ISSN 1831-9424

European Commission

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

Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context

Romano, E • Negro, P (editors)

Romano, E • Negro, P • Santarsiero, G • Masi, A • Butenweg, C

2023

Joint Research Centre

EUR 31561 EN

Contact information
Email: JRC-REEBUILD@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC130997

EUR 31561 EN

Print	ISBN 978-92-68-04610-4	ISSN 1018-5593	doi:10.2760/28953	KJ-NA-31-561-EN-C
PDF	ISBN 978-92-68-04611-1	ISSN 1831-9424	doi:10.2760/30640	KJ-NA-31-561-EN-N

Luxembourg: Publications Office of the European Union, 2023

How to cite this report: Romano, E., Negro, P., Santarsiero, G., Masi, A. and Butenweg, C., *Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context - REEBUILD: Integrated techniques for the seismic strengthening and energy efficiency of existing buildings,* edited by E. Romano and P. Negro, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/30640, JRC130997.

REEBUILD

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

Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context

Editors:

Elvira Romano, Joint Research Centre, European Commission
Paolo Negro, Joint Research Centre, European Commission

Authors:

Elvira Romano, Joint Research Centre, European Commission
Paolo Negro, Joint Research Centre, European Commission
Giuseppe Santarsiero, University of Basilicata
Angelo Masi, University of Basilicata
Christoph Butenweg, SDA Engineering

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Foreword

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

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

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

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

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

In a policy context, REEBUILD provides scientific advice to support the development of an action plan, which shall supplement existing European Union policies and initiatives in the field of buildings' renovation. Crucially, the European Green Deal (COM (2019)640) emphasises the need for a Renovation Wave (COM (2020)662), supported by the New European Bauhaus ([1]) (COM (2021)573) to create sustainable, inclusive and beautiful living spaces. The plans to put the European Green Deal into effect further contribute to the economic recovery following the COVID-19 pandemic. In the Energy Performance of Buildings Directive (EPBD) (Directive 2018/844) and the recent proposal for its revision (Proposal COM 2021/802), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM (2020)98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (Commission SWD 2016/205) encourages investment in disaster risk reduction, integrating "Build Back Better" principles for a more resilient built environment. The European Framework for Action on Cultural Heritage (Commission SWD 2018/491), emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development ([2]) (UN, 2015/A/Res/70/1) and the Sustainable Development Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

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

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

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

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

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

This report deals with the main outcomes carried out within Action 1 concerning the simplified prioritisation of the EU existing buildings needing combined seismic and energy retrofit, along with a focus on the Italian context due to the huge variability of its building stock.

Acknowledgements

The Pilot Project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" or REEBUILD is financed by the European Union under the Commission Decision C(2019) 3874 final of 28 May 2019.

Editors

Elvira Romano

Paolo Negro

Authors

Elvira Romano

Paolo Negro

Giuseppe Santarsiero

Angelo Masi

Christoph Butenweg

Abstract

The urgent need to speed up the renovation of the European built environment, making it more energy-efficient and less carbon intensive over its entire life cycle, is a key-priority in the EU to mark a turning-point towards the green transition by 2050. Furthermore, the existing building stock in the EU seismic prone regions is also affected by seismic vulnerability leading to significant social and economic impacts due to the extensive damage or collapse of buildings in case of seismic events, as demonstrated by past and more recent earthquakes (e.g. 1999 Athens, 2009 L'Aquila, 2012 Emilia Romagna, 2016 Central Italy). Hence, the effort to consider an integrated approach for making existing buildings simultaneously safe and sustainable is of paramount importance. In this framework, the pilot project '*Integrated techniques for the seismic strengthening and energy efficiency of existing buildings*' or REEBUILD aims to define retrofit solutions able to achieve the reduction of seismic vulnerability and the increase of energy efficiency of the EU existing building stock, at the same time and in the least invasive way. This holistic approach consequently leads to significant environmental benefits by reducing the carbon dioxide (CO_2) emissions and the waste generated by means of building replacement actions, as well as minimises economic losses and fatalities due to future earthquake disasters, supporting several EU policies related to the sustainable renovation of buildings.

This technical report presents part of the study carried out within the Action 1 '*Overview and classification of technologies for seismic strengthening and energy upgrading of existing buildings*' of REEBUILD, addressing a simplified analysis for the prioritisation of the EU existing building typologies needing combined seismic and energy retrofit. This investigation serves as crucial basis to foster a wide modernisation of the EU existing building stock by facilitating the selection of suitable integrated renovation strategies. In fact, the huge number and diversity of the EU building typologies typically make the possibility of a rapid renovation for a large fraction of existing buildings complex. Hence, the first part of the report focuses on an overview of the main characteristics of the EU residential building stock, focusing on its age, building type, and size. These investigations are combined with the mapping of the EU in seismic hazard zones and climatic zones to define a framework identifying the building typologies requiring seismic strengthening and reduction of energy inefficiency in indicative regions. Specifically, the selection of EU priority Member States is first carried out to subsequently identify specific regions in these countries based on different combinations of seismic hazard and climatic conditions. A correlation among the age of the residential building stock in each region, the period of implementation of seismic codes and energy regulations, and the construction material of the buildings is presented to provide a simplified portrait of EU residential buildings most needing seismic and energy retrofit. The second part of the report presents a focus on the Italian context to analyse the prioritisation of the existing residential building typologies in this country, due to the huge variability of its building stock in terms of construction technologies. The evolution of seismic design code and seismic zonation, as well as the development of energy efficiency regulations in Italy is first summarised to provide general remarks on the seismic vulnerability and energy inefficiency of the Italian existing buildings. Following this synopsis, the Italian masonry and reinforced concrete (RC) residential building typologies most needing combined seismic and energy retrofit are presented.

1 Introduction

The European building stock, considering both residential and non-residential segments, accounts for 25 billion square meters of built-up area (BPIE, 2011), of which 20 billion erected before 1990, thus representing an ageing built environment compliant neither with the recent energy efficiency regulations, nor with modern seismic design code requirements.

