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Simplified Guidelines for Retrofitting Scenarios in the European Countries

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Abstract: A large part of the European building stock was built before implementing the recent energy and structural codes, resulting in buildings characterized by deficiencies in terms of comfort, energy savings and structural safety. The retrofitting and rehabilitation of the existing building stock need to be adequately performed, aiming to improve the seismic and energy performance simultaneously. The work summarized here is dedicated to defining priority scenarios for buildings' retrofitting to improve the seismic safety and energy efficiency of the European Union (EU) building stock. First, the state of the EU building stock is analysed in terms of buildings' age, types of structures, energy efficiency, energy consumption and energy poverty. Then, the EU climate demands are presented, namely the regions with higher temperature variations, i.e., heating or cooling degree days. The EU seismic risk is also presented and discussed in terms of average annual losses, average annual economic losses and average annual life losses. Based on these input parameters, nine seismic–climate regions in the EU are proposed using a simplified approach. Finally, retrofitting scenarios are proposed for two types of buildings (i.e., masonry and reinforced concrete) based on their seismic–climate region.

Keywords: building stock; climate indicators; seismic retrofitting; energy retrofitting

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1. Introduction

A large part of the European building stock was built before implementing the recent energy and structural codes, resulting in buildings characterized by deficiencies in terms of comfort, energy savings and structural safety [1]. Regarding the last aspect, it is particularly relevant that most of the buildings located in seismic-prone regions were designed before the enforcement of current seismic regulations and with no modern concepts of antiseismic detailing and philosophies, such as capacity design. Thus, the structural safety of these buildings may not be satisfactory when subjected to seismic actions, but it could also hamper any refurbishment investment in the case of an earthquake [2]. Therefore, the transition toward a neutral carbon society needs to go through the structural strengthening of the existing building stock regarding seismic actions.

According to a recent report by the European Commission, the construction industry is accountable for 36% of carbon dioxide emissions, 40% of energy usage and 55% of electricity consumption in the European Union (EU) [3]. The majority of energy consumption and carbon dioxide emissions stem directly from the heating and cooling of buildings. The inadequate energy performance of existing buildings in the EU can be attributed to the belated implementation of the first energy codes for buildings, which only became official in the 1970s, by which point approximately 66% of the current EU building stock had already been constructed. Improving the energy efficiency of buildings can play a pivotal role in realizing the objectives outlined by the United Nations and the New European Green Deal, namely, reducing emissions of greenhouse gases that contribute to climate change to zero by 2050.

Roughly 40% of buildings in the EU are situated in seismic zones and constructed with inadequate safety measures, with 65% of these structures requiring both seismic and energy retrofitting. While independent retrofitting approaches for seismic [4] or energy purposes [5,6] are accessible and frequently utilized, comprehensive SpEU techniques that integrate both aspects are yet to be developed, validated and implemented. The most common insulation building materials used to improve a building's energy efficiency can be classified into three categories: (a) conventional insulation materials [7]; (b) insulation materials including nano-insulation materials [8]; and (c) smart insulation materials such as phase-change materials [9]. The economic issues and limitations lead to the need to use low-cost and conventional materials, such as external thermal insulation composite systems for infilled reinforced concrete (IRC) buildings' envelopes [10]. However, this technique only provides energy upgrading, neglecting the seismic safety of the building. An adequate upgrade of this technique would have great potential due to the low unitary cost of the intervention.

Concerning the strategies available to reduce the IRC buildings' seismic vulnerability, three different approaches are available: (a) global structure retrofitting (i.e., introducing steel braces or reinforced concrete (RC) shear walls or energy dissipation devices) [11]; (b) local retrofitting [12]; and (c) combining global and individual retrofitting measurements. The choice of the most suitable techniques depends on the desired performance standards as well as economic considerations, and potentially other non-technical factors. Some research works were recently carried out on strengthening solutions to reduce the seismic vulnerability and collapse probability of masonry infill walls (MIW) [13], using techniques such as fibre-reinforced polymers [14], engineered cementitious composites and textile-reinforced mortar (TRM) [15,16].

Various performance assessment methodologies are only available for a specific field, i.e., seismic safety and energy performance, and most of them were developed for new buildings. Seismic vulnerability assessment tools are based on a quantitative four-step evaluation consisting of hazard, structural, damage and loss analysis [17]. Several detailed [18] and simplified [19] numerical tools are available to simulate the behaviour of non-strengthened IRC building structures. However, they need proper calibration and validation to assess their capabilities to simulate the behaviour of retrofitted structures with SpEU solutions. The energy/environmental efficiency assessment is carried out through hygrothermal, life cycle (LC) analysis [20,21] and LC energy assessment [22]. Building sustainability assessment is based on European (DGNB) [23] or non-European rating systems (BREEAM) [24]. A holistic performance assessment methodology that combines sustainability, energy and structural performance indicators for existing IRC buildings is missing. It will allow decision-making bodies to identify buildings requiring renovation and to optimise those interventions.

Consequently, enhancing the current building inventory to become more sustainable, energy-efficient and resilient is crucial. The substantial investments earmarked over the next ten years for achieving a climate-neutral society by 2050 (EUR 1 bn in the EU; EUR 145 M in Portugal) under the European Green Deal demonstrate the paramount significance of this issue for the future of our communities. These strategies must also be consistent with the Sendai Framework Action Plan for Disaster Risk Reduction 2015–2030 and the United Nations' 2030 Agenda to fulfil all of the outlined objectives.

Based on this motivation, this research aims to define priority scenarios for buildings' retrofitting to simultaneously improve the seismic safety and energy efficiency of the EU building stock. First, the state of the EU building stock is analysed in terms of buildings' age, types of structures, energy efficiency, energy consumption and energy poverty. Then, the EU climate demands are presented, namely, the regions with higher temperature variations, i.e., heating or cooling degree days. The EU seismic risk is also presented and discussed in terms of average annual losses, average annual economic losses, and average annual life losses. Based on these input parameters, nine seismic–climate regions in the EU are proposed using a simplified approach. Finally, retrofitting scenarios are proposed for two types of buildings (i.e., masonry and reinforced concrete) based on their seismic–climate region.

The definition of the priority regions for which the combined seismic plus energy retrofitting has more impact on the building's performance and on the society as well requires the correlation of three different data inputs: (i) EU building stock characteristics (i.e., buildings age, type of constructions (i.e., masonry or reinforced concrete, buildings' distribution, energy poverty and energy consumption); (ii) EU climate (i.e., heating and cooling degree days); and (iii) EU seismic risk (average annual losses, average annual economic losses, average annual life losses), as shown in Figure 1. The data concerning these three inputs are presented and discussed in Section 2. This information will support the definition of seismic–climate scenarios in the EU using a simplified approach. Finally, retrofitting scenarios will be proposed based on the seismic–climate location in the EU.

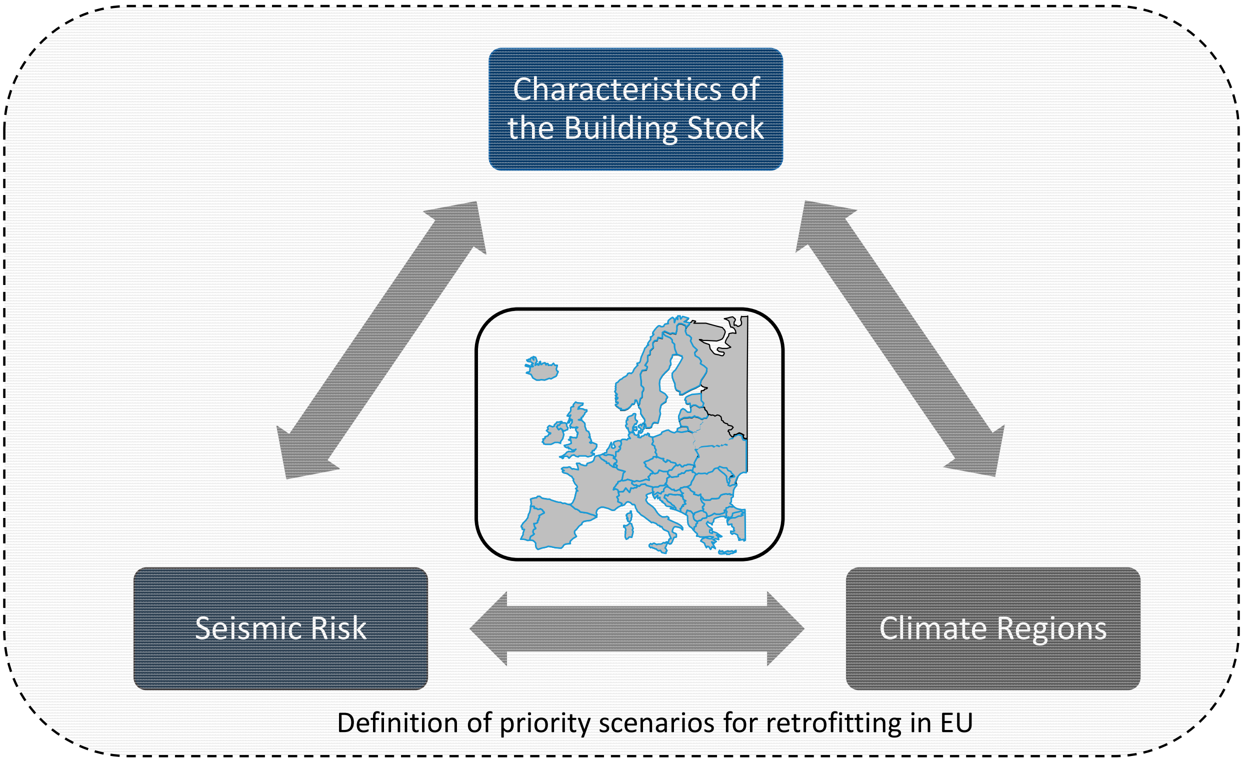


Figure 1. Flowchart of the identification process of scenarios for retrofitting interventions in the EU.

2. Overview of the EU Building Stock

2.1. General Characteristics

According to public data from the EU Buildings Observatory, a majority of buildings in the EU are residential and were erected prior to 1969 [25]. A significant portion of Europe's building inventory is over 50 years old, with many structures still in use that are over a century old. Over 40% of residential buildings were constructed before the 1960s, when energy regulations for buildings were limited. Several factors impact the energy efficiency of buildings, including the performance of heating systems and building envelopes, climatic conditions, building attributes and societal conditions. Information regarding typical heating consumption levels for the existing stock by age demonstrates that the most substantial potential for energy savings is associated with older buildings.

In certain instances, buildings constructed during the 1960s exhibit inferior performance compared to those from earlier periods. The historical U-value data reinforces the insufficiency of insulation in older buildings, which is unsurprising given the limited insulation standards during that era. Countries with the highest proportion of older buildings include Denmark, Sweden, France, the Czech Republic and Bulgaria, with a significant construction boom between 1961 and 1990.

About half of the EU building stock is older than 50 years, which means that it has already completed its conventional life and may need retrofitting or a replacement of building components due to durability-related issues.

The first edition of the European seismic codes (e.g., Eurocodes) in the EU was published in 1990, meaning about 77% were built before [1], and in several countries the implementation was done over the years after. Based on that, it may be concluded that the existing EU building stock may need both seismic and energy retrofitting since they may be inefficient and/or seismically vulnerable.

The age distribution of existing buildings and the proportion of new buildings within the total stock serve as reliable indicators of the overall efficiency of the building stock. A higher proportion of newly constructed dwellings built with more efficient standards generally corresponds to a better overall energy performance of the building stock. Figure 2 depicts the distribution of buildings' construction in the years up to 2014, revealing that the majority of buildings in most EU countries are over fifty years old. However, in some countries such as Spain, Cyprus and Ireland, there is a noticeable percentage of recent buildings (i.e., less than 20 years old).

