fourth trading phase (https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en).

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

Table 2. SSD methodology – energy, environmental, and structural performance results in economic terms for the four case studies.

Results in economic terms	Case study 1		Case study 2		Case study 3		Case study 4	
	Pre-renovation	Post-renovation	Pre-renovation	Post-renovation	Pre-renovation	Post-renovation	Pre-renovation	Post-renovation
STEP 1 Energy cost [k€]	630.8	486.3	1174.8	739.9	1055.6	762.2	1378.7	684.3
STEP 2 Environmental cost [k€]	9.7	18.5	7.4	14.4	19.9	32.8	12.7	21.2
STEP 3 Structural cost (expected loss) [k€]	234.0	3.5	102.7	2.5	87.8	6.8	85.9	76.9
STEP 4 Global assessment parameter [k€]	**874.5**	**508.3**	**1284.8**	**756.8**	**1163.4**	**801.9**	**1477.3**	**782.4**

Source: Romano et al. (2023c, d).

Figure 9. Simplified method – total life cycle cost over time for four case studies – Step 3.

Source: Romano et al. (2023c, d).

renovated buildings equal to 50 years, and the potential credits achieved at the end-of-life time due to the recycle/reuse of materials/components. It is worth noting that the recycle and reuse of materials and components do not achieve credits only in case study 4, thus reducing the final value of economic savings at its end-of-life time. The ΔIRPP metric, calculated for the four case studies, confirmed the economic savings found by applying the SSD methodology. Specifically, cost reductions between the pre-and post-renovation states were found to be equal to 71 %, 55 %, 61 %, 39 %. Furthermore, the payback period for the four case studies, considering a remaining economic life of 50 years, was estimated equal to approximately 16, 17, 18 and 20 years, respectively. These periods can be reduced, if fiscal incentives are considered (e.g. Sisma Bonus and Eco Bonus mechanisms in Italy). Beyond the renovation benefits, it is worth focusing on the advantages of the proposed simplified method. It allows users to select the most effective renovation technology by easily comparing the results of the seismic, energy and environmental performances of a renovated building. Results are expressed in monetary terms facilitating understanding of performance and renovation benefits by different stakeholders. Another key simplification refers to the assessment of the IRPP before and after renovation to calculate the expected annual seismic losses and costs due to energy consumption at the extended lifetime stage. The ease of computation is ensured by the use of generalised seismic (i.e. fragility) and energy (i.e. thermal energy demand vs heating degree days) performance curves based on simulation procedures for the combination of representative building classes and renovation technologies. Further research is needed to enrich the catalogue of generalised curves and extend the application of the proposed method to a larger number of representative building classes in Europe.

5. Regional prioritisation and impact of renovation

Integrated renovation can provide a risk-proofed, sustainable, and inclusive built environment in a cost-efficient way.

Building renovation is a multidimensional problem. Different priority and impact metrics should be employed depending on the sector (seismic safety, energy efficiency, socioeconomic vulnerability) and the geographical focus. Metrics should further rely on the aim of renovation plans to accomplish the highest impact on a single sector or most spread impact across multiple ones.

The pilot project provides a framework for regional prioritisation and impact assessment, along with a set of open access data, ranking indicators and impact metrics which can inform a more focussed approach in local, regional and European policy making.

5.1. Overview

The pilot project collected policy measures for enhancing the seismic and energy performance of buildings across EU Member States. The measures were reviewed to understand gaps and best practices which may facilitate further implementation.

An integrated analysis framework was developed to prioritise regions for building renovation across the EU-27. The framework employs open access harmonised data and state-of-the-art methodologies and models to assess seismic risk, energy performance of buildings, and socioeconomic vulnerability.

The integrated analysis framework was further developed to formulate alternative renovation scenarios, perform regional impact assessments and cost–benefit analysis considering the renovated building stock across the EU-27.

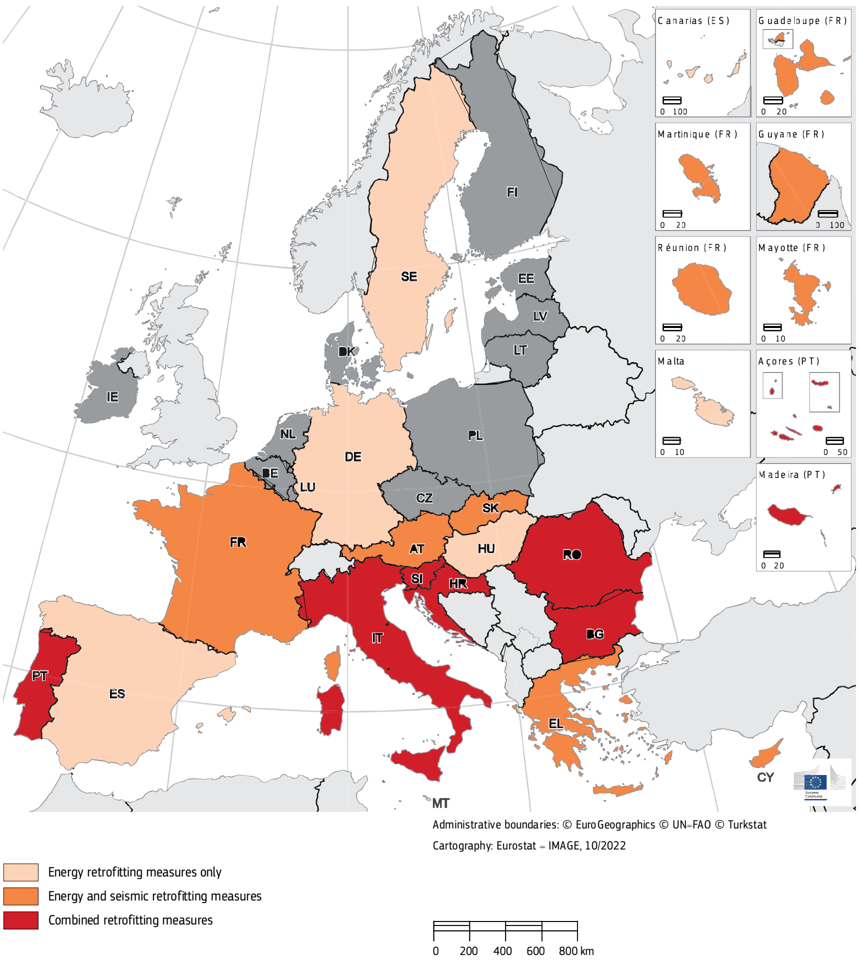
The pilot project develops the ‘Building renovation makerspace’ digital platform to share information and increase awareness in support of building renovation in the EU.