This figure indicates the urgent need to focus on two main aspects related to the construction sector, i.e. sustainability and safety, also considering the huge burdens buildings produce on environment, along with potential detrimental impacts on economy and society when safety requirements are not fulfilled. The building sector is one of the key-consumers of energy in Europe, showing a consequent unsatisfactory trend also in terms of greenhouse gas (GHG) emissions. Indeed, buildings are responsible for 40 % of the EU energy consumption and 36 % of the EU total CO_2 emissions (COM (2020)662), exerting a significant ecological pressure. In particular, the highest amount of energy use in a building refers to the operational stage of its life cycle, consequently becoming a huge source of carbon emissions mainly for heating and cooling, and electricity demands. Thus, outdated buildings with their inefficient energy consumption considerably contribute to the detrimental impacts of the climate change. It is evident that old and more obsolete buildings, resulting the vast majority of the EU existing building stock, represent one of the largest unrealised potential for cost-effective energy and emissions savings. The achievement of an energy-efficient built environment by boosting renovation solutions for obsolete and ageing buildings is a high-priority issue for Europe, as it represents not only an effective key to meet the EU ambitious energy and climate targets, but it can also generate economic and social benefits, fulfilling the sustainable development principles. Nevertheless, the annual energy renovation rate of the EU building stock is still very low, being equal to only 1%. Thus, the European Commission has recently emphasised the need for a large-scale upgrading of the EU existing building stock in line with the Renovation Wave strategy (COM (2020)662), in order to ensure that the building sector effectively plays its fundamental role in both reducing the GHG emissions by at least 55% below 1990 levels by 2030 and achieving the overarching goal of climate-neutrality by 2050, set off by the first European Climate Law (Regulation (EU) 2021/1119). The recent proposal for the revision of the Energy Performance of Building Directive (EPBD) (Proposal COM 2021/802) also supports these objectives, updating the existing regulatory framework to reflect higher ambitions and more pressing needs in climate and social action through the increase of the rate of energy renovation of the EU existing building stock to make it more resilient and accessible.

However, any action aimed at achieving exclusively the optimization of the energy performance of existing buildings without simultaneously addressing structural safety could be a business dead-end, mainly in seismic prone regions. In case of an earthquake, the damage due to an inadequate seismic performance of buildings may possess considerably high economic, environmental, and social impacts, as demonstrated in recent earthquakes, also leading to a high likelihood of the loss of energy retrofit intervention, if any. Emblematic examples in this direction refer to the aftermath of the 2012 Emilia earthquake (in Italy) showing various damaged buildings characterised by broken new high-performance windows and solar panels, as well as wrecked thermal insulation elements clustered on top of their ruins (Marini et al., 2014).

These concerns underline that an integrated renovation of the EU existing building stock is a crucial goal to make cities safe and sustainable and to increase the competitiveness of construction sector, also supported by the the New European Bauhaus initiative (COM(2021)573) to create sustainable, beautiful and inclusive living spaces, in line with the European Green Deal priority (COM(2019)640). Indeed, building sector is a low-replacement industry and 85-95% of the current building stock will still be in use in 2050. Hence, in the last decade, the importance of promoting integrated approaches for design/retrofit of buildings has been recognised by the scientific community, drawing particular attention to multi-performance, Life Cycle Thinking (LCT)-based methodologies (e.g. Lamperti Tornaghi et al., 2018, Pohoryles et al. 2020, Romano et al., 2020, Passoni et al., 2021, Caruso et al., 2021, Menna et al., 2022, Passoni et al., 2022, among others).

In the above context, the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life-cycle perspective. A crucial initial step to carry out an effective integrated renovation of the EU existing building stock deals with the identification of building typologies most needing combined seismic and energy retrofit. Indeed, buildings in Europe vary remarkably in terms of their function, typology, and main architectural, and technological features. Accordingly, the requalification needs of existing buildings can be very different depending on the age of construction, the location, the structural typology and the material characteristics (Marini et al., 2014).

This report aims to provide a portrait of the EU building stock to identify the potential buildings most needing seismic and energy upgrading, as basis to proceed with the selection of effective retrofit technologies. Following this introduction, Section 2 first investigates the EU residential building stock to provide an overview of its main characteristics in terms of age, building type, size, and construction material. Subsequently, the EU territory is mapped in seismic hazard zones and climatic zones. Based on these results, a simplified analysis for the prioritisation of the EU residential buildings most requiring seismic strengthening and improvement of energy efficiency is presented by concentrating on selected EU Member States characterised by severe seismic-climatic scenarios. Section 3 presents a focus on the prioritisation of the Italian building typologies most needing combined seismic and energy retrofit, separately analysing masonry and RC residential building stocks, due to their huge region-by-region variability in terms of construction technologies. Final remarks and conclusions are summarised in Section 4, also providing potential future developments for the definition of a comprehensive inventory of the existing building typologies, mainly referring to the Italian context.

2 The EU existing building stock

The EU existing building stock accounts for 25 billion square meters of floor area, of which 75% is composed by residential buildings and 25% by non-residential ones. The residential building segment includes different types of single family houses (SFH) (e.g. detached, semi-detached, and terraced houses) and multi-family houses (MFH), corresponding to apartment blocks, accommodating several households from 2 to 15 units or in some case more than 20-30 units (e.g. social housing or high rise residential buildings). The non-residential building segment comprises a more complex and heterogeneous sector compared to the residential one. The retail and wholesale buildings consists of the largest portion of the non-residential building stock, while office buildings are the second biggest category with a floor area corresponding to one quarter of the total non-residential floor space (BPIE, 2011). Based on this general analysis, hereinafter the investigation on the main characteristics of the European building stock will focus on dwellings/residential buildings.

2.1 Overview of the main characteristics of the EU existing residential building stock

Generally, the construction period, the geometric dimensions (e.g. number of storeys, floor area, etc.), and the main structural system or construction material (e.g. RC, masonry, steel, etc.) are key parameters for the assessment of both the energy and the seismic performances of existing buildings. Hence, the collection and analysis of statistics related to the European dwellings or residential buildings, retrieved by different sources depending on data availability, refer to the following aspects:

- **Age** - The analysis refers to the EU distribution of the number of dwellings **by year of construction.** It was carried out according to the statistical data retrieved from the 2011 Population and Housing Census of the European Statistical System (ESS) by means of the Census Hub web-channel ([3]).

- **Building types** - The analysis is related to the EU distribution of the number of dwellings by **residential building types** in terms of (i) one-dwelling buildings, which is indicative of SFHs, (ii) two-dwelling buildings, and (iii) three or more dwelling buildings, representing MFHs. The investigation was carried out according to statistical data retrieved from the 2011 Population and Housing Census of the ESS by means of the Census Hub web-channel.

- **Size** – The analysis concerns the EU distribution of number of dwellings based on the **useful floor area** ([4]). It was carried out according to statistical data retrieved from the 2011 Population and Housing Census of the ESS by means of the Census Hub web-channel. Furthermore, the investigation on the average floor area per dwelling of SFHs and MFHs in the EU Member States is carried out according to the data retrieved by the dedicated tool developed within the 2012-2014 'Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings (nZEB) in Europe' (ENTRANZE) project. This project supports policy making by providing the required data, analysis and guidelines to achieve a fast and strong penetration of nZEB within the existing national building stocks. Specifically, the ENTRANZE tool contains an in-depth description of the characteristics of buildings (e.g. thermal quality, size, age, type, ownership structure) and related energy systems in the former EU-28 and Serbia. Data on size were considered for the scope of this analysis.

