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

Policy practice and regional impact assessment for building renovation

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REEBUILD

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Policy practice and regional impact assessment for building renovation

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Contents

Foreword

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

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

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

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

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

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

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(1) https://europa.eu/new-european-bauhaus/index_en

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

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

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

The present report summarises work performed as part of the fourth action towards (*i*) the investigation of the current state-of-practice in existing seismic and energy efficiency related policy measures (e.g. legislation, incentives), (*ii*) the identification of priority regions for intervention by considering seismic risk, energy performance of buildings and socioeconomic vulnerability, and (*iii*) the identification of regional renovation scenarios along with the assessment of their impact.

Acknowledgements

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Abstract

The work presented in this report provides scientific support to building renovation policies in the EU by promoting a holistic point of view on the topic. Integrated renovation can be seen as a nexus between European policies on disaster resilience, energy efficiency and circularity in the building sector. An overview of policy measures for the seismic and energy upgrading of buildings across EU Member States identified only a few available measures for combined upgrading. Regulatory framework, financial instruments and digital tools similar to those for energy renovation, together with awareness and training may promote integrated renovation. A framework for regional prioritisation of building renovation was put forward, considering seismic risk, energy efficiency, and socioeconomic vulnerability independently and in an integrated way. Results indicate that prioritisation of building renovation is a multidimensional problem. Depending on priorities, different integrated indicators should be used to inform policies and accomplish the highest relative or most spread impact across different sectors. The framework was further extended to assess the impact of renovation scenarios across the EU with a focus on priority regions. Integrated renovation can provide a risk-proofed, sustainable, and inclusive built environment, presenting an economic benefit in the order of magnitude of the highest benefit among the separate interventions. Furthermore, it presents the unique capability of reducing fatalities and energy consumption at the same time and, depending on the scenario, to a greater extent.

Executive summary

The work presented in this report aims to provide scientific support to building renovation policies in the EU by promoting a holistic point of view on the topic. As part of the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD, the report presents (*i*) an overview of collected policy measures (e.g. legislation, incentives) for enhancing the seismic and energy performance of buildings across the EU Member States that included seismic risk in their national risk assessment in 2015, (*ii*) a framework for regional prioritisation across the EU-27, considering seismic risk, energy efficiency, and socioeconomic vulnerability independently and in an integrated way, and (*iii*) an extended framework for assessing the impact of seismic retrofitting, energy efficiency upgrading, and integrated renovation. Indicators for regional prioritisation address loss of life, space heating energy consumption, economic loss associated with seismic repair and energy cost, as well as socioeconomic indicators. Impact assessment metrics involve benefit-to-cost ratios and reductions in the above indicator values.

Policy context

The report provides scientific advice to support the development of policies and action plans, which should supplement the existing framework of EU policies and initiatives in the field of building renovation. To address the low energy efficiency of the existing building stock, building renovation in the EU is supported by the European Green Deal and the Renovation Wave. Yet, the proposal for the revised Energy Performance of Buildings Directive encourages measures related to seismic risk and fire safety, whereas the New European Bauhaus envisions sustainable, inclusive and beautiful living spaces. The Union Civil Protection Mechanism and the Action Plan on the Sendai Framework highlight disaster prevention investments and the integration of risk reduction and cohesion policies. Holistic approaches are crucial to the effective implementation of multidimensional policies, as they can enhance resilience to natural disasters, and thus create a stable environment for risk-proofed investments.

Key conclusions

The work performed provides a framework for regional prioritisation and impact assessment along with a set of data, indicators, rankings, and impact metrics which can inform a more focussed approach in local, regional or European policy making. In addition to direct benefits of improved structural safety and energy efficiency, building renovation may serve as a socioeconomic driver, with a potential employment boost and improvements in living conditions of socially vulnerable groups.

Prioritisation of building renovation is a multidimensional problem and different indicators should be employed depending on the sectoral and geographical focus, along with the aim of specific renovation plans. Single and multi-sectoral integrated indicators can capture the different aspects of prioritisation while handling complexity and filtering out severe disparities (e.g. among economic loss due to energy cost and seismic repair).

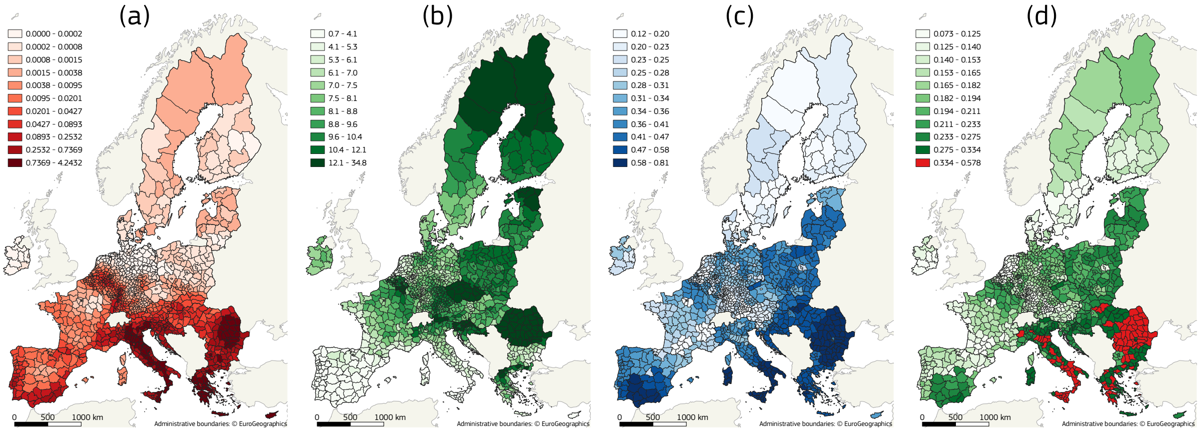
The renovation impact is sensitive to assumptions regarding the renovation cost, the inflation of construction cost and energy prices, and the planning period (i.e. time over which renovation is effective). Overall, the efficiency of a renovation strategy increases along with its capacity to target buildings with specific attributes rather than generic classes. Still, integrated renovation was found capable of providing a risk-proofed, sustainable, and inclusive built environment in a cost-efficient way.

Main findings

Although measures for promoting energy upgrading are present in all the considered Member States, measures for seismic strengthening are less common, while measures that target seismic and energy renovation at the same time were identified only in six countries. Regulatory frameworks, 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.

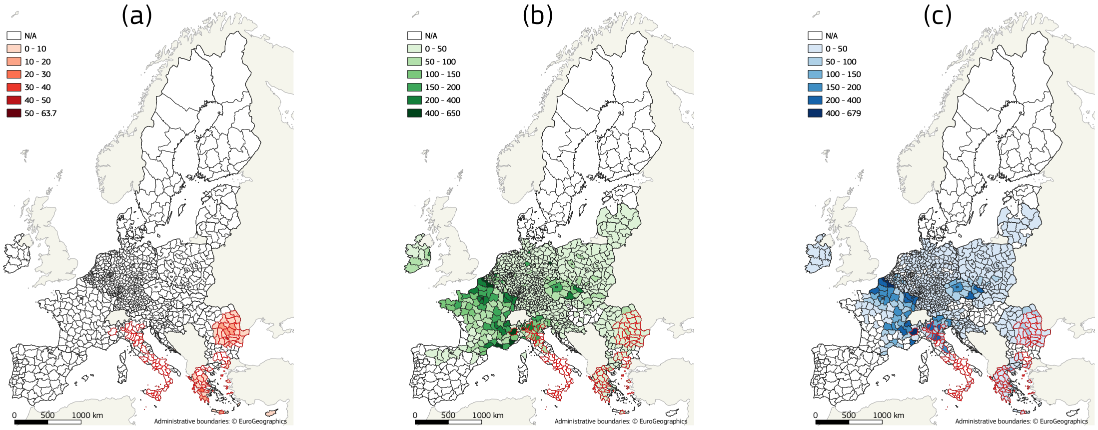
Regions from Italy over to Croatia, Romania, Bulgaria and Greece are of high priority for seismic retrofit interventions. French, German, Italian, and Romanian regions emerge as those of high priority for energy efficiency interventions, followed by northern and central EU regions. Prioritisation based on socioeconomic indicators shifts the focus to southern and eastern European regions, which follows more closely the trends of seismic risk. A multi-sectoral integrated indicator combining all normalised indicators of economic loss, loss of life, energy consumption and socioeconomic vulnerability was found capable of encompassing all previous trends, promoting renovation mainly in regions of Romania, Italy, Greece and Bulgaria (Figure E. 1.).

Figure E. 1. (a) seismic risk – average annual economic loss ratio, $AAELR_{eq}$ ($\cdot 10^{-3}$), (b) energy performance - average annual economic loss ratio, $AAELR_{en}$ ($\cdot 10^{-3}$), (c) socioeconomic vulnerability index, *SVI*, and (d) multi-sectoral integrated indicator combining seismic risk, energy performance, and socioeconomic vulnerability, $I_{eq-en-SVI,3}$ (in red: top 100 regions with the highest index value), in residential EU-27 buildings at NUTS-3 (Gkatzogias et al., 2022a)



In terms of renovation impact, the economic benefit due to integrated renovation is in the order of magnitude of the highest economic benefit among the seismic and energy renovation ones (or even higher) (Figure E. 2.). Moreover, it exhibits the unique capability of reducing fatalities due to earthquakes and energy consumption at the same time, and depending on the scenario, to a greater extent than separate interventions.

Figure E. 2. Average annual benefit in terms of economic loss, $\Delta AAEL$ (million euro) due to (a) seismic retrofit, (b) energy efficiency upgrading, and (c) integrated renovation (in red borders: top 100 priority regions based on a multi-sectoral integrated indicator) (Scenario 3.2, Gkatzogias et al., 2022b)



Related and future JRC work

JRC will continue fostering holistic approaches of renovation in support of the EU policies with improvements on data, models and methodologies, priority indicators and renovation scenarios. 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, hazard, and vulnerability. **Energy performance** refers to the capability of a building class to provide a desired living comfort to occupants in terms of dwelling internal air temperature, as a function of climatic conditions and building energy attributes. **Socioeconomic vulnerability** measures socioeconomic development, smart, sustainable, and inclusive growth, and social progress. **Single** and **multi-sectoral integrated indicators** combine base indicators from a single sector (e.g. economic loss due to seismic repair and loss of life) or multiple ones (e.g. economic loss due to seismic repair and energy cost), respectively. The **renovation impact** reflects the benefit in absolute terms derived from a renovation scenario, along with its significance and economic feasibility.

1 Introduction

The pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD was launched with a view to promoting a holistic approach for the renovation of buildings across Europe. 30% of European buildings are located in areas of moderate seismic hazard where the design peak ground acceleration (*PGA*) is at least 0.1g (Crowley et al., 2020), whereas buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU, making them the single largest energy consumer in Europe (COM (2020)662). Hence, the reduction of seismic vulnerability of European buildings together with an increase in their energy efficiency is of utmost importance for the European environmental targets, resilience, and economy, and can be most efficiently addressed through a holistic approach, as it has been demonstrated in recent studies (e.g. Calvi et al., 2016; Bournas, 2018; Pohoryles et al., 2020; Menna et al., 2021).

To address the low energy efficiency of the existing building stock, building renovation in the EU Member States (EU-27) is supported by the European Green Deal (COM 2019/640), the Renovation Wave (COM 2020/662), and the recent proposal for the revised Energy Performance of Buildings Directive (COM 2021/802). While renovation efforts are driven by energy efficiency enhancements, the Energy Performance of Buildings Directive encourages the Member States to also consider measures related to fire safety and seismic risk. In fact, the issue of seismic safety is recognised in the 2020 long-term renovation strategies of Croatia, Cyprus, Hungary, Italy, Romania, Slovenia, and Spain (SWD 2021/365).

Seismicity is higher in the Mediterranean, Balkan and central European countries, as shown in Figure 1, which displays the mean *PGA* with a return period of 475 years, based on the European Seismic Hazard Model 2020 (ESHM20, Danciu et al., 2021). Areas in white indicate regions with no seismic hazard, while blue colours indicate comparatively low hazard, yellow and orange indicate moderate hazard, and red and purple colours indicate high seismic hazard. Figure 2 presents the heating degree days (*HDD*s) as an average over the years 2010–2019 (Eurostat, 2020a; Gkatzogias et al., 2022a), which is a useful proxy for representing climatic conditions associated with the energy demand for heating buildings. Conversely to the distribution of seismic hazard, northern European countries and alpine regions present more demanding climatic conditions with respect to heating needs, as indicated by darker shades of blue and purple in Figure 2.

Figure 1. Mean values of *PGA* on reference rock with exceedance probability of 0.21% in one year (return period of 475 years), based on ESHM20 (Danciu et al., 2021, available from EFEHR, http://hazard.efehr.org) (© ETH Zurich, 2022)

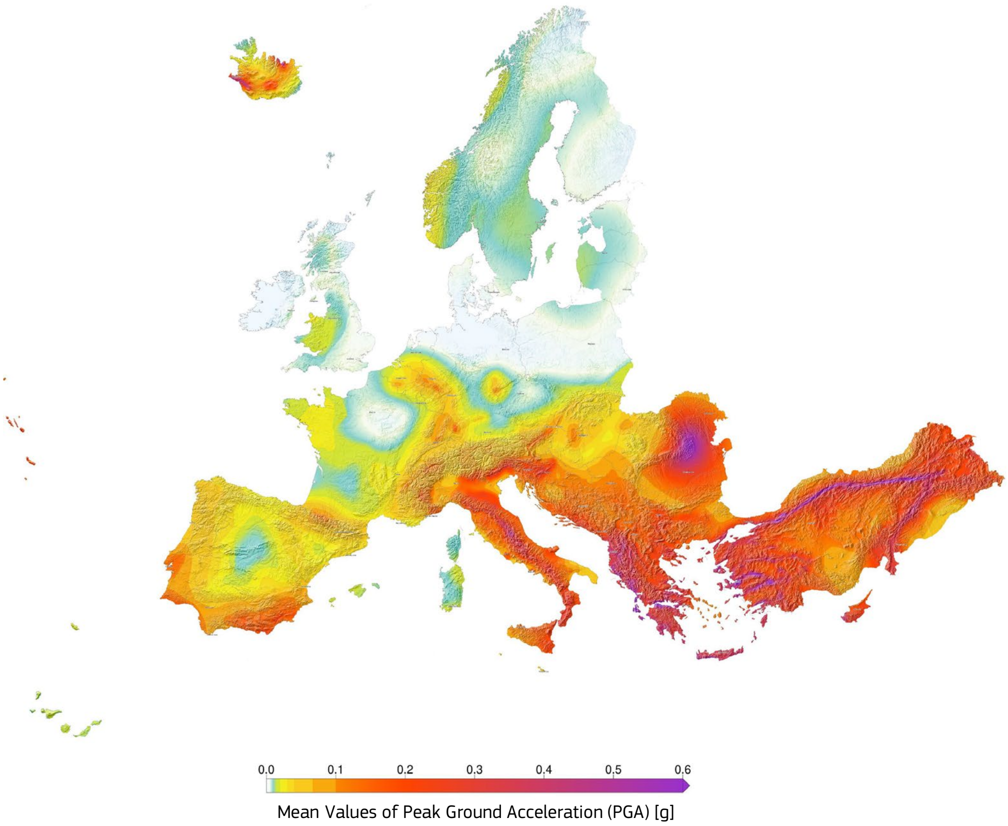
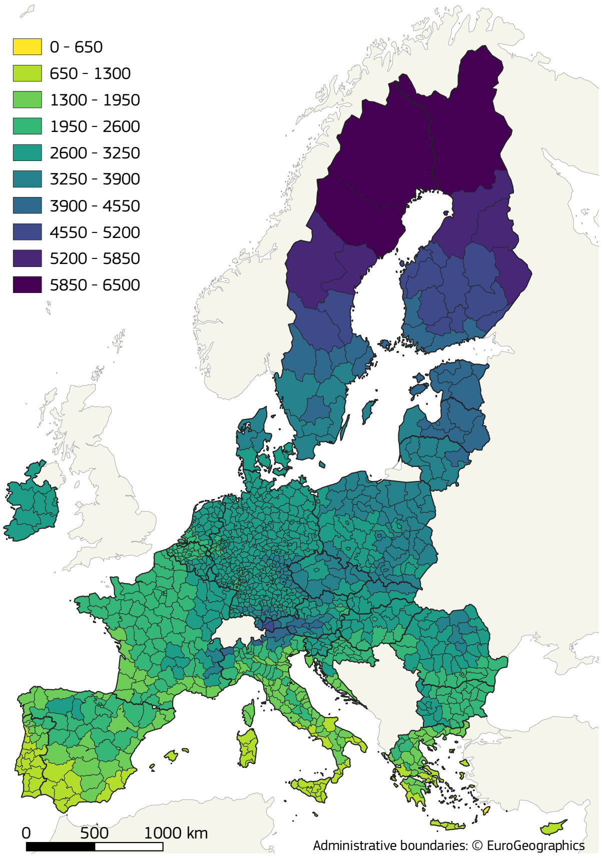


Figure 2. Average *HDD* values (2010–2019) in the EU-27 at NUTS-3 (2) level (Source: Eurostat, 2020a (data); Gkatzogias et al., 2022a (analysis))



Apart from the diverse seismic and climatic conditions across the EU-27 and at a regional level, the vulnerability of buildings in terms of economic loss (due to seismic repair and energy cost) and fatalities (due to earthquakes) presents also a significant spatial variation. Figure 3a displays the distribution of buildings built with no seismic design considerations and with a low seismic design code level (Gkatzogias et al., 2022a) as a qualitative indication of vulnerability. It is seen that in regions of high seismicity (Figure 1), described earlier, high percentages of buildings appear vulnerable to earthquakes, implying potentially high seismic risk, which in turn is also a function of exposure (e.g. number of buildings and population). Likewise, Figure 3b, presents the regional percentages of buildings with thermal transmittance values of walls (U_w) higher than or equal to 1.6 W/(m^2K) as an indicator of the vulnerability of buildings in terms of economic loss associated with energy cost. Considering the spatiotemporal evolution of energy efficiency codes across the EU-27 (Gkatzogias et al., 2022a), the selected U_w value in this example roughly corresponds to buildings constructed before 2000 in Spain, before the 80s in Greece, Italy, and Romania, and before the 70s in France. Northern countries due to harsher climatic conditions (e.g. Germany, Finland and Sweden in Figure 2) exhibit lower values even since the 40s. Yet, the energy performance of buildings in terms of energy consumption and cost is ultimately a function of exposure, climatic conditions, and vulnerability.

In view of the above considerations, the report presents the results of an EU-wide regional assessment integrating analytically exposure, seismic and climatic conditions, and physical vulnerability taking into account a wide range of structural and energy attributes of buildings to estimate seismic risk and energy performance. Building renovation is prioritised among European regions considering seismic risk, energy performance of buildings and socioeconomic vulnerability, both independently and in an integrated way. Furthermore, the report summarises work on the identification and analysis of scenarios for seismic and energy renovation of buildings, again both independently and in an integrated way, providing insights into the renovation cost and benefit in terms of reduction in economic loss, loss of life and energy consumption.

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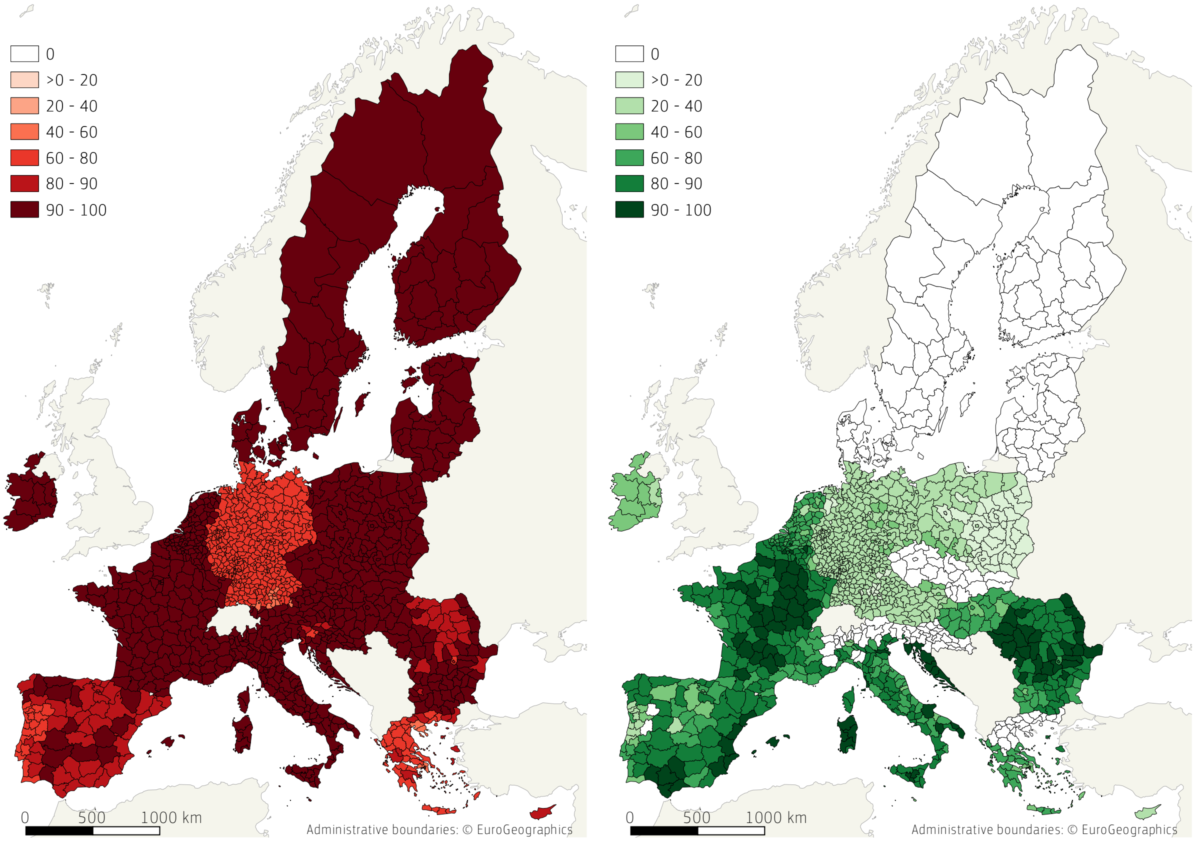
(2) According to the Nomenclature of Territorial Units for Statistics (NUTS) 2021 classification (https://ec.europa.eu/eurostat/web/nuts/background)

Figure 3. Percentage of residential buildings at NUTS-3 level with (a) no seismic design and low seismic design code level, (b) thermal transmittance of walls $U_w \geq 1.6$ W/(m^2K) (Source: Seismic exposure data for GADM administrative levels from ESRM20, Crowley et al., 2021; mapping to NUTS and energy analysis by Gkatzogias et al., 2022a)



Following this introduction, Chapter 2 provides an overview of implementing measures, e.g. legislation, incentives and guidance, for the upgrading of buildings across 16 EU Member States that included seismic risk in their national risk assessment in 2015. Chapter 3 summarises the integrated analysis framework for the regional assessment of existing buildings across the EU-27 and for the impact assessment of renovation scenarios. Chapters 4 and 5 illustrate through representative examples the output of the regional assessment for existing buildings and the renovation scenarios, respectively. Main conclusions are presented in Chapter 6.