5.2. State-of-practice in policy measures

Policy measures ensuring the seismic safety and energy efficiency of buildings across EU Member States were collected and reviewed. 16 EU Member States that included seismic risk in their 2015 national risk assessment were considered (Butenweg et al., 2022). Legislation, strategies and financing instruments for the energy efficiency upgrading of buildings are implemented in all the 16 countries. Policy measures for seismic strengthening were found in 11 out of the 16 Member States. Specific measures that target both seismic and energy renovation were identified only in six countries (Figure 10).

Significant progress is observed in policy measures related to the energy efficiency upgrading of buildings. This may not come as a surprise, considering that EU Member States need to comply with EU legislation. As set forth in the Energy Performance of Buildings Directive (Directive 2018/844), Member States have recently prepared their long-term renovation strategies[16] to improve the energy performance of their building stock, setting out clear objectives and milestones on their way to full decarbonisation by 2050. A sheer will for advances in this sector is reflected on the increased number of national strategies and programmes implemented over the years (e.g. SWD 2021/365), with increasingly higher targets for energy efficiency and ambitious cuts in carbon emissions. Overall, many measures are available for enhancing the energy efficiency of buildings, fostering the implementation of energy

Figure 10. Overview of identified policy measures for building renovation in 16 EU Member States.



Source: Butenweg et al. (2022).

[16] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en.

performance certificates, building renovation passports and nearly zero-energy buildings. Likewise, different financial instruments (e.g. loans with low interest rates, reduced taxes, etc.) have been introduced (Zangheri et al., 2021) to enable building renovations.

Policy measures for seismic strengthening of buildings are less homogenous across the EU. To a certain extent, this is related to the diverse seismicity of European regions. The publication rates of National Annexes to Eurocode 8 for the seismic design of structures (Athanasopoulou et al., 2019)[17], are lower in the northern countries due to the low seismic hazard. However, even in countries with higher seismic risk, policy measures for seismic renovation are generally less common than those for energy upgrades. Reconstruction and inspection programmes along with updates in seismic codes are often triggered by significant seismic events.

A few paradigms pave the way towards policy measures for combined renovation. The 2015 national programme for the energy efficiency of multi-family residential buildings in Bulgaria targets mainly energy upgrading of buildings but includes considerations for structural rehabilitation. The Ecosisma bonus (Law 2017/205) and Superbonus (Law 2020/77) in Italy offer tax deductions for combined renovation of buildings. A recent law in Portugal (Decree–Law 95/2019) addresses requirements for energy efficiency, seismic and fire safety, acoustics and accessibility. The national programme for increasing the energy performance of apartment buildings in Romania (Ordinance 18/2009) although conceived for energy renovation works, it was later extended (Order 589/1154/2015) to include requirements for a detailed seismic evaluation of buildings. The Building Cards instrument in Slovenia will provide guidance on measures to promote renovations including energy efficiency, fire, and seismic safety (SWD 2021/365). The issue of seismic safety is recognised in the national recovery and resilience plans[18] of Croatia, Italy, France, Romania and Slovenia, and the 2020 long-term renovation strategies of Croatia, Cyprus, Hungary, Italy, Romania, Slovenia and Spain.

Further actions need to be taken to promote holistic renovations. Regulatory framework, financial instruments, and digital tools similar to those for energy renovation are capable to promote seismic and integrated renovation as well. Building performance should be seen from a broad perspective when designing measures for multi-owner buildings and vulnerable households, or measures linking rental contracts with minimum requirements and certificates. Successful examples of financial instruments from the energy sector (e.g. tax incentives, green bonds and loans) can be adapted to improve building performance as a whole according to regional requirements. Digital tools such as building passports and smart sensors may serve diverse requirements (structural, thermal, etc). Awareness campaigns are required to inform professionals, owners and tenants on the current risk of the existing buildings stock and on the financial, structural and environmental benefits of renovation. Training and certification of professionals, along with further scientific development, will ensure adequate skills and know-how in integrated renovation methods.

5.3. Priority regions for building renovation

An integrated analysis framework was developed to prioritise regions for building renovation across the EU-27. It builds on the recommendation of the 2019 Global Assessment Report on Disaster Risk Reduction (UNDRR, 2019) for a more holistic representation of the human, social, economic and ecological impact of seismic events, and the EU disaster resilience goals (COM 2023/61) for evidence-based understanding of the economic and social impact of disaster risks. The integrated framework (Gkatzogias et al., 2022a, c) combines three analysis routes that assess (*i*) seismic risk to buildings and occupants, (*ii*) energy performance of residential buildings, and (*iii*) socioeconomic vulnerability. A joint model describes the spatial

[17] https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-8-design-structures-earthquake-resistance.

[18] https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en.

distribution of buildings (number, type, area, replacement cost) and associated population. A wealth of open-access state-of-the-art data and models related to seismic hazard, climatic conditions, physical and social vulnerability, along with energy performance modelling in Europe were employed. Primary metrics for regional assessment and prioritisation include loss of life, economic loss (cost for seismic repair and cost for space heating energy) and energy consumption. The estimated metrics from each assessment route were used to form single-sector integrated indicators (e.g. seismic indicator addressing economic loss and loss of life) and multi-sectoral integrated indicators combining seismic and/or energy and/or socioeconomic metrics.

Seismic risk is estimated to 270 fatalities and a repair cost of 4.6 billion euro a year in residential EU buildings. Both losses highlight European regions of moderate-to-high seismicity and vulnerability, as well as densely built and populated areas. Italian regions stand out in rankings both in terms of frequency (i.e. number of regions within the top 100) and priority (i.e. ranking position), especially in the case of economic loss. Considering frequency, they are followed by Greek or Romanian regions depending on the considered metric (economic loss or fatalities), along with dense urban areas of Spain, Croatia, Bulgaria, France, Portugal, Austria, Cyprus, Slovenia and Germany. On many occasions, the number of buildings and occupants, and the value of buildings bring regions of moderate hazard ahead of high seismicity regions. On the other hand, normalising loss to the above variables (Figure 11a), yields more robust indicators for comparing regions. Normalised loss increases the priority and frequency of Romanian and Greek regions, and excludes regions of Austria, France, Germany and Portugal from the top 100. The top 100 regions based on a single-sector integrated indicator that combines normalised economic loss and loss of life incorporates 67 % and 73 % of the total repair cost and fatalities in the EU.