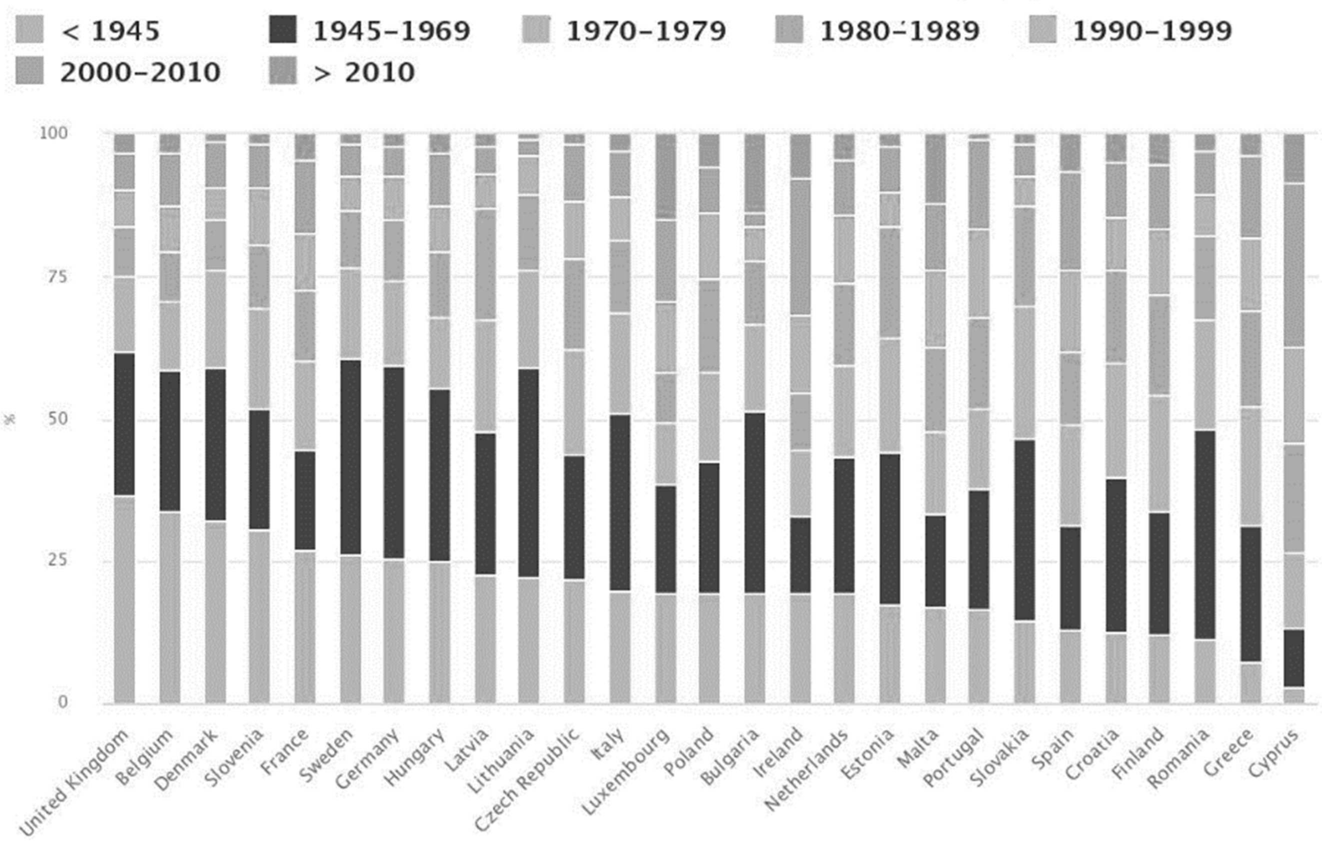


Figure 2. Distribution of building construction by year in EU countries up to 2014. (Sources: EU Buildings Factsheets).

Concerning the buildings constructed before 1945, Belgium (34%), Denmark (32%), Slovenia (30%) and France (27%) have the most significant percentage. Romania (37%), Lithuania (36.9%), Sweden (34.3%) and Germany (34.1%) are the countries with a larger percentage of buildings built between 1945 and 1969. Between 1970 and 1979, all the countries presented similar rates, but the highest one was achieved by Slovakia (23.3%). Between 1980 and 1989, the percentage of buildings in the EU countries varies between 9 and 20%. The highest rate is observed in Cyprus. Between 1990 and 1999, the same observation can be drawn. Cyprus (17%), Malta (14%) and Ireland (13.3%) are the countries with large percentages of buildings. Finally, Cyprus (>29%) and Ireland (>15%) have the highest rates of buildings built after 2000.

According to the European Union Commission, multi or single dwellings (residential) distribution differs from country to country. On average, about 52.7% are single-family dwellings and 47.3 are multi-family dwellings. Countries such as Ireland, Belgium and the Netherlands have a high percentage of single-family dwellings (87%, 73% and 70%, respectively). On the other hand, Estonia, Italy and Spain have the most multi-family dwellings (75%, 74% and 71%, respectively). The type of dwelling directly impacts the space heating energy performance since different insulation characteristics imply different specific space heating consumption (due to other wall areas in contact with the outdoors).

2.2. Seismic Vulnerability of the Building Stock

Masonry buildings are prevalent in Europe and are, on average, older than RC ones. For example, the Italian building stock comprises about 3.7 million RC buildings and 7.2 million masonry buildings. Moreover, by 1981, about 86% of masonry buildings were already constructed. The year 1981 is a year of a massive seismic classification due to the consequences of the 1980 Irpinia-Basilicata destructive earthquake. Additionally, the first seismic design code for masonry structures was issued only in 1987, which means that almost the totality of masonry buildings were designed without any seismic criteria. Recent earthquakes such as the one in 2016 demonstrated the problem dimension at the Italian scale [26]. The same approach can be taken at the European scale, even though northern European countries have lower seismic hazards than the European Mediterranean ones [27].

The low strength of the masonry units (both stone or brick) and mortar affects the wall capacity under vertical and seismic loads. Additionally, the irregular disposition of the masonry units and the excessive mortar beds' thickness reduces the wall's vertical and seismic capacity [28]. On the other hand, the irregular wall arrangement due to the dimension of stone/brick elements and the weak connection among the different wall leaves are responsible for the masonry disintegration when subjected to lateral loads. It is pretty standard in older buildings.

The poor connection between transverse walls (i.e., corner walls), the connection between walls and the floors/slabs (diaphragm effect) and the roofs contribute to avoiding the possibility of developing a "box behaviour". The retrofitting of a masonry structure must ensure that the "box behaviour" effect is guaranteed.

All these deficiencies are responsible for activating local mechanisms, such as wall overturning, inhibiting global seismic behaviour, which is usually more efficient [29].

Structural failures due to earthquakes do not affect environmental measures, such as CO_2 emissions or energy consumption, in a direct way as they are rather abrupt events. It might not be intuitive to include them when examining energy reduction policies. However, their impact on the local economies can be devastating. When quantified with absolute economic measures, it can be seen that the economic losses they can bring about can be comparable to those due to energy deficiencies.

One of the most relevant problems was the lack of connection between transverse walls, roofs or floors. The "box behaviour" is fundamental to achieving good seismic performance of a masonry structure.

Undoubtedly, structural deficiencies play a much more important role in the seismic-prone areas of the European south. Buildings are frequently subjected to seismic events in countries that are located in seismic-prone regions. In such places, structural deficiencies are often brought to the surface by major seismic events. Moreover, seismic standards have improved considerably during the last 50 years, both in terms of the prescribed loads and detailing measures, as opposed to concrete and structural steel codes, for example, which have received much fewer significant updates.

The Eurocode 8 [30] provides a classification for structural elements of RC structures, differentiating them as either structural or non-structural. Structural elements are further classified into primary members (SP) or secondary members (SS). Primary members (SP) are considered part of the structural system that can withstand seismic demands, and are designed and detailed for earthquake resistance. Secondary elements, however, are not considered part of the seismic-resisting system, and their strength and stiffness against seismic actions are neglected. They are designed and detailed to only support gravity loads when subjected to seismic actions, and are not required to meet all Eurocode 8 [30] requirements but are designed and detailed to maintain the support of gravity loads when subjected to the displacements caused by the seismic actions.

Non-structural elements (NS) are composed of various architectural, mechanical or electrical components and systems that are not load-bearing elements in the seismic design due to their lack of strength or the way they are connected to the structure. Among these elements, masonry infill walls play a significant role in the seismic performance of RC buildings. Eurocode 8 [30] recognizes that infill panels are part of the non-structural-elements group.

Following the last major earthquakes in the EU, different types of damage have occurred and affected the RC structures [31]. During seismic events, reinforced concrete structures can experience different types of damage, including but not limited to, inadequate detailing of stirrups and hoops (Damage Type 1), issues with longitudinal reinforcement detailing (Damage Type 2), reduced shear and flexural capacity of elements (Damage Type 3), insufficient shear capacity of structural joints (Damage Type 4), strong-beam weak-column mechanism (Damage Type 5), short-column mechanism (Damage Type 6), structural irregularities (Damage Type 7), pounding (Damage Type 8), damage to secondary elements (Damage Type 9) and damage to nonstructural elements (Damage Type 10).

The structural primary elements are associated with the first eight damage types, while the ninth damage type is related to secondary structural members and the tenth damage type specifically pertains to infill walls and other non-structural elements. Based on the post-earthquake damage survey assessment, it can be concluded that there is an interdependence among the last five types of damage. The damage observed during the post-earthquake field trips indicates that masonry infill walls cannot be considered as non-structural or secondary elements and cannot be ignored from the expected building seismic behaviour [32,33]. Based on these observations, it is apparent that infill walls, especially those located in the building envelope, play a crucial role as they can alter the overall structural behaviour of the building. Proper retrofitting is necessary to prevent out-of-plane (OOP) collapse. Infill walls were responsible for over 30% of the rehabilitation costs of buildings damaged by earthquakes [34].

2.3. Energy Deficiencies of the Building Stock

The poor buildings' energy efficiency is due to the later development and implementation of regulations and functional requirements in European countries. The first building energy codes were published in the 1960s in the Scandinavian countries [35]. Later, other countries have progressively introduced some regularly updated standards, especially to match European directives. From the energy perspective, the first Energy Performance of Buildings European Directive was issued in 2002 [36], although most European countries already have developed their national standards since the beginning of the 1990s. Once again, the masonry building stock at the European level has been built mostly without any energy efficiency rule.

The most significant deficiencies concerning the energy efficiency are due to inadequate thermal insulation provided by the building envelope and due to the roof and windows characteristics. Additionally, inefficient mechanical services providing heating, cooling and domestic hot water needs are responsible for high energy consumption, especially in older buildings. Finally, old lighting systems can further increase the energy need and CO_2 emissions.

An essential aspect of masonry buildings is related to the fact that load-carrying components constitute the building envelope. Therefore, some limitations are present in the insulation interventions, contrarily to RC buildings for which the building envelope (infills) can even be replaced.

According to the latest EU report [25], the energy used for space heating seems to be the most important end-use in the residential sector (68%). Countries such as Italy, Poland, Belgium, Luxembourg and Finland have a high percentage of energy consumption for space heating (>69%). The average percentage of the energy consumption in the EU for space heating is 67.74%, which is quite significant. On the one hand, the climate conditions can be strongly linked with higher needs for space heating (such as Finland, Denmark and Poland). On the other hand, the poor energy efficiency of buildings plays a significant role, particularly in countries such as Italy or Croatia that have a more moderate climate. Space cooling emerges with high importance in Malta (15%), Bulgaria (5%) and Cyprus (5%). The other ways of consuming energy are water heating (second most relevant), lighting, appliances (third most relevant) and cooking (fourth most relevant).

The average annual specific consumption per m^2 for all types of buildings in the EU was approximately 180 kWh/m^2 in 2013. However, there are variations among countries, with Malta having the lowest consumption at 47 kWh/m^2, followed by Portugal and Cyprus at 70 kWh/m^2, while Romania has the highest consumption at 300 kWh/m^2 (or 290 kWh/m^2 in Latvia and Estonia), which is significantly higher than the EU average. It is worth noting that even countries with similar climates exhibit substantial differences in consumption, such as Sweden with 210 kWh/m^2, which is 18% lower than Finland. The differences can be attributed in part to climatic conditions and statistical definitions.

The final energy consumption in households in 2020 is shown in Figure 3. This parameter focuses on the energy spent in households for heating purposes and how the amelioration of buildings can contribute to energy-saving plans. The data were extracted by Eurostat, which collects information on total energy consumption in households split by fuel category. This parameter is highly related to the climate conditions and the country's population size. Above the average European line (7618), it is possible to find Germany (57,743), France (39,619), Italy (31,138), Poland (20,993), Spain (14,448) and the Netherlands (9460). The countries with low final energy consumption are Albania (504), Cyprus (362), Luxembourg (461), Malta (313) and Montenegro (243).