2 State-of-practice in policy measures

2.1 Overview

Considering the significant impact of the building sector on the overall energy demand and greenhouse gas emissions in the EU, along with the need for energy demand reductions due to the recent global energy crisis, the renovation of the existing, energy inefficient building stock becomes more than ever a critical priority. The strategy for an EU external energy engagement (JOIN 2022/23), part of the REPowerEU package (3), aims, among others, to make energy efficiency and savings a global priority, and support the global transition to more circular economy as the means to reduce energy consumption. Through additional policies and initiatives of the European Green Deal (COM 2019/640), such as the Renovation Wave (COM 2020/662) and the implementation of the Energy Performance of Buildings Directive (Directive 2018/844), Member States are encouraged to increase renovation rates to achieve climate-neutrality targets set out for 2050. REEBUILD aims to promote a new holistic perspective on building renovation, integrating energy upgrading with structural interventions to protect buildings from earthquakes.

The importance of the seismic and energy efficient renovation measures is reflected on legislation, standards, incentives, etc. As part of REEBUILD, policy measures related to building renovation in 16 EU Member States that included seismic risk in their national risk assessment in 2015 were collected (Butenweg et al., 2022) to gain better understanding of best practices which may serve as a point of reference for further implementation. A distribution of the measures collected in the project by sector (seismic strengthening, energy upgrading or both) and class (legislation and standards, programmes, strategies, guidance, and other) is provided in Figure 4. Programmes refer to financing instruments, incentives involving provision of funding, benefits, etc., whereas strategies address national strategies and action plans. The figure clearly illustrates that the majority of measures in the 16 Member States are related to energy upgrading. Significantly less measures refer to seismic strengthening and even less to both sectors, noting here that a measure was classified as “seismic strengthening and energy upgrading” when reference to both sectors was made, without necessarily including provisions for combined or integrated renovation.

Figure 4. Distribution of collected policy measures in 16 EU Member States that included seismic risk in their 2015 national risk assessment (Source: Gkatzogias et al., 2021)

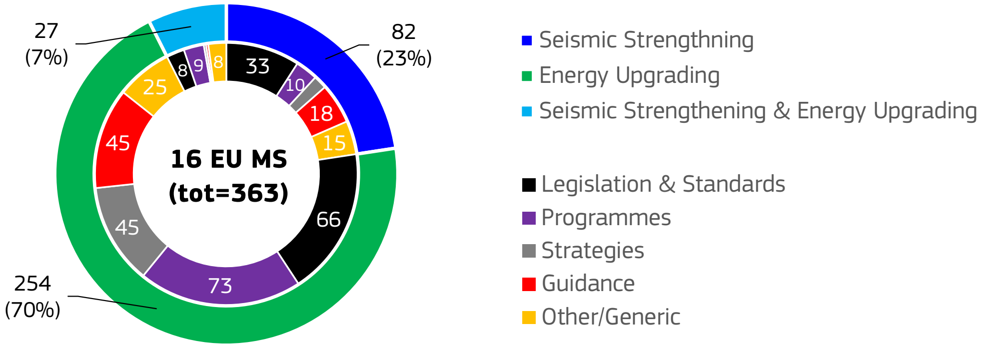


Figure 5 presents an overview of the measures implemented for building renovation in the 16 EU Member States. While measures for promoting energy upgrading are present in all the considered countries, specific measures for seismic strengthening (e.g. the implementation of Eurocode 8–Part 3, CEN, 2005, or specific programmes for seismic retrofitting) are only found in some of them. Finally, specific measures that target seismic and energy renovation at the same time were identified only in six countries. It is noted though, that such measures do not necessarily promote integrated renovation, but mainly ensure that energy efficiency upgrading is only applied after structural safety is verified.

Significant advances in energy upgrading measures may not come as a surprise, given that all Member States have to comply with EU directives for energy efficiency and the energy performance of buildings (e.g. Directive 2018/844), and transpose them into national legislation. Looking ahead, as set forth in the Energy Performance of Buildings Directive, all EU Member States have recently prepared their latest long-term renovation strategies for improving the energy performance of their existing building stock, setting out clear objectives and milestones

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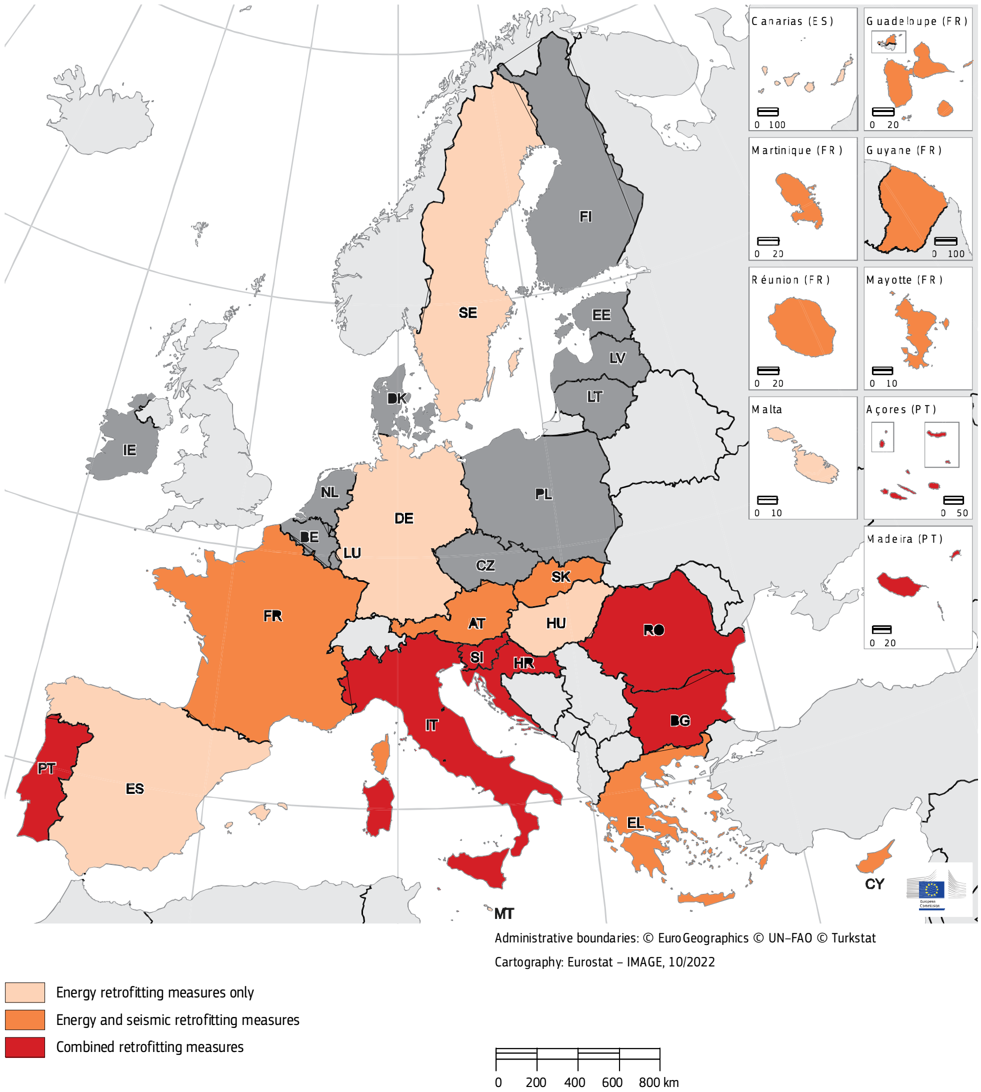
(3) https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

on their way to full decarbonisation by 2050. The success of this approach is reflected on each country by the increased number of national strategies and programmes implemented over the years, with increasingly higher targets in terms of energy efficiency and ambitious reductions in carbon emissions. Overall, many relevant strategies and programmes have been implemented over the years in all countries, and are currently available for enhancing the energy efficiency of existing buildings, fostering the implementation of energy performance certificates, building renovation passports and nearly zero-energy buildings. Additionally, different financial instruments (e.g. loans with low interest rates, reduced taxes, etc.) have been introduced to encourage building owners to renovate their homes.

Figure 5. Overview of collected policy measures for building renovation in the 16 EU Member States that included seismic risk in their 2015 national risk assessment (Butenweg et al., 2022)



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In the case of seismic strengthening of buildings, Figure 5 appears to be less homogenous across the studied Member States. This is related to the differences in seismicity among the countries. For instance, there is a lack of legislation, guidelines and standards in countries located in low seismic hazard regions. However, to date, even in cases of higher seismic risk, policy measures for seismic retrofit are generally less extended compared to energy upgrading ones. Reconstruction and inspection programmes, and updates of seismic codes are often triggered by significant earthquakes. In countries prone to the seismic hazard, renovation activities, considering not only energy upgrading but also the seismic retrofit of buildings, are needed. Regulatory frameworks and financial tools similar to those for energy renovation are capable to promote such activities. As a prerequisite for their success, information and awareness campaigns should be developed and put in place, addressing not only professionals in the building sector but also building owners and tenants. Such campaigns are required to inform about the current effective risk, and thus create a greater demand for deep renovations of buildings.

Combined seismic strengthening and energy upgrading measures are not addressed in most countries under consideration, although the two issues may be covered independently by separate or even the same building code. The lack of measures to simultaneously address seismic strengthening and energy efficiency may be the result of the combined effect of diverse seismic hazard across the EU, limited technical knowledge on integrated renovation, and low awareness of the issue and the potential benefits. The issue of seismic safety is recognised in the national recovery and resilience plans (4) of Croatia, Italy, France, Romania, and Slovenia, and the 2020 long-term renovation strategies of Croatia, Cyprus, Hungary, Italy, Romania, Slovenia, and Spain.

2.2 Integrated renovation of buildings

Some notable examples of policy measures for combined seismic strengthening and energy efficiency upgrading or integrated renovation of buildings are described in the following.

While no specific legislation or standards for combined renovation exist in Bulgaria, many renovation programmes include considerations for structural rehabilitation in their funding mechanisms. Measures target mainly energy upgrading and address measures to improve the structural/seismic performance of the building implicitly, as long as these are technically justified (e.g. the 2015 national programme for the energy efficiency of multi-family residential buildings).

Several building codes and programmes were introduced since the 1980s in Italy to improve the seismic and energy performance of buildings, and nowadays, Italy employs comprehensive measures for combined renovation. Ecobonus (Law 2016/232) supports energy efficiency renovations with tax deductions in the range of 50–75% (70–75% for interventions in common parts of multi-owner buildings extended to more than 25% of the building envelope or when retrofit measures result in specific energy performance). Sismabonus (Law 2016/232) offers a tax deduction equal to 50% (over 5 years) of the incurred seismic strengthening expenses for buildings in specific seismic zones. The benefit increases up to 80% as a function of the seismic risk classification of the renovated structure and up to 85% for interventions in common parts of multi-owner buildings. Both measures provide credit transfer options to suppliers of materials and services or to financial entities. Ecobonus and Sismabonus were more recently combined to Ecosisma bonus (Law 2017/205) to provide a tax deduction up to 85% for energy efficiency upgrading implemented together with seismic strengthening. In the context of recovery from the COVID-19 pandemic, Law 2020/77 introduced Superbonus for single and multi-owner buildings, providing a 110% tax deduction of expenses.

Renovation of buildings in Portugal was performed until 2019 without the requirement to consider the seismic capacity and potential need for seismic retrofit. Nevertheless, a recently published law (Decree-Law 95/2019), along with approving the use of the Eurocodes, laid out the conditions under which renovation works are subject to assessing the seismic vulnerability, as well as designing seismic strengthening measures, e.g. based on structural degradation/modification, etc. Interestingly, apart from the seismic assessment and retrofit of buildings, Decree-Law (95/2019) addresses requirements for energy efficiency, fire safety, acoustics, and accessibility, thus creating a unique opportunity for the holistic renovation of buildings.

A situation similar to Bulgaria is seen in Romania, where the national programme for increasing the energy performance of apartment buildings (Ordinance 18/2009) was conceived mainly for energy renovation works, but it was later extended (Order 589/1154/2015) to include requirements for a detailed seismic evaluation of buildings prior to carrying out energy upgrading works.

The Building Cards instrument will be introduced in Slovenia by 2024. The instrument will provide guidance on recommended and required measures to promote gradually wider renovations, including energy efficiency along with fire and seismic safety aspects (SWD 2021/365).

2.3 Promoting holistic renovations

As legislation, standards and guidelines for seismic strengthening are missing in many Member States, integrated renovation may not be easy to implement. Nevertheless, as shown in the regional impact assessment of renovation scenarios (Chapter 5), in many regions of the EU it would appear reasonable to implement combined measures to enhance both the seismic safety and the energy efficiency of buildings. Based on the review of measures in the considered 16 Member States (Butenweg et al., 2022), the following general comments can be made with regard to measures for further promotion of integrated building renovation.

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(4) https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en

Upgrading the energy performance of seismically deficient buildings deserves special attention. Coupling funding for energy efficiency interventions with structural/seismic strengthening, particularly in seismic regions of moderate and high seismicity (e.g. Ecosisma bonus in Italy, Law 2017/205) ensures the structural integrity of renovated buildings, and safeguards relevant investments. In regions of low seismic risk, integrating structural and energy renovations may still be beneficial from different points of view, e.g. to avoid investing energy funds on buildings that are not structurally sound due to ageing.

The amount of funding in energy efficiency upgrades could be a function of the improvement in the energy performance of buildings, confirmed by energy performance certificates (e.g. Austria, Cyprus, Greece, Italy etc.). The latter could also serve as measures of the impact of energy renovation policies, as in the long-term renovation strategy of Sweden (SWD 2021/365). Similar certificates could be adopted to describe the seismic capacity or risk of buildings, as in the case of Italy (Law 2016/232), considering simple classification criteria, a small number of risk classes, and measurable target performance levels.

Tax incentives for renovation works appear to be particularly suitable measures (SWD 2021/365). Incentives could include VAT reductions, as implemented in Cyprus (Piripitsi et al., 2017), or income tax deductions, as applied in Italy (Law 2017/205), and Sweden (SWD 2021/365). Investments in the banking sector and other credit institutions or even governments and municipalities through green bonds (e.g. as in Sweden, Torvanger et al., 2021) may be used to raise further capital for renovation measures. Similarly, green/eco loans (e.g. as in Malta, SWD 2021/365) may facilitate building owners and tenants to finance environmentally friendly and energy saving products and services. Such financial instruments may be extended to seismic upgrading in countries prone to earthquakes, coupled with seismic insurance.

Measures targeting vulnerable and low-income households could be considered to a larger extent, addressing energy poverty and housing quality simultaneously. Notable examples include the energy incentives advice scheme for vulnerable households in Malta, enabling the replacement of old and inefficient appliances, but also the ZERO500 programme in Slovenia, financing energy efficient renovation measures (SWD 2021/365).

Split-incentive barriers could be overcome through gradually linking rental contracts and property value with minimum energy and/or seismic performance requirements. In France, owners of worst-performing properties in terms of energy efficiency are banned from increasing rent between two lettings without performing energy renovations. This is expected to reach an obligation to renovate by 2023, when dwellings exceeding certain limits in final energy consumption will not be able to be rented out (SWD 2021/365).

Efforts for introducing measures specifically targeting multi-owner buildings, as in the cases of Ecosisma bonus in Italy (Law 2017/205), and the state housing development fund in Slovakia (Gerőházi and Szemző, 2015), could be intensified.

Member States could benefit from transnational cooperation, e.g. between neighbouring countries that face climatic conditions, seismic risk, and similar challenges in the implementation of energy policies and the real estate market. A transnational approach could lead to faster and more effective solutions. For instance, similar approaches could be sought for developing renovation measures among Greece and Cyprus, or Austria and Germany.

Measures for integrated renovation of buildings will benefit from the digital transition in the building sector, for instance, by including in technical building passports harmonised information on the energy and seismic performance, before and after renovation. Smart sensors monitoring the energy consumption and structural health of buildings, can provide useful real-time information to interested actors, and activate systems for seismic protection in case of earthquakes.

Together with policy measures, training and certification of professionals, further scientific development will be required to ensure adequate know-how in integrated renovation methods. Web-based applications can further support professional development, awareness and wider uptake of solutions for integrated renovation. Expert training could create new job opportunities; the Caritas welfare association in Germany provides free-of-charge energy-saving consultation at homes by properly trained long-term unemployed personnel (5).

Finally, awareness campaigns at local, national, and European level will attract more building owners, tenants and other actors to combined upgrading strategies. The financial, structural, and environmental benefits need to be communicated through proper channels.

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(5) https://www.stromspar-check.de/en/english

3 Integrated framework for regional prioritisation and impact assessment

3.1 Regional assessment and prioritisation

A framework for regional assessment and prioritisation was proposed in Gkatzogias et al. (2022a) (Figure 6a). The framework combines three assessment routes addressing seismic risk to existing buildings and occupants, energy performance of existing buildings, and socioeconomic indicators. The three routes use a common exposure model. Exposure models describe the spatial distribution of the building/dwelling count and area, population and replacement cost of a building stock, characterised in terms of building classes, which here address both structural and energy attributes. Specifically, the seismic exposure model of the European Seismic Risk Model 2020 was adopted (ESRM20, Crowley et al., 2021, available from the European Facilities for Earthquake Hazard and Risk, EFEHR (6), © Eucentre Foundation, 2022). In order to perform integrated regional assessments of seismic risk and energy performance, the seismic exposure model was subsequently extended (Gkatzogias et al., 2022a) to include energy performance attributes.

Seismic risk assessment involves the estimation of the probability and magnitude of undesirable consequences resulting from potential future earthquakes. Consequences were expressed in terms of loss, and therefore the total probability theorem was applied to estimate risk, combining exposure, seismic hazard, and vulnerability. Seismic hazard is represented by the probability of exceedance of different levels of ground motion intensity, with surface ground shaking being the main contributor to building damage and loss. The ESHM20 was used (Danciu et al., 2021, available from EFEHR (7), © ETH Zurich, 2022). The adopted ESRM20 vulnerability models (Romão et al., 2021) combined fragility functions and consequence (damage-to-loss) models. Seismic physical vulnerability represents the probability of loss to a given building class, conditional on the level of surface ground shaking intensity. Seismic loss was expressed as direct economic loss (i.e. cost of repair) and loss of life (i.e. occupant fatalities). A frequency-based seismic performance assessment was performed to estimate the risk metrics of average annual economic loss ($AAEL_{eq}$) and average annual loss of life ($AALL$), considering all potential earthquakes that affect a specific site over a given period and their associated frequencies of occurrence. Seismic risk was assessed for both residential and commercial buildings across the EU.

The energy performance of residential buildings was estimated within a deterministic context. Herein, energy performance refers to the capability of a building class to provide a desired living comfort to occupants in terms of dwelling internal air temperature, as a function of the climatic conditions and the energy attributes of the building class. The energy performance was quantified by the space heating energy consumption (i.e. energy loss) and energy cost (i.e. economic loss). Climatic conditions were estimated from outside air temperature measurements, represented by *HDD*s (Eurostat, 2020a), and averaged over a 10-year period. Energy performance attributes comprised the thermal transmittance of the building envelope, adopted from the INSPIRE (8) and ENTRANZE (9) projects (Birchall et al., 2014; ENTRANZE and Enerdata, 2008a, b), and the building geometry. A physics-based artificial neural network (Veljkovic et al., 2023) was employed to estimate the average annual energy consumption ($AAEC$) using as input climatic and building stock data. The average annual energy consumption was translated to average annual economic loss ($AAEL_{en}$) using energy prices for residential use (Grave et al., 2016; Eurostat, 2020b) adjusted to 2020. Considering the significant increase in energy prices in 2022, it is commented here that the expected economic benefit due to energy efficiency upgrading increases as the cost of energy increases in the long term (i.e. when the inflation of energy prices outpaces inflation of other costs, Gkatzogias et al., 2022b).

Three composite indicators were adopted to quantify socioeconomic development, smart, sustainable, and inclusive growth, and social progress. These indicators were the regional EU Human Development Index (HDI) (Bubbico and Dijkstra, 2011; Eurostat, 2019a, b, 2020c), the EU2020 index (Becker et al., 2020), and the regional EU Social Progress Index (SPI) (Annoni and Bolsi, 2020). The selected composite indicators, measuring socioeconomic wellbeing, were combined to a single measure to express socioeconomic vulnerability (SVI) (Gkatzogias et al., 2022a).