Residential EU buildings consume annually more than 1900 TWh for heating at a cost of 180 billion euro[19]. The indicator type has a more pronounced effect on rankings based on heating energy consumption and cost. Annual loss highlights densely built and populated regions extending from Spain and France westwards to Austria and Hungary, and towards the north to Sweden and Finland; most of the regions belong to France and Italy. Energy renovation of the building stock in the above regions will have the highest economic benefit. Loss normalised to the number of buildings shifts priority towards northern Europe (Finland and Sweden), but still focus on urban areas with a strong presence of German regions, followed by French and Italian ones. Normalising energy consumption both to the number of buildings and the regional climatic conditions[20], to highlight the effect of inefficient building envelopes, shifts priority from northern to central and southern Europe, mainly Italy, followed by Germany and France. Conversely, when exploring the cost of energy normalised to the size and value of the building stock (Figure 11b), the prioritisation introduces many regions in south-eastern and central Europe (e.g. Romania followed by regions in Belgium, Czechia, Slovenia, Croatia and Greece). A single-sector integrated indicator combining energy consumption and cost highlights regions mainly from Germany and Italy, followed by Romania and France. 18 % of the total energy cost and 17 % of the total energy consumption in the EU are rooted in the top 100 regions derived from the integrated indicator.

Building renovation is a driver of employment growth and improvements in living conditions of socially vulnerable groups. This is in line with EU policies and initiatives such as the Renovation Wave, the Recovery and Resilience Facility[21], and the Cohesion Policy 2021–2027[22]. Socioeconomic

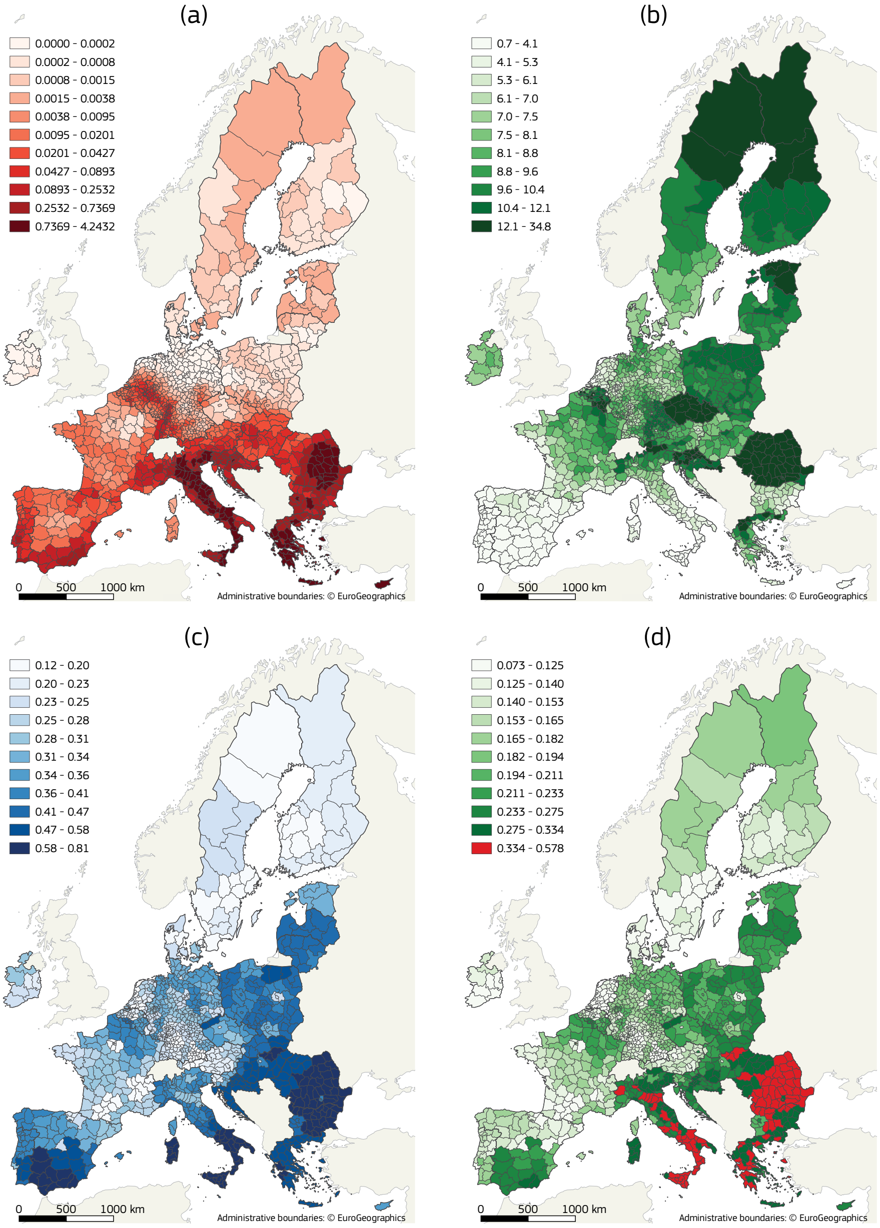
[19] Energy prices correspond to 2020.

[20] Climatic conditions are represented by heating degree days, i.e. a variable calculated from outside air temperature measurements, and used to estimate heating energy requirements.

[21] https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en.

[22] https://ec.europa.eu/regional_policy/en/2021_2027/.

Figure 11. Annual economic loss of residential buildings (normalised to their value) due to (a) seismic repair, and (b) heating energy consumption; (c) socioeconomic vulnerability; (d) multi-sectoral indicator integrating seismic risk, energy performance, and socioeconomic vulnerability (in red: top 100 regions with the highest indicator value).



Source: Figure 11a: Data in the Global database of administrative areas system from European Seismic Risk Model 2020 (Crowley et al., 2021, available from EFEHR, http://risk.efehr.org), Mapping to the 2021 Nomenclature of territorial units for statistics classification system by JRC (Gkatzogias et al., 2022a); Figure 11b–d: Gkatzogias et al. (2022a).

vulnerability quantifies socioeconomic development, smart, sustainable and inclusive growth, and social progress. Prioritisation based on socioeconomic vulnerability shifts the focus to southern and eastern European regions (Figure 11c), which follows more closely the trends of seismic risk. The top 100 regions with the highest socioeconomic vulnerability accumulate annually 6 % of the energy consumption and cost, 31 % of fatalities, and 25 % of the repair cost in the residential EU building stock.