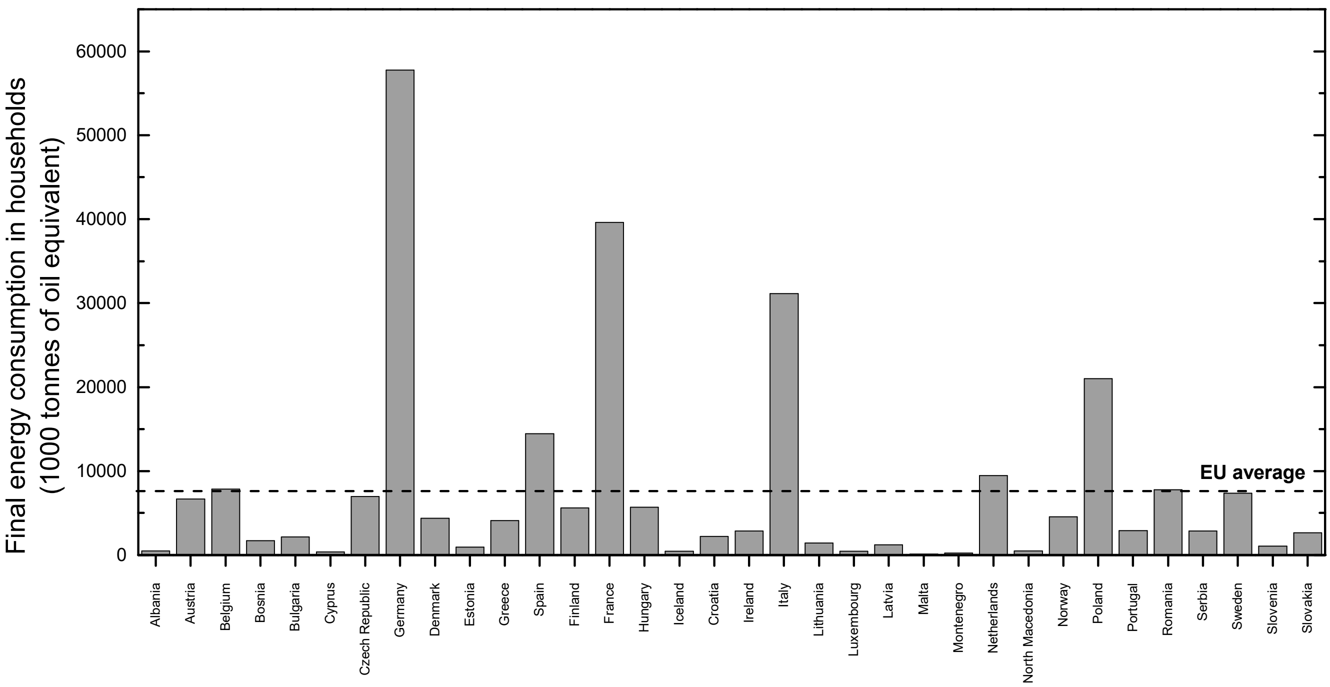


Figure 3. Final energy consumption in households in 2020 (Sources: EU Buildings Factsheets).

One of the most critical parameters under discussion is the percentage of the population unable to keep their home adequately warm (i.e., energy poverty). According to Eurostat, the average rate in Europe was 7.3% in 2018, which means that more than fifty million people were in this position. From the country-by-country analysis, it is possible to highlight the high percentages in Bulgaria (33.7%), Lithuania (27.9%), Greece (22.7%), Cyprus (21.9%), Portugal (19.4%) and Italy (14.1%).

Based on the above results, it can be concluded that addressing the above issues of older buildings via suitable seismic plus energy retrofitting solutions seems to be very promising in reducing the energy consumption and seismic vulnerability of the current building stock. That is why many states are already offering incentives to citizens to renovate their dwellings based on certain goals. An energy upgrade of a given building is an investment that can be achieved at reasonable costs and will have an immediate effect on its consumption. Nonetheless, as stated earlier and explained further below, an energy upgrade will not be effective when applied in a building of questionable structural integrity due to safety reasons.

2.4. Brief Considerations on the Climate Conditions

The Köppen–Geiger climate classification is the most widely used climate classification system. This classification divides the climate into five main climatic groups based on seasonal precipitation and temperature patterns [1]. The main five groups are tropical, arid, temperate, continental and polar.

The parameters used to understand the building energy requirements are the heating degree days (HDD) and cooling degree days (CDD). They are quantitative indices that reflect the demand for energy to heat or cool buildings. Both variables are derived from measurements of the outside temperature. According to Eurostat, the baseline temperatures for HDDs and CDDs are 15 °C and 24 °C, respectively. The outside temperature difference with the baseline temperature gives the HDD and CDD indexes. The sum of the index over the year results in the annual HDD and CDD. According to the Eurostat database (Eurostat), the available data for the HDD and CDD started in 1979 up to 2020. It should be underlined that these indicative indexes are related to average country values, which means that there are regions in each country that may have higher HDD and/or CDD than the average value estimated by Eurostat.

The correlation between the average national HDD and CDD indexes in 2020 is shown in Figure 4a. As expected, countries with high HDD such as Denmark or Sweden have at the same time a low CDD. The same can be said regarding countries with high CDD, such as Malta or Cyprus, that simultaneously have a short number of HDD. The most critical scenario can be described with countries with medium/high CDD and HDD at the same time, such as Hungary, Bulgaria, Italy, Spain and Greece. They are expected to consume more energy for space heating and cooling.

Another critical issue that can be highlighted is that the countries with higher HDD have, at the same time, the lowest percentage of the population unable to keep homes adequately warm (e.g., Finland and Sweden). Typically, this trend is observed in the north European countries. However, some countries present dangerous results concerning this relationship, i.e., medium/high HDD and a high percentage of the population unable to keep homes adequately warm. The highlighted countries are Lithuania, Romania, Bulgaria, Italy and Greece. Energy retrofitting measures would greatly benefit these countries, allowing them to find a balance between seasons without needing to spend much energy on space heating or cooling.

No direct relationship between the HDD and the building energy consumption can be found, as shown in Figure 4c. Nonetheless, countries such as Spain, Poland, Italy, France and Germany present a higher ratio between these two parameters, which means that energy retrofitting would help to reduce energy consumption for space heating due to the high HDD.

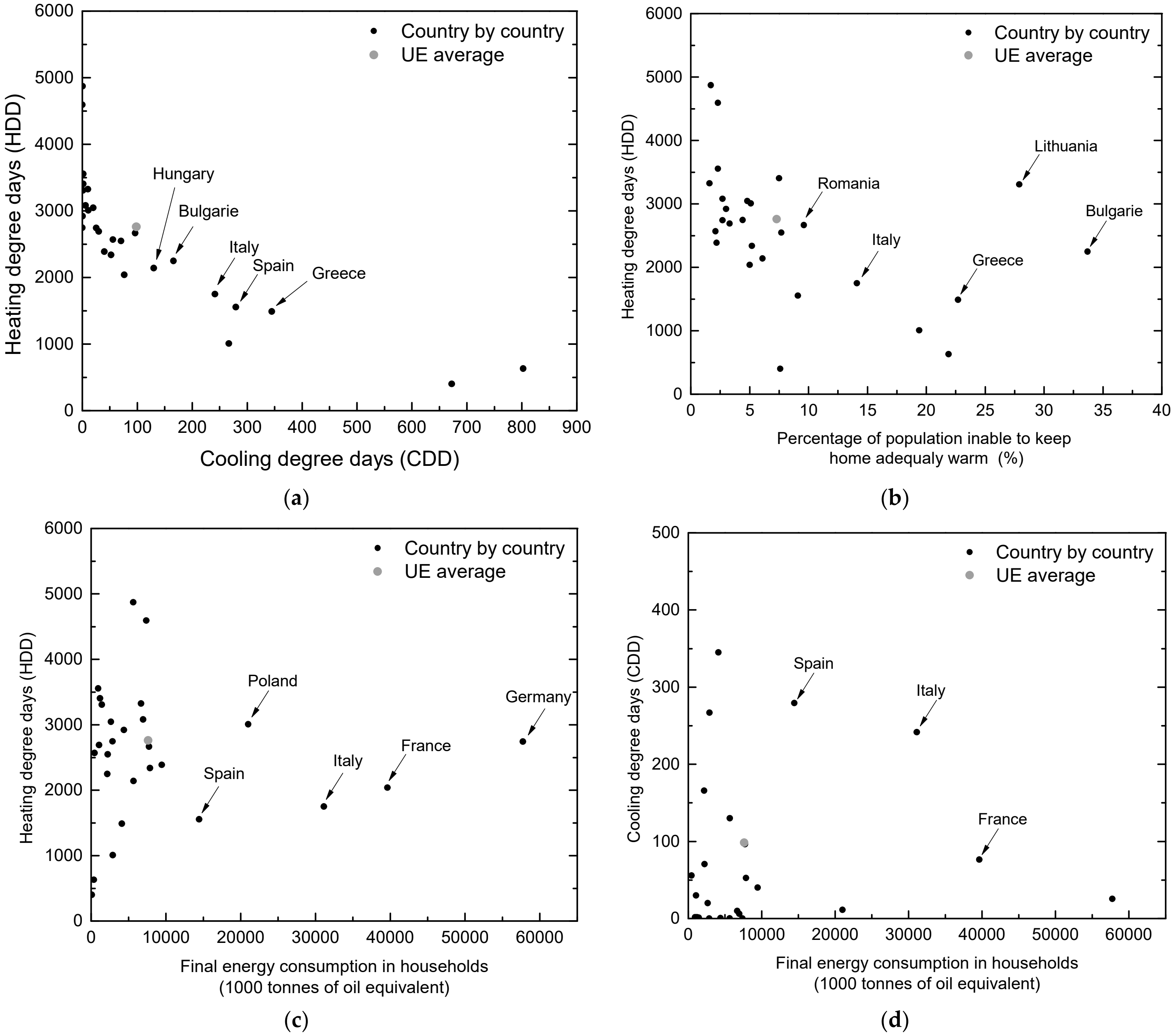


Figure 4. Climate data and building energy performance: (**a**) HDD vs. CDD; (**b**) HDD vs. energy poverty; (**c**) HDD vs. building energy consumption; and (**d**) CDD vs. building energy consumption (Sources: EU Buildings Factsheets).

In the same way, no clear trend is observed in the analysis of CDD versus the building energy consumption. Again, countries such as Spain, Italy and France presented a high ratio between these two parameters.

From the analysis of the HDD and CDD range distribution over the EU, a considerable variation can be observed for each country, which means that the analysis of the EU climate should be performed region by region. For example, the average HDD in Bulgaria is 2273, but the maximum value of 3036 is reached in the Smolyan region (BG424 in NUT 3 subdivision), about 34% higher. The same can be pointed out concerning the CDD since the average value found for Bulgaria is 160, but the maximum value of 379 was reached in the Yambol region (BG 343 in NUT 3 subdivision), about 136% higher. This observation is more notorious in the HDD when compared with the CDD ones.