- **Construction material** - The EU distribution of the number of dwellings/residential buildings by main construction material is analysed. National statistical institutes providing these data are limited to few EU Member States, i.e. Bulgaria, Italy, Greece, Portugal, and Romania. In order to overcome this issue, the 2010-2014 'Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation' (NERA) project was considered. The latter aimed to achieve an improvement and a long-term impact in the assessment and reduction of vulnerability of constructions and citizens to earthquakes. Among its various results, the outcomes related to the European Building Inventory Database were considered for the scope of this analysis.

Specific results related to the above-mentioned four main aspects are presented in the following.

2.1.1 Dwellings in Europe by year of construction

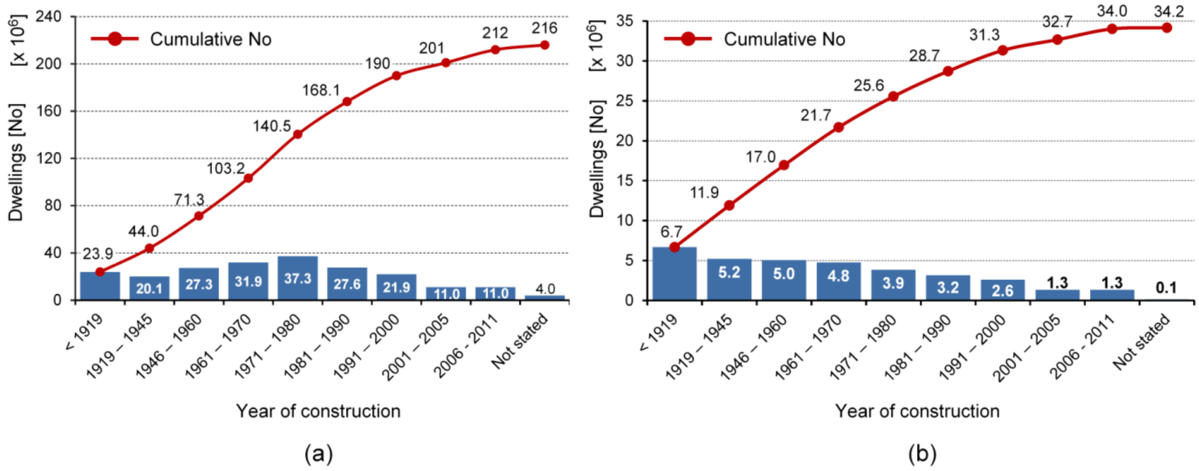
The age of a building represents an essential indicator in the light of its renovation. Indeed, different construction technologies are associated with different years of construction, becoming essential data for the assessment of the structural/seismic and energy performances of existing buildings. Furthermore, the year of

([3]) European Statistical System (ESS) - Census Hub, https://ec.europa.eu/CensusHub2.
([4]) Useful floor space (or useful floor area) indicates the dwelling floor area measured inside the external walls.

construction becomes also an indicator of the share of existing buildings, which have exhausted their design service life, equal to 50 years for ordinary buildings, and require technical assessment.

The statistics of the number of dwellings in both residential and non-residential buildings by year of construction for the period pre-1919 - 2011 in Europe (i.e. 27 EU Member States (EU-27), along with Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) are reported in Annex 1-Table 1, according to data retrieved by the 2011 Population and Housing Census of the ESS. The analysis of these figures points out that the total share of dwellings in Europe results equal to more than 250 million, of which more than 216 million are distributed in the EU-27, whereas the remaining 34 million are concentrated in the other investigated European countries (i.e. Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) (Figure 1).

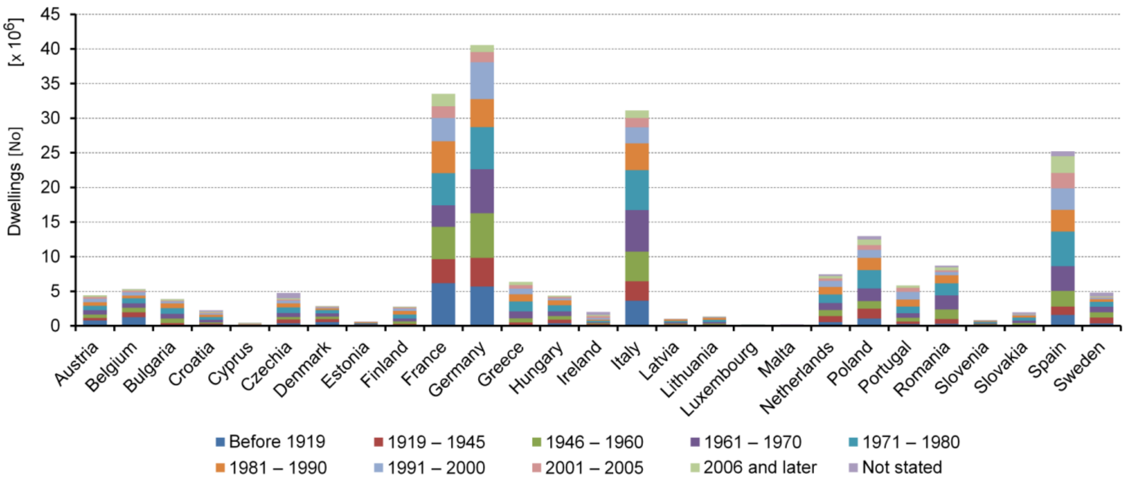
Figure 1. Distribution of number of dwellings in residential and non-residential buildings by year of construction (pre-1919-2011) in (a) EU-27, and (b) Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom.



Source: Data - ESS, EU Population and Housing Census, 2011

A focus on the distribution of the number of dwellings in both residential and non-residential buildings by year of construction, solely referring to the EU-27, is depicted in Figure 2, based on the 2011 Population and Housing Census data of the ESS (Annex 1-Table 1).

Figure 2. Distribution of number of dwellings in residential and non-residential buildings by year of construction (pre-1919-2011) in each of the EU-27

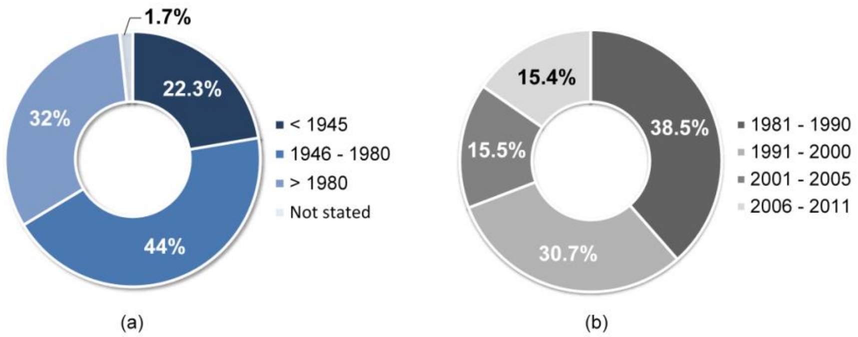


Source: Data - ESS, EU Population and Housing Census, 2011.