Multi-sectoral integrated indicators highlight the regions that benefit from integrated renovation more than separate interventions. They are capable of capturing the different patterns of prioritisation among different sectors, handling complexity and filtering out severe disparities (e.g. among economic loss due to energy cost and seismic repair). Economic loss indicators integrating seismic risk with energy performance of buildings result in a high priority of seismic regions in Romania, Greece, Italy, Slovenia, Croatia and Bulgaria (ordered by decreasing number of regions), where the highest economic benefit from integrated renovation was found. Integrating in addition socioeconomic vulnerability, results in a shift of priority to south-eastern Europe. A multi-sectoral integrated indicator combining all normalised indicators of economic loss, loss of life, energy consumption and socioeconomic vulnerability promotes renovation mainly in regions of Romania, Italy, Greece and Bulgaria (Figure 11d). Approximately 10 % of the energy consumption and cost, 61 % of fatalities, and 49 % of repair cost derive from the top 100 regions highlighted by the multi-sectoral integrated indicator.

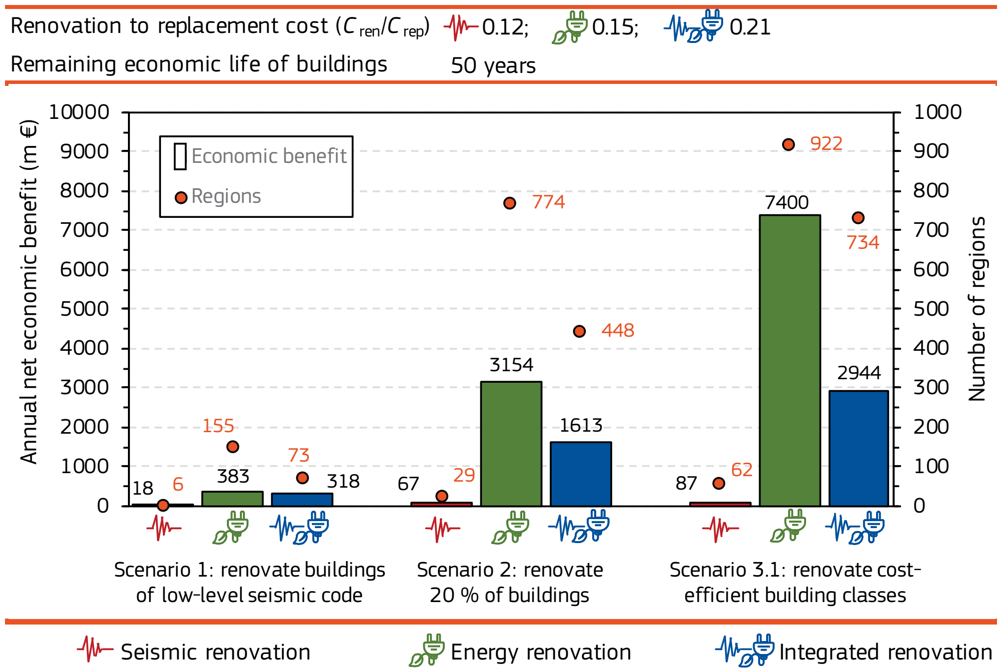
5.4. Renovation impact

The integrated analysis framework was further developed to investigate the impact of renovation scenarios across the EU-27. Specifically, the framework was extended to formulate alternative renovation scenarios, perform regional impact assessments and cost–benefit analysis considering the renovated building stock (Gkatzogias et al., 2022b, c). Regional assessments of seismic risk and energy performance for renovated buildings employ the same seismic hazard, climatic conditions, and distributions of buildings and population as in the case of existing buildings (Section 5.3). Yet, each building class is mapped to an upgraded seismic vulnerability and energy performance class to model the effect of renovation. A series of impact metrics were introduced to investigate the reductions (benefit) in economic loss, loss of life, and space heating energy consumption, annually or over the remaining economic life of buildings (over which the renovation is effective). Impact metrics further assess the scenario in terms of affected buildings and population, and naturally its economic feasibility, considering the effect of different renovation costs and remaining lives of buildings. The economic feasibility refers to the capacity of a single or multiple building classes within a region or multiple regions to generate net economic benefit due to renovation (i.e. reduction in economic loss minus the cost of renovation).

Scenario 1 investigates the impact of renovating building classes that were constructed according to specific levels of seismic design codes. Seismic renovation was found to be economically feasible in a few regions across the EU-27, characterised by quite high seismic risk and low renovation cost. The scenario is more promising for the energy efficiency upgrading of buildings constructed with no or low seismic design considerations, as these are characterised by low energy performance. Even so, energy renovation alone would involve a high risk of renovation investment loss due to their low seismic safety, contrary to integrated renovation. As an example, an integrated approach allows renovating buildings designed with a low-level seismic code in a cost beneficial way in 73 regions across the EU-27 (1151 investigated regions), as opposed to 155 and only six regions in the case of energy efficiency and seismic upgrading, respectively. Energy and integrated renovation yield similar net economic benefits (Figure 12) and energy savings, though integrated renovation saves in addition 44 lives a year (compared to 19 of seismic renovation). In Figure 12, the costs of seismic and energy renovation are based on average values obtained from various studies, while the cost of integrated renovation is assumed 25 % lower than applying separately each type of renovation (Gkatzogias et al., 2022b).

Scenario 2 investigates the impact of renovating specific percentages of the regional building stocks. Renovated buildings comprise those classes with the highest individual economic feasibility for renovation (i.e. highest net economic benefit) until the preselected percentage is reached. Overall, increasing the percentage of renovated buildings, decreases the net economic benefit, thus the efficiency of the scenario. Across the EU-27, integrated renovation of 20 % of the building stock is economically

Figure 12. Cumulative annual net economic benefit for regions across the EU-27 where renovation is cost-beneficial.



Source: Data from Gkatzogias et al. (2022b).

feasible in 448 regions, as opposed to 774 for energy efficiency upgrading, and just 29 for seismic strengthening (Figure 12). Integrated renovation allows upgrading the seismic safety of structures in a cost-efficient way to a much larger extent than seismic renovation alone, saving more lives (i.e. 30 more in a year). It further presents a net economic benefit (approximately 1.6 billion euro a year in Figure 12) and energy savings (79 TWh) in the same order of magnitude as energy efficiency upgrading (3.2 billion euro and 127 TWh, respectively).