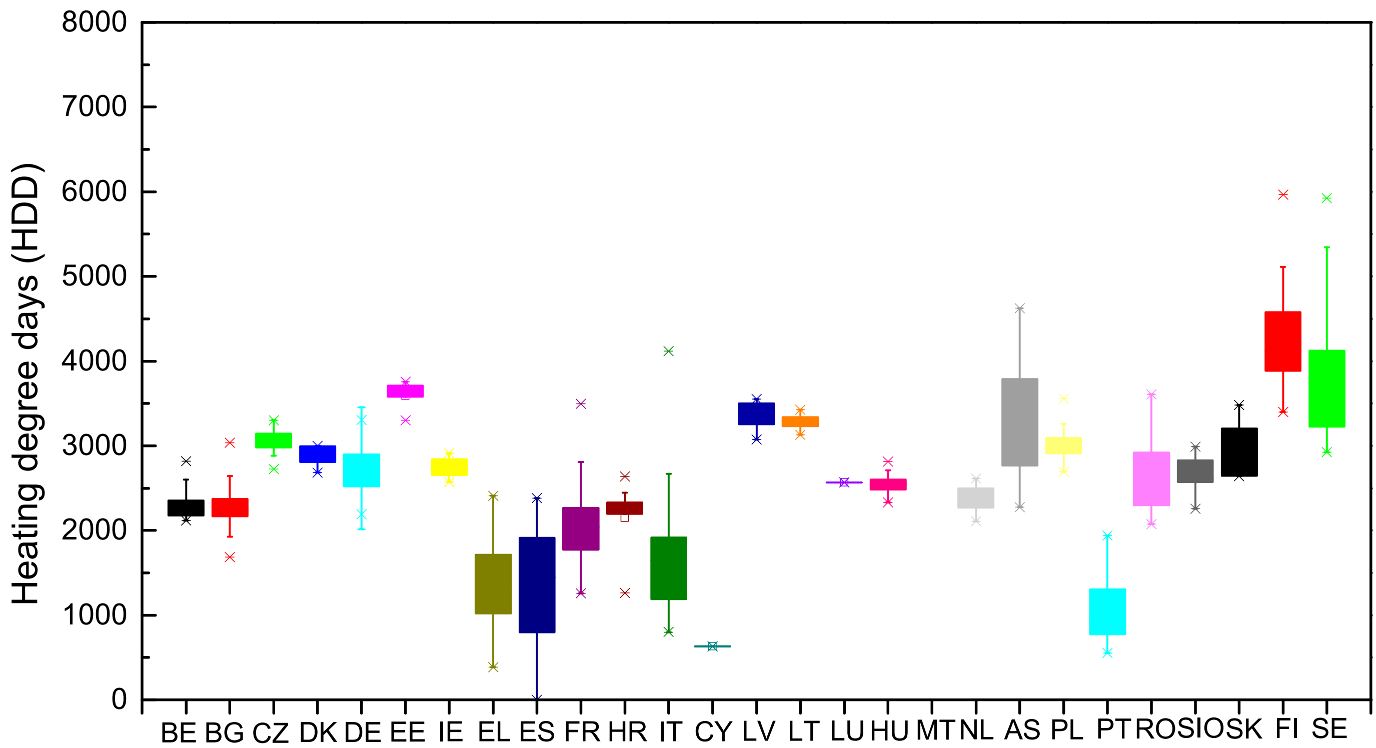
In Italy, the average HDD found for the country was 1646, but the minimum and maximum values found were 800 (Cagliari) and 4119 (Valle d'Aosta/Vallée d'Aoste), about

−52% and +150%, respectively. The average CDD found was 246, and the minimum and maximum values found were 1.3 (Sondrio) and 457 (Napoli), which are −99% and +50%, respectively.

A box plot concerning the heating (HDD) and cooling degree days (CDD) according to NUTS 3 subdivision is presented in Figure 5a,b. The box plot, also called a box and whisker plot or box chart, represents key values from summary statistics. Each Y column of data is represented as a separate box in each of these plots. The countries' nomenclatures supply the X-axis tick labels. By default, the box is determined by the 25th and 75th percentiles. The whiskers are determined by the 5th and 95th percentiles. Additional values are represented, including the minimum, median, mean, maximum, the 1st and 5th percentiles and the 95th and 99th percentiles.

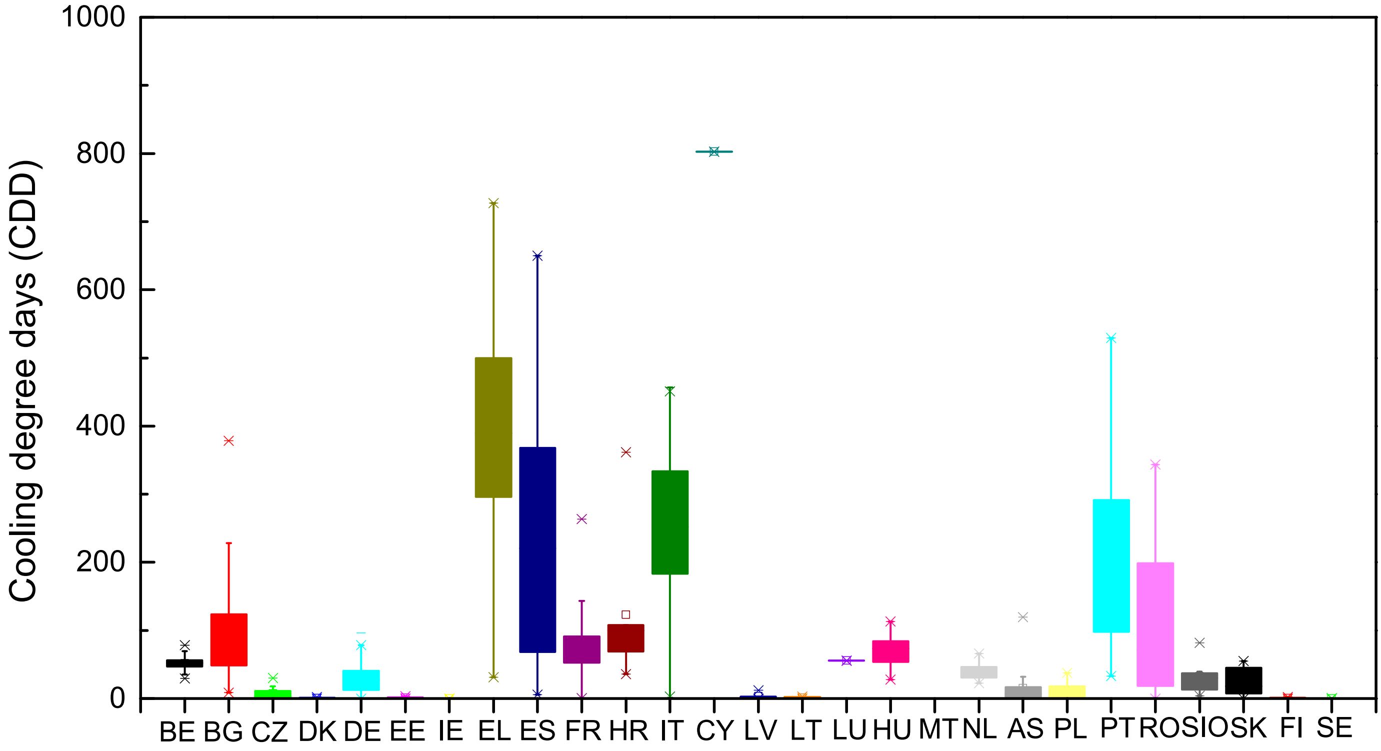
From this analysis, it can be seen that the countries with larger HDD variations are Greece, Spain, Italy, Austria, Portugal and Romania. Concerning the CDD variations, the countries with larger dissimilarities are Bulgaria, Greece, Spain, Italy, Portugal and Romania.

Figure 5c presents the ratio computed between the minimum and average HDD values, maximum and average HDD values, minimum and average CDD values and maximum and average CDD values. The most critical ones are the ratio between the maximum (HDD and CDD) and the average value found for each country since it is directly related to higher needs for energy consumption. The countries with higher variation in terms of HDD (i.e., the ratio between the maximum and average HDD) are Italy (+150%), Portugal (+90%), Greece (+78%) and Spain (+71%). Concerning the higher variation in terms of CDD (i.e., the ratio between the maximum and average HDD), it can be observed that the higher variation can be found in Austria (+700%), Czech Republic (+316%) and Denmark (+316%). However, the effect of this variation is more important for higher average CDD and/or HDD values.

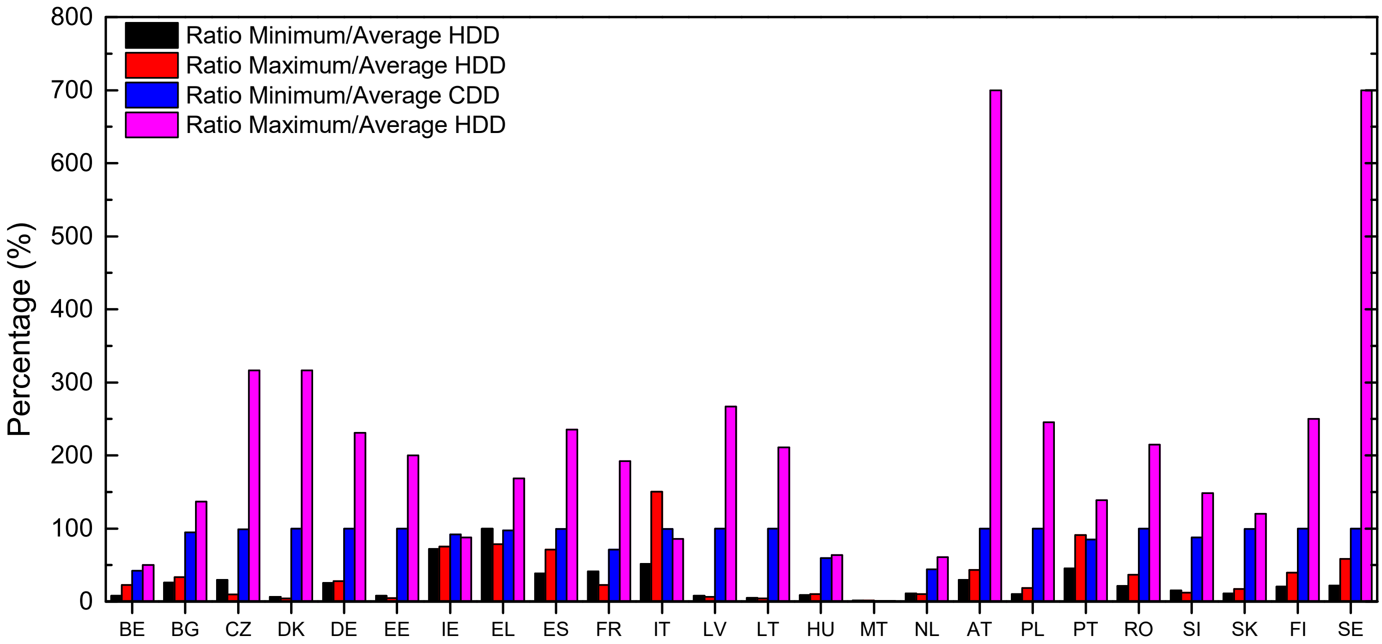


(**a**)

Figure 5. *Cont.*



(**b**)



(**c**)

Figure 5. (**a**) Heating degree days; (**b**) cooling degree days; and (**c**) ratio between minimum/maximum HDD and CDD values and the average ones for each country (Sources: EU Buildings Factsheets).

The identification of the countries that most need energy retrofitting measures needs to be performed by interpolating the HDD, energy poverty (i.e., the percentage of the population unable to keep homes adequately warm) and buildings' energy consumption. The countries that present higher values in these three categories are the ones that should be the focus of energy retrofitting. According to Pohoryles et al. [37], HDD values are more significant since heating and hot water account for the high energy consumption in Europe.

Future investigations must be performed towards a European Map that presents the distribution of the buildings' energy efficiency based on the climates and characteristics of buildings. Then, it will be possible to compute the annual average losses due to the energy required for heating and cooling space.

2.5. Seismic Risk

The buildings that most need seismic retrofitting depend on the respective seismic risk. It is estimated that 30% of EU buildings are located in areas of moderate seismic hazard (where the design peak ground acceleration, PGA, is at least 0.1 g). The seismic risk can be computed as the product between seismic hazard, exposure and vulnerability.

Gkatzogias et al. [38] presented the EU seismic risk results in which average annual losses (AAL) in USD per country were computed. It is possible to observe that the country with the highest AAL is Italy by far. After that, Greece, Romania, France and Germany come in the following positions. The ranking of AAL is strongly influenced by the level of seismic hazard but also the country's size and the exposure value, hence the average annual loss ratio (which is the AAL divided by the replacement value, AALR).

The analysis of the AALR highlights countries where the losses are high relative to the exposure value. So, countries with lower construction costs are often higher. To look at the areas where absolute losses are expected to be high but not necessarily due to the higher replacement costs of the buildings, another risk metric has been considered, namely the average annual loss per building.

From the analysis of the AALR, it can be observed that the ten countries with higher AALR are Cyprus (1.32‰), Greece (1.11‰), Romania (0.93‰), Italy (0.76‰), Bulgaria (0.58‰), Slovenia (0.39‰), Croatia (0.35‰), Austria (0.12‰), Hungary (0.11‰), Portugal (0.11‰) and Slovakia (0.11‰). The countries with lower AALR are Finland, Ireland, Lithuania and Sweden.