The estimated metrics from each assessment route (Figure 6a) were used to form indicators and identify priority regions (Chapter 4). The proposed indicators address separately single metrics of seismic risk (i.e. economic

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(6) http://risk.efehr.org/

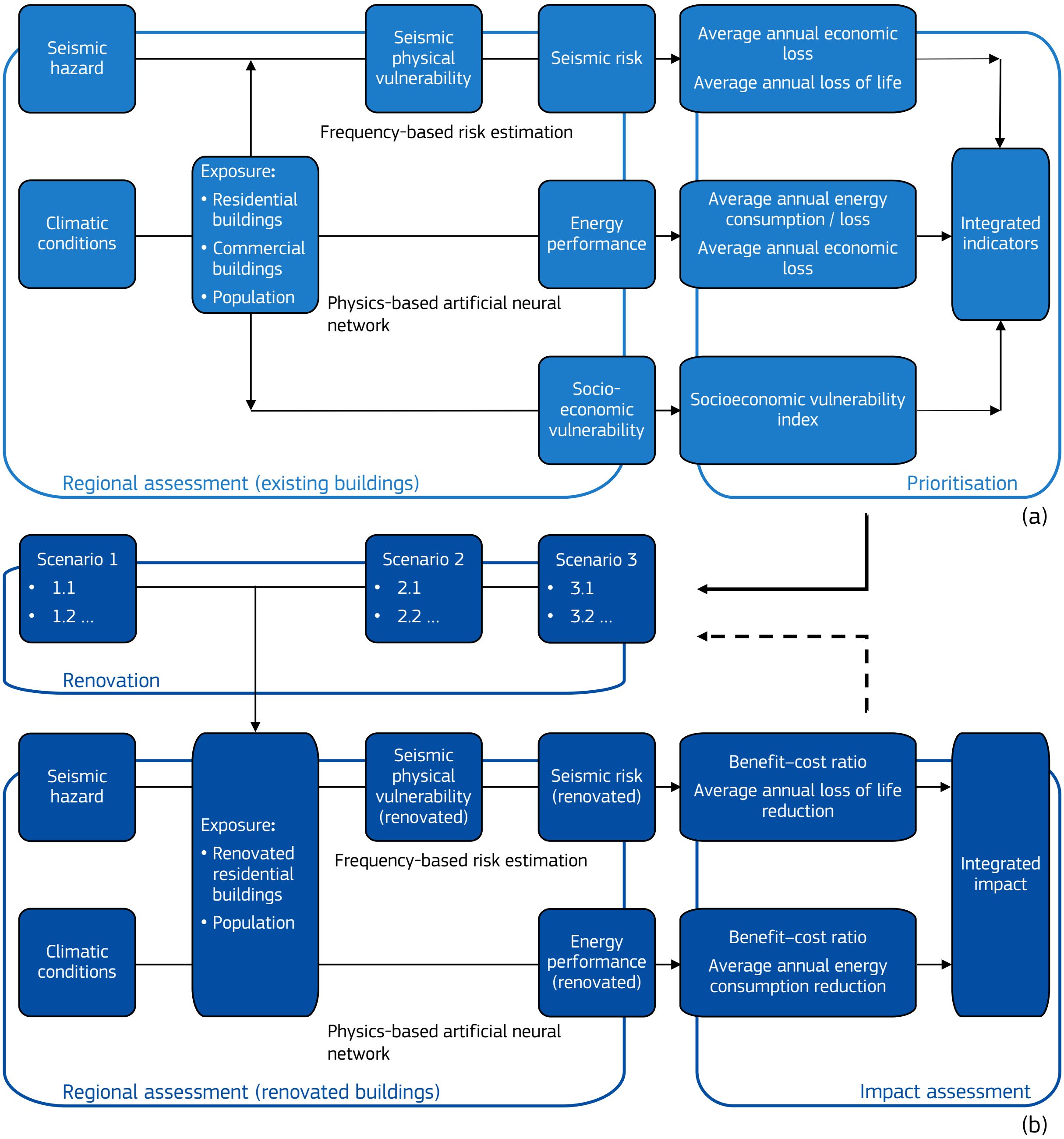
(7) http://hazard.efehr.org/en/home/

(8) Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems (https://cordis.europa.eu/project/id/314461).

(9) Policies to Enforce the Transition to Nearly Zero-Energy Buildings in the EU-27 (https://www.entranze.eu).

loss, loss of life), energy performance of buildings (i.e. energy consumption, energy cost) and socioeconomic vulnerability. Alternatively, multiple metrics (i.e. component indicators) may be combined to form single-sectoral integrated indicators (e.g. seismic indicator addressing the components of economic loss and loss of life) or multi-sectoral integrated indicators combining seismic and/or energy and/or socioeconomic metrics.

Figure 6. Framework for (a) regional assessment, and prioritisation, and (b) renovation, and impact assessment (Gkatzogias et al., 2022b)



In the case of integrated indicators, all involved component indicators were normalised to a 0–1 range, and an equal weight was assigned to each one of them. This decision was made, first, to avoid complexity and subjectivity, e.g. arising from assigning a monetary value to aspects such as loss of life or socioeconomic vulnerability. Second, the specific approach was driven by an attempt to filter out severe disparities among different aspects even in the case when they were expressed in the same units. For instance, in the majority of the EU-27 regions, the average annual economic loss related to heating energy cost was found considerably higher than average annual economic loss related to seismic repair cost. Prioritising regions based on the sum of economic losses alone would mainly highlight regions in need for energy retrofit. Such an approach is reasonable in terms of monetary loss but fails to address life-safety and socioeconomic aspects of seismic risk mitigation or their relevant significance compared to energy savings and environmental impact in regional prioritisation for building renovation. Furthermore, it disregards the need for risk-proofed investments on energy renovation (Directive 2018/844; SWD 2016/205) and the uncertainty associated with the probabilistic assessment of risk compared to the deterministic estimation of energy performance. Nevertheless, approaches other than the one adopted here may be explored based on expert judgement and/or the specific objectives of the regional assessment.

More than 20 indicators for regional prioritisation were investigated to address seismic risk, energy performance, and socioeconomic indicators in absolute (e.g. *AAEL* in euro) and normalised form (average annual economic loss normalised to the building replacement value *AAELR*, or integrated indicators).

The different components of the adopted framework (Figure 6a), addressing the development of the exposure model, environmental excitation models in terms of seismic hazard and climatic conditions, physical vulnerability models, the methodologies used to estimate seismic risk, energy performance of buildings, and socioeconomic vulnerability, along with the proposed indicators for regional prioritisation are described in detail in Gkatzogias et al. (2022a).

3.2 Renovation scenarios and impact assessment

The integrated framework was complemented in Gkatzogias et al. (2022b) by the formulation of alternative renovation scenarios, the iteration of regional assessments considering the renovated building stock, and the evaluation of the impact of renovation scenarios (Figure 6b). Renovation scenarios were explored addressing the residential building stock, and their impact was presented on maps across the EU-27 regions.

Renovation scenarios were defined considering seismic, energy, and integrated retrofit of various combinations of building classes per region or multiple regions at the same time. Retrofit targeted a predefined improved seismic and/or energy performance of buildings, quantified by an upgrade of the seismic design code level (i.e. no, low, moderate, high), an increase of the lateral force coefficient (i.e. fraction of the building weight specified as the lateral design force in the seismic design code), and/or the reduction of thermal transmittance of the building envelope to target values, respectively (Gkatzogias et al., 2022b).

Regional assessments of seismic risk and energy performance of the renovated buildings were performed by employing the same seismic hazard, climatic conditions and exposure models as in the case of existing buildings. Yet, each building class was mapped to an upgraded seismic vulnerability and energy performance class to model the effect of renovation according to the considered renovation scenario (i.e. seismic, energy, or integrated retrofit). A frequency-based seismic performance assessment and the physics-based artificial neural network were used to evaluate the seismic and energy performance of the renovated building stock through the average annual economic loss (cost of seismic repair, space heating energy cost), average annual loss of life, and average annual space heating energy consumption.

The impact of the investigated scenarios was evaluated at the regional level through cost–benefit analysis with a view to providing insight on economic savings per scenario and region. Benefit-to-cost ratios (*BCR*s) were estimated, considering the effect of variable planning periods and cost of renovation. *BCR*s addressed only average annual loss due to seismic repair and energy cost. Although the benefit due to the reduction in the average annual loss of life and CO_2 emissions (derived from seismic and energy upgrading) can be transformed to cost, these metrics did not enter the benefit-to-cost ratio calculation. Instead, the reduction of fatalities and energy consumption (i.e. an implicit measure of greenhouse gas emissions) were calculated for each scenario and used as separate impact metrics. This decision was made for the sake of consistency with the definition of the integrated indicators for regional prioritisation described earlier. Furthermore, following the approach of separate consideration of these impact metrics, complexity and subjectivity, e.g. arising from assigning a monetary value to loss of life, is avoided, while the relevant contribution in the scenario efficiency is more explicitly acknowledged. Nevertheless, different approaches may be investigated by assigning monetary value to fatalities (e.g. Porter, 2021) and/or to emissions (e.g. similarly to the EU Emissions Trading System, Directive 2018/410).

Different strategies were followed for the definition of renovation scenarios. According to Scenario 1, the building classes in the exposure model of residential buildings, addressing both structural and energy attributes, were first mapped to macro-taxonomy classes. Mapping was based on engineering judgement, considering for the sake of simplicity only the seismic design code level in the definition of macro-taxonomy. Subsequently, Scenario 1 investigated the impact (or benefit) of renovating predefined macro-taxonomy classes within a region. Instead, Scenarios 2 and 3 take into account the complete taxonomy string of building classes, and promote their renovation based on specific selection criteria. Scenario 2 investigates the impact of renovating predefined fractions of the building stock within a region. The building classes to be renovated are selected based on their individual benefit-to-cost ratio. Finally, Scenario 3 selects building classes for renovation based on their *BCR* value, so that renovation is always beneficial in economic terms, and therefore the fraction of the building stock that is renovated is unknown at the start of the impact analysis process. Specifically, Scenario 3.1 promotes for renovation all building classes presenting individually $BCR \geq 1.0$ within a region, whereas Scenario 3.2 considers all building classes that result in a cumulative *BCR* (referring to the group of renovated classes) approximately equal to unity. The investigated scenarios are summarised in Table 1.

An important feature of both Scenarios 2 and 3 is that the building classes that are promoted for renovation differ by renovation type due to their prioritisation and selection on the basis of *BCR*, which is different for seismic, energy, or integrated renovation per building class. This is in contrast to the strategy followed by Scenario 1, where a specific macro-taxonomy class is promoted for renovation regardless of the renovation type.

Table 1. Definition of alternative renovation scenarios.

Scenario		**Renovation type**
1	Renovate macrotaxonomy classes	Seismic retrofit
		Energy efficiency upgrading
		Integrated renovation
2	Renovate percentage of building stock (classes selected based on *BCR* per class)	Seismic retrofit
		Energy efficiency upgrading
		Integrated renovation
3.1	Renovate building classes with $BCR \geq 1$ (per class)	Seismic retrofit
		Energy efficiency upgrading
		Integrated renovation
3.2	Renovate building classes with cumulative $BCR \approx 1$	Seismic retrofit
		Energy efficiency upgrading
		Integrated renovation

In Table 1, renovation may consist of structural retrofitting against earthquakes (eq), energy efficiency upgrading of building envelopes (en), or both within an integrated (int) renovation approach. Among the metrics used to assess the impact of renovation scenarios, *BCR* represents the economic benefit derived from renovation over a planning period *t*, normalised to the cost of renovation (C_{ren}). The benefit is quantified by the difference between absolute average annual economic loss in existing and renovated buildings ($\Delta AAEL$), and the planning period is the length of time over which the renovation is effective. *t* was assumed equal to the remaining economic life of the asset in years (see Table 2). The spatial and material-based variation of the replacement and renovation cost was approximately considered by normalising both the renovation benefit and renovation cost to the present value of replacement cost (C_{rep}). C_{ren} was assumed proportional to C_{rep}, so that their ratio remains constant. According to the above definitions, *BCR* may take any non-negative value, with $BCR = 0$ indicating a renovation strategy that has no economic effect on mitigating risk and/or energy inefficiency, and $BCR > 1$ indicating a beneficial renovation strategy for which the economic benefit is higher than the renovation cost. $BCR = 1$ represents finally the case when the economic benefit fully compensates for the renovation cost but does not yield a net economic benefit. Finally, the variability of renovation cost and planning period was considered according to Table 2 to investigate their effect on *BCR*s and renovation scenarios.

Table 2. Considered variability in renovation cost and planning period (Gkatzogias et al., 2022b).

Variable	**Range**		
$(C_{ren} / C_{rep})_{\mathrm{eq}}$	0.06	0.12	0.24
$(C_{ren} / C_{rep})_{\mathrm{en}}$	0.08	0.15	0.30
$(C_{ren} / C_{rep})_{\mathrm{int}}$	0.10	0.21	0.41
t (years)	100	50	35

Further metrics were employed to assess the impact of renovation scenarios in economic and non-economic terms (Table 1). Specifically, the difference between average annual economic loss due to seismic repair and energy consumption ($\Delta AAEL_{eq}$, $\Delta AAEL_{en}$, $\Delta AAEL_{int}$), average annual loss of life ($\Delta AALL$), and average annual space heating energy consumption ($\Delta AAEC$) before and after renovation, were calculated by renovation type. These metrics, represent measures of annual benefit due to renovation in absolute terms, i.e. monetary value, number of fatalities, and energy consumption for $\Delta AAEL$, $\Delta AALL$, and $\Delta AAEC$, respectively. The net average annual economic benefit was also calculated ($\Delta AAEL_{net}$) as the benefit resulting from the renovation of a building class (or classes) while excluding the cost of renovation.

The average benefit in terms of economic loss ($\Delta AELR$), fatalities per hundred thousand occupants ($\Delta ALLR$), and energy consumption ($\Delta AEC_{bldg/HDD}$) over the entire planning period (t years) was also estimated, and provided as a fraction of the replacement cost, the average number of occupants over a 24-hour period, and the number of buildings and corresponding regional heating degree days value, respectively. These normalised benefits over the planning period, were used here to represent the *renovation potential* of individual building classes, defined as their capacity to save economic loss, lives and energy when they are renovated.

The number of the renovated buildings (i.e. fraction of a class, single class or multiple classes) and the associated replacement cost and number of occupants served as additional impact metrics, indicating the significance and scalability of a renovation strategy. These metrics were provided in most cases normalised to the total number of buildings (pc_N), total replacement cost, and total number of average occupants of the regional building stock. The *impact of a renovation scenario* is ultimately a function of the renovation potential of the building classes selected for renovation, and the distribution of buildings (or replacement cost) and occupants in these classes, while its economic feasibility can be described by a cumulative *BCR*.

A significant differentiation among the indicators used in regional prioritisation (Figure 6a) and the impact metrics employed in the assessment of renovation scenarios (Figure 6b) should be stressed here. Regional indicators based on primary metrics, such as *AAEL*, *AALL*, *AAEC* and their normalised counterparts consider the entire regional building stock. For example, the regional *AAELR* indicator was defined as the ratio of *AAEL* over the total replacement cost of buildings within a region (irrespective of their damage or loss state). On the contrary, relevant metrics in impact assessment consider only the renovated building stock. Regarding the previous example, *AAELR* in impact assessment is equal to the regional one when all buildings within a region are renovated.

4 Priority EU regions for building renovation

In this chapter selected georeferenced regional results are discussed, derived from implementing the framework for regional prioritisation (Section 3.1) in the EU-27 for residential buildings. Priority regions are presented indicatively based on indicators that address separately aspects of seismic risk (i.e. economic loss, loss of life), energy performance of buildings (i.e. energy consumption, energy cost) and socioeconomic vulnerability (i.e. *SVI*). Subsequently, the output of multi-sectoral integrated indicators is highlighted. Considering the above metrics and context, regional prioritisation does not aim to identify a unique ranking of regions. On the contrary, an effort was made to showcase the differentiation of results when multiple aspects are considered, and ideally identify regions where building renovation may have the highest and most spread impact. Detailed prioritisation results derived from all primary seismic risk, energy performance, socioeconomic vulnerability, and integrated indicators for 1151 NUTS-3 regions (10) are provided in Gkatzogias et al. (2022a) for residential buildings, along with seismic risk prioritisation results for commercial buildings.

4.1 Seismic risk

Average annual economic loss ($AAEL_{eq}$) and loss of life ($AALL$) measure absolute loss aggregated from all building classes within a region. In broad terms, the distribution of absolute average annual loss follows the pattern of seismicity. However, apart from the seismic hazard, prioritisation based on $AAEL_{eq}$ and $AALL$ is affected by the vulnerability of the building stock and modelling uncertainty. As $AAEL_{eq}$ is an aggregated metric, prioritisation further depends on the number and the value (aggregated replacement cost) of buildings within regions. Likewise, $AALL$ depends on the number of occupants (i.e. distribution of population). The top 100 priority regions from each indicator include regions from Austria, Bulgaria, Croatia, Cyprus, France, Germany, Greece, Italy, Spain, Portugal, Romania and Slovenia, and both indicators present a similar distribution of regions among these countries. Absolute average annual loss rankings highlight European regions of moderate-to-high seismicity, emphasising densely built and populated (urban, big city) areas. Both indicator rankings are characterised by the strong presence of Italian regions, followed by Greek or Romanian ones depending on the considered measure.

The normalised average annual loss for residential buildings, i.e. $AAEL_{eq/bldg}$ and $AALLR$, are measures of absolute average annual loss per building or per 100,000 inhabitants, i.e. distributed over the total number of buildings and occupants, and disregarding the expected damage/loss by building class within a region. Compared to the absolute economic loss indicator, $AAEL_{eq/bldg}$ assigns higher risk to regions with high average annual economic losses relative to the number of buildings. This may be the case of dense urban areas with high absolute annual loss and a large share of mid- and high-rise buildings (e.g. central and southern divisions of Athens). $AAEL_{eq/bldg}$ further highlights regions of high seismicity with lower number of buildings (e.g. Ionian islands in Greece), and excludes altogether regions from Croatia, France and Portugal. Overall, prioritisation based on $AAEL_{eq/bldg}$ and $AALLR$ facilitates comparison of regions with notable differences in the size of the building stock. However, $AAEL_{eq/bldg}$ is still affected by the value of the building stock (i.e. the replacement cost). The average annual economic loss ratio $AAELR_{eq}$, mapped in Figure 7a, represents a more robust normalised indicator, useful for comparing diverse regions in terms of both number and value of buildings. In this context, it may be seen as the aggregated average annual economic loss normalised to the total value of the building stock within a region, or as the ratio of the average annual economic loss of a single (average) building within the region (i.e. $AAEL_{eq/bldg}$) to its (average) replacement cost. $AAELR_{eq}$ highlights regions with high $AAEL_{eq/bldg}$ and low construction cost, placing Romanian and Greek regions on top of Italian ones and excluding regions of Austria, Germany, and Spain, captured by $AAEL_{eq/bldg}$. Likewise, $AALLR$ (Figure 7b) shifts down in the top 100 ranking densely populated areas (e.g. Naples), or even excludes them (e.g. Rome, Milan, Turin), compared to the absolute loss of life indicator. It further assigns higher risk to regions with high average annual fatalities relative to the population (e.g. Vrancea in Romania, Achaea and the Ionian islands in Greece, Ferrara and L'Aquila in Italy, Dubrovnik-Neretva in Croatia). In addition, $AALLR$ excludes from the top 100 ranking, the capital regions of Austria and Portugal, and the Bas-Rhin (France) region which includes the city of Strasbourg.

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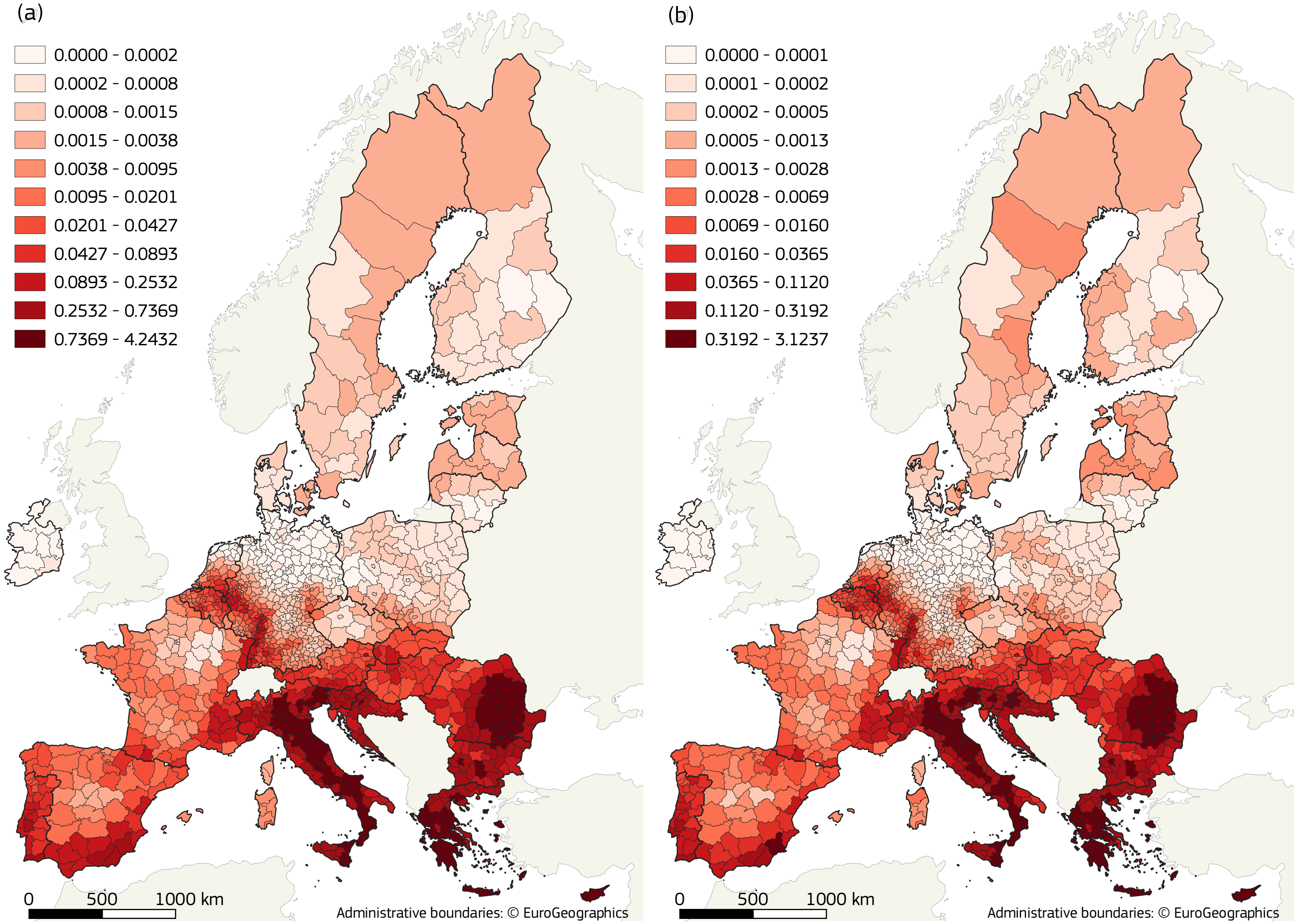
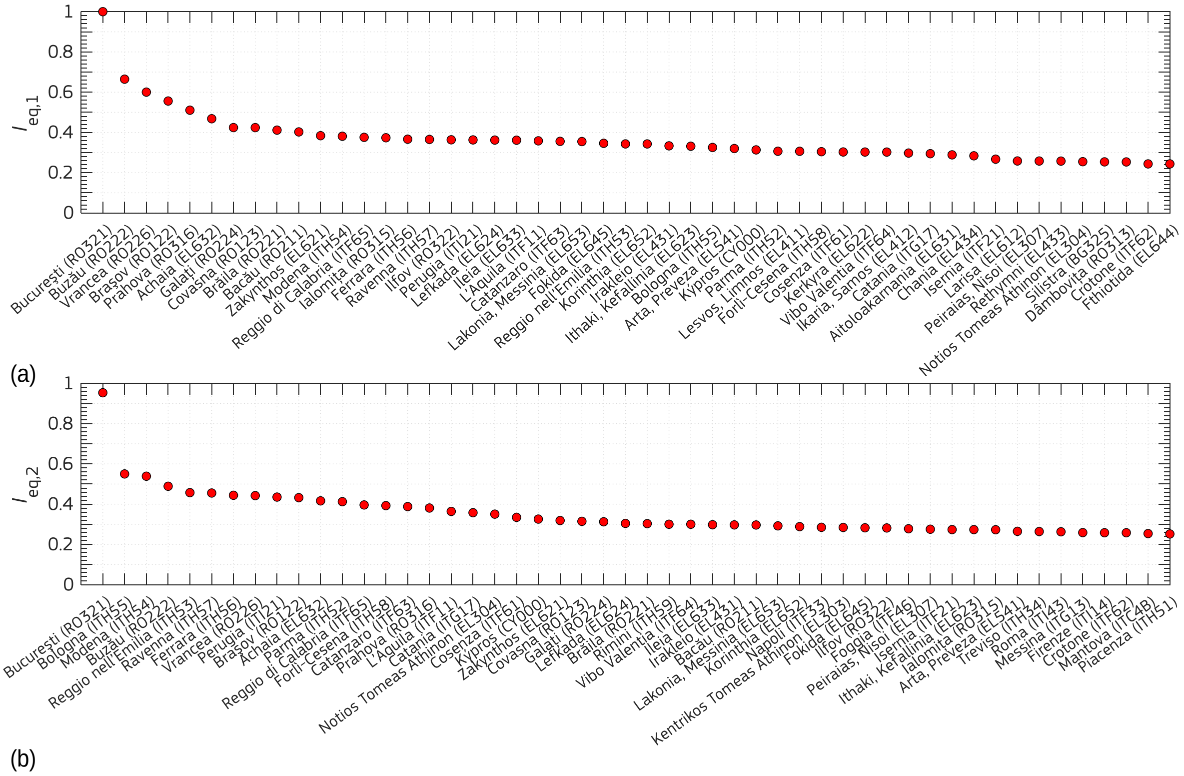
(10) NUTS 2021 classification, excluding outermost regions and Åland, FI200, Finland.