Scenario 3 identifies the maximum fraction of buildings and associated building classes that can be renovated in a cost-beneficial way. Two different variations were explored. Scenario 3.1 promotes for renovation all the building classes that are individually economically feasible to renovate, i.e. those classes that exhibit net economic benefit when renovated on a standalone basis. Scenario 3.2 considers all the building classes that can be renovated cost-beneficially as a group. In this context, Scenario 3.2 exploits the net economic benefit derived from Scenario 3.1 to renovate additional building classes which would not be beneficial to renovate on a standalone basis. According to Scenario 3.1, integrated renovation is economically beneficial in 734 regions out of the considered 1151. Although this is lower than in the case of energy efficiency upgrading (922 regions), it represents a vast increase when compared to the 62 regions identified for seismic renovation, exhibiting a significantly increased impact in reducing fatalities across the EU (i.e. twice as many saved lives as seismic renovation alone). At the same time, the economic benefit (Figure 12) and the reduction in energy consumption are in the same order of magnitude with energy efficiency upgrading, and as shown in the following case study (Section 5.4.1) occasionally higher.

Overall, the magnitude of the renovation impact depends on the scenario efficiency and the economic assumptions. The efficiency of a renovation strategy increases along with its capability to target buildings with specific attributes rather than generic classes. Inevitably, this comes at the cost of increased complexity. Irrespective of the renovation scenario and type (i.e. seismic, energy, integrated), the renovation impact is sensitive to the renovation and replacement cost, the inflation of construction cost and energy prices, and the remaining life of buildings. The energy prices used to translate energy consumption to cost correspond to the year 2020. Considering the significant rise of energy prices in 2022, the expected economic benefit due to energy renovation increases as the cost of energy increases in the long term.

Seismic and energy renovation of buildings may easily extend to additional aspects of renovation. Integrated renovation is expected to be even more beneficial in high seismic risk regions of southern Europe if energy consumption for space cooling is considered, due to the hot climate of these regions and the expected increased benefit due to energy upgrading. In regions at low seismic risk, seismic renovation may attract little interest. However, structural interventions to improve the safety of the ageing building stock under vertical loads, environmental actions or other hazards may be relevant, and these can be investigated through the integrated framework presented herein.

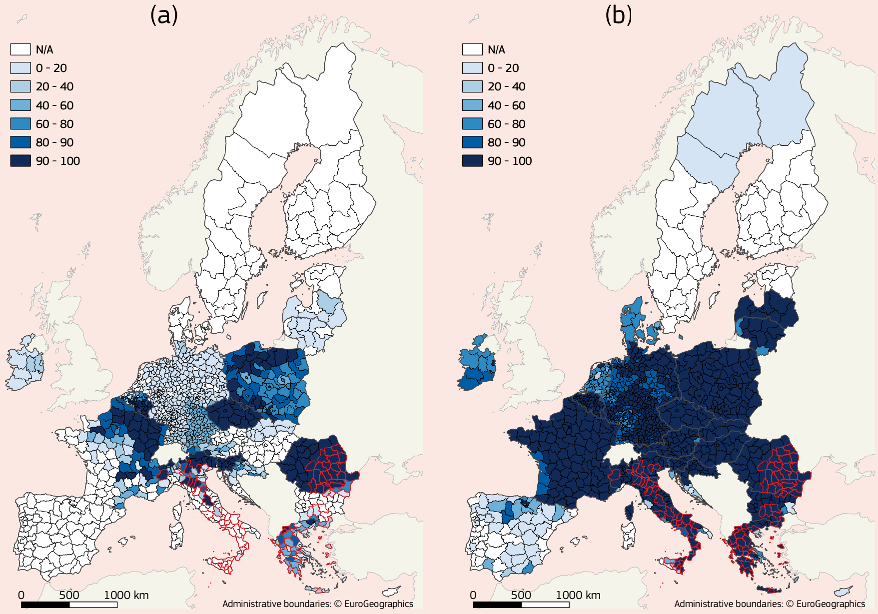
5.4.1. Case study: priority regions in the spotlight

The impact of renovation scenario 3 is presented with a focus on priority regions. The case study considers renovation scenarios 3.1 and 3.2, applied to 100 priority regions. Regions were selected according to a multi-sectoral integrated indicator that considers seismic risk, energy efficiency and socioeconomic vulnerability. The indicator highlights regions of Bulgaria, Greece, Italy and Romania (Figure 13). Scenario 3 can be implemented in a region if at least one building class that can generate net economic benefit when renovated is present. An important feature of the scenario is that the building classes promoted for renovation differ by renovation type, since classes are prioritised based on their capacity to result in economically feasible renovations, which in turn is different for seismic, energy, or integrated renovation. The renovation impact by scenario and renovation type is presented in Table 3. The case of renovating the entire building stock within the priority regions is also included in Table 3 for comparison purposes, since the negative net economic benefits indicate an economically inefficient strategy irrespective of the renovation type.

Scenario 3.1 renovates building classes that exhibit individually a net economic benefit. In this context, the scenario indicates the benefit for individual building owners to renovate their homes. According to Table 3, the cumulative benefit for owners of the buildings that are promoted for renovation within the 100 priority regions is 78, 708, and 742 million euro a year for seismic, energy, and integrated renovation, respectively. Integrated renovation saves annually twice as many lives as seismic strengthening, and approximately 27 TWh of energy consumption a year which is somewhat reduced compared to energy efficiency upgrading. In addition, it enables renovation in more regions than separate renovations, and approximately the same percentage of buildings as energy renovation, exhibiting a striking improvement compared to seismic renovation. Financing schemes may be explored by transferring part of the renovation cost to state authorities, hence increasing the benefit for the owners, or increasing the number of regions where renovation becomes economically advantageous.

Scenario 3.2 renovates building classes that exhibit a cumulative net economic benefit. As this scenario takes advantage of the net economic benefit derived from scenario 3.1 to renovate more buildings, it is more suitable when the renovation cost and benefit are handled by a central funding entity. Integrated renovation according to scenario 3.2 increases the percentage of renovated buildings from 36 % to half the building stock (Table 3), at an additional annual cost of 230 million euro (i.e. 742 – 512 in Table 3) compared to scenario 3.1. Likewise, integrated renovation saves 113 lives and 35 TWh a year which represent 68 % and 52 % of the relevant benefits if all buildings were renovated. Overall, integrated renovation has either an impact which is more beneficial compared to seismic strengthening and energy efficiency upgrading, or slightly inferior to the latter depending on the considered impact metric (Table 3). Specifically, the number of renovated buildings and saved lives increase, whereas the net economic benefit and the number of

Figure 13. Scenario 3.2 – percentage of renovated buildings due to (a) integrated renovation (renovation to replacement cost ratio C_{ren} / C_{rep} = 0.21), and integrated renovation with a 50 % reduction in renovation cost (C_{ren} / C_{rep} = 0.10) (in red borders: top 100 regions based on a multi-sectoral indicator integrating seismic risk, energy efficiency and socioeconomic vulnerability).