Moreover, Gkatzogias et al. [38] computed the average annual economic losses ratio (AAELR). The countries with higher AAELR are Cyprus (1.16‰), Greece (0.90‰), Italy (0.58‰), Croatia (0.42‰) and Bulgaria (0.31‰). Conversely, the countries with low AAELR are Lithuania, Latvia, Poland, Sweden, Estonia, Denmark, Finland and Ireland. The comparison between the AAELR and AALR shows that the countries follow a linear trend (grey line). Romania is the country furthest from this trend, but not significantly.

In addition, Crowley [39] computed the average annual life loss (AALL) by the number of occupants and loss of life. This parameter was given per 100,000 occupants to avoid very low numbers. Because this metric is one of those proposed by the Sendai Framework for Disaster Risk Reduction, the countries with higher AALL are Greece (0.36), Cyprus (0.18), Croatia (0.17), Bulgaria (0.12), Italy (0.09), Austria (0.09), Slovenia (0.08) and Romania (0.07). From the relationship between the AALR and the AALL, shown in Figure 6a, it is possible to observe that Greece appears to be the country with the highest correlation (i.e., high AALR and high AALL). It can also be stated that Cyprus, Romania, Italy and Bulgaria present high AALR and medium–high AALL at the same time.

Finally, the last parameter that must be analysed is the average annual economic losses (AAEL) per building. Cyprus, Greece and Italy are clearly on the front line of this parameter, followed by Croatia, Austria, Slovenia and Spain. The countries with low AAEL per building are Estonia, Ireland and Finland.

A specific trend cannot be concluded from the analysis of the relationship between AALR and AAEL per building, shown in Figure 6b. For example, Cyprus and Italy present an increasing linear trend, i.e., the AALR increases with the increase in the AAEL per building. However, the same was not observed for other countries such as Romania, Bulgaria and Slovenia.

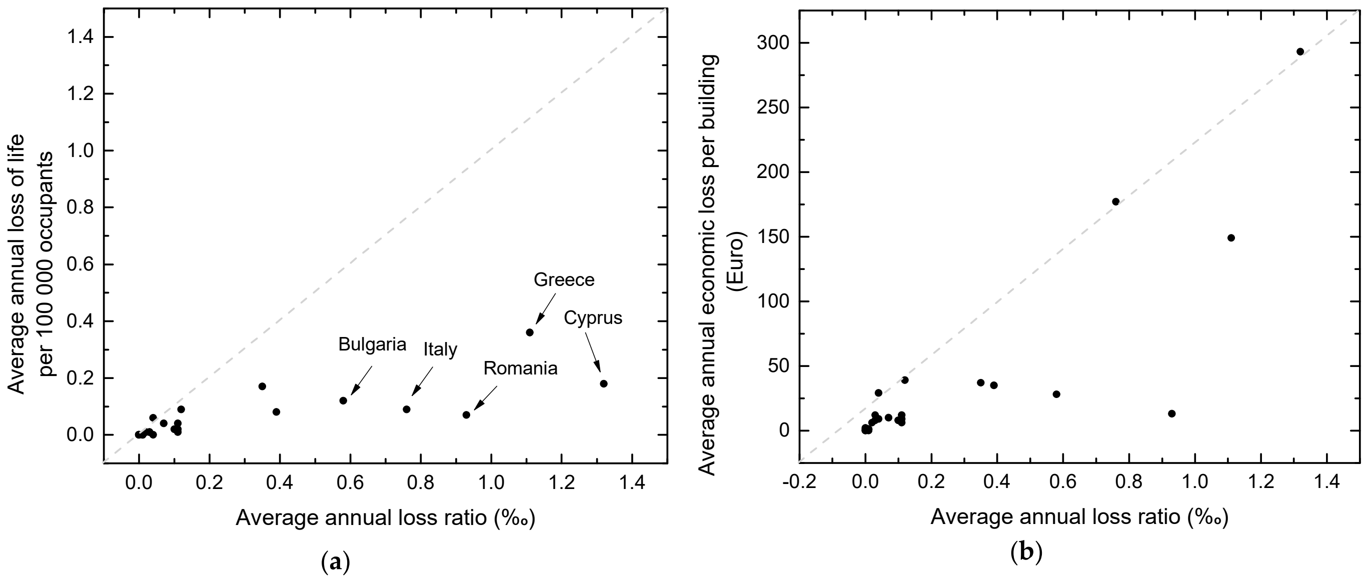


Figure 6. (**a**) Comparison between AALL and AALR; and (**b**) AAEL per building and AALR.

Furthermore, one example of regulation is the Greek Interventions Regulation, also known as KANEPE [40], which is a legal framework designed to regulate the provision of emergency liquidity assistance by the Bank of Greece to Greek banks. KANEPE was introduced in 2015 during a period of economic turbulence in Greece, and it establishes a set of criteria that must be met by banks in order to receive emergency funding. These criteria include the need for the bank to have sufficient collateral and the requirement for the bank to submit a business plan outlining how it will return to financial stability. The aim of KANEPE is to ensure that emergency funding is only provided to banks that have a viable long-term future and that the risks to the Greek taxpayer are minimized. This regulation is fundamental in a post-earthquake scenario.

3. Identification of Relevant Scenarios Based on Climate and Seismic Risk Maps

Combined seismic and energy upgrading is essential for countries exposed simultaneously to high seismic hazards and climatic exposures. Butenweg (2021) proposed a methodology to identify European countries and regions with a higher correlation between seismic and energy upgrading. A score-based approach was proposed to determine whether combined upgrading is required for a building in a specific region, depending on the seismic hazard level and the climatic conditions. The authors proposed a score-based approach to identify these countries. The score is calculated based on the seismic hazard level in terms of PGA and the indicators HDD and CDD for the climatic conditions.

The strategy adopted to identify the relevant scenarios for combined structural plus energy retrofitting herein proposed is based on the inputs from the EU seismic risk (i.e., average annual expected losses ratio), climate maps (heating and cooling) and characteristics of the EU building stock (total building energy consumption, energy poverty). First, the analysis is performed at the macro-level perspective, i.e., using country average values.

The relationship between the AALR and the HDD is shown in Figure 7a. It can be seen that several countries simultaneously have low AALR and high HDD (e.g., Finland and Sweden), which means that energy retrofitting would be adequate for this type of region. On the other hand, it is possible to observe countries with simultaneous low AALR and HDD (e.g., Malta and Portugal). Countries such as the Netherlands, Ireland and Denmark have medium–high HDD combined with low AALR. The most critical scenario is the combination of medium–high AALR with medium–high HDD, such as in Romania, Italy and Bulgaria.

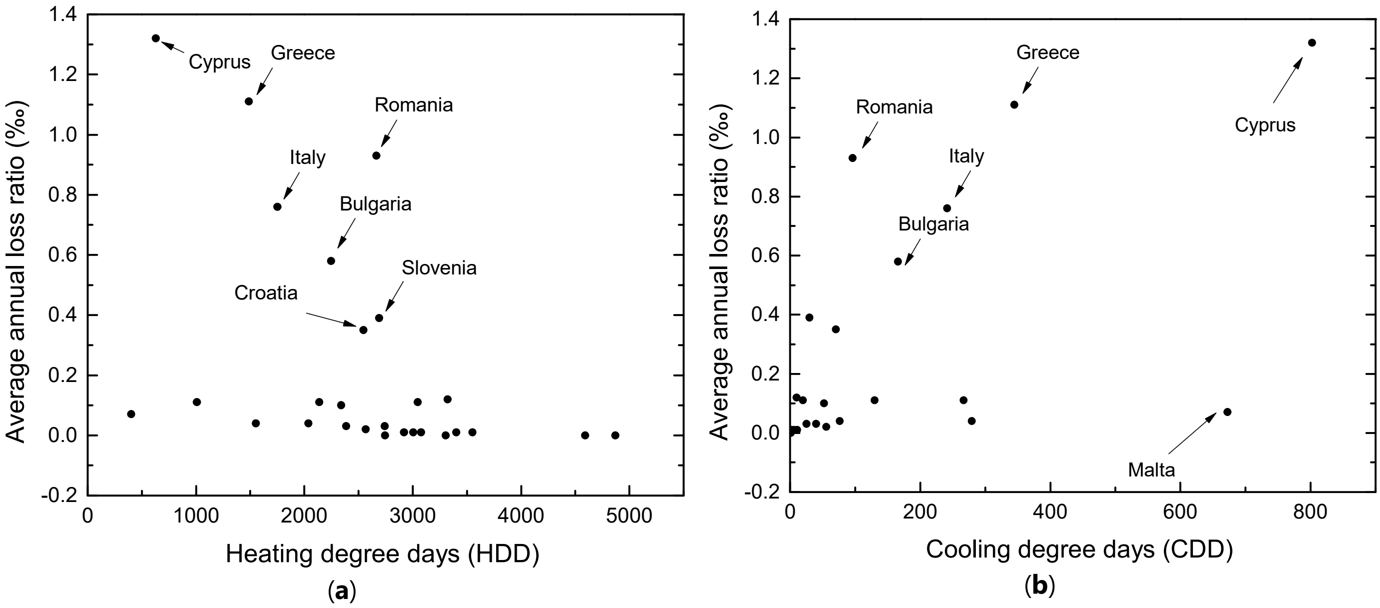


Figure 7. Definition of priority regions: (**a**) AALR vs. HDD; and (**b**) AALR vs. CDD.

The same observation can be made for the relationship between CDD and AALR, shown in Figure 7b. It can be observed that Cyprus is a country with high AALR and CDD simultaneously. After that, Greece, Italy, Bulgaria and Romania have higher AALR and CDD. The remaining countries, typically north and central European Countries, have low CDD and AALR. Malta is the second country with a higher CDD but has a low AALR.

The definition of climate plus seismic scenarios for each region of the EU is herein performed based on the two inputs: AALR and a climate indicator (CI). Nine different EU zones are herein proposed based on the combination of AALR and CI. The zones were defined based on the EU's AALR and CI range values. Three different levels of AALR are proposed: low (AALR < 0.30‰); medium (0.30‰ $\leq$ AALR < 0.60‰); and high (AALR $\geq$ 0.60‰). The CI was computed for each country according to Equation (1). Then, three different levels are proposed: low (CI < 1500); medium (1500 $\leq$ CI < 3000); and high (CI $\geq$ 3000). Thus, the seismic–climate matrix for the definition of the EU zone is presented in Figure 8.

$$CI = HDD + CDD \tag{1}$$

It should be stressed that CI greatly depends on the HDD and more minorly on CDD. The relationship between HDD and CDD justifies this, i.e., HDD is much higher in almost all countries than CDD. Since a significant part of the building energy consumption is due to heating spaces, highly dependent on the HDD, the CI herein proposed represents the climate severity representative of each country well. However, it is expected that the CDD will increase significantly in future years due to climate change. The characteristics of each combined seismic and climate scenario are presented in Table 1.

The results concerning the association of the EU countries to the respective seismic–climate zone (SCZ), using average country reference data, are presented in Table 2 and Figure 8b. Additionally, the seven countries with a higher percentage of the population unable to warm their homes were highlighted. One of the EU and United Nations' objectives is to reduce the population's portion under energy poverty conditions. For example, Portugal has a high percentage of energy poverty and is located in SCZ_A (i.e., low CI and low AALR). Usually, low-energy and seismic strengthening measures are recommended for zone A. However, in the case of Portugal, strong energy retrofitting measures are recommended to reduce the percentage of the population in energy poverty conditions.