The majority of the EU Member States accounts for a total number of dwellings below 5 million, whereas some countries such as Cyprus, Estonia, Luxembourg, Malta, and Slovenia exhibit a total distribution equal to less than 1 million. Germany, France, Italy, and Spain represent the top EU countries, since they account for the highest number of dwellings varying into the range 25-40 million. It is worth noting that in all EU-27 the highest share of EU dwellings was built between 1946 and 1980.

The data analysis on the age of dwellings in Europe (i.e. EU-27, along with Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) may be facilitated by grouping the dwellings distribution by three main construction periods, namely (i) before 1945, (ii) 1946-1980, and (iii) after 1980. Figure 3a depicts the percentage of the total number of dwellings in Europe for each of the three periods above. The highest share, accounting for 44 % of the total number of dwellings in Europe, refers to the period 1946-1980. This figure demonstrates that the majority of the European dwellings are ageing since they were built between more than 60 and 40 years ago, thus they have already exhausted their design service life (i.e. 50 years) or are approaching to its end. This share is followed by the segments of dwellings built after 1980 and before 1945, equal to about 32 % and 22 %, respectively, of the total number of dwellings in Europe. A focus on the distribution of dwellings built within the three decades referring to the period 1980-2011 has been carried out to identify the highest percentage of dwellings built after 1980 (Figure 3b). Results shows that the first decade (i.e. 1980-1990) was characterised by the highest share, accounting for 38 % of the total number of dwellings erected between 1980-2011. The sum of the percentages of dwellings built into the periods pre-1945, 1945-1980, and 1980-1990, i.e. 22 %, 44 %, and 12 %, respectively (compared to the total number of dwellings built in Europe in the period before 1919-2011), demonstrates that nearly 79 % of European dwellings was built before 1990, thus they are compliant neither with modern energy efficiency provisions (Bournas, 2018), nor with modern seismic design requirements (Crowley et al., 2021).

Figure 3. Percentage distribution of dwellings in residential and non-residential buildings in Europe (a) grouped into three periods of construction, and (b) between 1980 - 2011



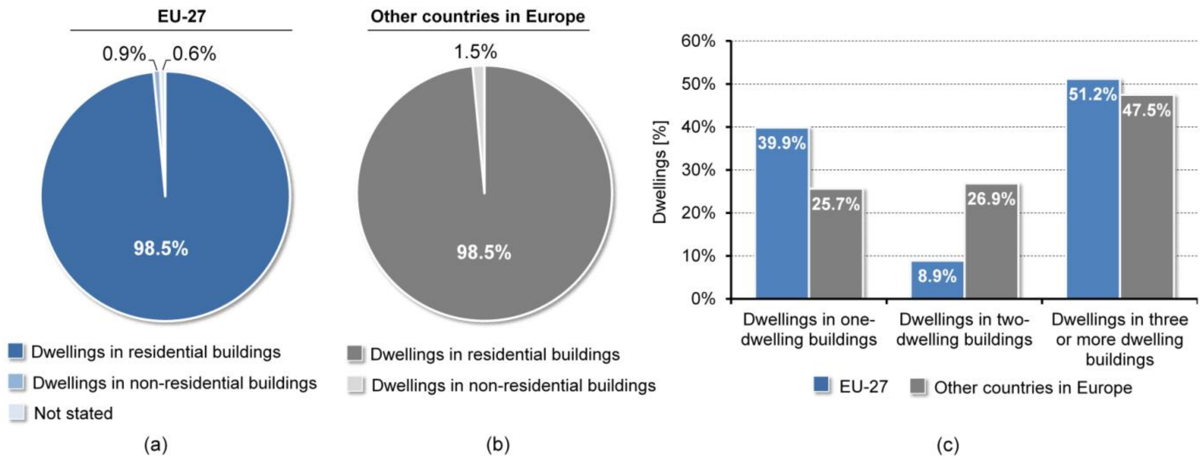
Source: Data - ESS, EU Population and Housing Census, 2011.

2.1.2 Dwellings in Europe by building type

The investigation on building type is fundamental to draw an accurate portrait of the EU building stock. Indeed, the type of dwelling in terms of SFH or MFH has a significant impact on the energy performance for space heating and cooling, since different insulation characteristics imply specific space heating and cooling consumption influenced by different building envelope components depending on the building type.

In general, the SFH stock in Europe accounts for the highest percentage of floor area of residential buildings equal to 64 %, whereas the share of the apartment blocks is equal to 36 % (BPIE, 2011). In order to provide a more detailed analysis, the statistics related to the number of dwellings located in residential buildings by building type, namely one-dwelling buildings (i.e. SFH), two-dwelling buildings, and three or more dwelling buildings (i.e. MFH) in Europe (i.e. EU-27, along with Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) are reported in Annex 1-Table 2, according to data retrieved from the 2011 Population and Housing Census of the ESS. Data on the number of dwellings in non-residential buildings are also included in Annex 1-Table 2. The analysis of these figures shows that nearly the total segment of dwellings in Europe is located in residential buildings, accounting for 98.5 % in the EU-27 (Figure 4a). The same percentage is inferred in the other investigated European countries (i.e. Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) (Figure 4b). Focusing on residential buildings, Figure 4c shows that the number of dwellings in three- or more-dwelling buildings results the highest share in both EU-27 and the other investigated countries in Europe. In the EU-27 this segment is followed by the shares of dwellings in one-dwelling buildings (i.e. nearly 40 %) and two-dwelling buildings, although the latter accounts for a very low percentage equal to nearly 9 %. A contrary portrait is inferred for the other investigated countries in Europe, exhibiting nearly equal shares of dwellings in one- and two-dwelling buildings with a slightly higher percentage related to the two-dwelling buildings equal to nearly 27 %.