Source: Gkatzogias et al. (2022b).

affected occupants were found to be lower, albeit close to the values of energy renovation. Impact maps from this scenario (Figure 13) can be equally tailored to national or regional authority requests, aiming to maximise the percentage of renovated buildings and the affected population rather than yield a net economic benefit. In the latter case, when renovation is not economically feasible (e.g. white regions in Figure 13a), funding from a central entity (e.g. at European level) that partially covers the cost of renovation may be explored (e.g. 50 % of cost in Figure 13b).

Table 3. Cumulative impact assessment for 100 priority regions (selected according to a multi-sectoral integrated indicator considering seismic risk, energy efficiency, socioeconomic vulnerability).

Top 100 priority regions			
	Buildings (million)	10.6	
	Population (million)	30.6 (average number of occupants over 24 hours)	
	Renovation to replacement cost (C_{ren}/C_{rep})	(Seismic) 0.12; (Energy) 0.15; (Integrated) 0.21	
	Remaining economic life of buildings	50 years	

Renovation scenario		**Scenario 3.1**			**Scenario 3.2**			**Renovate entire building stock**		
		Seismic	Energy	Integrated	Seismic	Energy	Integrated	Seismic	Energy	Integrated
Annual benefit	Net economic loss (m €)	78	708	742	12	567	512	-4225	-1610	-2298
	Fatalities (no)	55	—	100	71	—	113	167	—	167
	Energy consumption (TWh)	—	29.5	26.5	—	38.5	35.0	—	67.7	67.7
Scala-bility	Affected regions (no)	47	66	73	47	66	73	100	100	100
	Renovated buildings (%)	4	37	36	13	47	50	100	100	100
	Affected population (%)	6	36	34	13	47	46	100	100	100

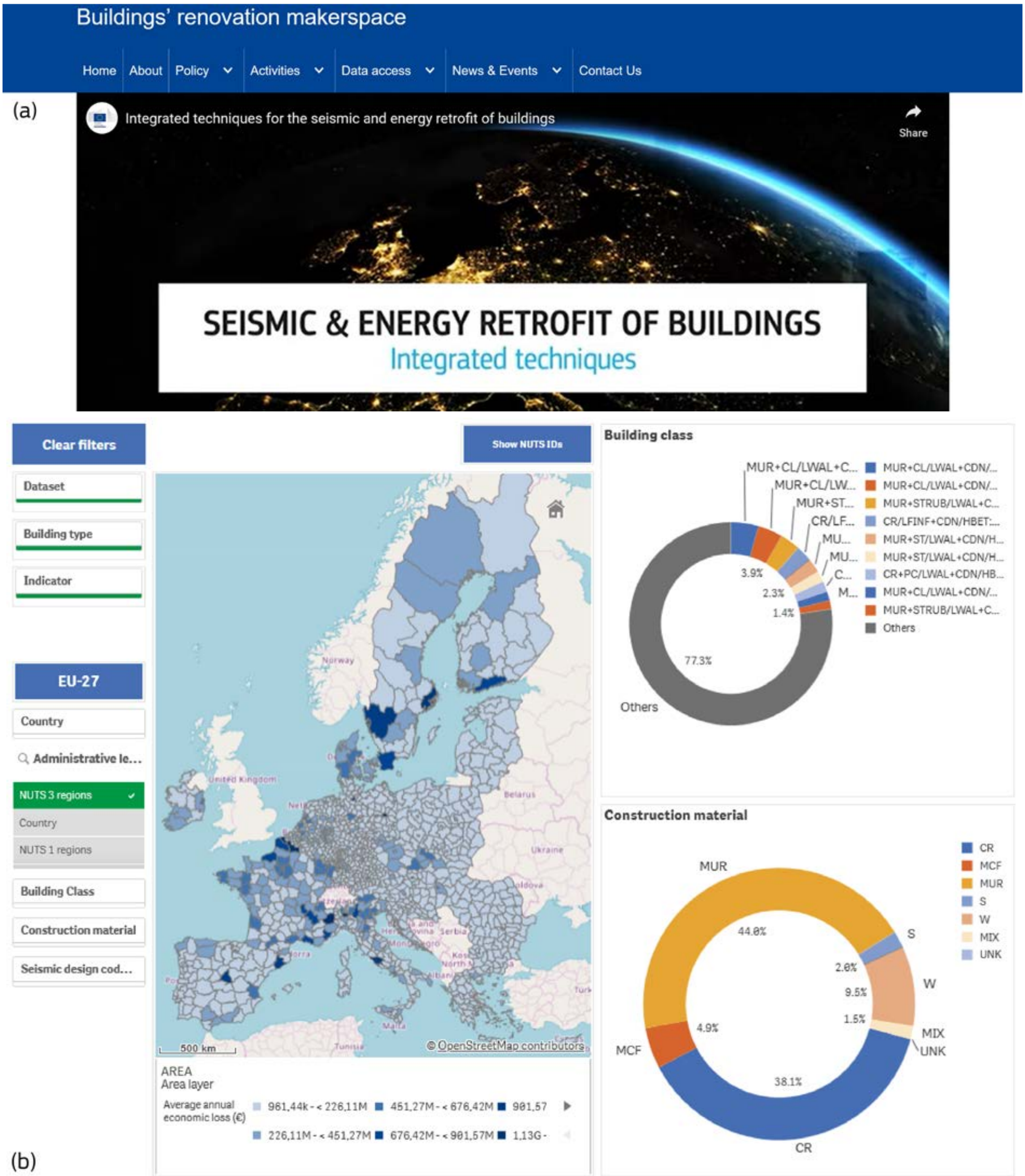
Seismic renovation; Energy renovation; Integrated renovation

Source: Gkatzogias et al. (2022b).

5.5. Outreach

A digital platform is developed to visualise and share the pilot project output. The platform (Figure 14) includes geo-referenced data at different administrative levels of the 2021 nomenclature of territorial units for statistics classification system. Data address building stock attributes, population, seismic risk and energy performance addressing both existing and renovated buildings, socioeconomic indicators, and policy measures. Visualisation tools provide open access to the data through interactive maps and charts. The web platform further includes sections on the pilot project objectives, policy background, the different activities of the project, and a database of publications and promotional material.

Figure 14. Building renovation makerspace: (a) homepage; (b) data visualisation: deaggregation of annual economic loss due to heating energy consumption by region, building class and construction material.



Source: https://buildings-renovation-makerspace.jrc.ec.europa.eu.