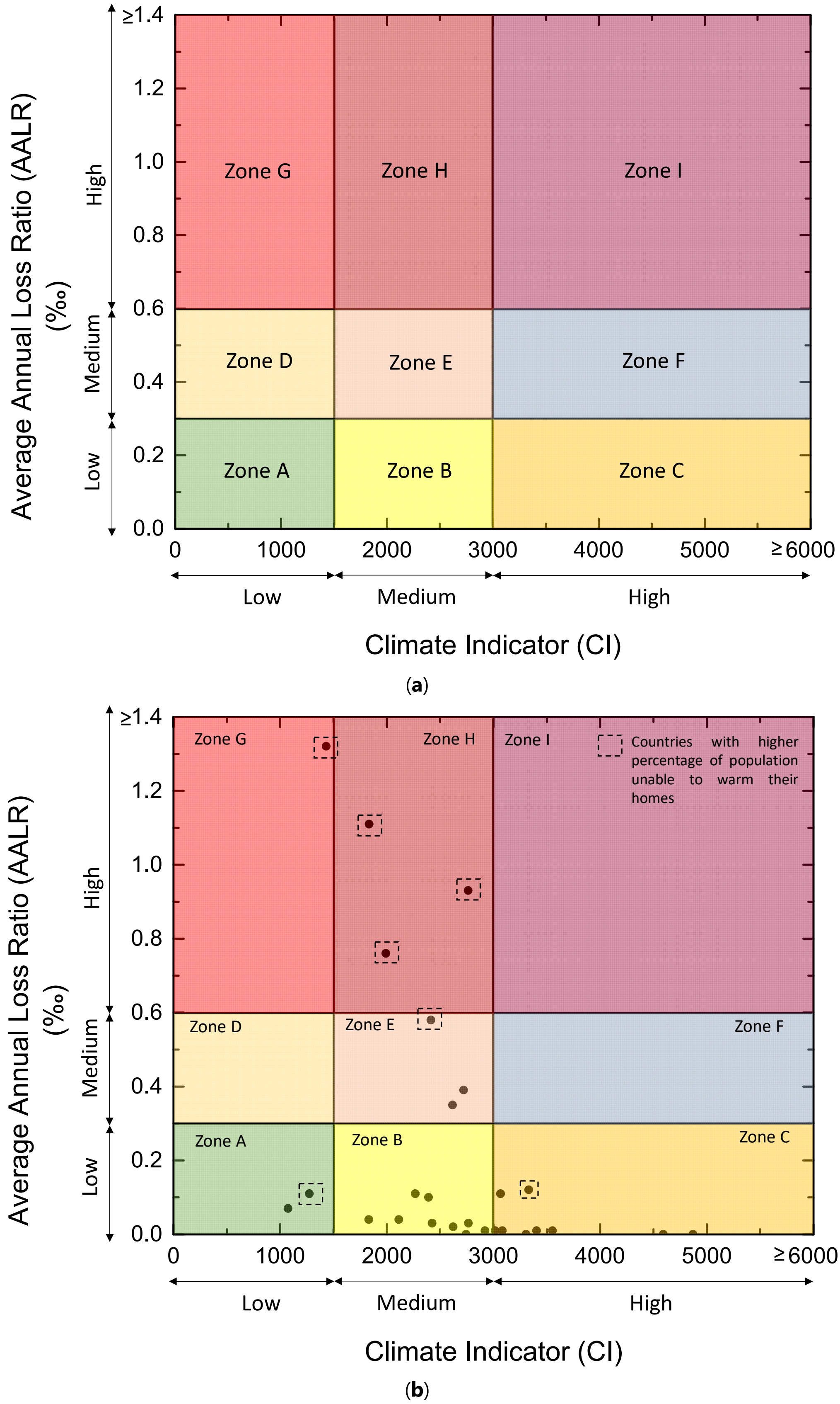


Figure 8. Seismic–climate zone matrix: (**a**) schematic layout; (**b**) average country values.

Table 1. Definition of seismic–climate zones (SCZ).

Seismic–Climate Zone	AALR (‰)	CI	General Recommendation on Retrofitting
A	<0.30	<1500	Low energy retrofitting Low seismic retrofitting
B	<0.30	1500 ≤ CI < 3000	Medium energy retrofitting Low seismic retrofitting
C	<0.30	≥3000	High energy retrofitting Low seismic retrofitting
D	0.30 ≤ AALR < 0.60	<1500	Low energy retrofitting Medium seismic retrofitting
E	0.30 ≤ AALR < 0.60	1500 ≤ CI < 3000	Medium energy retrofitting Medium seismic retrofitting
F	0.30 ≤ AALR < 0.60	≥3000	High energy retrofitting Medium seismic retrofitting
G	≥0.60	<1500	High energy retrofitting Low seismic retrofitting
H	≥0.60	1500 ≤ CI < 3000	High energy retrofitting Medium seismic retrofitting
I	≥0.60	≥3000	High energy retrofitting High seismic retrofitting

Table 2. Distribution of EU countries over the seismic–climate zones proposed.

Countries	AALR (‰)	HDD	CDD	CI	Percentage of the Population Unable to Warm Their Homes (%)	SCZ
Austria	0.12	3323	10	3333	1.6	C
Belgium	0.10	2340	52	2392	5.2	B
Bulgaria	0.58	2247	166	2413	33.7	E [A]
Cyprus	1.32	630	803	1433	21.9	G [A]
Czech Republic	0.01	3079	6	3085	2.7	C
Germany	0.03	2741	25	2766	2.7	B
Denmark	0.01	2921	0.6	2922	3	B
Estonia	0.01	3553	1.7	3555	2.3	C
Greece	1.11	1489	345	1834	22.7	H [A]
Spain	0.04	1553	279	1832	9.1	B
Finland	0	4871	0.4	4871	1.7	C
France	0.04	2038	76.4	2114	5	B
Hungary	0.11	2138	130	2268	6.1	B
Croatia	0.35	2547	70.5	2618	7.7	E
Ireland	0	2744	0	2744	4.4	B
Italy	0.76	1750	241	1991	14.1	H [A]
Lithuania	0	3305	1.06	3306	27.9	C [A]
Luxembourg	0.02	2567	55.6	2623	2.1	B
Latvia	0.01	3404	1.7	3406	7.5	C
Malta	0.07	402	672	1074	7.6	A
Netherlands	0.03	2386	40.1	2726	2.2	B
Poland	0.01	3006	11.2	3017	5.1	C
Portugal	0.11	1008	266	1274	19.4	A [A]
Romania	0.93	2666	96.4	2762	9.6	H [A]
Sweden	0	4593	0.08	4593	2.3	C
Slovenia	0.39	2691	29.8	2721	3.3	E
Slovakia	0.11	3047	20	3067	4.8	C

[A]–Country with a high percentage of population unable to warm their homes.

From the results, it can be seen that there are no countries located in zones D, F and I. Portugal and Malta are positioned in zone A. Zone B comprises Belgium, Germany, Denmark, Spain, France, Hungary, Ireland, Luxembourg and the Netherlands. Zone C includes Austria, Czech Republic, Finland, Estonia, Lithuania, Latvia, Poland and Slovakia. Zone E comprises Bulgaria, Croatia and Slovenia. Zone G includes Cyprus. Finally, Greece, Italy and Romania belong to zone H.

Once again, it should be underlined that the data used for selecting the seismic–climate scenario are based on average values found for each country. Different regions can be positioned in different SCZs in each country, depending on the seismic plus climate demands. The strategy herein recommended to perform this analysis involves interpolating this input data at the region level (i.e., using NUTS 1 or NUTS 3), as Gkatzogias et al. [38] indicated.

The identification of relevant seismic–climate zones herein proposed is based on the inputs from the seismic risk (i.e., average annual expected losses) and climate indicators (heating and cooling degree days). A detailed analysis was performed at a macro level (i.e., country level). Regional zonation must be a priority in the future for defining priority regions in the EU by correlating seismic and climate inputs for each admin level. Some regions are suggested for each seismic–climate zone based on seismic risk and climate indicators (Table 3). It should be noted that these are some examples and not the total number of regions in the EU.

Table 3. List of relevant regions for each seismic–climate zone.

CSZ	Country/Region
A	Porto (Portugal) Valletta (Malta)
B	Lagos (Portugal) Madrid (Spain) Barcelona (Spain) Montana (Bulgaria) Bratislava (Slovakia) Berlin (Germany)
C	Tyrolean Oberland (Austria) Norrbotten County (Sweden) Unterallgäu (Germany) Aosta (Italy) Krakow (Poland)
D	Lisboa (Portugal)
E	Primorsko-Goranska (Croatia) Olt County (Romania)
F	Kardzhali Province (Bulgaria) Suceava County (Romania)
G	Calabria (Italy)
H	Ljubljana (Slovenia) Galati (Romania)
I	Covasna (Romania)

Moreover, the lack of an EU energy vulnerability map was identified, which will allow the regions with a higher number of buildings with poor energy efficiency to be identified. Future studies must prioritize developing this new map and integrate it with the seismic risk map towards a future EU seismic plus energy risk map.

4. Definition of Scenarios for Retrofitting Strategies in the European Union

The present section proposes scenarios for retrofitting specific building typologies located in the different seismic–climate zones defined. The recommended retrofitting strategies depend highly on the building seismic design, energy efficiency and the seismic–climate demand. For example, if a building typology is located in zone A (i.e., low climate indicators and low expected seismic losses), the seismic retrofitting is only addressed if the seismic vulnerability assessment, according to Eurocode 8 [30], concludes that it is necessary. No seismic retrofitting is required if the building verifies the Eurocode 8 safety assessment methodology. The same exercise needs to be carried out regarding energy efficiency.

In the case of relevant seismic and climate indicators, the synergy between the seismic and energy retrofitting interventions needs to be prioritised in the rehabilitation of existing EU building stock. This new approach will reduce energy consumption and CO_2 emissions while buildings' seismic vulnerability is reduced. It will also be possible to take advantage of the existing policies proposed by the EU and use the incentives to complement the energy retrofitting and reduce buildings' seismic vulnerability.

For this purpose, nine different types of building typologies are considered concerning their seismic design and energy efficiency, namely, low seismic design (LSD) combined with low energy efficiency (LEE); high seismic design (HSD) combined with low energy efficiency (LEE); or low seismic design (LSD) combined with high energy efficiency (HEE). The building typologies matrix is presented in Figure 9.

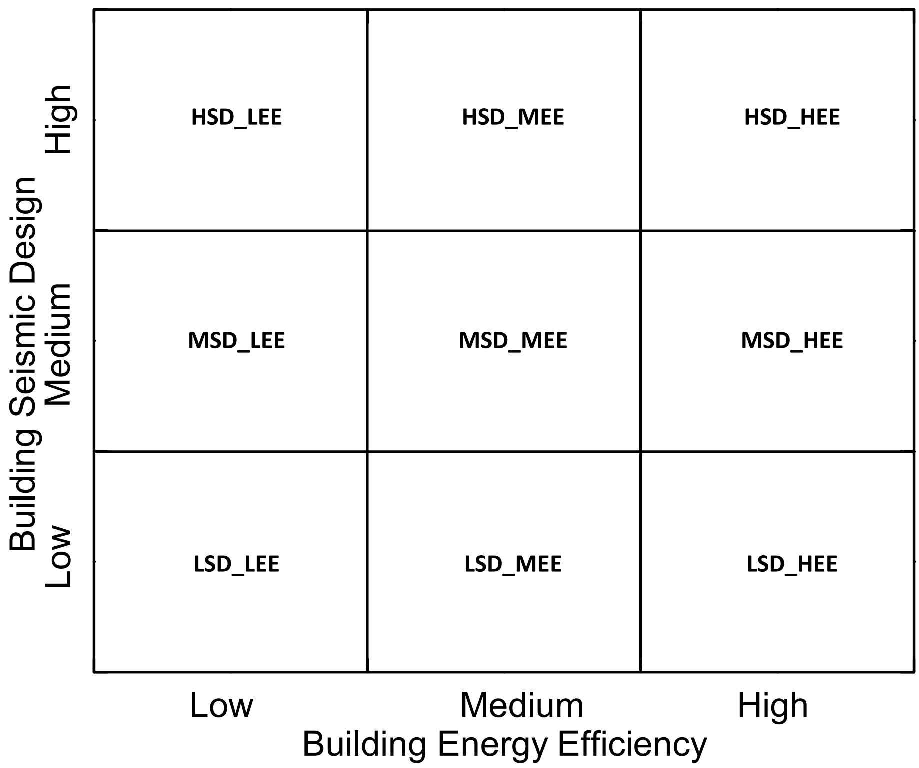


Figure 9. Building typologies matrix.

From the seismic vulnerability and energy efficiency point of view, these nine typologies represent the possible different building typologies existing in the EU building stock. The most vulnerable typologies are the LSD_LEE, LSD_HEE, and HSD_LEE for different reasons. The typology LSD_LEE is related to buildings with low (or no) seismic design and low/poor energy efficiency. The buildings constructed before 1970 can represent the LSD_LEE typology, considering the EU's implementation date of the first seismic and energy codes (around 1970).

The typology LSD_HEE is related to buildings with low or no seismic design and high energy efficiency. Buildings with a year of construction before 1970 that were recently subjected to energy strengthening can be representative of this typology.