Figure 7. Seismic risk: average annual (a) economic loss ratio $AAELR_{eq}$ ($\cdot 10^{-3}$), and (b) loss of life ratio $AALLR$ ($\cdot 10^{-5}$) in residential EU-27 buildings at NUTS-3 (Source: GADM data from ESRM20, Crowley et al., 2021, available from EFEHR, http://risk.efehr.org; JRC mapping to NUTS by Gkatzogias et al., 2022a)



The single-sector integrated indicator $I_{eq,1}$ (combining $AAELR_{eq}$, and $AALLR$) and $I_{eq,2}$ (combining $AAEL_{eq/bldg}$, $AAELR_{eq}$, and $AALLR$), were found adequate to capture the different modes of prioritisation described earlier. For example, selecting the top 100 priority regions from $AAEL_{eq}$, $AAEL_{eq/bldg}$, $AAELR_{eq}$, $AALL$, and $AALLR$, results in 152 unique NUTS-3 regions. I_{eq2} identified 142 (92%) of these regions within its top 152. Likewise, I_{eq1} captured 99% of the regions included in the top 100 $AAELR_{eq}$ and $AALLR$ listings. Figure 8 presents the top 50 priority regions based on $I_{eq,1}$ and $I_{eq,2}$. $I_{eq,1}$ prioritises regions by assigning an equal weight (importance) to the normalised average annual economic loss ratio and the number of fatalities per 100,000 occupants, and addresses regions irrespective of building count, value, and population concentration. $I_{eq,2}$ considers additionally an absolute measure of loss per building. According to relevant definitions (Gkatzogias et al., 2022a), both $I_{eq,i}$ and component indicators range within 0–1, i.e. $I_{eq,i}$ = 0 and 1 correspond to the extreme cases of having all component indicators equal to 0 and 1, respectively.

Figure 8. Residential buildings: Top 50 priority regions based on single-sectoral integrated indicators: (a) $I_{eq,1}$ combining average annual economic loss ratio ($AAELR_{eq}$) and average annual loss of life ratio ($AALLR$), and (b) $I_{eq,2}$ combining average annual economic loss per building ($AAEL_{eq/bldg}$), $AAELR_{eq}$, and $AALLR$ (Gkatzogias et al., 2022a)



4.2 Energy performance

Prioritisation of regions based on average annual energy consumption ($AAEC$) is affected by climatic conditions, the energy performance attributes of building classes (thermal transmittance values and number of storeys), the size of the building stock (i.e. area of heated occupied dwellings), along with modelling uncertainty. The average annual economic loss ($AAEL_{en}$) is affected in addition by energy prices. Energy consumption and cost are highly correlated, indicating similar patterns. Apart from the expected tendency for higher values in colder climates (following the pattern of HDDs), absolute indicators are mainly controlled by the number of buildings and related heated floor area. In fact, among the highest ranked regions are densely built and populated areas, common to both indicator rankings, encompassing Turin, Milan, Rome, Berlin, Hamburg, Stockholm, Barcelona, and Nord (France) including Lille. Regions in the top 100 rankings include NUTS-3 from 13 Member States, largely represented by French regions, followed by Italian ones. These regions consume and pay the most in energy bills. Assuming that a regional prioritisation is led by total figures of energy use and cost, these are the areas where renovation may have the highest impact in absolute terms.

The former indicators may be also normalised to the total number of buildings per NUTS-3 region, i.e. $AAEL_{en/bldg}$ and $AAEC_{bldg}$. In this case, prioritisation highlights regions with high heating expenses and energy consumption per building, and/or urban regions with high share of mid- and high-rise buildings (multi-family buildings).

Common highly ranked regions among the two indicators include cold-climate areas of Europe, (e.g. in northern Italy and Germany), and big cities and urban regions (e.g. Paris, Milan, Turin, Berlin, and Dresden). The top 100 rankings derived from $AAEL_{en/bldg}$ and $AAEC_{bldg}$ include regions from Austria, Belgium, Finland, France, Germany, Italy and Sweden, with a strong presence of German regions (i.e. 50%), followed by French and Italian regions (i.e. 10% each). In both cases, normalised indicators emphasise German regions over French ones, highlighted by non-normalised indicators. In addition, Finish regions rank higher, whereas Italian ones move in lower positions. In conclusion, although there is still a significant share of highly ranked urban areas, the overall difference of normalised indicators lies in an evident shift towards northern Europe, ruling out southern areas with low normalised energy consumption (and cost) due to warmer weather conditions. Prioritisation based on $AAEC_{bldg}$ follows the climate condition pattern more closely than all other indicators. Prioritisation based on $AAEL_{en/bldg}$, which builds on $AAEC_{bldg}$, moves to higher ranking positions German and Swedish regions, and lowers the priority of Austrian, Estonian and Finnish ones due to the consideration of energy prices. For the same reason, $AAEL_{en/bldg}$ gives less priority to regions in other Baltic and central-east European countries.

Figure 9a identifies priority regions based on the normalised economic loss indicator $AAELR_{en}$. (i.e. economic loss normalised to the replacement cost). $AAELR_{en}$ highlights regions with high average space heating energy expenses relative to the replacement cost, both referring to an average building within the region. As in the case of seismic risk, $AAELR_{en}$ is useful for comparing diverse regions in terms of both size and value of the exposure, thus it represents a more robust normalised indicator compared to $AAEL_{en/bldg}$. Highly ranked regions according to $AAELR_{en}$ are located in Romania, whose regions comprise 40% of all regions within the top 100 ranking and include almost all regions of the country (i.e. 40 out of the 42). The rest of the regions are distributed mainly among Belgium, Czechia, and Slovenia. Compared to $AAEL_{en/bldg}$, $AAELR_{en}$ shifts priority towards the central-east European zone, with moderately cold climate and small values of average building replacement cost. The role of the exposure value in prioritisation is evident when $AAELR_{en}$ and $AAEL_{en/bldg}$ top 100 rankings are compared. $AAEL_{en/bldg}$ shifts priority westwards due to the low energy price in central and eastern Europe, whereas $AAELR_{en}$ more to the east due to the low values of replacement cost.

In Figure 9b, regions are prioritised based on $AAEC_{bldg/HDD}$; this is an indicator that provides an overview of regional energy consumption per building and *HDD* value, thus eliminating the effect of the buildings stock size and climate severity. $AAEC_{bldg/HDD}$ highlights regions with high energy consumption per building irrespective of climatic conditions. It emphasises regions with potentially inefficient building envelopes (high thermal transmittance values), energy systems (losses in the energy network), and user behaviour. Compared to $AAEC_{bldg}$, $AAEC_{bldg/HDD}$ maintains in high-ranking positions Paris, Hauts-de-Seine, Milan, and Turin. Additionally, it introduces Italian cities and urban regions (e.g. Bologna, Genoa, Rome, Naples), and central Athens. Overall, Italian regions represent a 43% share within the top 100, followed by regions of Germany and France. Furthermore, $AAEC_{bldg/HDD}$ shifts the priority from northern European regions (with building insulation properties and heating systems adjusted to relevant climatic conditions and energy cost) to central and southern European regions with higher potential for energy efficiency improvement.

The single-sectoral integrated indicator I_{en} (Figure 10) combines $AAEL_{en/bldg}$, $AAELR_{en}$, and $AAEC_{bldg/HDD}$ by assigning an equal weight (importance) to each component. Individual prioritisations based on $AAEL_{en}$, $AAEC$, $AAEL_{en/bldg}$, $AAEC_{bldg}$, $AAELR_{en}$, and $AAEC_{bldg/HDD}$ are more diverse compared to the case of seismic risk (Section 4.1), hence the efficiency of I_{en} in capturing the different modes of prioritisation of all six component indicators was found somewhat reduced (compared to $I_{eq,2}$). I_{en} captured 73% of the unique regions obtained separately from the six component indicator top 100 rankings (i.e. 230 out of 314). The top 100 ranking based on I_{en} include regions mainly from Germany and Italy, followed by Romania and France.

Figure 9. Energy performance: (a) average annual economic loss ratio $AAELR_{en}$ ($\cdot 10^{-3}$), and (b) average annual energy consumption per building and HDD $AAEC_{bldg,HDD}$ (kWh/HDD) (Gkatzogias et al., 2022a)

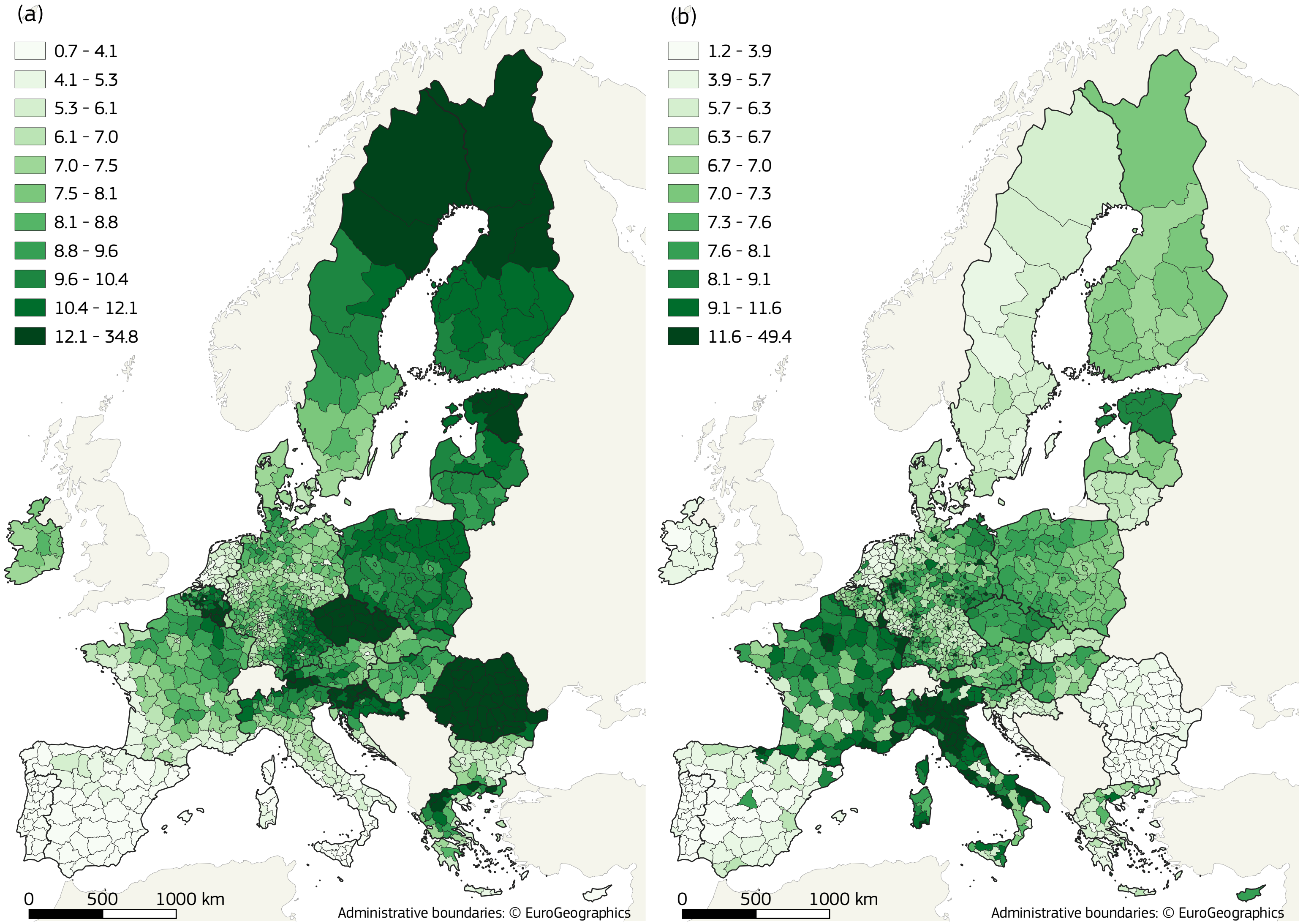
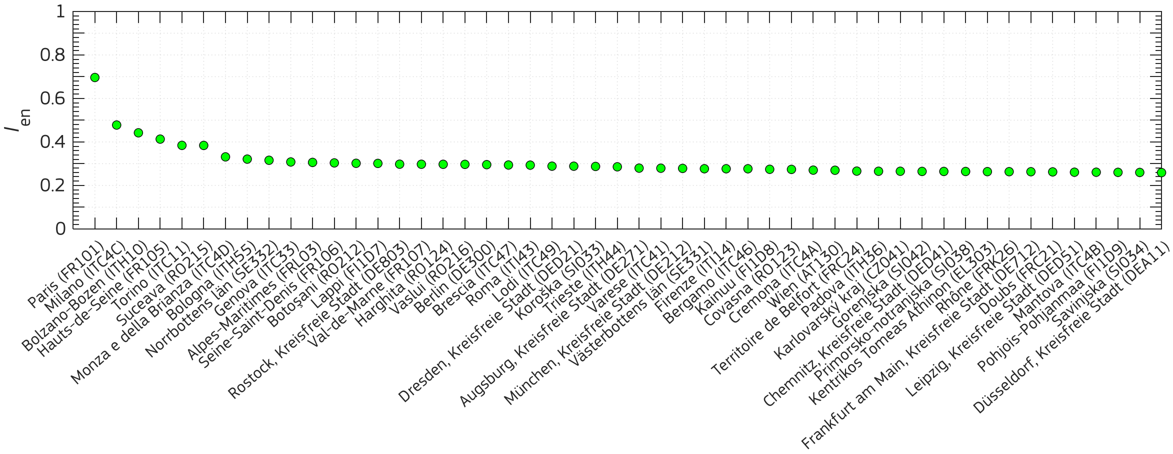


Figure 10. Residential buildings: Top 50 priority regions based on single-sectoral integrated indicator I_{en} combining average annual energy consumption per building and *HDD* ($AAEC_{bldg/HDD}$), average annual economic loss per building ($AAEL_{en/bldg}$), and average annual economic loss ratio ($AAELR_{en}$) (Gkatzogias et al., 2022a)



4.3 Socioeconomic vulnerability

The top 50 priority regions considering the socioeconomic vulnerability indicator (*SVI*) at NUTS-3 level are presented in Figure 11, whereas *SVI* is mapped across the EU-27 in Figure 12. *SVI* represents an effort to prioritise regions by assigning an equal weight to socioeconomic development, smart, sustainable, and inclusive growth, and social progress. It captures 90% of the unique regions (i.e. 144 out of 160) obtained from the top 100 EU-HDI, EU2020, and EU-SPI indicator rankings adapted to reflect socioeconomic vulnerability. The top 100 *SVI* list consists of most Bulgarian regions (i.e. 23 out of 28) while excluding Sofia and western regions of the country. Likewise, it includes most Romanian regions (i.e. 30 out of 42) while excluding Bucharest and the north-western part of the country. Finally, the top 100 *SVI* list includes regions in southern Italy (e.g. Calabria, Naples), three regions in northern Hungary, and regions in south-western Spain (e.g. Seville).

Overall, the top 100 *SVI* ranking shares 29 common NUTS-3 regions to $I_{eq,2}$. These include two regions of northern Bulgaria, 15 regions of southern Italy, and 12 regions of central and south-eastern Romania. On the other hand, the top 100 *SVI* list has only nine regions in common with I_{en}, all located in Romania, with two of them being also present in the top 100 $I_{eq,2}$ list (i.e. Braşov, Covasna).

Figure 11. Top 50 priority NUTS-3 regions based on socioeconomic vulnerability index *SVI* (Gkatzogias et al., 2022a)

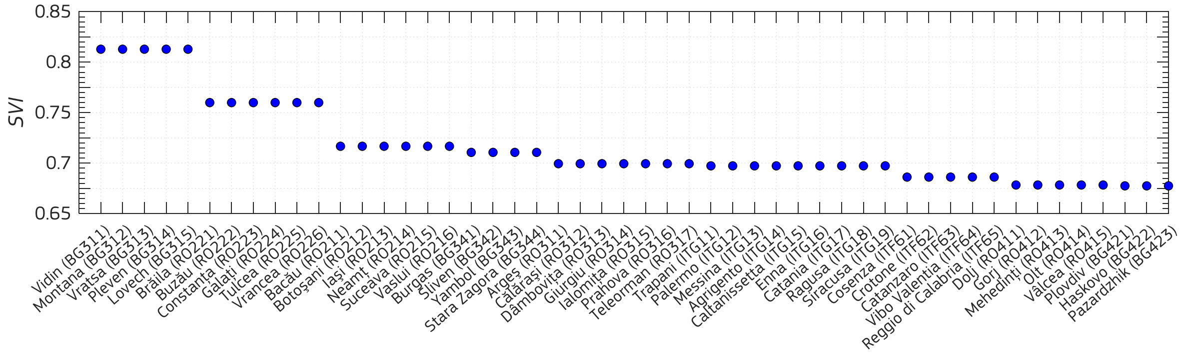
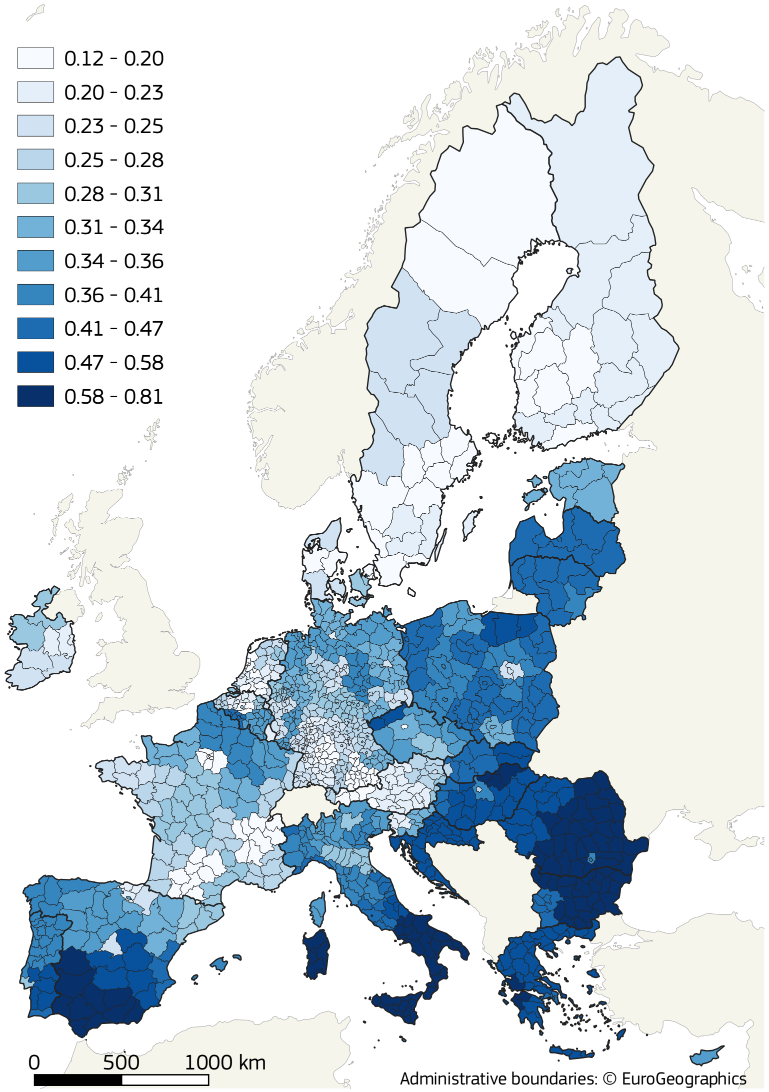


Figure 12. Socioeconomic vulnerability index *SVI* in the EU-27 at NUTS-3 level (Gkatzogias et al., 2022a)



Administrative boundaries: © EuroGeographics

4.4 Integrated prioritisation

Different multi-sectoral integrated indicators were investigated and mapped across the EU-27 NUTS-3 regions, considering at the same time seismic risk, energy performance and socioeconomic aspects. Results were presented for two different prioritisation approaches: *i*) selecting the top 100 out of the 1151 NUTS-3 regions ordered by decreasing values of integrated indicators, and *ii*) selecting first the top 200 out of the 1151 regions ordered by decreasing values of the component seismic risk indicators, and then selecting the top 100 out of the 200 regions ordered by decreasing values of multi-sectoral integrated indicators. Cases *i* and *ii* are depicted as sub-figures 'a' and 'b', resulting in the multi-sectoral indicators *I* and *I**, respectively, in Figure 13 and Figure 14. Sub-figures 'a' highlight in red the top 105 regions and in shades of green the rest 1046 regions. Sub-figures 'b' highlight in red the top 100 regions, and in green the rest of the initially selected 200 regions.