6. Conclusions

The pilot project provides scientific evidence for the integrated seismic and energy renovation of buildings. Technical guidelines are based on the analysis of the European building stock, renovation technologies, assessment methodologies and scenarios for renovation. These guidelines can help authorities at multiple levels with the practical implementation of bespoke strategies (e.g. long-term renovation strategies, recovery and resilience plans) that consider regional needs and leave no one behind. Optimised investments to modernise buildings in an energy-efficient, safe and sustainable way will improve the lives of millions of Europeans and create jobs in the construction ecosystem.

EU masonry and RC buildings particularly would benefit from combined seismic and energy renovation. At least 60–70 % of the building stock in examined regions of selected EU countries (e.g. Italy, Greece, Bulgaria, Romania) were built with no or low seismic design and energy efficiency requirements. Furthermore, focusing on the Italian building stock, nearly 20 % and 15 % of masonry and RC buildings, respectively, are within regions of high seismic hazard and severe climatic conditions.

A catalogue of seismic renovation technologies was provided along with their classification, identifying exoskeletons for masonry and RC buildings as promising solutions from a life cycle thinking perspective. Seismic renovation technologies were investigated, and average unit-cost ranges (Italian market-dependent) were proposed as a useful supporting tool in the preliminary phase of renovation projects to estimate budgets, enable project financing, and facilitate pre-screening of renovation strategies.

A catalogue of energy renovation technologies affecting the building envelope components was proposed, identifying external insulation for walls as highly compatible with the EU building stock. Energy renovation technologies were ranked in terms of attractiveness for combined renovation. Insulation of external wall air chambers, internal insulation of roofs, and internal insulation of external walls result in highly attractive renovation solutions, mainly due to low cost, high performance and low generated waste.

Identifying efficient schemes for combined renovation demands a comprehensive examination of technologies. A detailed assessment of existing scientific research highlights four main types of interventions, including (*i*) exoskeletons; (*ii*) interventions on the existing envelope, (*iii*) replacement of the existing envelope; and (*iv*) interventions on horizontal elements. Further development and experimental research is still required as many of the assessed technologies are still in a conceptual stage, while few have already been tested and validated.

Quantitative multi-performance assessment methods based on life cycle thinking represent the most appropriate tools to evaluate the benefits of combined seismic and energy renovation of existing buildings. Two main classes of renovation assessment methods were reviewed. Sector-specific methods include uncoupled methods for the quantitative assessment of the seismic, energy or environmental performance of buildings. Multi-performance assessment methods include qualitative sustainability rating systems and quantitative methods combining different life cycle performance metrics.

A simplified assessment method for evaluating the combined seismic and energy renovation benefits in a common language (i.e. economic terms) was introduced as an effective tool to facilitate interaction among different stakeholders. The proposed method assesses the seismic, energy and environmental performances of the combined renovation in equivalent costs in a life cycle perspective, without requiring complex analyses. The possibility to examine the final outcome of a total life cycle cost over time facilitates the decision-making process.

The benefits of integrated renovation were demonstrated by applying an existing method and a proposed simplified one to four EU representative residential and public buildings. The existing method expressed the seismic and energy efficiency improvement due to renovation in the four case studies in terms of total cost reduction. The proposed simplified method confirmed the renovation enhancement in terms of annual economic savings and payback period, also demonstrating its feasibility and ease of use.

Prioritisation and impact analysis are key to inform bespoke renovation plans at a regional, national or European scale. According to the integrated framework for regional analysis, earthquakes in the EU-27 introduce a risk of 270 fatalities and 4.6 billion euro of repair cost a year in residential buildings, which consume annually more than 1900 TWh for heating at a cost of 180 billion euro. Different priority indicators should be employed depending on the sectoral and geographical focus, as well as the aim of renovation plans. Single and multi-sectoral integrated indicators can capture the different aspects of prioritisation while handling complexity and filtering out severe disparities. Approximately 10 % of the energy consumption and cost, 61 % of fatalities, and 49 % of repair cost derive from 100 regions in south-eastern Europe, highlighted by an indicator integrating seismic risk, energy performance, and socioeconomic vulnerability.

Integrated seismic and energy renovation is more beneficial than separate interventions. The majority of buildings in seismic regions are vulnerable to earthquakes. Commonly, these buildings are also energy inefficient. Structural strengthening ensures that the investments on energy efficiency, financed in part by European funds, will endure through the extended service life of the building. Integrated renovation saves more lives, minimises the disturbance to occupants and services, reduces the initial cost (labour, scaffolding, etc.), optimises the use of construction materials and reduces the amount of demolition waste. In 100 priority regions based on a multi-sectoral integrated indicator, seismic, energy, and integrated renovation can save 78, 708, and 742 million euro a year, respectively. The renovation impact is sensitive to assumptions regarding the renovation cost, the inflation of construction cost and energy prices, and the extended service life of renovated buildings. Moreover, the efficiency of a renovation strategy increases when targeting buildings with specific attributes rather than generic classes. Still, integrated renovation exhibits the unique capability of reducing energy consumption and fatalities due to earthquakes at the same time, and depending on the scenario, to a greater extent.

Further action is needed to promote future-proof renovation. Although policy measures for promoting energy upgrading are present in the Member States, measures for seismic strengthening or measures that target seismic and energy renovation are less common. Regulatory framework, financial instruments and digital tools similar to those for energy renovation, together with awareness campaigns, training and certification of professionals, may support a wider and more efficient integrated renovation of buildings.

The integrated seismic and energy renovation is a model for the comprehensive improvement of the built environment in the spirit of the New European Bauhaus. Harmonised exposure data and the similar models and methodologies used to assess damage (e.g. Chapter 5; Molinari et al., 2020) can support multi-hazard risk assessment for increased resilience of buildings to natural hazards and climate change (e.g. Poljanšek et al., 2017; Athanasopoulou et al., 2020; Sousa et al., 2020). Fire safety in the built environment remains a major societal issue (Athanasopoulou et al., 2023) that integrated building renovation can address. The removal of harmful substances such as asbestos (Maduta et al., 2022) is a further opportunity of an encompassing strategy.

Contributing to the implementation of building renovation policies.

Practitioners and policymakers may use the reviews of seismic, energy and integrated technologies for building renovation to identify appropriate solutions for specific projects. Classifications by life cycle thinking criteria, compatibility, performance and cost are provided, which may be useful for preliminarily design, project financing, as well as larger scale renovation impact analyses.

The proposed simplified method for assessing the seismic, energy, and environmental performance of renovated buildings from a life cycle perspective provides a user-friendly tool for designers and practitioners. Transforming the performance results in economic terms facilitates different stakeholders to easily recognise the benefits from combined renovation.