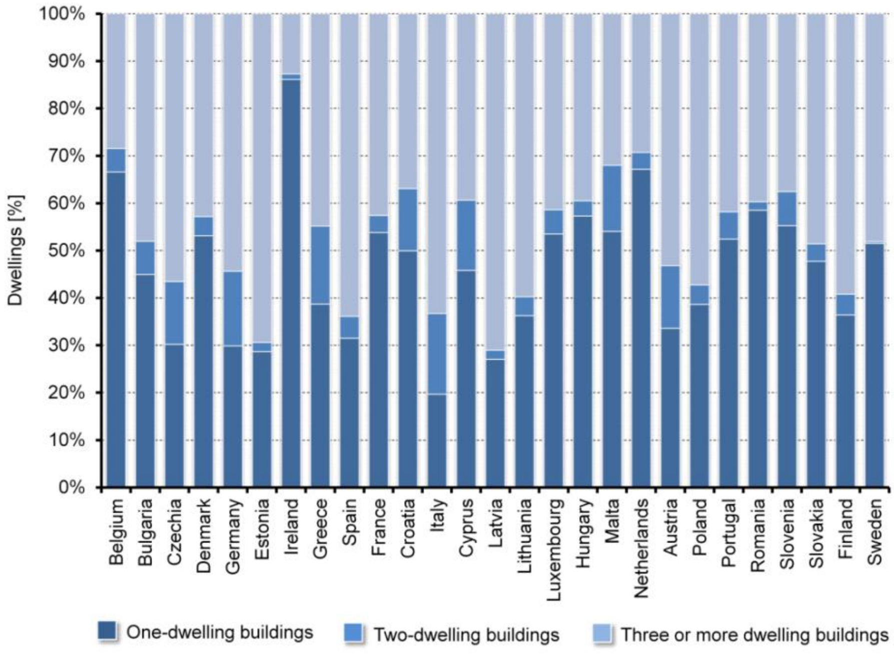
Figure 4. Dwellings in residential and non-residential buildings in (a) EU-27, and (b) Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom with (c) a zoom on the dwelling shares in residential buildings by building type.



Source: Data - ESS, EU Population and Housing Census, 2011

A focus on the distribution of dwellings by building type in each of the EU-27 is depicted in Figure 5.

Figure 5. Percentage distribution of dwellings in residential buildings by building type in EU-27



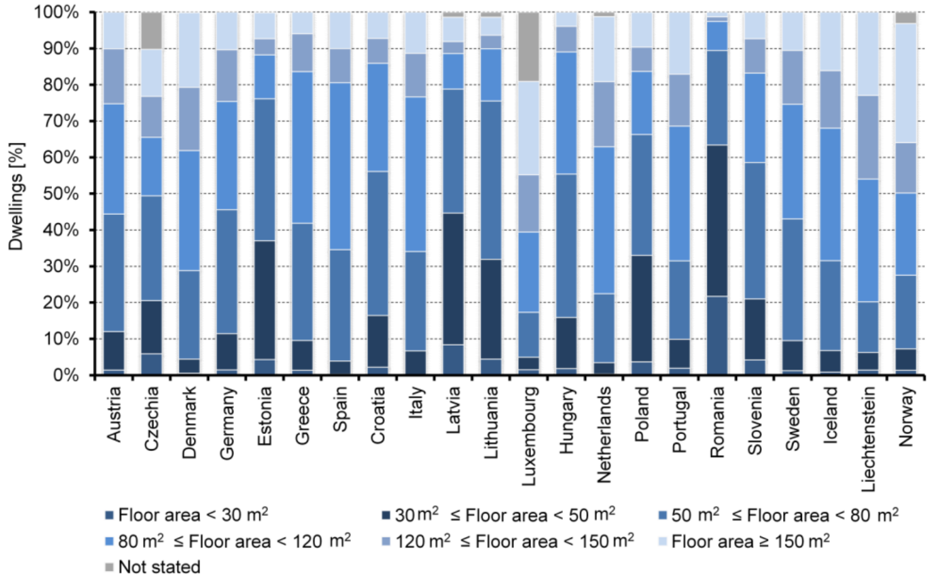
Source: Data - ESS, EU Population and Housing Census, 2011

Ireland results the country with the highest percentage of dwellings located in one-dwelling buildings (i.e. more than 80 %), followed by Belgium and the Netherlands (i.e. more than 60 %). Various countries account for more than 50 % of their dwellings located in one-dwelling buildings, e.g. Denmark, France, Luxembourg, Malta. Italy represents the country with the less number of dwellings in one-dwelling buildings (i.e. 20 %), counterbalanced by the highest number of dwellings located in three- or more-dwelling buildings (i.e. slightly more than 70 %). Generally, the countries exhibiting low percentages of dwellings in one-dwelling buildings equal to about 30 % are characterised by a high percentage of dwellings in three- or more-dwelling buildings resulting into the range 60-70 %, such as Estonia, Spain, and Latvia. Dwellings in two-dwelling buildings account for the lowest share in all the EU countries, reaching more than 10 % solely in few Member States, such as Czechia, Germany, Greece, Croatia, and Italy.

2.1.3 Dwellings in Europe by floor-area

The size of the total European dwelling stock is measured in useful floor area per dwelling (m^2/dwelling). The statistics of the number of dwellings by useful floor area in Europe (i.e. EU-27, along with Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) are reported in Annex 1-Table 3, according to data retrieved from the 2011 Population and Housing Census of the ESS. The distribution of dwellings by useful floor area for some EU Member States (data are not available for all the EU-27) is depicted in Figure 6, also including results for Iceland, Liechtenstein, and Norway. The highest share of dwellings in the majority of the investigated EU Member States accounts for a useful floor area resulting into the range 50-120 m^2. However, it is worth noting that a few EU Member States (i.e. Estonia, Latvia, Lithuania, Poland and Romania) are characterised by a relevant percentage (i.e. 30–40%) of dwellings accounting for a useful floor area equal to 30-49 m^2, thus the highest share of dwellings in these countries accounts for a useful floor area resulting into the range 30-80 m^2.

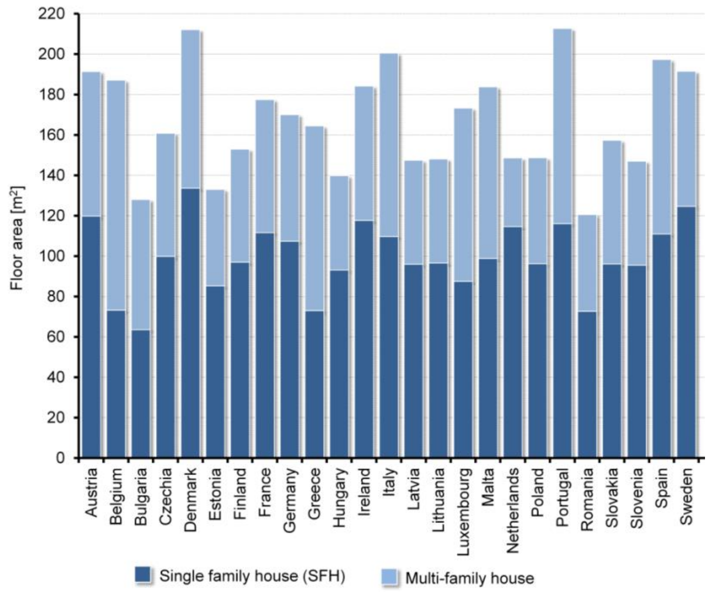
Figure 6. Percentage distribution of dwellings by useful floor area in Europe