I_{eq-en} consists of pure normalised seismic risk and energy performance economic indicators, and prioritises regions by assigning an equal weight to the ratios of average annual economic seismic and energy loss of a single (average) building within a region to its (average) replacement cost (Figure 13a). I_{eq-en} can be used to identify priority regions where ratios of renovation benefit to renovation cost are expected to be maximised (Gkatzogias et al., 2022b). Such an approach requires both cost and benefit to be defined in monetary terms. In this context, the indicator can be further populated with loss of life, and CO_2 emissions (due to space heating energy consumption and/or repair of buildings), if such relevant metrics are assigned with monetary values. I_{eq-en} captures 89% of the unique regions obtained separately from the top 100 $AAELR_{eq}$ and $AAELR_{en}$ rankings (i.e. 163 out of 184). The top 100 I_{eq-en} ranking includes all NUTS-3 regions of Romania and Slovenia (apart from two), 24 out of the 52 NUTS-3 regions of Greece, 18 regions across Italy, four regions in northern Croatia, and two regions in north-eastern Bulgaria, all characterised by high relevant economic loss due to both seismic repair and energy consumption. I^*_{eq-en} (Figure 13b) presents similar patterns to I_{eq-en} with 79 common regions in the top 100. Unsurprisingly, based on its definition, I^*_{eq-en} promotes regions of high seismic risk over regions of high average annual energy loss ratios. Among others, it excludes 17 regions of Romania, located in the northern and western part of the country. On the contrary, it introduces in the bottom of the top 100 ranking, 21 regions of higher $AAELR_{eq}$ from Italy, Greece, Bulgaria, Romania, the capital region of Croatia, and Cyprus.

$I_{eq-en-SVI,1}$ additionally considers socioeconomic vulnerability (*SVI*) in regional prioritisation, assigning an equal weight to the three component indicators (i.e. $AAELR_{eq}$, $AAELR_{en}$, *SVI*). $I_{eq-en-SVI,1}$ provides a wider perspective to the topic of building renovation that includes socioeconomic aspects. The multi-sectoral integrated indicator was found capable of capturing 80% of the unique regions obtained separately from the top 100 $AAELR_{eq}$, $AAELR_{en}$, and *SVI* rankings (i.e. 189 out of 236). Although $I_{eq-en-SVI,1}$ top 100 ranking includes 70 common regions to I_{eq-en}, it presents a shift of priority to south-eastern Europe in line with *SVI*; it includes all regions of Romania, twelve additional regions of Bulgaria, while excluding regions of northern Italy, and all Slovenian regions. $I^*_{eq-en-SVI,1}$, similarly to I^*_{eq-en}, excludes from the top 100 list the same 17 Romanian regions, while it adds to the bottom of the list 23 regions of higher $AAELR_{eq}$ from Bulgaria, Croatia, Greece, and Italy. $I_{eq-en-SVI,2}$ is useful for investigating renovation scenarios based on economic terms while considering socioeconomic aspects and loss of life (i.e. *AALLR*). The integrated indicator was able to capture 78% of the unique regions obtained separately from the top 100 $I_{eq,1}$, $AAELR_{en}$, and *SVI* rankings (i.e. 184 out of 236). Given the similarity of $AAELR_{eq}$ and *AALLR* modes of prioritisation (Figure 7), which also comprise the seismic component $I_{eq,1}$, the top 100 $I_{eq-en-SVI,2}$ introduces only three different regions compared to $I_{eq-en-SVI,1}$, located near the bottom of the list. These include two regions in north-eastern Hungary and one in southern Bulgaria, substituting three Greek regions. $I^*_{eq-en-SVI,2}$ top 100 ranking shares 75 common regions to $I_{eq-en-SVI,2}$, excluding approximately the same regions as $I^*_{eq-en-SVI,1}$, and introducing 25 regions from Bulgaria, Croatia, Greece, and Italy with higher $I_{eq,1}$ values.

Finally, $I_{eq-en-SVI,3}$ (Figure 14a) integrates all relevant normalised indicators (with equal weights), while aiming to capture the effect of both absolute and normalised indicators. Apart from economic loss ratio (i.e. $AAELR_{eq}$, $AAELR_{en}$), the indicator additionally considers economic loss per building (i.e. $AAEL_{eq/bldg}$, $AAEL_{en/bldg}$), which promotes renovation of urban regions. $I_{eq-en-SVI,3}$ further considers energy consumption per building and *HDD* (i.e. $AAEC_{bldg/HDD}$), which in turn promotes regions with building envelopes, network systems or user behaviour of low energy efficiency. By integrating loss of life (*AALLR*), energy consumption (implicitly indicating also greenhouse gas emissions), and socioeconomic aspects (*SVI*), $I_{eq-en-SVI,3}$ attempts to shift the focus from a purely economic perspective. The integrated indicator captures 73% of the unique regions obtained separately from the top 100 component indicator rankings (i.e. 178 out of 245). Furthermore, $I_{eq-en-SVI,3}$ top 100 ranking has 77 regions in common with $I_{eq-en-SVI,2}$. It excludes mainly north-western regions of Romania, seven regions from northern and western Greece, four regions of Bulgaria, and one in Croatia. On the other hand, it introduces the capital regions of France, Greece, Italy, along with 19 additional Italian regions (including the urban regions of Milan, Turin, Palermo, Bologna, Florence and Bari). $I^*_{eq-en-SVI,3}$ top 100 ranking has 80 common regions to $I_{eq-en-SVI,3}$, introducing mainly regions of Greece and Italy with high $I_{eq,2}$ values (Figure 14b).

Figure 13. Multi-sectoral integrated indicators combining average annual economic loss ratio due to seismic repair and energy consumption: (a) I_{eq-en}, and (b) I^*_{eq-en} based on prioritisation approaches (*i*) and (*ii*) at NUTS-3 level (in red: top 100 regions with the highest index value) (Gkatzogias et al., 2022a)

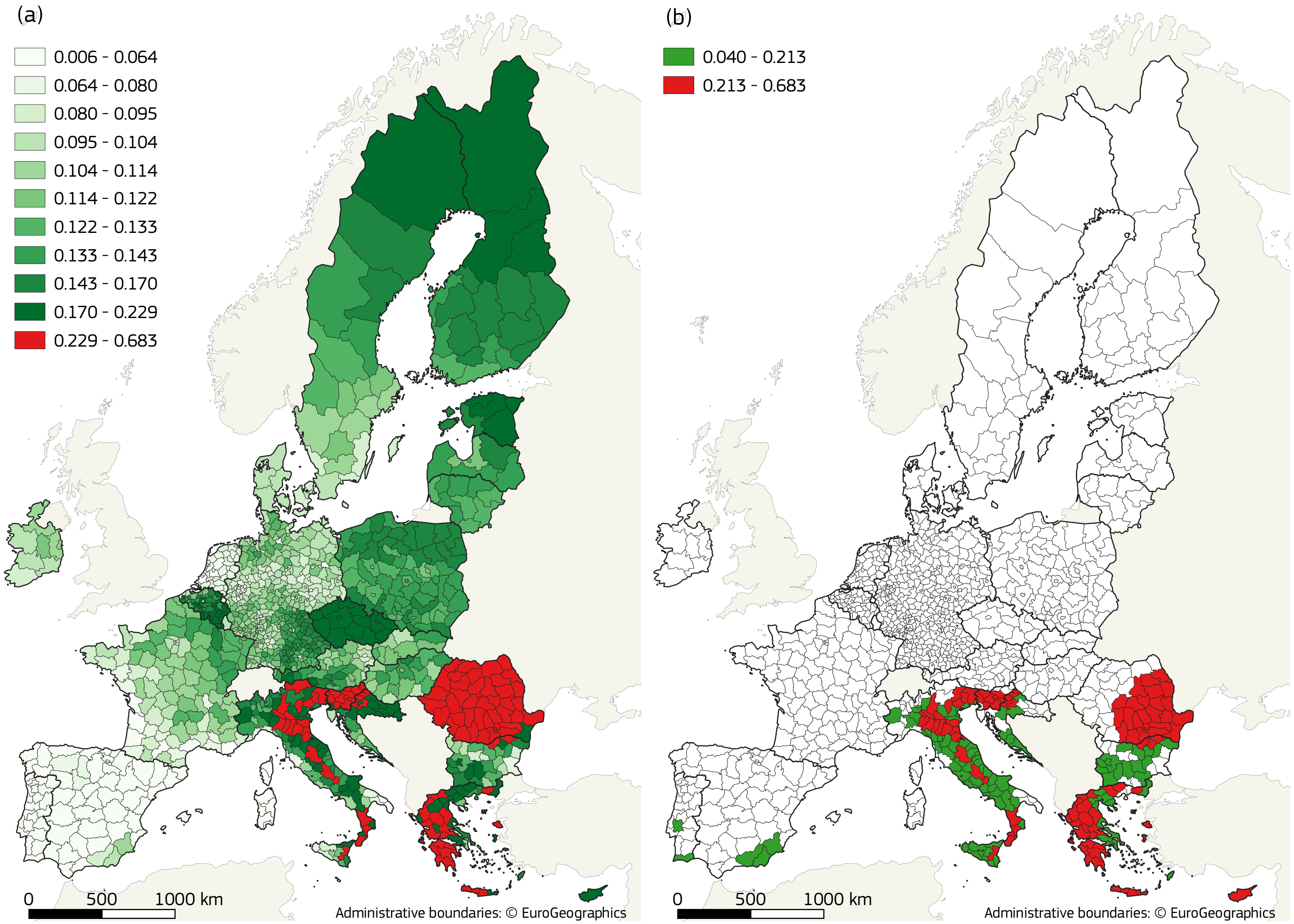
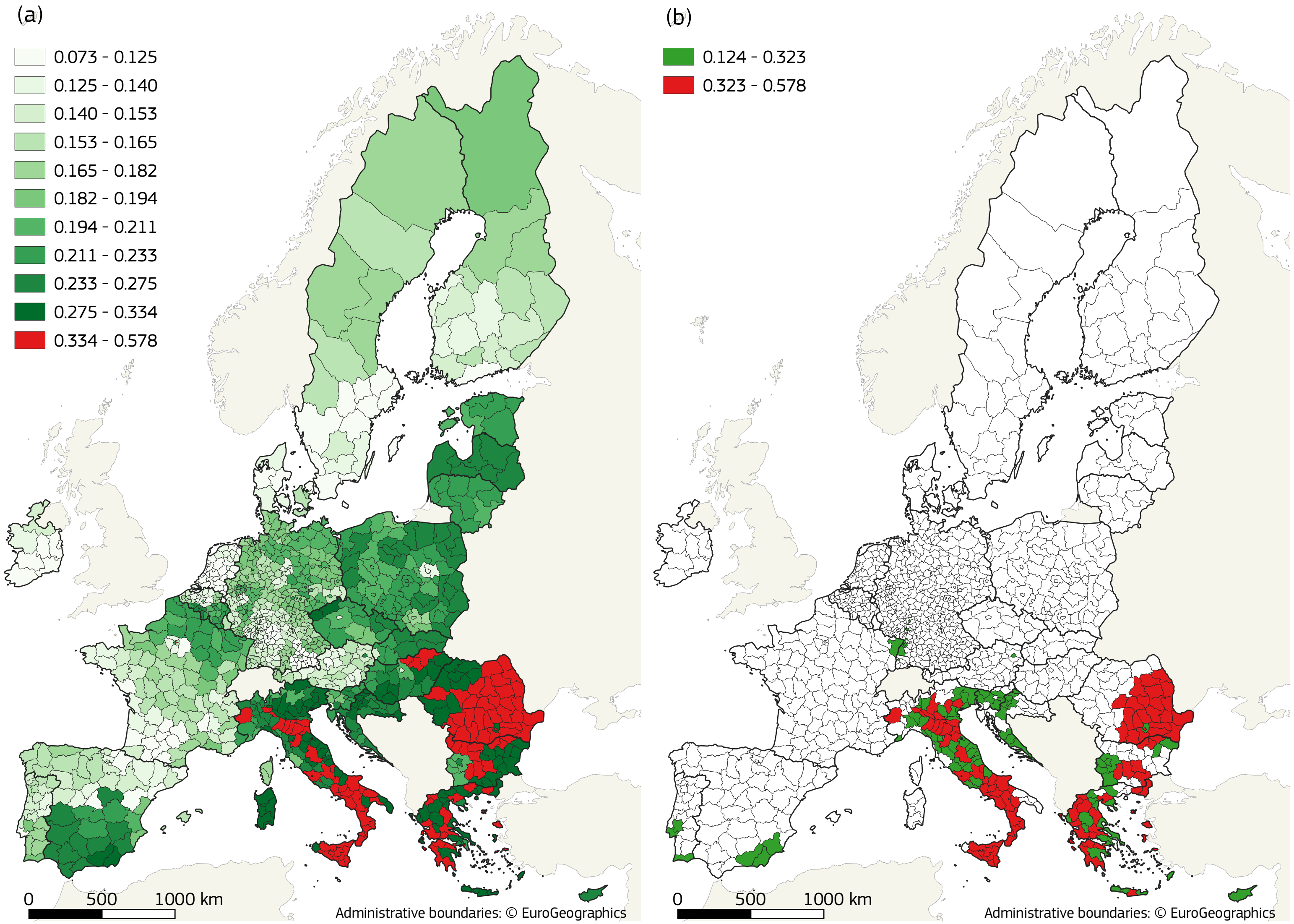


Figure 14. Multi-sectoral integrated indicators combining seismic risk, energy performance, and socioeconomic vulnerability: (a) $I_{\text{eq-en-SVI},3}$, and (b) $I^{*}_{\text{eq-en-SVI},3}$ based on prioritisation approaches (*i*) and (*ii*) in the EU-27 at NUTS-3 level (in red: top 100 regions with the highest index value) (Gkatzogias et al., 2022a)



5 Renovation impact

Selected georeferenced regional results are presented in this chapter, derived from implementing the impact assessment framework (Section 3.2) for 1151 NUTS-3 regions of the EU-27. *BCR*s along with additional impact metrics are first briefly presented in Section 5.1, referring to individual building classes, as if a single class is renovated within a region. In this context, Section 5.1 provides an overview of the *renovation potential* within regions. Subsequently, Sections 5.2–5.4 investigate cumulative *BCR* values and impact metrics (i.e. for the sum of the renovated buildings), according to the scenarios defined in Section 3.2. Accordingly, Sections 5.2–5.4 provide the *renovation impact* of scenarios in terms of *BCR*s and benefits in absolute terms derived from renovating multiple building classes within a single or multiple regions. In all cases (Sections 5.1–5.4), priority regions are based on the multi-sectoral integrated indicator $I^*_{\text{eq–en–SVI,3}}$ (Section 4.4) to facilitate comparisons.

The impact assessment of renovation scenarios does not aim to identify a unique renovation strategy in each region. On the contrary, an effort was made to showcase the differentiation of impact when renovation strategies of different complexity are considered. The less complex Scenarios 1 and 2 are presented briefly in Sections 5.2 and 5.3, respectively, whereas the more elaborate Scenario 3 is presented in detail in Section 5.4. A detailed presentation of the renovation potential and the impact for all scenarios and additional prioritisation schemes is provided in Gkatzogias et al. (2022b).

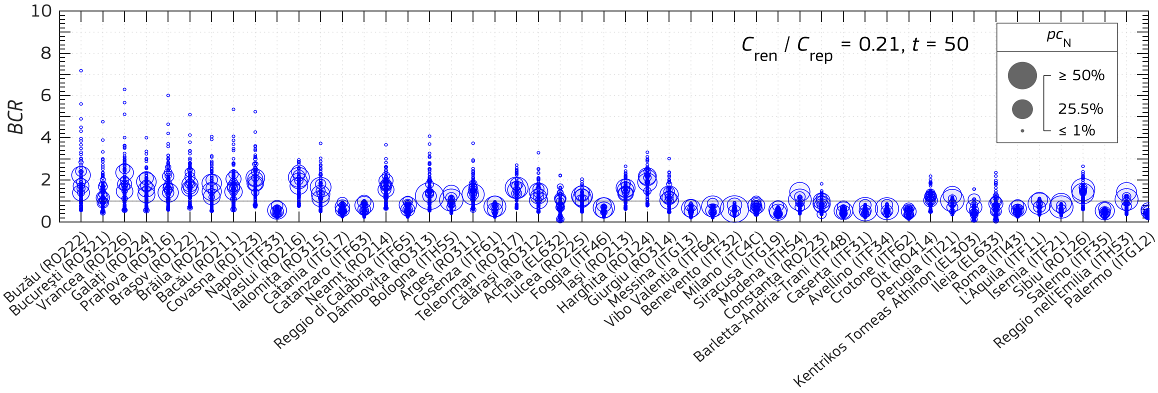
5.1 Benefit-to-cost ratios

Among the priority regions (Figure 14b), the seismic renovation potential in terms of *BCR* values was found to be high in Romanian and Greek regions, as opposed to Italian ones where the high renovation cost results in low *BCR*s. Interestingly, in regions where seismic retrofit may be economically beneficial (due to the presence of multiple building classes with *BCR* ≥ 1), the building classes with high *BCR* values exhibit in general also high potential for saving lives ($\Delta ALLR$). However, building classes with the highest share of buildings, replacement cost, and average number of occupants per region have low renovation potential, introducing further complexity in defining efficient seismic renovation strategies.

The share of the building classes with *BCR* ≥ 1.0 indicates a significantly higher economic potential due to energy efficiency upgrading, providing valuable margin for improving the impact of seismic retrofit through integrated renovation. A low renovation potential was observed mainly in Italian priority regions, associated primarily with the high renovation cost. In regions where energy upgrading is expected to be economically beneficial, the building classes with high potential for saving energy ($\Delta AEC_{bldg/HDD}$) exhibit in general high *BCR*s. Contrary to seismic retrofit, building classes with high *BCR*s accumulate the highest share of exposed assets.

The potential due to integrated renovation showcases a significant improve compared to seismic retrofit, while combining positive aspects from both types of renovation. On average, *BCR*s of building classes per region tend to increase compared to seismic retrofit, following a similar trend as in energy efficiency upgrading. Peak *BCR*s, albeit lower, are closer to the range of the values derived from seismic retrofit (which are generally higher than in energy efficiency upgrading). In regions where integrated renovation is expected to be economically beneficial, building classes with *BCR* ≥ 1.0 present the highest potential for saving lives and energy, and they integrate the highest share of buildings and population (Figure 15).

Figure 15. Integrated renovation: Benefit-to-cost ratios (*BCR*) per building class within top 50 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$ (considering seismic risk, energy efficiency, and socioeconomic vulnerability), renovation to replacement cost ratio C_{ren} / C_{rep} = 0.21, planning period t = 50 years, along with associated percentage of the regional building stock (pc_N) (Gkatzogias et al., 2022b)



5.2 Scenario 1

Scenario 1 investigates the impact of renovating all buildings within predefined macro-taxonomy classes for all NUTS3 regions across the EU, but with a focus on priority regions that were identified based on the multi-sectoral integrated indicator $I^{*}_{\mathrm{eq-en-SVI,3}}$. Macro-taxonomies were simplistically based here on a single structural attribute relevant to the seismic performance, i.e. the building seismic design code level, as this is expected to yield the highest benefit due to seismic retrofit, in economic terms or otherwise (e.g. reducing fatalities). The same macro-taxonomy classes were considered in energy efficiency upgrading and integrated renovation. Such a definition of macro-taxonomy classes further ensures a risk-proofed renovated building environment in the case of integrated renovation, since buildings of low seismic capacity are promoted for renovation. On the other hand, the same definition involves a high risk of renovation investment loss due to earthquakes when energy upgrading is only applied.

Accordingly, three sub-scenarios were investigated, corresponding to renovating buildings with no (CDN), low (CDL) and moderate (CDM) seismic design code level. According to the scenario definition, building renovation, and hence the associated benefit (i.e. reduction in economic loss, loss of life, and energy consumption), extend across most of the EU regions regardless of their seismic risk and/or energy performance. Yet, seismic retrofit according to Scenario 1 was found to be economically feasible in a few regions, characterised by quite high seismic risk and low renovation cost (Figure 16a). The scenario is deemed more promising in the case of energy efficiency upgrading (Figure 16b). Upgrading the energy performance of CDN buildings within all top 100 priority regions was found to be almost economically beneficial (cumulative *BCR* equal to 0.93), as CDN buildings within these regions are old and characterised by low energy performance (hence, high economic loss). An integrated approach allows renovating CDL buildings in a cost beneficial way in 73 regions across the EU (Figure 16c), as opposed to 155 and only 6 regions in the case of energy efficiency and seismic upgrading, respectively. If only the top 100 priority regions are considered, integrated renovation of CDL buildings is economically beneficial in 37 regions contrary to 30 regions in the case of energy efficiency upgrading. At the same time, integrated renovation of CDL buildings in the top 100 priority regions presents the highest average annual economic benefit among the three types of renovation and identical reduction in fatalities and energy consumption to seismic retrofit and energy efficiency upgrading, respectively (in line with the scenario definition). Scenario 1 is expected to be more cost-efficient if the granularity in the definition of macro-taxonomy classes is increased, i.e. by including additional structural but also energy attributes (e.g. construction date, height of buildings). Inevitably, this comes at the cost of increased complexity in scenario definition and implementation.