The review of policy measures across Member States provides best practices to facilitate further implementation of integrated renovation and shape action plans at the EU, national and regional level.

The integrated framework for regional prioritisation and impact analysis highlights the regions and building classes where each type of renovation is most suitable, hence it can be used to promote renovation to the public and increase renovation rates. EU, national and regional authorities may use the framework to assess the benefit of renovating specific building classes, percentages of the building stock, or maximise the percentage of renovated buildings and the affected population rather than yield a net economic benefit.

Renovation scenarios and impact maps can be tailored to EU, national and regional authority requests to include more in-depth local characteristics (e.g. renovation cost), or explore financing schemes by transferring part of the renovation cost to state authorities or a central funding entity at European level.

Recommendations on designing future building renovation policies.

Research and knowledge needs

Research into technologies for integrated renovation is still in its infancy. Further experimental validation and development and evaluation of new technologies on full-scale laboratory tests, as well as the implementation on real case-study buildings will help lifting integrated renovation from research to practice.

Average unit-cost ranges of common seismic renovation technologies estimated in all EU Member States will facilitate the initial decision-making process of renovation projects according to different geographical contexts.

Regarding the proposed method for the evaluation of the effect of combined renovation, further research is needed to enrich the catalogue of generalised seismic and energy performance curves used to compute the expected annual loss at the extended lifetime of renovated buildings.

Extending the integrated framework for regional prioritisation and impact assessment to additional aspects (e.g. energy consumption for space cooling, resilience to climate change, fire safety and other hazards) will enable the assessment of multi-hazard risk and wider benefits of renovation.

Inventories of georeferenced exposure data, designed specifically for assessing seismic risk and energy consumption at a local scale, will provide more accurate and detailed output.

Standardisation needs

Integrating novel seismic renovation technologies within standards and codes of practice will facilitate their application in building renovations.

Developing standards and codes of practice for integrated renovation technologies would accelerate the implementation of integrated building renovation projects.

Needs for updating existing policy

Enriching the existing regulatory framework, financial instruments, bespoke strategies (e.g. long-term renovation strategies, recovery and resilience plans) and digital tools for energy renovation to address seismic and integrated renovation will maximise the benefits of building renovation.

Awareness campaigns will inform stakeholders on the current risk of the existing buildings stock and on the social, financial, structural and environmental benefits of renovation.

Training and certification of professionals will ensure adequate skills and know-how in integrated renovation.

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List of abbreviations and definitions

BES	Building energy simulation
BIPV	Building integrated photovoltaics
C	Cost
CLT	Cross-laminated timber
COM	Commission Communication
CO_2	Carbon dioxide
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German sustainable building council)
ECCE	European Council of Civil Engineers
ECTP	European Construction, built environment and energy efficient building Technology Platform
EEX	European Energy Exchange
EFEHR	European Facilities for Earthquake Hazard and Risk
ELSA	European Laboratory for Structural Assessment
ENTRANZE	Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe
ESHM20	European Seismic Hazard Model 2020
ESRM20	European Seismic Risk Model 2020
ETICS	External thermal insulation composite system
ETS	Emission Trading System
EU	European Union
EUA	European Union emission Allowances
FRP	Fibre-reinforced polymers
GlobalABC	Global Alliance for Buildings and Construction
HDD	Heating degree day
IEA	International Energy Agency

IRPP	Integrated retrofit performance parameter
ISO	International Organization for Standardization
ISTAT	Istituto Nazionale di Statistica (Italian National Statistical Institute)
KOCED CMI	Korea Construction Engineering Development Collaboratory Management Institute
m	Million
NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
NUTS	Nomenclature of Territorial Units for Statistics
LCA	Life cycle assessment
LCEA	Life cycle energy assessment
PBEE	Performance-based earthquake engineering
RC	Reinforced concrete
ren	Renovation (referring to cost)
rep	Replacement (referring to cost)
SSD	Sustainable Structural Design methodology
SWD	Commission Staff Working Document
TABULA	Typology Approach for Building Stock Energy Assessment
TRM	Textile reinforced mortar
UN	United Nations
UNDRR	United Nations office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
$\Delta IPRR$	Difference in IRPP before and after renovation

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Annex A. Publications

Publications of the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD, consist of the following science-for-policy and technical reports. The reports are organised as follows:

Science-for-policy report summarising the pilot project output

Gkatzogias, K., Pohoryles, D., Romano, E., Bournas, D., Negro, P., Tsionis, G. and Dimova, S., *Integrated seismic and energy renovation of buildings*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/346428, JRC132940.

Science-for-policy reports on the output of project actions

Technologies for seismic and energy renovation

Romano, E., Negro, P., Marini, A., Belleri, A., Raph, O., Iancovic, I., Santarsiero, G., Masi, A. and Butenweg, C., *Overview of seismic and energy retrofit technologies for existing buildings needing combined upgrading*, Publications Office of the European Union, Luxembourg, 2023, JRC132445.

Technologies for combined renovation

Pohoryles, D. A, Bournas, D. A., Da Porto, F., Santarsiero, G. and Triantafillou, T., *Overview of combined seismic and energy upgrading technologies for existing buildings*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/63090, JRC130861.

Methodologies for assessing the effect of combined renovation

Romano, E., Negro, P., Formisano, A., Landolfo, R., Menna, C., Prota, A. and Hàjek, P., *Assessment methodologies for the combined seismic and energy retrofit of existing buildings*, edited by E. Romano and P. Negro, Publications Office of the European Union, Luxembourg, 2023, JRC131412.

Regional prioritisation and impact assessment

Gkatzogias, K., Veljkovic, A., Pohoryles, D., Tsionis, G., Bournas, D., Crowley, H., Norlén, H., Butenweg, C., Gervasio, H., Manfredi, V., Masi, A. and Zaharieva, R., *Policy practice and regional impact assessment for building renovation*, edited by K. Gkatzogias, G. Tsionis, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/883122, JRC131250.

Technical reports on the detailed work of the project actions

Technologies for seismic and energy renovation

Romano, E., Negro, P., Santarsiero, G., Masi, A. and Butenweg, C., *Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context*, Publications Office of the European Union, Luxembourg, 2023, JRC130997.

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Methodologies for assessing the effect of combined renovation

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Regional prioritisation and impact assessment

Butenweg, C., Gervasio, H., Gkatzogias, K., Manfredi, V., Masi, A., Pohoryles, D. A., Tsionis, G. and Zaharieva, R., *Policy measures for seismic and energy upgrading of buildings in EU Member States*, edited by D. Pohoryles, K. Gkatzogias and G. Tsionis, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/518982, JRC130039.

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