Source: Data - ESS, EU Population and Housing Census, 2011

Furthermore, the 2008 data on the average floor area of SFHs and MFHs in each EU Member States, except for Cyprus and Croatia (data are not available), are retrieved from the ENTRAZE tool. Figure 7 shows that SFHs account for a higher average floor area per dwelling than MFHs in the majority of Member States. Indeed, Belgium and Greece are the only countries with an average floor area per dwelling of MFHs higher than the one of the SFHs. The mean value of the average floor area per dwelling for SFHs and MFHs (considering all the investigated EU countries) is equal to 100 m^2 and 68 m^2, respectively. As for the results related to SFHs, Denmark exhibits the highest value of average floor area per dwelling, i.e. 134 m^2 and Bulgaria the lowest one, i.e. 64m^2. As for the MFHs, instead, Belgium and Hungary represent the countries with the highest, i.e. 114 m^2 and the lowest, i.e. 47 m^2, value of average floor area per dwelling, respectively.

Figure 7. Average floor area of SFH and MFH dwelling in EU-27 (except Cyprus and Croatia – not available data)

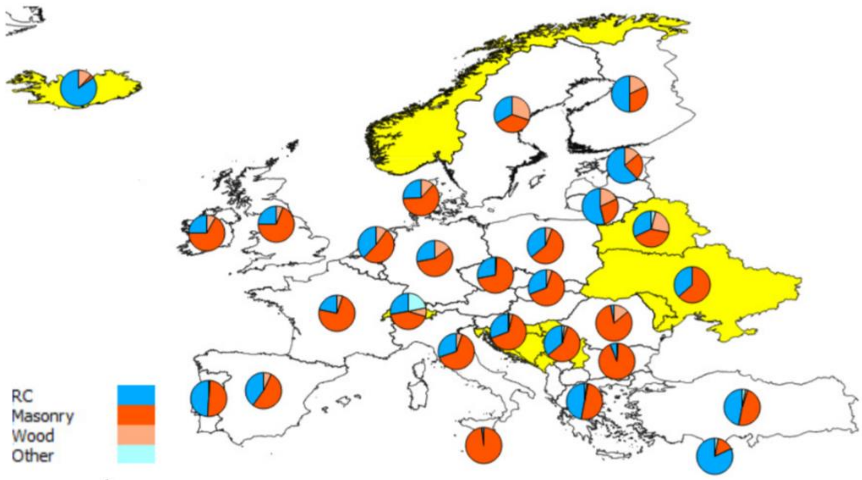


Source: Data – ENTRANZE tool, 2008

2.1.4 Residential buildings and dwellings in Europe by construction material

The distribution of the European buildings/dwellings by construction material refers to the analysis carried out in NERA project to achieve one of its outcomes and it is interpreted in form of the Europe's map (Ozcebe et al., 2014), depicted in Figure 8. The majority of the EU-27 accounts for masonry buildings, although some countries, such as Portugal, Cyprus, and Greece, exhibit higher proportions of RC constructions. However, the shares of RC buildings/dwellings identified in the other countries cannot be neglected. Fractions of masonry and RC buildings are followed by shares of timber buildings/dwellings concentrated only in few countries, such as Sweden, Finland, Germany, and Romania.

Figure 8. Fractions of buildings or dwellings by construction material in Europe (countries in yellow refer to dwellings)



Source: ©Ozcebe et al., 2014 (NERA project – D. 7.5)

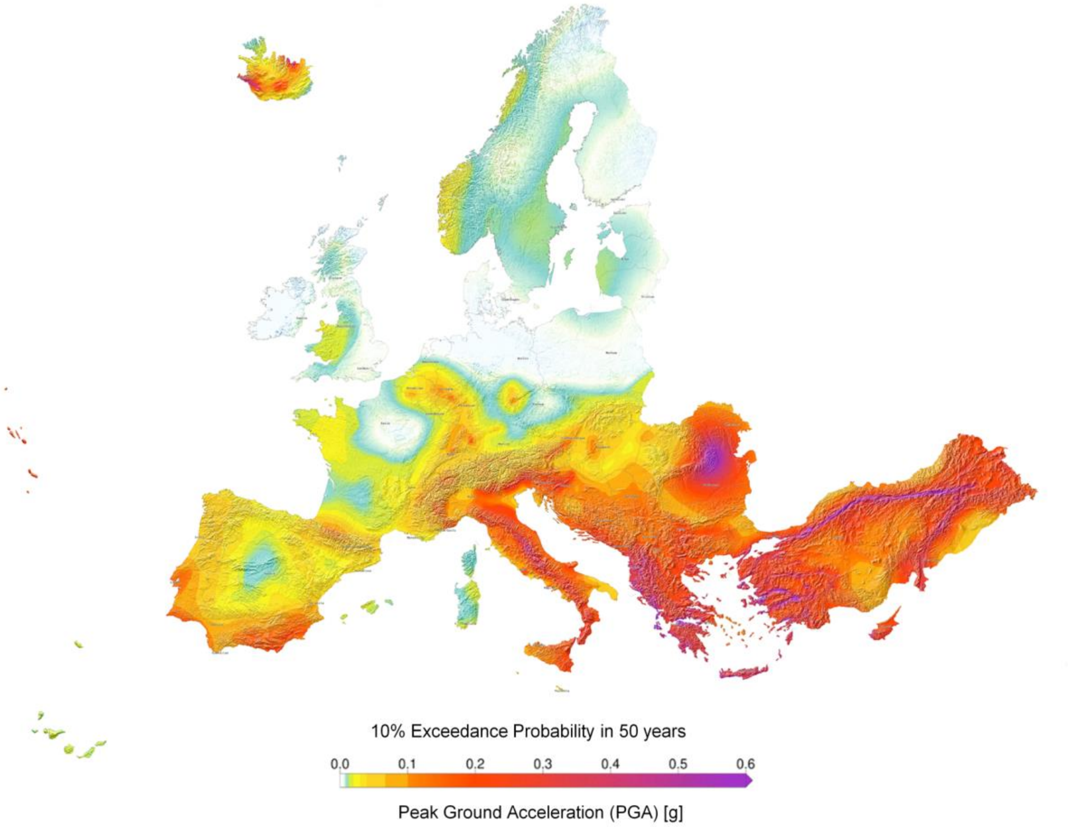
2.2 Mapping EU in seismic hazard and climatic zones

2.2.1 Seismic hazard zones of Europe

Seismic risk is determined by the combination of three main factors, namely (i) hazard, (ii) vulnerability, and (iii) exposure. Specifically, the seismic hazard of a territory is represented by the frequency and the intensity of potential earthquakes occurring in that specific area. Thus, seismic hazard can be defined as the probability of a potential earthquake occurring in a specific geographical area with a ground shaking intensity, expressed as an expected Peak Ground Acceleration (PGA) with an expected probability to be exceeded in an assumed time period.