5.3 Scenario 2

Renovation Scenario 2 follows a similar approach to Scenario 1. However, instead of investigating the economic feasibility of renovating predefined macro-taxonomy classes, the scenario targets the renovation of predefined fractions of the regional building stocks. Herein, investigated sub-scenarios correspond to renovating 10% and 20% of the regional building stocks, starting from the building classes with the highest *BCR*s and moving to the next ones of lower ratios, until the preselected percentages of buildings within each region are reached. In this context, building classes per region are prioritised based on their individual *BCR*, and therefore those promoted for renovation differ among regions and renovation type.

Overall, increasing the number of renovated buildings, results in decreasing the cumulative *BCR*s per region, and thus the efficiency of the renovation scenario. Across the EU, at the NUTS-3 level, integrated renovation of the 20% of the regional building stock exhibits cumulative *BCR*s ≥ 1.0 in 448 regions (out of the 1151) (Figure 17c), as opposed to 774 regions in the case of energy efficiency upgrading (Figure 17b), and just 29 in the seismic retrofit case (Figure 17a). Integrated renovation allows upgrading the seismic safety of structures in a cost-efficient way to a much larger extent than seismic retrofit alone, while it presents economic benefits with the same order of magnitude as energy efficiency upgrading. Given the indiscriminate renovation in all regions according to the preselected fractions of the regional building stocks, Scenario 2 comes in handy when the venture is funded by a single central entity and renovation is urged in regions with no expected net economic benefit. For example, implementing integrated renovation in the 20% of the building stock within the top 100 priority regions was assessed as economically beneficial for 64 regions. Although this share of regions represents an additional increase compared to the case of energy efficiency upgrading, 36 priority regions mainly in southern Italy, but also in Greece and Bulgaria, still do not provide a positive net economic benefit. Yet, if the cumulative *BCR* and net average annual economic benefit are calculated over all the top 100 regions, integrated renovation becomes economically viable for a central funding entity. This is also valid for energy efficiency upgrading but not seismic retrofit. In favour of integrated renovation, it further results in the highest net economic benefit, and approximately the same benefit in terms of loss of life and energy consumption.

Figure 16. Scenario 1 – Cumulative benefit-to-cost ratios (*BCR*s) derived from renovating buildings with low seismic design code level (CDL) for (a) seismic retrofit (renovation to replacement cost ratio C_{ren} / C_{rep} = 0.12, planning period t = 50 years), (b) energy efficiency upgrading (C_{ren} / C_{rep} = 0.15, t = 50), and (c) integrated renovation (C_{ren} / C_{rep} = 0.21, t = 50) (in red borders: top 100 priority regions based on the multi-sectoral integrated regional indicator $I^{*}_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, and socioeconomic vulnerability) (Gkatzogias et al., 2022b)

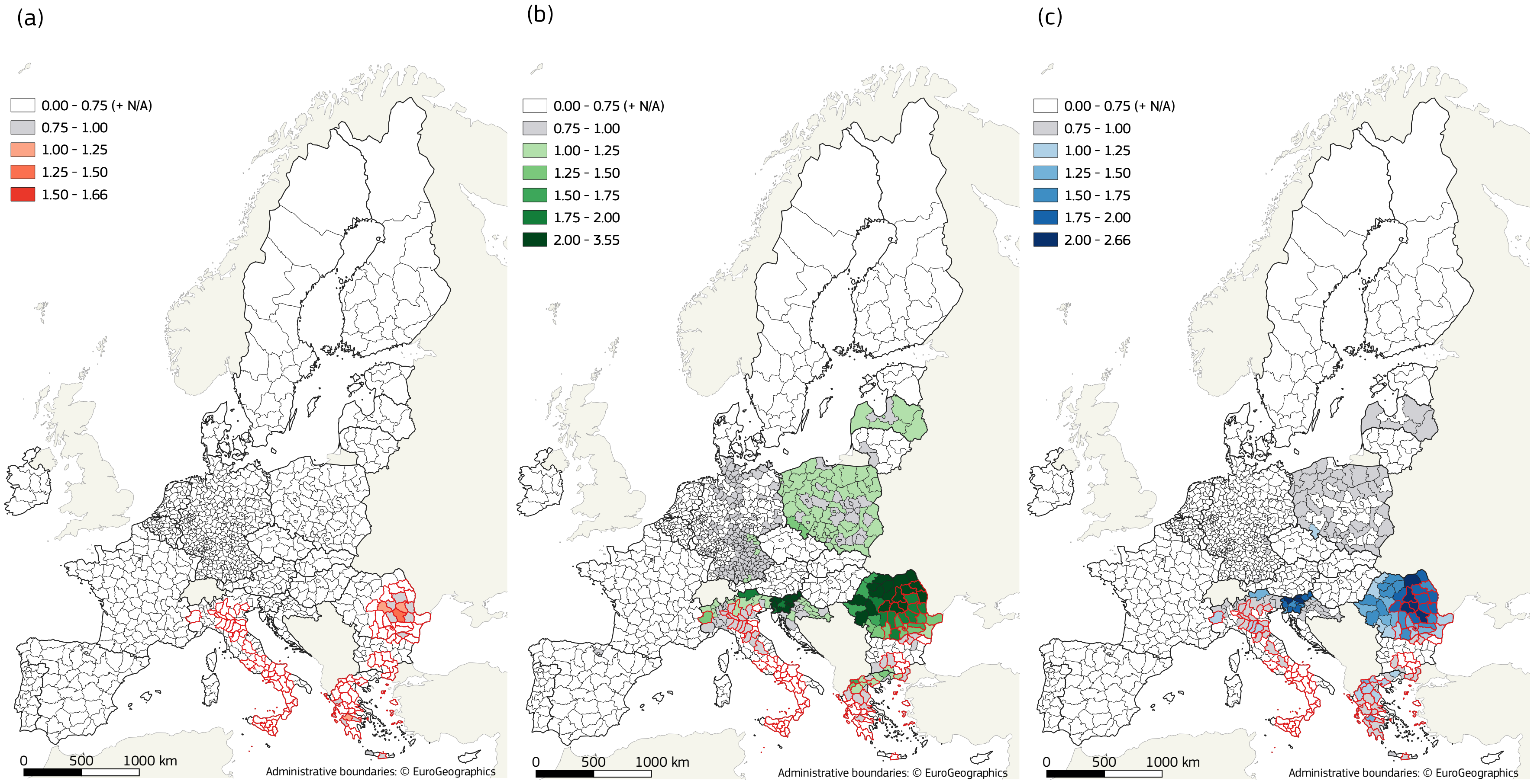
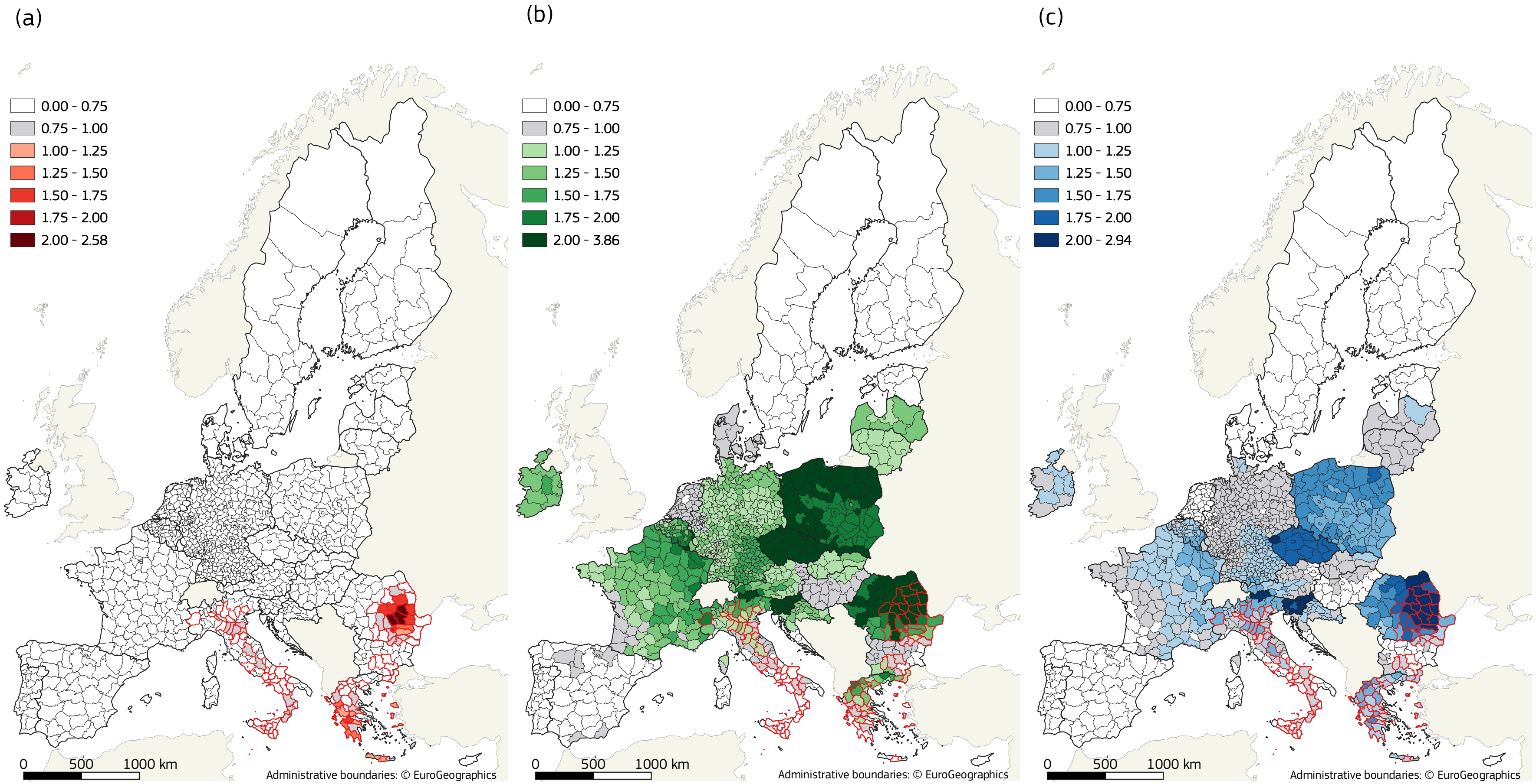


Figure 17. Scenario 2 – Cumulative benefit-to-cost ratios (*BCR*s) derived from renovating buildings with low seismic design code level (CDL) for (a) seismic retrofit (renovation to replacement cost ratio C_{ren} / C_{rep} = 0.12, planning period t = 50 years), (b) energy efficiency upgrading (C_{ren} / C_{rep} = 0.15, t = 50), and (c) integrated renovation (C_{ren} / C_{rep} = 0.21, t = 50) (in red borders: top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, and socioeconomic vulnerability) (Gkatzogias et al., 2022b)



5.4 Scenario 3

Contrary to the previous scenarios that investigate the attained benefit-to-cost ratios (and impact metrics) due to the renovation of predefined macro-taxonomy classes or fractions of the regional building stocks, Scenario 3 follows an inverse approach. Specifically, it aims to identify the maximum fraction of the regional building stock and the relevant building classes, the renovation of which always results in a cumulative *BCR* equal or larger than unity, thus in an economically advantageous renovation strategy.

5.4.1 Seismic retrofit

Figure 18 presents the cumulative benefit-to-cost ratios derived from implementing Scenario 3. Scenario 3.1 renovates the building classes within a region that present individually $BCR \geq 1.0$, whereas Scenario 3.2 the building classes that result in a cumulative *BCR* approximately equal to one (denoted on the figure as $\Sigma BCR \approx 1.0$). Therefore, both scenarios can be implemented only if at least one building class with an individual $BCR > 1.0$ is present in the region under consideration, i.e. a marked difference with Scenario 2. For comparative purposes, the figure reports also the cumulative benefit-to-cost ratio that correspond to renovating the entire regional building stock. The priority regions shown in the figure are based on the multi-sectoral integrated indicator $I^{*}_{\text{eq–en–SVI},3}$. Figure 18 depicts the case of $C_{\text{ren}} / C_{\text{rep}} = 0.12$ and $t = 50$ years. Renovating building classes with individual *BCR*s ≥ 1.0 according to Scenario 3.1 results in a cumulative benefit-to-cost ratio in the range of 1.05–2.24 within the top 50 priority regions, indicating an economic benefit which exceeds the cost of renovation over the planning period. On the other hand, Scenario 3.2 takes advantage of this available margin to renovate more building classes which would not be beneficial to retrofit on a stand-alone basis. Therefore, cumulative ratios derived from Scenario 3.2 are close to unity. In the above context, Scenario 3.2 may be of interest to state authorities, aiming to maximise the percentage of renovated buildings and the affected population rather than yielding a net economic benefit.

The absence of data for Scenario 3.1 in Figure 18 derives from the lack of even a single building class with an individual $BCR \geq 1.0$, resulting also in the absence of data for Scenario 3.2. This is the case for all Italian regions in the figure (i.e. 24 out of the 50 priority regions), due to their high renovation and replacement cost. It should be recalled, though, that replacement cost does not consider regional variations, but it is defined at the national level by material and settlement type (Section 3.2). The significant differentiation of cost among regions of different countries, renders renovation economically beneficial in regions with significantly lower seismic risk (in terms of the regional *AAELR* indicator) compared to Italian ones (e.g. Iaşi in Romania vs. Modena in Italy). Finally, identical cumulative *BCR* values among Scenario 3.1 and 3.2 in Figure 18 (e.g. coinciding circles in the case of Constanța, Romania) indicate that in Scenario 3.2 no additional classes (compared to Scenario 3.1) can be renovated in a cost-beneficial way. In a similar context, when Scenario 3.2 values are equal to the cumulative *BCR* corresponding to the renovation of the 100% of the building stock, it is economically beneficial to renovate all buildings within a region.

For the lowest considered renovation cost and the longest planning period ($C_{\text{ren}} / C_{\text{rep}} = 0.06$ and $t = 100$ years in Table 2), Scenario 3.2 results in a cost-beneficial renovation of the entire building stock in most of the Romanian and Greek regions within the top 50 priority regions. On many occasions, Scenario 3.2 is capable of renovating the entire building stock while at the same time retaining a high cumulative *BCR* value. For example, renovating all buildings in Bucharest yields an economic benefit which is four times higher than the renovation investment. Interestingly, the same is valid for 18 out of the 24 Italian regions, nevertheless, exhibiting lower economic benefits. Milan and Palermo are the only Italian regions where Scenarios 3.1 and 3.2 cannot result in beneficial renovation despite the significant renovation cost reduction and planning period elongation. On the contrary, the highest renovation cost and the shortest planning period ($C_{\text{ren}} / C_{\text{rep}} = 0.24$ and $t = 35$ years in Table 2) result in beneficial renovation of building classes only in 15 Romanian regions (Gkatzogias et al., 2022b).

Figure 19 presents the geospatial distribution of the impact of renovation Scenario 3.2, implemented across the 1151 NUTS-3 regions of the EU-27 for $C_{\text{ren}} / C_{\text{rep}} = 0.12$ and $t = 50$ years. The impact is presented in terms of the regional percentage of buildings renovated cost-beneficially (pc_{N}), and the associated average annual benefit in terms of economic loss ($\Delta AAEL$) and fatalities ($\Delta AALL$). The maps assign data only to regions where Scenario 3.2 is implemented (i.e. where it yields cost-beneficial renovation) irrespective of their seismic risk, and therefore regions of high seismic risk may be shown in white colour if the cumulative $BCR < 1.0$. Contrary to Scenario 2, where benefit is spread across all considered regions, here benefit ($\Delta AAEL$, $\Delta AALL$) is concentrated in regions of high seismic risk and relatively low to medium renovation cost. Scenario 3.2 allows renovation in regions of Bulgaria, Croatia, Cyprus, Greece, Italy, and Romania.

Focusing on the top 100 priority regions, Scenario 3.2 identified 47 regions where seismic retrofit is economically beneficial, whereas the renovated building stock corresponds to 13% of the buildings, 5% of the replacement value, and 13% of occupants of the existing building stock (within the top 100 regions). The impact assessment of Scenarios 3.1 and 3.2 is summarised in Table 3. Cumulative *BCR*s presented in the table are, by definition of Scenario 3, higher than one (as opposed to Scenarios 1 and 2). The difference of the net economic benefit $\Delta AAEL_{net}$ among the two scenarios in the table (i.e. 77.79 – 12.36 = 65.43 million euro) represents the available economic margin which is invested in the case of Scenario 3.2 to renovate additional building classes, increasing the number of renovated buildings, and the associated replacement cost and number of occupants (compared to Scenario 3.1). Likewise, the annual benefit in terms of saved lives increases by 30% in Scenario 3.2, corresponding to 72% (i.e. 71 / 167) of the lives that would be saved if all buildings were renovated.

Although Scenario 3 results in economically advantageous seismic retrofit in 47 out of the 100 priority regions, the percentage of renovated buildings remains low. This is primarily associated with the exclusion of Italian regions from renovation (except for Ravenna, ITH57, Figure 19) that represent the largest share of buildings (54%), replacement cost (84%) and occupants (64%) within the priority regions.

Figure 18. Scenario 3 – seismic retrofit: cumulative *BCR* values per scenario (*BCR* ≥ 1, Σ*BCR* ≈ 1, 100%) within top 50 priority regions (based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, socioeconomic vulnerability) for renovation to replacement cost ratio C_{ren} / C_{rep} = 0.12 and planning period t = 50 years (Gkatzogias et al., 2022b)

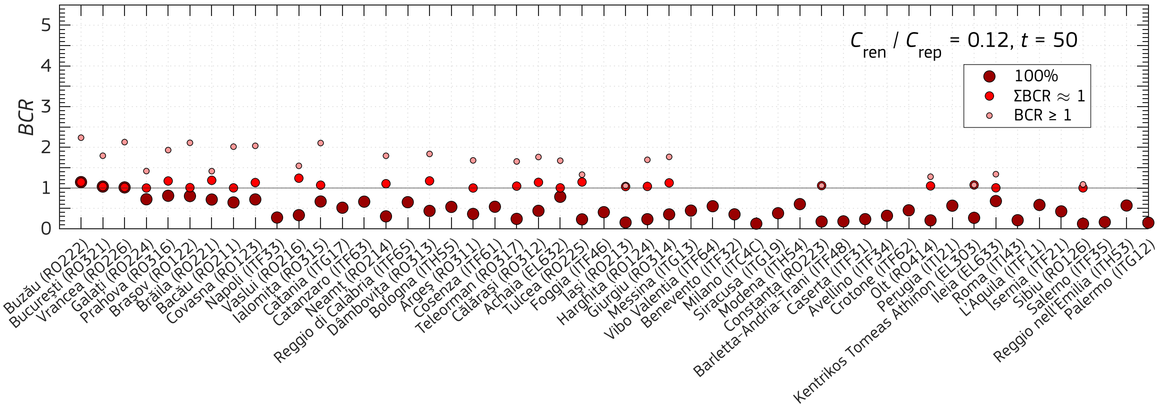
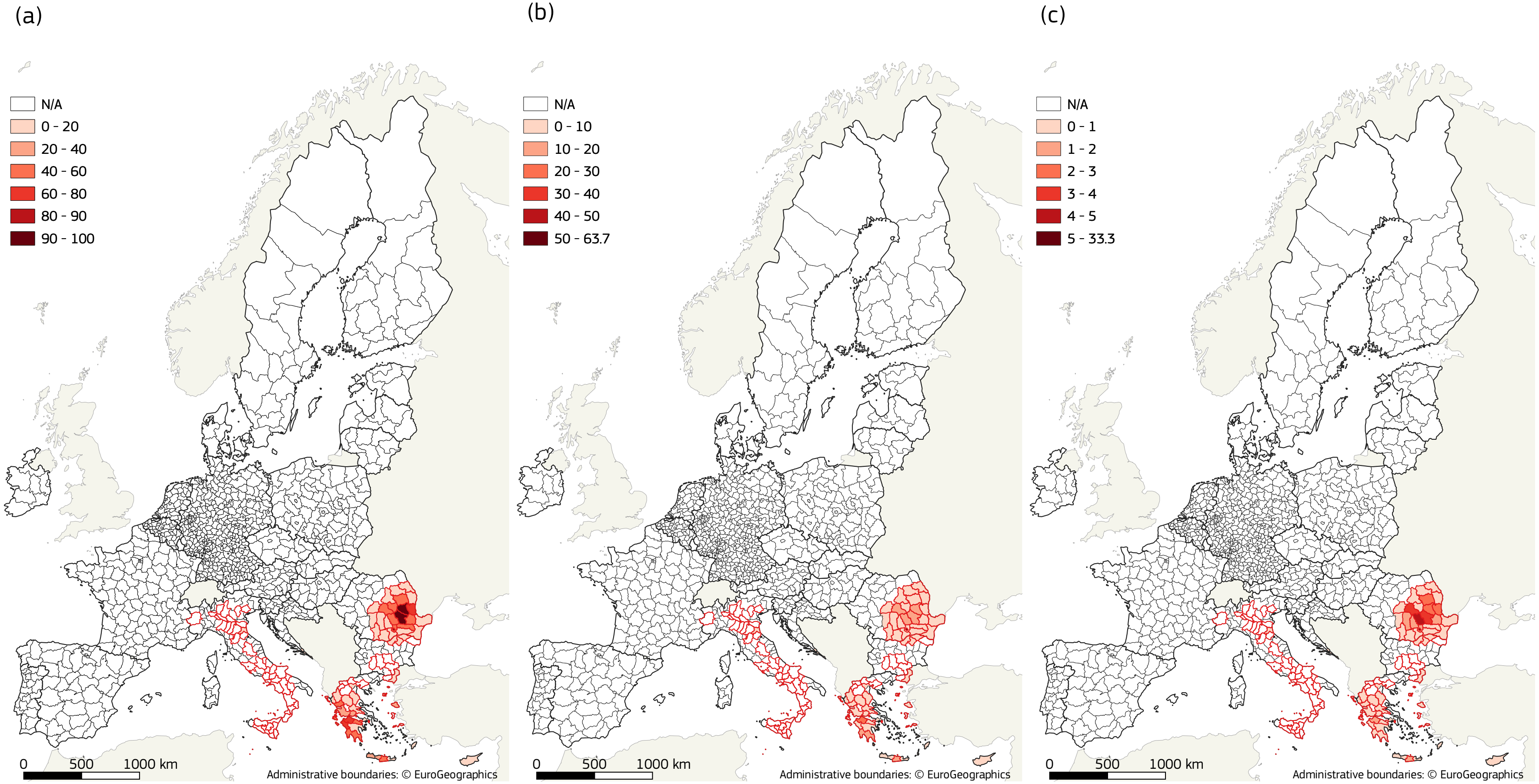


Table 3. Scenario 3 – seismic retrofit: Impact assessment for the top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$ (considering seismic risk, energy efficiency, socioeconomic vulnerability), renovation to replacement cost C_{ren} / C_{rep} = 0.12 and planning period t = 50 years, (Gkatzogias et al., 2022b).