The typology HSD_LEE is dedicated to buildings with high/modern seismic design (e.g., according to Eurocode 8) and low energy efficiency. The first energy codes emerged in Europe after 1980, with low energy demands. The modern codes (e.g., after 2000) require high insulation demands, resulting in buildings with high energy efficiency. A building designed according to Eurocode 8 (i.e., seismic design) and the first energy codes implemented in the 1980s can represent the HSD_LEE typology.

Two types of building structures are suggested to be analysed since they represent most of those existing in the EU building stock: masonry (M) structures and reinforced concrete (RC) structures. Tables 4 and 5 present the nomenclature adopted for each building typology that will be suggested for the different retrofitting scenarios. Other types of structures such as wood were excluded from this recommendation since they are not representative of the EU building stock.

Table 4. Definition of reinforced concrete building typologies proposed for retrofitting scenarios.

Nomenclature	Building Seismic Design	Building Energy Efficiency
RC_LSD_LEE	Low	Low
RC_HSD_LEE	High	Low
RC_LSD_HEE	Low	High

Table 5. Definition of masonry building typologies proposed for retrofitting scenarios.

Nomenclature	Building Seismic Design	Building Energy Efficiency
M_LSD_LEE	Low	Low
M_HSD_LEE	High	Low
M_LSD_HEE	Low	High

The present section aims to propose retrofitting scenarios, taking into account the type of building structure (i.e., M or RC), seismic design (i.e., LSD, MSD or HSD), energy efficiency (i.e., LEE, MEE or HEE) and seismic–climate zone (i.e., scenario SCZ_A, SCZ_B, SCZ_C, SCZ_D, SCZ_E, SCZ_F, SCZ_G, SCZ_H or SCZ_I).

For each retrofitting scenario (i.e., combination of building typology and seismic–climate zone), a datasheet containing information related to the seismic–climate zone (seismic and climate indicators), building performance type (seismic design, energy efficiency and particular building characteristics), possible retrofitting recommendations and examples of EU cities/regions is proposed. The framework of the datasheets produced for each retrofitting scenario is shown in Figure 10.

Moreover, apart from the suggestions included in each retrofitting scenario, special attention must be dedicated to isolated and aggregated buildings. It is recommended that different types of masonry are considered (regular or irregular arrangement of blocks, dry or mortared joints) in the case of masonry structures. It is also suggested that vertical and/or plan irregularities of structural and non-structural elements (such as infill walls) are considered since they are responsible for multiple failures on these types of structures.

The framework for defining the different retrofitting scenarios is based on a three-step procedure. Step 1 defines the seismic–climate zone. Step 2 defines the building performance type that will be located in the seismic–climate zone. The third step is dedicated to retrofitting recommendations based on the input data from Step 1 and Step 2. A maximum of 81 retrofitting scenarios can be extracted from this framework for each type of structure (i.e., masonry or reinforced concrete structure). Only six retrofitting scenarios are herein presented for each type of structure. They were selected based on the level of demand (i.e., seismic and/or climate) and the low performance of buildings. Six retrofitting scenarios are herein proposed (Figures 11–16).

As previously mentioned, the retrofitting scenarios herein proposed were developed assuming a seismic–climate matrix approach, i.e., by considering AALR and CI indicators. It should be stressed that this work needs to be performed by considering the economic losses estimated due to the energy consumption of buildings. The climate indicator (HDD plus CDD) gives a perspective of the heating and cooling needs but does not reflect the real energy efficiency of buildings in that zone.

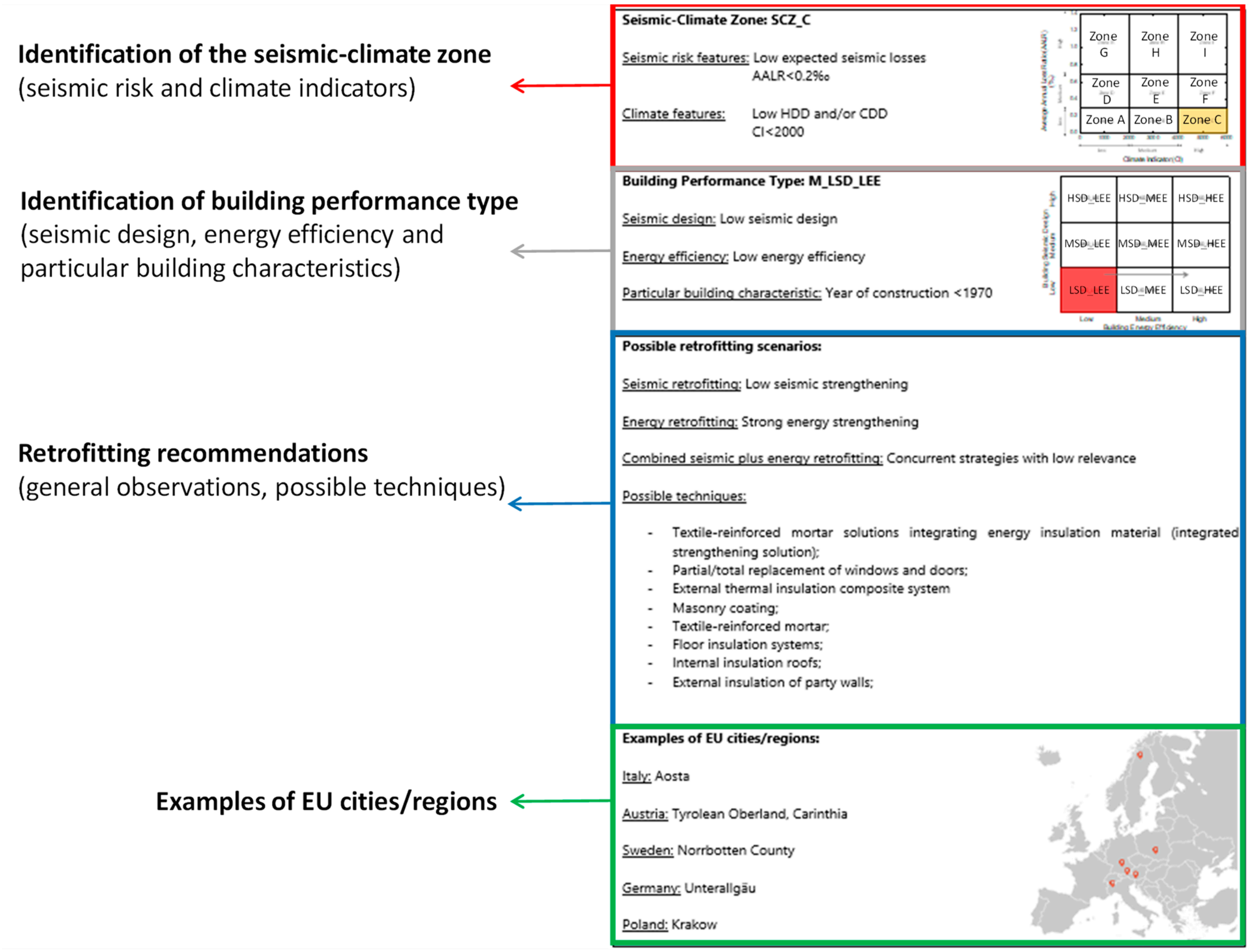


Figure 10. Framework of the datasheets produced for each combination.

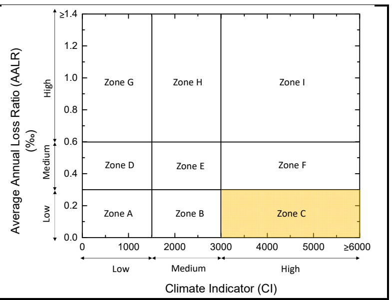
On one hand, the AALR was estimated by performing an accurate assessment considering the actual seismic building vulnerability, exposure and hazard. On the other hand, energy efficiency is only associated with climate indicators. The energy codes are more demanding in countries subjected to high heating demands. Thus, the buildings designed according to these codes are more energy-efficient than others not designed according to modern energy codes but located in countries with lower heating (or cooling) demands.

Nonetheless, it is crucial to study the list of cities herein highlighted for future combined seismic plus energy retrofitting, namely, Vienna (Austria), Carinthia (Austria), Grad Sofiya (Bulgaria), Plovidv (Bulgaria), Dubrovacko-Neretvanska (Croatia), Grad Zagreb (Croatia), Splitsko-Dalmatinska (Croatia), Paphos (Cyprus), Larnaka (Cyprus), Lafkosia (Croatia), Ammochostos (Croatia), Lemesos (Croatia), Peloponnese (Greece), Arge (Greece), Crete (Greece), Thessaly and Central Greece (Greece), Epirus (Greece), Attica (Attica), Macedonia and Thrace (Greece), Emilia Romagna (Italy), Umbria (Italy), Molise (Italy), Abruzzo (Italy), Toscana (Italy), Friuli-Venezia Giulia (Italy), Marche (Italy), Veneto (Italy), Campania (Italy), Basilicata (Italy), Bucuresti (Romania) and Region of Murcia (Spain).

Seismic-Climate Zone: SCZ_C

Seismic risk features: Low seismic losses expected
AALR < 0.3‰

Climate features: High HDD and/or CDD
CI≥3000

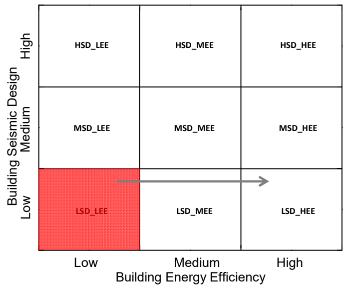


Building Performance Type: M_LSD_LEE

Seismic design: Low seismic design

Energy efficiency: Low energy efficiency

Particular building characteristic: Year of construction < 1970



Possible retrofitting scenarios:

Seismic retrofitting: Low seismic strengthening

Energy retrofitting: Strong energy strengthening

Combined seismic plus energy retrofitting: Concurrent strategies with low relevance

Possible techniques:

- Textile-reinforced mortar solutions integrating energy insulation material (integrated strengthening solution);
- Partial/total replacement of windows and doors;
- External thermal insulation composite system
- Masonry coating;
- Textile-reinforced mortar;
- Floor insulation systems;
- Internal insulation roofs;
- External insulation of party walls;

Examples of EU cities/regions:

Italy: Aosta

Austria: Tyrolean Oberland, Carinthia

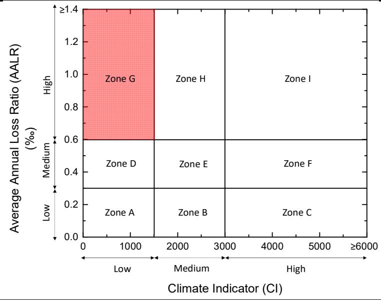
Sweden: Norrbotten County

Germany: Unterallgäu

Poland: Krakow

Figure 11. Retrofitting scenario 1: SCZ_C and M_LSD_LEE.

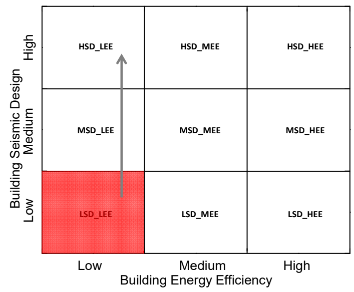
Seismic-Climate Zone: SCZ_G



Seismic risk features: High seismic losses expected
AALR≥0.6‰

Climate features: Low HDD and/or CDD
CI < 1500

Building Performance Type: M_LSD_LEE



Seismic design: Low seismic design

Energy efficiency: Low energy efficiency

Particular building characteristic: Year of construction < 1970

Possible retrofitting scenarios:

Seismic retrofitting: Strong seismic strengthening

Energy retrofitting: Low energy strengthening

Combined seismic plus energy retrofitting: Concurrent strategies with low relevance

Possible techniques:

- Masonry coating
- Grout injection
- Steel dowels
- Horizontal and vertical steel ties
- Intramural tying
- Bed-joint reinforced repointing
- Stiffening of floors
- Strengthening of openings with steel frame
- Textile-reinforced mortar based solutions for external walls

Examples of EU cities/regions:

Italy: Calabria

Cyprus: Paphos, Larnaka, Lefkosia, Ammochostos, Lemesos

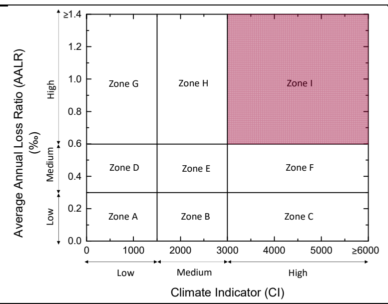
Greece: Crete

Figure 12. Retrofitting scenario 2: SCZ_G and M_LSD_LEE.