Focusing on Europe, low, moderate, and high seismic hazard zones can be identified depending on specific PGA ranges corresponding to PGA ≤ 0.1g, 0.1g < PGA < 0.25g, and PGA ≥ 0.25g, respectively, with the 10 % exceedance probability in 50 years (return period of 475 years) on a uniform rock site condition (average seismic shear-wave velocity $V_{S,30}$=800 m/s), according to the 2020 European seismic hazard map (Figure 9). The latter is based on the 2020 update of the European Seismic Hazard Model (ESHM20), recently released (i.e. 16 December 2020) (Danciu et al., 2021). The map illustrates low hazard areas coloured in white, green to yellow (PGA ≤ 0.1g), moderate hazard areas in orange to red (0.1g < PGA < 0.25g), and high hazard areas in dark red to purple (PGA ≥ 0.25g). Turkey, Greece, Albania, Italy, and Romania represent the countries with the highest hazard in Europe, followed by the other Balkan countries. However, high seismic hazard can be also observed in some regions of Austria, France, Germany, Iceland, Portugal, and Spain, among others.

Figure 9. 2020 European Seismic Hazard Map

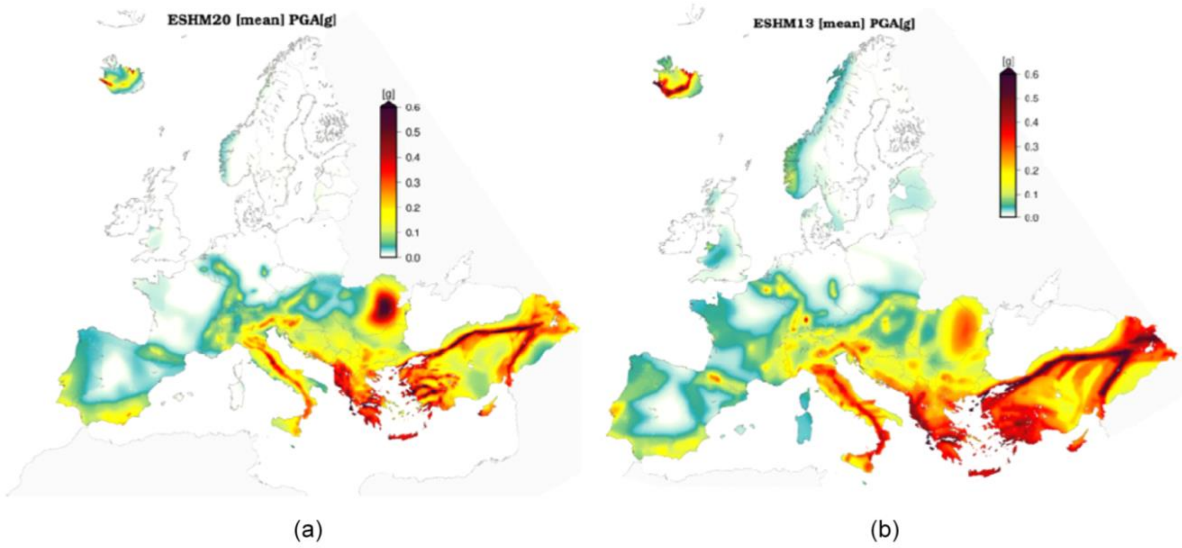


Source: ©Danciu et al., 2021 (CC BY 4.0)

The 2020 ESHM map is an updated version of the 2013 ESHM one, as depicted in Figure 10. Both maps have a similar spatial pattern, although the 2020 map shows lower seismic hazard levels in most of the areas with the highest reduction observed in Iceland. However, some regions in Romania, Albania, Greece, Western Turkey, southern Spain, and southern Portugal exhibit increased seismic hazard levels. The differences between the two maps are likely due to the updated seismogenic sources and new backbone ground motion models. Further details can be found in Danciu et al. (2021).

It is worth noting that specific zonation maps based on seismic hazard for each EU Member State are included in the corresponding National Annexes to Eurocode 8 (CEN, 2004).

Figure 10. Comparison of European hazard maps for (a) ESHM20 and (b) ESHM13)

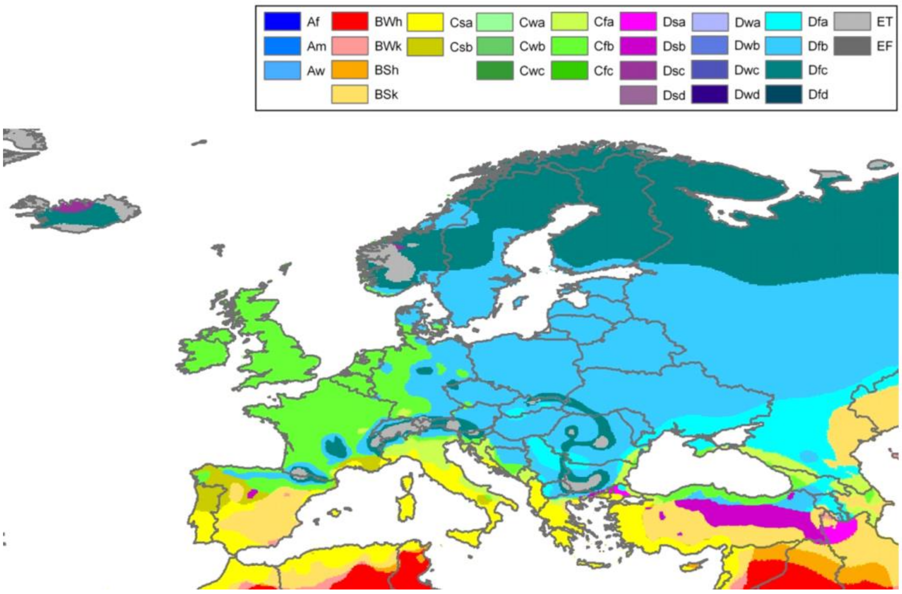


Source: © Danciu et al., 2021 (CC BY 4.0)

2.2.2 Climatic zones of Europe

The most widely used climate classification map refers to the Köppen-Geiger system, originally developed by the meteorologist and climatologist Wladimir Köppen around 1900. The scheme is based on seasonal precipitation and temperature patterns defining five main climatic groups, which are identified by capital letters, denoted as first level letters, as follows: (A) tropical, (B) arid, (C) temperate, (D) continental and (E) polar. These groups are further subdivided into different sub-groups by means of additional second and third level letters designating climatic details of the season characteristics for each broad group (Figure 11); details are provided in Peel et al. (2007). According to the Köppen-Geiger system, Europe consists of four main climatic zones: (i) Csa, (ii) Csb, (iii) Dfb, and (iv) Dfc (Figure 11). Hence, the design/retrofit of buildings in southern European countries has to cope with warm temperature, dry and hot summer; whereas cold temperature, humidity and cool summer have to be considered for the design/retrofit of buildings located in northern European countries.