Impact metric	**Scenario 3.1**	**Scenario 3.2**	**100%**
	BCR ≥ 1	**ΣBCR ≈ 1**	
Regions of implementation	47	47	100
Cumulative *BCR*	1.59	1.04	0.33
Average annual economic loss benefit $\Delta AAEL$ (million EUR)	209.16	298.55	2062.31
Net average annual economic loss benefit $\Delta AAEL_{net}$ (million EUR)	77.79	12.36	-4225.22
Average annual loss of life benefit $\Delta AALL$ (fatalities)	55	71	167
Average annual energy consumption benefit $\Delta AAEC$ (GWh)	-	-	-
Buildings	421331	1331098	10591686
Replacement cost (million EUR)	53882.69	117385.11	2578871.82
Average occupants (over 24 hrs)	1804493	3950521	30595128
Buildings (%)	4	13	100
Replacement cost (%)	2	5	100
Average occupants (%)	6	13	100

Figure 19. Scenario 3.2 – seismic retrofit: (a) Percentage of renovated buildings (pc_N), (b) average annual benefit in terms of economic loss ($\Delta AAEL$, million euro), and (c) average annual benefit in terms of fatalities ($\Delta AALL$), for renovation to replacement cost ratio C_{ren} / C_{rep} = 0.12, planning period t = 50 years (in red borders: top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, and socioeconomic vulnerability) (Gkatzogias et al., 2022b)



5.4.2 Energy efficiency upgrading

Figure 20 presents the cumulative benefit-to-cost ratios derived from implementing Scenarios 3.1 and 3.2 as a means to mitigate the energy inefficiency of buildings. The priority regions shown in the figure are based once again on the multi-sectoral integrated indicator $I^*_{eq\text{–}en\text{–}SVI,3}$. The figure depicts the case of $C_{ren} / C_{rep} = 0.15$ and $t = 50$ years. Renovating building classes with individual BCRs ≥ 1.0 according to Scenario 3.1 results in a cumulative benefit-to-cost ratio in the range of 1.02–2.56 within the top 50 priority regions, indicating an economic benefit which exceeds the cost of renovation over the planning period. Scenario 3.2 does not provide an evident advantage in renovating additional building classes (as in the case of seismic retrofit, Figure 18) and the cumulative BCR values from the two scenarios look similar, apart from the case of two Greek regions. Nevertheless, BCR values are not representative of the renovation impact in absolute terms. In fact, small reductions in the cumulative BCR values among the two scenarios may integrate a large number of additional buildings, building value and occupants, thus exhibiting a strong impact on mitigating energy inefficiency (Gkatzogias et al., 2022b). Notwithstanding the last remark, when Scenarios 3.1, 3.2, and the case of renovating the entire building stock result in the same cumulative BCR value in Figure 20 (e.g. coinciding circles in Vaslui, Romania), then all buildings within a region are renovated by Scenario 3.1 and no additional classes are renovated by Scenario 3.2.

Absence of data for Scenarios 3.1 and 3.2 is observed in 19 Italian regions in Figure 20, primarily due to the high associated renovation (and replacement) cost. In the rest of the Italian regions (i.e. Milan, Bologna, Modena, Reggio Emilia, Perugia) a certain fraction of buildings may be renovated in a cost-beneficial way, however, the cumulative BCR values of these regions for Scenario 3.1 remain low. In Romanian regions, certain cases of Scenario 3.2 with high cumulative BCRs (rather than being close to unity) indicate the renovation of the entire building stock.

For the lowest considered renovation cost and the longest planning period ($C_{ren} / C_{rep} = 0.08$ and $t = 100$ years, Table 2), Scenario 3.1 results in a cost-beneficial renovation of the entire building stock in 38 out of the top 50 priority regions, whereas Scenario 3.2 in all 50 regions. Romanian regions reach cumulative BCR values of up to 9.4 implying a quite high economic benefit compared to the renovation investment. On the contrary, the highest renovation cost and the shortest planning period ($C_{ren} / C_{rep} = 0.30$ and $t = 35$ years) result in beneficial renovation of building classes only in 10 Romanian regions (less than those in the case of seismic retrofit). Further details on the effect of the variability of cost and planning period are provided in Gkatzogias et al. (2022b).

Figure 21 presents the geospatial distribution of the impact of renovation Scenario 3.2, implemented across the EU-27 for $C_{ren} / C_{rep} = 0.15$ and $t = 50$ years. The impact is presented in terms of the regional percentage of buildings which can be cost-beneficially renovated (pc_N), and the associated average annual benefit in terms of economic loss ($\Delta AAEL$), and energy consumption ($\Delta AAEC$). By comparing the maps with those derived from seismic retrofit (Figure 19), the extent of the energy renovation impact becomes immediately apparent in terms of both magnitude of metrics and spatial distribution of regions where energy upgrading is beneficial. Scenario 3.2 results in beneficial renovation in all EU Member States apart from Cyprus, Denmark, Estonia, Finland, Malta, Portugal, and Sweden.

Considering the top 100 priority regions (highlighted in red borders in Figure 21), Scenario 3.2 identified 66 regions where energy efficiency upgrading is economically beneficial, as opposed to 47 in the case of seismic retrofit. Energy efficiency upgrading is not economically beneficial in 29 priority regions in southern Italy, four priority regions in Greece, and one in Bulgaria. A net average annual economic benefit of 141.12 million euro (calculated as $\Delta AAEL_{net,Scenario\ 3.1} - \Delta AAEL_{net,Scenario\ 3.2}$ from Table 4) is invested back in renovation in Scenario 3.2, increasing the number of renovated building classes compared to Scenario 3.1. Overall, the number of renovated buildings, and the associated replacement cost and number of occupants increase from 37%, 25%, and 36%, in Scenario 3.1, to 47%, 37%, and 47%, in Scenario 3.2, respectively. Likewise, the benefit in terms of average annual energy consumption increases to 38523 GWh which corresponds to 57% of the energy that would be saved if all buildings were renovated.

Figure 20. Scenario 3 – energy efficiency upgrading: cumulative *BCR* values per scenario (*BCR* ≥ 1, Σ*BCR* ≈ 1, 100%) within top 50 priority regions (based on the multi sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, socioeconomic vulnerability) for renovation to replacement cost ratio C_{ren} / C_{rep} = 0.15 and planning period *t* = 50 years (Gkatzogias et al., 2022b)

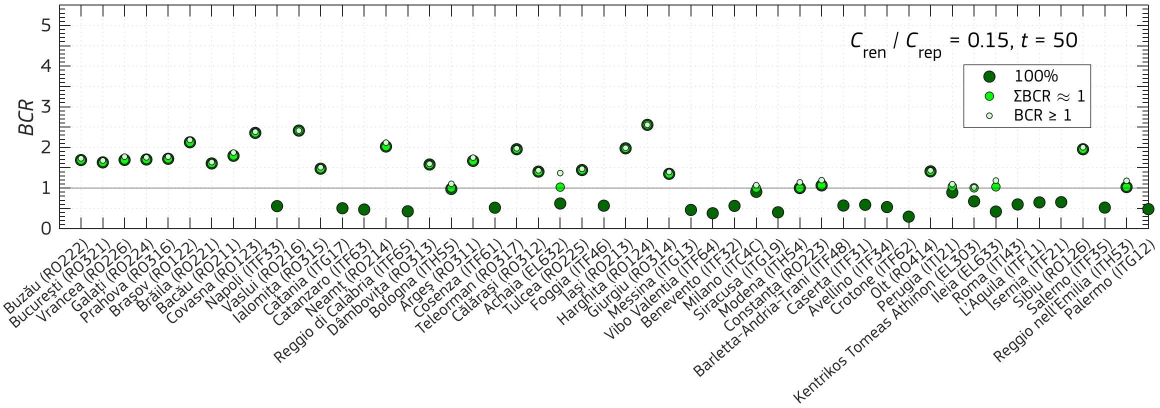
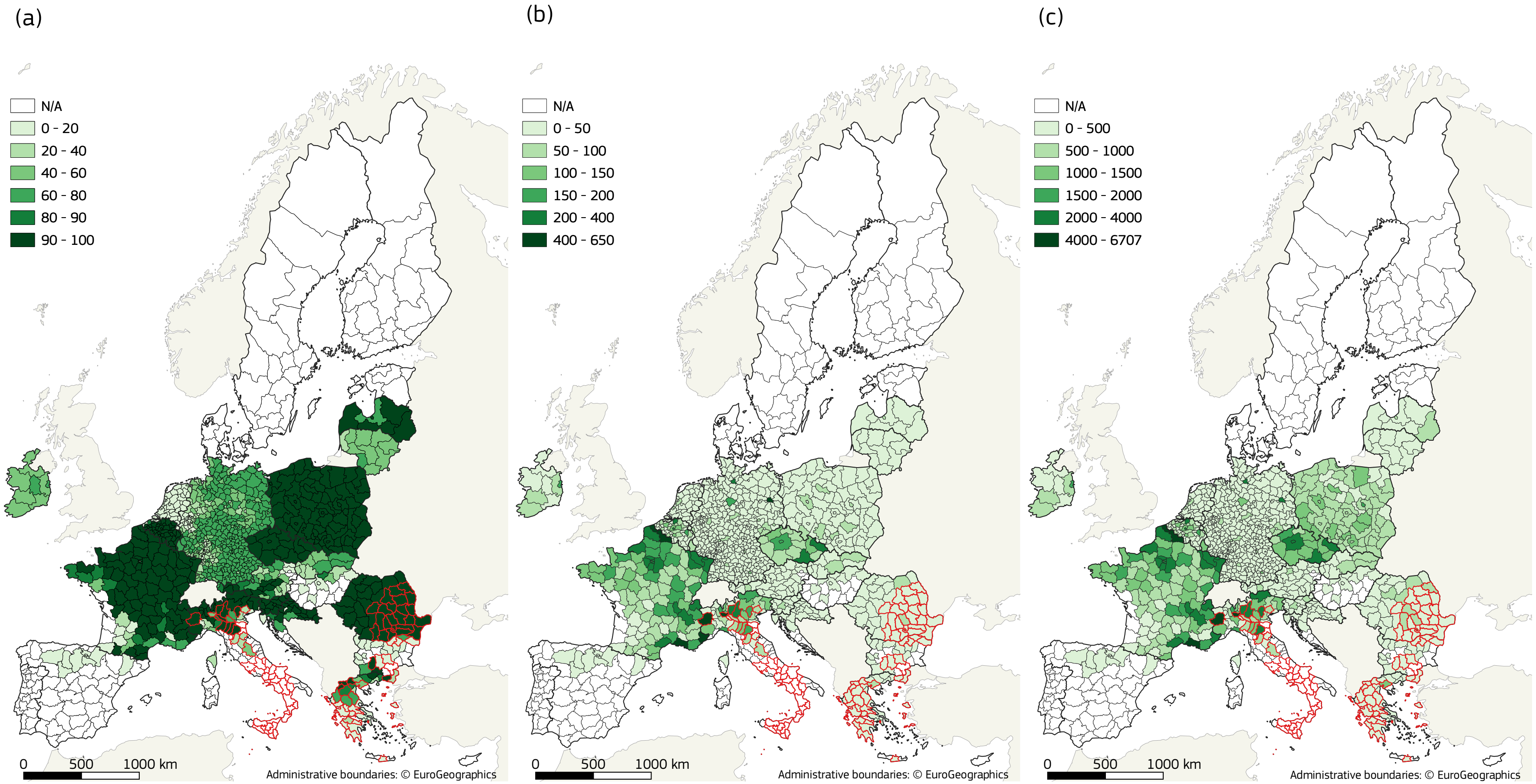


Table 4. Scenario 3 – energy efficiency upgrading: Impact assessment for the top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$ (considering seismic risk, energy efficiency, socioeconomic vulnerability), renovation to replacement cost C_{ren} / C_{rep} = 0.15 and planning period *t* = 50 years, (Gkatzogias et al., 2022b).

Impact metric	**Scenario 3.1**	**Scenario 3.2**	**100%**
	BCR ≥ 1	**ΣBCR ≈ 1**	
Regions of implementation	66	66	100
Cumulative *BCR*	1.36	1.19	0.80
Average annual economic loss benefit $\Delta AAEL$ (million EUR)	2648.55	3499.45	6249.65
Net average annual economic loss benefit $\Delta AAEL_{net}$ (million EUR)	707.65	566.53	-1609.77
Average annual loss of life benefit $\Delta AALL$ (fatalities)	-	-	-
Average annual energy consumption benefit $\Delta AAEC$ (GWh)	29494.07	38522.75	67657.15
Buildings	3951536	4951193	10591686
Replacement cost (million EUR)	636857.71	962363.32	2578871.82
Average occupants (over 24 hrs)	11055075	14390638	30595128
Buildings (%)	37	47	100
Replacement cost (%)	25	37	100
Average occupants (%)	36	47	100

Figure 21. Scenario 3.2 – energy efficiency upgrading: (a) Percentage of renovated buildings (pc_N), (b) average annual benefit in terms of economic loss ($\Delta AAEL$, million euro), and (c) average annual benefit in terms of energy consumption ($\Delta AAEC$, GWh), for renovation to replacement cost ratio C_{ren} / C_{rep} = 0.15, planning period t = 50 years (in red borders: top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, and socioeconomic vulnerability) (Gkatzogias et al., 2022b)



5.4.3 Integrated renovation

Figure 22 presents the cumulative benefit-to-cost ratios derived from implementing Scenarios 3.1 and 3.2 as a means to mitigate both seismic risk and energy inefficiency of buildings through integrated renovation. The figure depicts the case of C_{ren} / C_{rep} = 0.21 and t = 50 years for the top 50 priority regions based on $I^*_{eq-en-SVI,3}$, similarly to the cases of seismic retrofit (Figure 18) and energy efficiency upgrading (Figure 20). Renovating building classes with individual *BCR*s ≥ 1.0 according to Scenario 3.1, results in a cumulative benefit-to-cost ratio in the range of 1.01–2.23 within the top 50 priority regions, with the upper value being closer to the case of seismic retrofit. Yet, cumulative *BCR*s derived from Scenario 3.2 tend to higher-than-one values, as in the case of energy efficiency upgrading, implying that a higher number of buildings, compared to seismic retrofit, can be renovated in a cost-beneficial way. Furthermore, absence of data for Scenarios 3.1 and 3.2 is observed in 17 Italian regions in Figure 22, i.e. less than those in seismic retrofit and in energy efficiency upgrading, providing a good indication of the beneficial effect of integrated renovation.

For the lowest considered renovation cost and the longest planning period (C_{ren} / C_{rep} = 0.10 and t = 100 years, Table 2), Scenario 3.1 results in a cost-beneficial renovation of the entire building stock in 41 out of the top 50 priority regions, whereas Scenario 3.2 in all 50 regions, thus exceeding the number of regions calculated in energy efficiency upgrading. Romanian regions reach cumulative *BCR* values up to 8.7, maintaining a high economic benefit. On the other hand, the highest renovation cost and the shortest planning period (C_{ren} / C_{rep} = 0.41 and t = 35 years) result in beneficial renovation of building classes in 17 Romanian regions.

To investigate the beneficial effect of integrated renovation in absolute terms, Figure 23a and Figure 24 present the geospatial impact of Scenario 3.2, implemented across the EU-27 for C_{ren} / C_{rep} = 0.21 and t = 50 years. The impact is presented in terms of the regional percentage of renovated buildings (p_{C_N}), and the associated average annual benefits Δ*AAEL*, Δ*AALL*, and Δ*AAEC*. Scenario 3.2 results in beneficial renovation in all the EU Member States apart from Cyprus, Denmark, Estonia, Finland, Hungary, Malta, Portugal, Spain, and Sweden. Overall, economically beneficial renovation is feasible in 734 regions out of the 1151 considered NUTS-3 across the EU-27. Although the number of regions is lower than in the case of energy efficiency upgrading (i.e. 922 regions in Figure 21), it represents a vast increase when compared to the 62 regions identified in the case of seismic retrofit (Figure 19) showing a significant impact in reducing fatalities across the EU. At the same time, the economic benefit and the reduction in energy consumption are in the same order of magnitude as in the case of energy efficiency upgrading, and occasionally higher. Impact maps in the form of Figure 19, Figure 21, Figure 23a and Figure 24 further provide valuable guidance by highlighting the regions where each type of renovation is most suitable for implementation.

Interestingly, when only the top 100 priority regions are considered (selected on the basis of seismic risk, energy inefficiency, and socioeconomic vulnerability), integrated renovation according to Scenario 3 has either an impact which is more beneficial compared to both seismic retrofit and energy efficiency upgrading, or slightly inferior to the latter, depending on the scenario and considered impact metric (Table 5 vs. Table 3 and Table 4). In Scenario 3.2, the number of renovated buildings, and the average annual benefit in terms of economy and fatalities were found to be increased. On the contrary, the net average annual benefit, the replacement cost, and the number of average occupants, were found to be lower, albeit close to the values of the energy efficiency upgrading case. Scenario 3.2 identified 73 regions where integrated renovation is economically beneficial, as opposed to 47 and 66 in the cases of seismic retrofit and energy upgrading, respectively. Integrated renovation was not found economically beneficial in 25 priority regions in southern Italy, and two in Bulgaria.

Among the two scenarios in integrated renovation, the number of renovated buildings, and the associated replacement cost and number of occupants increase from 36%, 22%, and 34%, in Scenario 3.1, to 50%, 34%, and 46%, in Scenario 3.2, respectively, for an additional annual investment of 229.53 million euro. The benefits in terms of average annual loss of life and energy consumption are also increased according to Table 5 and represent 68% and 52% of the relevant benefits if all buildings were renovated.

Scenario 3.1 can be used to indicate the benefit for individual building owners to renovate their homes. Impact maps derived from this scenario can thus be employed to promote renovation to the public and increase renovation rates. The efficiency of 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. As Scenario 3.2 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. Impact maps from this scenario (Figure 23a) 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 23a), funding from a central entity (e.g. at European level) that partially covers the cost of renovation may be explored. As an example of the latter remark, Figure 23b illustrates the percentage of the regional building stocks across the EU that can be renovated beneficially according to Scenario 3.2 for the same planning period but at a reduced renovation cost compared to Figure 23a. The reduced renovation cost models here partial funding (e.g. by a central entity) equal to 50%. The extent of beneficial renovation becomes immediately apparent in Figure 23b; in 1064 out of the 1151 regions across the EU, integrated renovation is beneficial for high percentages of the regional building stocks, as opposed to 734 regions in Figure 23a. Reduced funds by the central entity may be explored in this hypothetical scheme (i.e. less than 50%), ensuring that renovation remains advantageous for the regional/national authorities.

Naturally, in many of the 734 (or 1064) regions cited above, seismic retrofit may attract little interest due to the low associated risk (e.g. regions in central Europe). However, the extent to which seismic upgrading becomes feasible is a strong indication of the beneficial effect integrated renovation, and, in general, holistic approaches may have in increasing the efficiency of renovation strategies. For example, structural interventions aiming to improve the capacity of the ageing European building stock under vertical loads, environmental actions or other hazards (e.g. induced seismicity due to gas extraction) may be more relevant in such regions and can be investigated through the proposed framework.

Figure 22. Scenario 3 – integrated renovation: cumulative *BCR* values per scenario (*BCR* ≥ 1, Σ*BCR* ≈ 1, 100%) within top 50 priority regions (based on the multi sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, socioeconomic vulnerability) for renovation to replacement cost ratio C_{ren} / C_{rep} = 0.21 and planning period *t* = 50 years (Gkatzogias et al., 2022b)

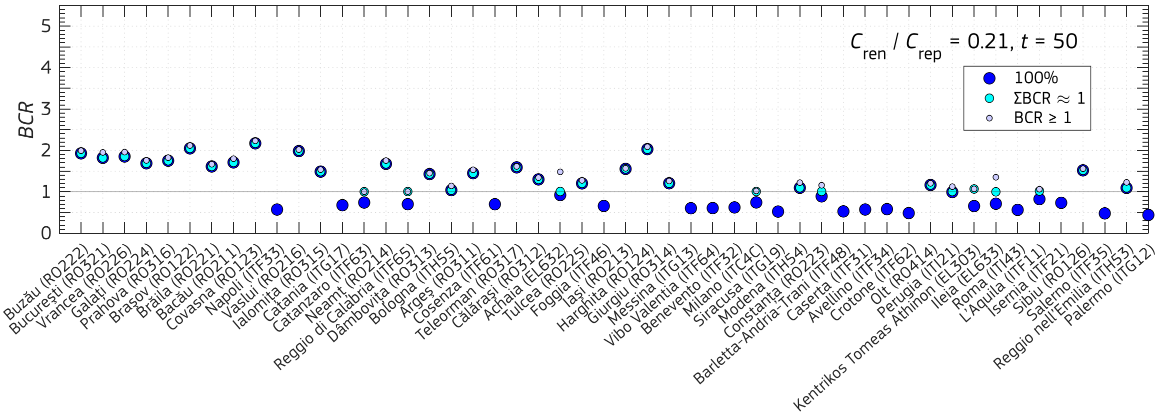


Table 5. Scenario 3 – integrated renovation: Impact assessment for the top 100 priority regions based on the multi-sectoral integrated regional indicator $I^*_{eq-en-SVI,3}$ (considering seismic risk, energy efficiency, socioeconomic vulnerability), renovation to replacement cost C_{ren} / C_{rep} = 0.21 and planning period *t* = 50 years, (Gkatzogias et al., 2022b).