Seismic-Climate Zone: SCZ_I

<u>Seismic risk features:</u> High seismic losses expected
AALR≥0.6‰

<u>Climate features:</u> High HDD and/or CDD
CI≥3000

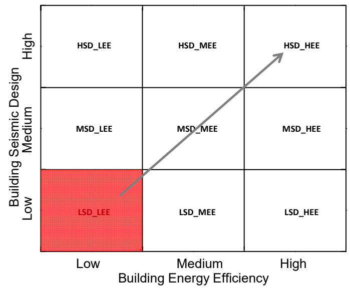


Building Performance Type: M_LSD_LEE

<u>Seismic design:</u> Low seismic design

<u>Energy efficiency:</u> Low energy efficiency

<u>Particular building characteristic:</u> Year of construction < 1970



Possible retrofitting scenarios:

<u>Seismic retrofitting:</u> Strong seismic strengthening

<u>Energy retrofitting:</u> Strong energy strengthening

<u>Combined seismic plus energy retrofitting:</u> Concurrent strategies should be prioritized

<u>Possible techniques:</u>
- Masonry coating
- Grout injection
- Steel dowels
- Horizontal and vertical steel ties
- Intramural tying
- Bed-joint reinforced repointing
- Stiffening of floors
- Strengthening of openings with steel frame
- Textile-reinforced mortar based solutions for external walls
- Textile-reinforced mortar solutions integrating energy insulation material (integrated strengthening solution);
- Partial/total replacement of windows and doors;
- External thermal insulation composite system

Examples of EU cities/regions:

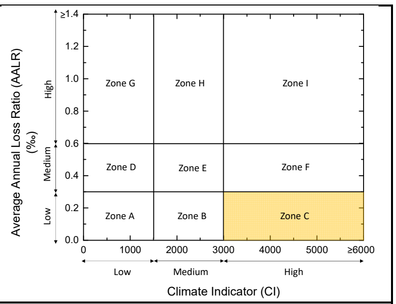
<u>Italy:</u> Veneto

Figure 13. Retrofitting scenario 3: SCZ_I and M_LSD_LEE.

Seismic-Climate Zone: SCZ_C

Seismic risk features: Low seismic losses expected AALR < 0.3‰

Climate features: High HDD and/or CDD CI≥3000

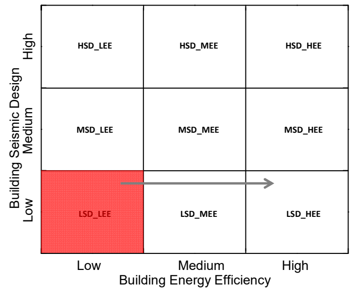


Building Performance Type: RC_LSD_LEE

Seismic design: Low seismic design

Energy efficiency: Low energy efficiency

Particular building characteristic: Year of construction < 1970



Possible retrofitting scenarios:

Seismic retrofitting: Low seismic strengthening

Energy retrofitting: Strong energy strengthening

Combined seismic plus energy retrofitting: Concurrent strategies with low relevance

Possible techniques:

- External thermal energy insulation
- Total replacement of windows and doors
- Floor insulation systems
- Internal insulation roofs
- External insulation of party walls
- Prefabricated units for external wall insulation
- System of facade refurbishment with cement panels sheathing
- External insulation of flat roofs
- Thermal insulation of external wall air chambers
- External insulation of sloped roofs

Examples of EU cities/regions:

Italy: Aosta

Austria: Tyrolean Oberland, Carinthia

Sweden: Norrbotten County

Germany: Unterallgäu

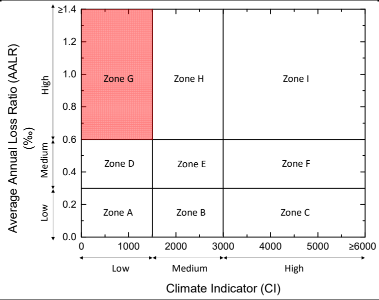
Poland: Krakow

Figure 14. Retrofitting scenario 4: SCZ_C and RC_LSD_LEE.

Seismic-Climate Zone: SCZ_G

Seismic risk features: High seismic losses expected
AALR≥0.6‰

Climate features: Low HDD and/or CDD
CI < 1500

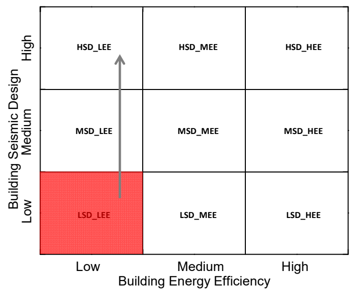


Building Performance Type: RC_LSD_LEE

Seismic design: Low seismic design

Energy efficiency: Low energy efficiency

Particular building characteristic: Year of construction < 1970



Possible retrofitting scenarios:

Seismic retrofitting: Strong seismic strengthening

Energy retrofitting: Low energy strengthening

Combined seismic plus energy retrofitting: Concurrent strategies with low relevance

Possible techniques:

- RC Jacketing of columns and beam-column joints
- Steel jacketing of columns and beam-column joints
- FRP jacketing of columns and beam-column joints
- RC shear walls
- Steel braces
- Retrofitting of masonry infill walls in the buildings envelope
- System of facade refurbishment with cement panels sheathing
- Textile-reinforced mortar solutions integrating energy insulation material
- Timber-based panels in the buildings envelope
- Engineered exoskeletons
- Replacement of existing masonry infill walls in the building envelope

Examples of EU cities/regions:

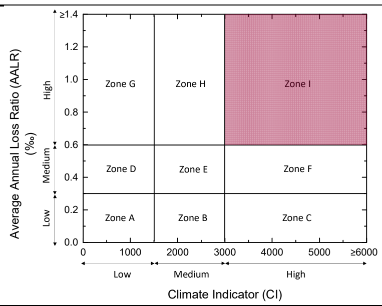
Italy: Calabria

Cyprus: Paphos, Larnaka, Lefkosia, Ammochostos, Lemesos

Greece: Crete

Figure 15. Retrofitting scenario 5: SCZ_G and RC_LSD_LEE.

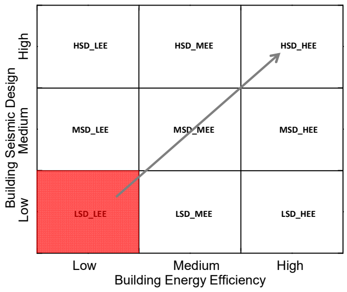
Seismic-Climate Zone: SCZ_I



<u>Seismic risk features:</u> High seismic losses expected AALR≥0.6‰

<u>Climate features:</u> High HDD and/or CDD CI≥3000

Building Performance Type: RC_LSD_LEE



<u>Seismic design:</u> Low seismic design

<u>Energy efficiency:</u> Low energy efficiency

<u>Particular building characteristic:</u> Year of construction < 1970

Possible retrofitting scenarios:

<u>Seismic retrofitting:</u> Strong seismic strengthening

<u>Energy retrofitting:</u> Strong energy strengthening

<u>Combined seismic plus energy retrofitting:</u> Concurrent strategies should be prioritized

<u>Possible techniques:</u>
- System of facade refurbishment with cement panels sheathing
- Textile-reinforced mortar solutions integrating energy insulation material
- Timber-based panels in the buildings envelope
- Total replacement of windows and doors
- Floor insulation systems
- External insulation of flat roofs
- Internal insulation of roofs
- RC, steel and FRP Jacketing of columns and beam-column joints
- RC shear walls
- Steel braces
- Retrofitting of masonry infill walls in the buildings envelope
- Engineered exoskeletons
- External thermal insulation composite system

Examples of EU cities/regions:

<u>Italy:</u> Veneto

Figure 16. Retrofitting scenario 6: SCZ_I and RC_LSD_LEE.

Butenweg (2021) performed a simplified identification of areas with both kinds of exposure, i.e., seismicity (i.e., hazard) and climate conditions. The author proposed a study for the combined retrofitting of the following cities: Pleven (moderate seismic hazard), Sofia (moderate seismic hazard), Plovdiv (high seismic hazard) and Blagovgrad (high seismic hazard); Zadar (low seismic hazard), Osijek (low seismic hazard), Split (moderate seismic hazard), Primorje-Gorski-kotar (moderate seismic hazard), Dubrovnik (high seismic hazard) and Zagreb (high seismic hazard); Munich (low seismic hazard), Lindau (low seismic hazard) and Aachen (moderate seismic hazard); Andros (moderate seismic hazard), Kosani (low seismic hazard) and Dykiti Makedonia (low seismic hazard); Athens (medium/high seismic hazard) and Thessaloniki (medium/high seismic hazard); Sassari, Bari, Como, Verbano-Cusio-Ossola and Aosta (low seismic hazard), Salerno, Pisa, Vicenza and Bolzano (moderate seismic hazard) and Naples, Perugia, Bergamo and Trento (high seismic hazard); Cluj and Bistrita (low seismic hazard), Satu Mare and Hargita (moderate seismic hazard), and Buchurest, Vrancea and Covasna (high seismic hazard).

Butenweg (2021) pointed out that the area-related approach with the score is only a helpful indicator of prioritising countries and regions for combined actions. However, that does not mean that combined measures in countries with low to moderate seismicity are not required. Combined upgrading is also relevant for countries with lower scores, as a high percentage of buildings were built without sufficient seismic safety measures. Especially in countries with low to moderate seismicity, seismic design rules were often ignored and seismic codes were introduced during the 1990s.

5. Final Observations and Future Works

This research work provides a set of retrofitting scenarios for the EU based on the characteristics of the EU building stock and EU seismic and climate features. The proposed scenarios were defined based on a simplified approach, i.e., based on climate and seismic risk indicators. Apart from the climate and seismic risk inputs, the definition of priority regions for the combined seismic plus energy retrofitting should also be performed based on each country's energy consumption and energy poverty. The proposed scenarios help define priority regions for seismic, energy, or combined seismic plus energy retrofitting in the EU. A different set of building typologies are suggested for further study based on their seismic design and energy efficiency. Therefore, their characteristics must be adapted according to the typical characteristics of buildings in each country (i.e., architecture, structure, materials).

Other authors suggest that the impact of the existing building stock in Europe in terms of economic losses and emissions due to climate exposure needs to be addressed. The average annual costs due to heating/cooling buildings for the buildings in the exposure model could be estimated based on combining the heating/cooling degree days with models of heating/cooling costs for different building classes. The average annual CO_2 emissions due to heating/cooling of different building classes would also need to be estimated. Based on this information, it will be possible to obtain average annual economic losses due to energy consumption and/or CO_2 emissions. Therefore, this new evaluation will be merged with the average annual economic losses due to seismic exposure towards a new EU map. Efforts should be made to identify the most critical scenarios requiring intervention due to high seismic losses (economic and loss of life), energy costs, and CO_2 emissions. These new maps should be constructed across the NUTS3 regions in Europe.

As future works, a parametric study is suggested to evaluate the impact of the retrofitting measures suggested for each seismic–climate scenario. The effect of those retrofitting measures should be compared to the existing conditions of the building stock.

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Abbreviations

AAELR	Average Annual Economic Losses Ratio
AAL	Average Annual Losses
AALL	Average Annual Life Loss
AALR	Average Annual Loss Ratio
BREEAM	Building Research Establishment Environmental Assessment Method
CDD	Cooling Degree Days
CI	Climate Indicator
CO_2	Carbon Dioxide
DGNB	German Sustainable Building Council
EU	European Union
HDD	Heating Degree Days
HEE	High Energy Efficiency
HSD	High Seismic Design
IRC	Infilled Reinforced Concrete
LC	Life Cycle
LEE	Low Energy Efficiency
LSD	Low Seismic Design
M	Masonry
MEE	Moderate Energy Efficiency
MIW	Masonry Infill Walls
MSD	Moderate Seismic Design
NS	Non-structural elements
OOP	Out-of-Plane
RC	Reinforced Concrete
SCZ	Seismic Climate Zone
SP	Primary members
SS	Secondary members
TRM	Textile-Reinforced Mortar
U-value	Thermal transmittance

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