Impact metric	**Scenario 3.1**	**Scenario 3.2**	**100%**
	BCR ≥ 1	**ΣBCR ≈ 1**	
Regions of implementation	73	73	100
Cumulative *BCR*	1.32	1.14	0.78
Average annual economic loss benefit Δ*AAEL* (million EUR)	3095.77	4154.19	8311.97
Net average annual economic loss benefit $\Delta AAEL_{net}$ (million EUR)	741.58	512.04	-2298.25
Average annual loss of life benefit Δ*AALL* (fatalities)	100	113	167
Average annual energy consumption benefit Δ*AAEC* (GWh)	26505.36	35042.89	67657.15
Buildings	3827331	5261696	10591686
Replacement cost (million EUR)	572199.59	885244.32	2578871.82
Average occupants (over 24 hrs)	10352712	13926651	30595128
Buildings (%)	36	50	100
Replacement cost (%)	22	34	100
Average occupants (%)	34	46	100

Figure 23. Scenario 3.2 – integrated renovation: Percentage of renovated buildings (pc_N) for (a) renovation to replacement cost ratio C_{ren} / C_{rep} = 0.21, planning period t = 50 years, and (b) C_{ren} / C_{rep} = 0.10, t = 50 (in red borders: top 100 priority regions based on $I^*_{eq-en-SVI,3}$) (Gkatzogias et al., 2022b)

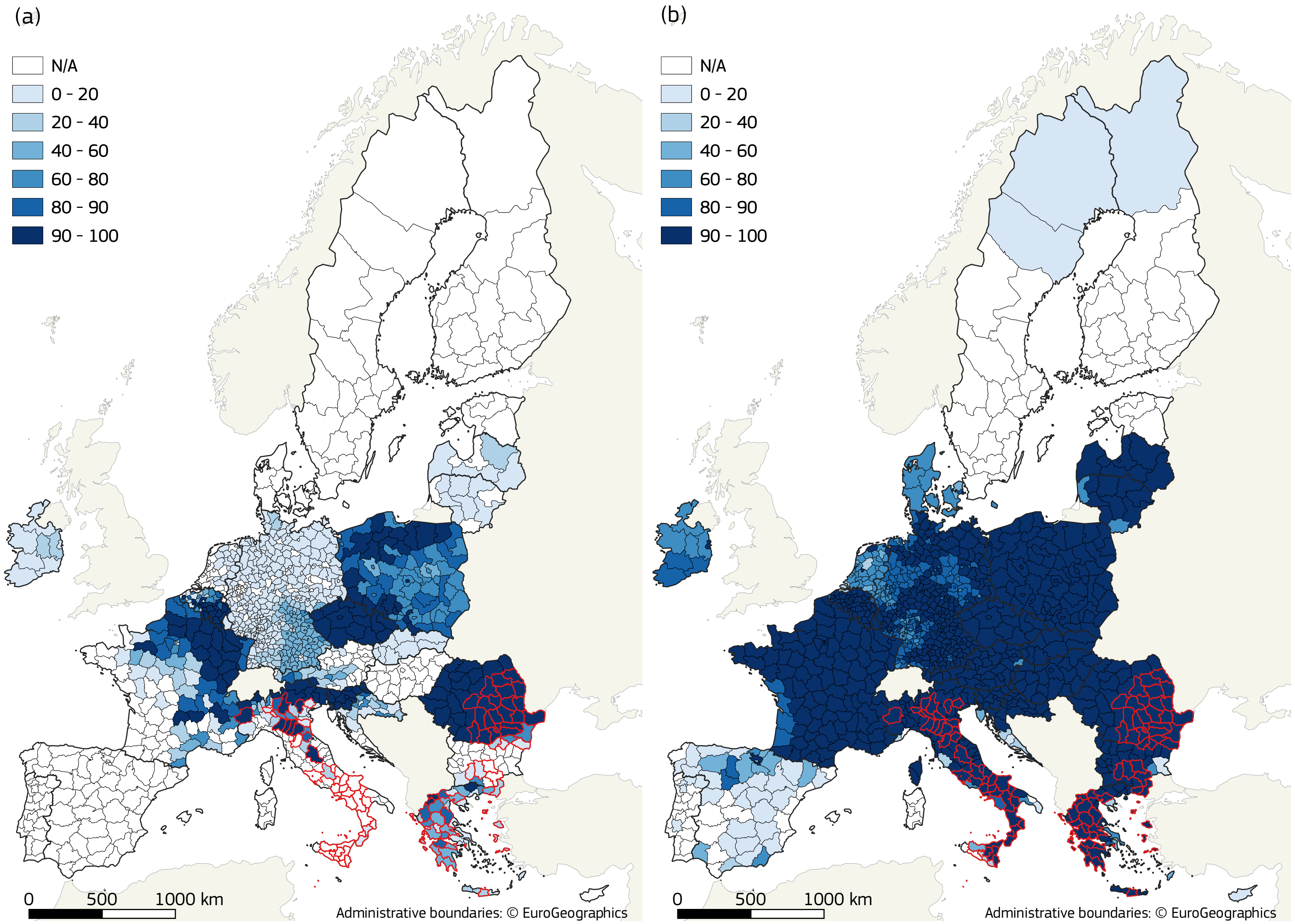
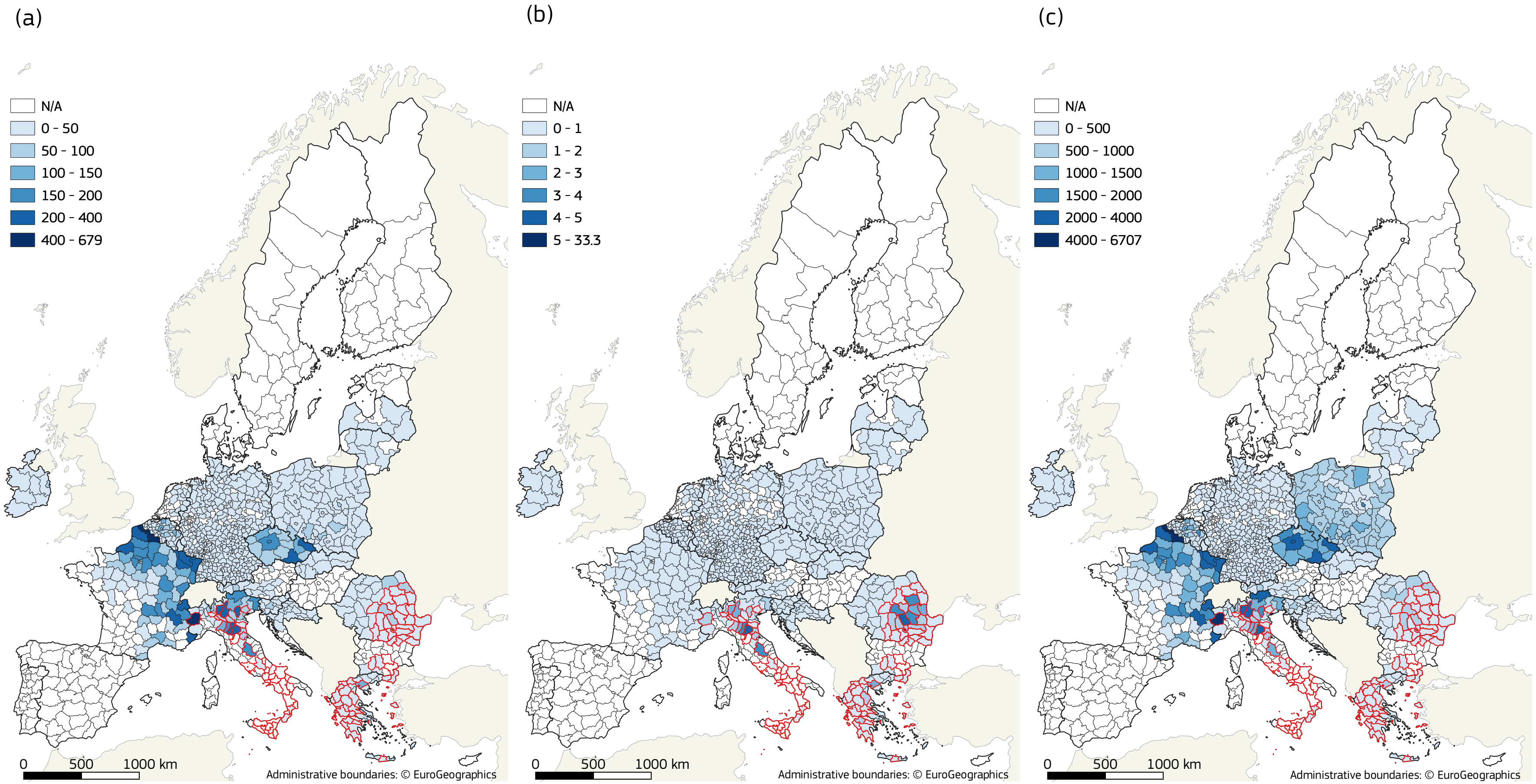


Figure 24. Scenario 3.2 – integrated renovation: average annual benefit in terms of (a) economic loss ($\Delta AAEL$, million euro), (b) fatalities ($\Delta AALL$), and (c) energy consumption ($\Delta AAEC$, GWh) for renovation to replacement cost C_{ren} / C_{rep} = 0.21, planning period t = 50 years (in red: top 100 priority regions based on the multi-sectoral integrated regional indicator $I^{*}_{eq-en-SVI,3}$, considering seismic risk, energy efficiency, socioeconomic vulnerability) (Gkatzogias et al., 2022b)



6 Conclusions

6.1 Policy measures for seismic and energy upgrading of buildings

To address the low energy efficiency of the existing building stock, building renovation in the EU is supported by the European Green Deal and the Renovation Wave. The recent proposal for the revised Energy Performance of Buildings Directive encourages measures related to seismic risk and fire safety, whereas the New European Bauhaus initiative envisions sustainable, inclusive and beautiful living spaces. The Union Civil Protection Mechanism and the Action Plan on the Sendai Framework highlight disaster prevention investments and the integration of risk reduction and cohesion policies.

Stemming from the European legislation for energy efficiency and energy performance of buildings, strategies and programmes for energy upgrading, with increasingly higher targets over time, are implemented in all EU Member States. Policy measures for seismic strengthening are only found in 11 out of the 16 EU Member States that included seismic risk in their national risk assessment in 2015. Specific measures that target seismic and energy renovation at the same time were identified only in six countries.

Among the 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 and includes considerations for structural rehabilitation. The Ecosisma bonus and Superbonus schemes in Italy offer tax deductions for combined renovation of buildings. A recent law in Portugal 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, although conceived for energy renovation works, it was extended 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. The issue of seismic safety is recognised in the national recovery and resilience plans of Croatia, Italy, France, Romania, and Slovenia, and the 2020 long-term renovation strategies of Croatia, Cyprus, Hungary, Italy, Romania, Slovenia, and Spain.

Regulatory framework (e.g. measures for multi-owner buildings and vulnerable households, linking rental contracts with minimum performance requirements, performance certificates), financial instruments (e.g. tax incentives, green bonds and loans – potentially related to the improvement of performance) and digital tools (e.g. building passports, smart sensors) similar to those for energy renovation are capable to promote also seismic and integrated renovation. Awareness campaigns should 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 know-how in integrated renovation methods.

6.2 Priority regions for renovation

Prioritisation of building renovation is a multidimensional problem and different indicators should be employed depending on the sectoral and geographical focus, along with the aim of specific renovation plans. Single and multi-sectoral integrated indicators are capable of capturing the different aspects of prioritisation while handling complexity and filtering out severe disparities (e.g. economic loss due to energy cost and seismic repair).

Absolute average annual loss rankings in terms of repair cost and fatalities due to earthquakes highlight European regions of moderate-to-high seismicity and vulnerability, emphasising densely built and populated areas. Italian regions govern absolute loss rankings, both in terms of frequency (i.e. number of regions within the top 100) and priority (i.e. relevant ranking position), especially in the case of economic loss. Considering frequency, they are followed by Greek or Romanian regions depending on the considered measure, 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, e.g. Spanish regions ahead of Greek ones. On the other hand, normalising loss to the above variables, places Romanian and Greek regions on top of Italian ones (or in general increases their priority), increases their frequency, and excludes regions of Austria, France, Germany and Portugal from the top 100 rankings.

Absolute average annual loss rankings in terms of energy consumption and cost highlight 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. Average annual loss indicators normalised to the number of buildings shift 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. Integrating energy consumption with the number of buildings in a region and climatic conditions shifts priority from northern to central and southern Europe, mainly Italy, followed by Germany and France. Conversely, when exploring the cost of energy integrated with the size and value of the building stock, the prioritisation introduces many regions in south-eastern and central Europe (e.g. Romania followed by regions in Belgium, Czechia, Slovenia, Croatia, and Greece).

In addition to direct benefits (i.e. structural safety and energy efficiency improvement), building renovation may serve as a socioeconomic driver in a region, with a potential employment boost and improvements in living conditions of socially vulnerable groups. This is very much in line with relevant EU policies and initiatives such as the Renovation Wave, the Recovery and Resilience Facility ([11]), and the Cohesion Policy 2021–2027 ([12]). Prioritisation based on socioeconomic indicators shifts the focus to southern and eastern European regions, which follows more closely the trends of seismic risk.

Multi-sectoral integrated indicators, integrating seismic risk with the energy performance of the building stock, highlight regions that would benefit from an integrated seismic and energy retrofit approach. In these regions, integrated renovation is expected to be more beneficial over separate interventions. Integrated indicators in pure economic loss terms 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 retrofit was found. Integrating additionally 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 was found capable of encompassing all previous trends, promoting renovation mainly in regions of Romania, Italy, Greece, and Bulgaria.

6.3 Renovation potential and impact

The renovation potential and the impact of scenarios were investigated across the EU-27, emphasising the top 100 priority regions (i.e. Italian, Greek, Romanian, and Bulgarian regions in order of frequency). These were selected on the basis of a multi-sectoral integrated indicator which considers seismic risk, energy efficiency, and socioeconomic vulnerability.

The renovation potential reflects the capacity of each individual building class within a region to be renovated in a cost beneficial way, save lives, and reduce energy consumption.

Among the investigated priority regions, the seismic renovation potential of building classes in terms of benefit-to-cost ratios (*BCR*), and the potential for saving lives were found to be high in Romanian and Greek regions, as opposed to Italian (due to the high renovation cost). The economic potential due to energy efficiency upgrading was found significantly higher (though remaining low in Italy), providing valuable margin for improving the impact of seismic retrofit through integrated renovation. Building classes with high potential for saving energy exhibit in general high *BCR* values. The potential due to integrated renovation showcases a significant improve compared to seismic retrofit, while combining positive aspects from both types of renovation. For integrated renovation, building classes with $BCR \geq 1.0$ present the highest potential for saving lives and energy, and they integrate the highest share of buildings and population, similarly to energy efficiency upgrading.

The renovation impact reflects the benefit in absolute terms, derived from renovating multiple building classes in single or multiple regions according to the considered renovation scenario. It further describes the significance of a renovation scenario in terms of the number and value of renovated buildings, affected population, and naturally its economic feasibility, expressed through a cumulative *BCR*.

Scenario 1 investigated the impact of renovating macro-taxonomy classes within a region, defined on the basis of the building seismic design code level. Seismic retrofit according to Scenario 1 is economically feasible in a few regions characterised by quite high seismic risk and low renovation cost. The scenario is more promising for energy efficiency upgrading. Specifically, upgrading the energy performance of buildings without seismic design (CDN) within all top 100 priority regions is almost economically beneficial, as these buildings are characterised by low energy performance. An integrated approach allows renovating buildings designed with a low-level seismic code (CDL) in a cost beneficial way in 77 regions across the EU, as opposed to 155 and only six regions in the case of energy efficiency and seismic upgrading, respectively. Scenario 1 is expected to be

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(11) https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en

(12) https://ec.europa.eu/regional_policy/en/2021_2027/

more cost-efficient if the granularity of macro-taxonomy classes is increased by including additional structural and energy attributes, at the cost of increased complexity.

Scenario 2 investigated the impact of renovating 10% or 20% of the regional building stocks. The building classes to be renovated were selected based on their individual *BCR*. Increasing the number of renovated buildings, results in decreasing the cumulative *BCR*s per region, and thus the efficiency of the scenario. Across the considered 1151 EU regions, integrated renovation of 20% of the building stock exhibits cumulative *BCR*s ≥ 1.0 in 448 regions, as opposed to 774 regions for energy efficiency upgrading, and just 29 for seismic retrofit. Integrated renovation allows upgrading the seismic safety of structures in a cost-efficient way to a much larger extent than seismic retrofit alone, while it presents an economic benefit in the same order of magnitude as energy efficiency upgrading. The cumulative *BCR* and net economic benefit calculated over all the top 100 regions demonstrate that integrated renovation becomes economically viable for a central funding entity. In the latter case, integrated renovation also results in the highest net economic benefit and approximately the same benefit in terms of loss of life and energy consumption.

Scenario 3 identifies the maximum fraction of buildings and the building classes, the renovation of which results in a cumulative *BCR* equal to or higher than unity. Two different variations were explored. Scenario 3.1 promotes for renovation all building classes presenting individually *BCR* ≥ 1.0 within a region, thus it can be used to indicate the benefit for individual building owners to renovate their homes, and promote renovation to the public. Scenario 3.2 considers all building classes that result in a cumulative *BCR* approximately equal to unity. It exploits the net economic benefit derived from Scenario 3.1 to renovate additional building classes which would not be beneficial to renovate on a stand-alone basis. This renders Scenario 3.2 more suitable when renovation funds are handled at a regional, national or European level. According to Scenario 3.2, integrated renovation is economically beneficial in 734 regions out of the 1151 considered. Although the number of regions is lower than in the case of energy efficiency upgrading, it represents a vast increase when compared to the 62 regions identified for seismic retrofit, showing a significantly increased impact in reducing fatalities across the EU. At the same time, the economic benefit and the reduction in energy consumption are in the same order of magnitude with energy efficiency upgrading, and occasionally higher.

Irrespective of the renovation type, the renovation potential and impact are sensitive to assumptions regarding the renovation and replacement cost, the inflation of construction cost and energy prices, and the planning period. Overall, the efficiency of a renovation strategy increases along with its capability of targeting buildings with specific attributes rather than generic classes. Inevitably, this comes at the cost of increased complexity.

Integrated renovation is expected to be even more beneficial in high seismic risk regions of southern Europe if loss associated with energy consumption for space cooling is taken into account, due to the hot climate of these regions and the expected increased benefit due to energy efficiency upgrading. In regions at low seismic risk, seismic retrofit attracts little interest. However, structural interventions to improve the safety of the ageing building stock under vertical loads, environmental actions or other hazards could be relevant; these can be investigated through the integrated framework presented herein.

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List of abbreviations and definitions

AAEC	Average Annual Energy Consumption
AAEL(*R*)	Average Annual Economic Loss (Ratio)
AALL(*R*)	Average Annual Loss of Life (Ratio)
AEC	Average Energy Consumption (over period of *t* years)
AELR	Average Economic Loss Ratio (over period of *t* years)
ALLR	Average Loss of Life Ratio (over period of *t* years)
BCR	Benefit-to-cost ratio
bldg	Building
C	Cost
CD	Code Design level
CDL	Code Design level: Low (building designed for lateral resistance using allowable stress method)
CDM	Code Design level: Moderate (building designed for lateral resistance with limit state method)
CDN	Code Design level: No (absence of seismic design)
CEN	Comité Européen de Normalisation (European Committee for Standardisation)
COM	Commission Communication
EFEHR	European Facilities for Earthquake Hazard and Risk
en	Energy
ENTRANZE	Policies to ENforce the TRAnsition to Nearly Zero-Energy Buildings in the EU-27
eq	Earthquake
ESHM20	European Seismic Hazard Model 2020
ESRM20	European Seismic Risk Model 2020
EU	European Union
g	Acceleration of gravity
G	Giga
GADM	Global database of administrative areas
HDD	Heating Degree Day
HDI	Human Development Index
I	Single/multi-sectoral index
I_{en}	Single-sector integrated indicator considering normalised average annual economic loss ratio due to space heating energy consumption, average annual economic loss (due to energy consumption) per building, average annual energy consumption per building and *HDD*
$I_{\text{eq,1}}$	Single-sector integrated indicator considering normalised average annual economic loss ratio due to seismic repair and average annual loss of life ratio
$I_{\text{eq,2}}$	Single-sector integrated indicator considering normalised average annual economic loss ratio due to seismic repair, average annual economic loss due to seismic repair per building, and average annual loss of life ratio
$I^{(*)}_{\text{eq–en}}$	Multi-sectoral integrated indicator considering normalised average annual economic loss ratios due to seismic repair and space heating energy consumption (*: indicator promoting regions of high seismic risk)

$I^{(*)}_{\mathrm{eq-en-SVI},1}$	Multi-sectoral integrated indicator considering normalised average annual economic loss ratios due to seismic repair and space heating energy consumption, and socioeconomic vulnerability (*: indicator promoting regions of high seismic risk)
$I^{(*)}_{\mathrm{eq-en-SVI},2}$	Multi-sectoral integrated indicator considering normalised average annual economic loss ratios due to seismic repair and energy consumption, average annual loss of life ratio, and socioeconomic vulnerability (*: indicator promoting regions of high seismic risk)
$I^{(*)}_{\mathrm{eq-en-SVI},3}$	Multi-sectoral integrated indicator considering normalised average annual economic loss ratios due to seismic repair and space heating energy consumption, average annual loss of life ratio, average annual economic loss (seismic repair and energy consumption) per building, average annual energy consumption per building and *HDD*, and socioeconomic vulnerability (*: indicator promoting regions of high seismic risk)
INSPIRE	Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems
int	Integrated
k	Kilo
JOIN	Joint communication
m	Metre
MS	Member States
N	Number of buildings, dwellings, etc
NUTS	Nomenclature of Territorial Units for Statistics
PGA	Peak Ground Acceleration
pc	Percentage or ratio
ren	Renovation (referring to cost)
rep	Replacement (referring to cost)
SPI	Social Progress Index
SVI	Socioeconomic Vulnerability Index
SWD	Commission Staff Working Document
t	Planning period
UN	United Nations
U_w	Wall thermal transmittance value
Wh	Watt-Hour
Δ	difference between two values

List of figures

List of tables

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