Figure 11. Europe's map of the Köppen–Geiger climate classification system.



Group	Sub-groups	
1st Level	2nd Level	3rd Level
A (Tropical)	f (Rainforest)	
	m (Monsoon)	
	w (Savannah)	
B (Arid)	W (Desert)	
	S (Steppe)	
		h (Hot)
		k (Cold)
C (Temperate)	s (Dry summer)	
	w (Dry winter)	
	f (No dry season)	
		a (Hot summer)
		b (Warm summer)
		c (Cold summer)
D (Continental)	s (Dry summer)	
	w (Dry winter)	
	f (No dry season)	
		a (Hot winter)
		b (Warm winter
		c (Cold winter)
		d (Very cold winter)
E (Polar)	T (Tundra)	
	F (Frost)	

Source: Peel at al., 2007 (CC BY-NC-SA 2.5) – Addition of the table for letter symbol definition

The Köppen-Geiger climate classification system enables a widely accepted climatic zoning of Europe. However, it results rather generic for the purpose of the energy retrofit of buildings, thus it is essential to integrate it by means of specific criteria aimed at precisely defining the need for energy requirements of existing buildings to effectively improve their energy efficiency. Energy uses that are affected by climate conditions are mainly space heating and space cooling, so the Heating Degree Days (HDD) and the Cooling Degree Days (CDD) parameters become valid tools to identify EU climatic zones. HDD and CDD are weather-based technical indexes derived from outside air temperature measurements on a daily basis and used to estimate the heating and cooling energy demands of buildings, respectively. According to Eurostat, the calculation of HDD relies on a base temperature, defined as the mean daily outside air temperature above which indoor heating is not required. The base temperature is set to a constant value equal to 15°C, thus HDD is calculated according to Equation (1):

$$HDD = \begin{cases} \sum_i (18°C - T_m^i), & for\ T_m^i \leq 15°C \\ 0, & for\ T_m^i > 15°C \end{cases} \tag{1}$$

where:

T_m^i is the mean outside air temperature of day i;

18°C is the constant value set for the indoor temperature.

Similarly, the calculation of CDD relies on a base temperature, defined as the mean daily outside air temperature below which indoor cooling is not required. The base temperature is set to a constant value equal to 24°C, thus CDD is calculated according to Equation (2):

$$CDD = \begin{cases} \sum_i (T_m^i - 21°C), & for\ T_m^i \geq 24°C \\ 0, & for\ T_m^i < 24°C \end{cases} \tag{2}$$

where:

T_m^i is the mean outside air temperature of day i,

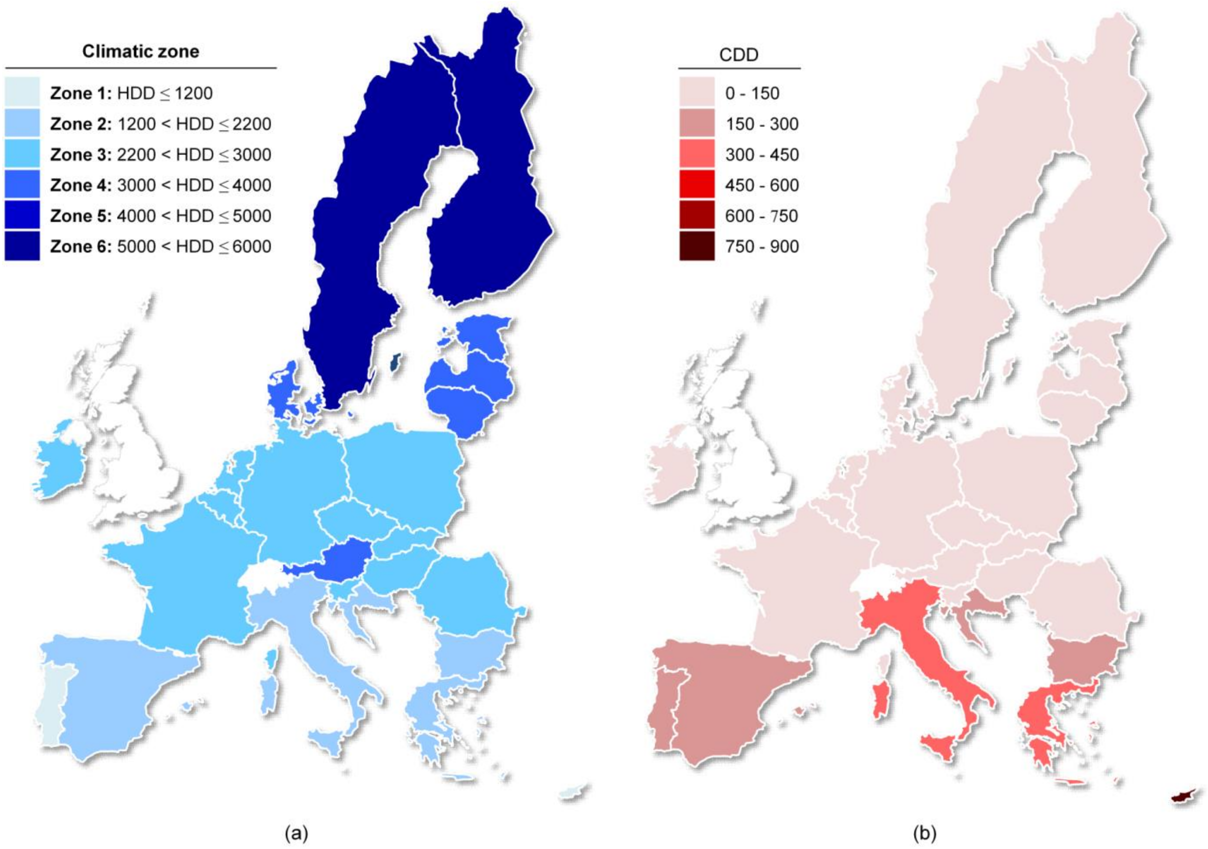
21°C is the constant value set for the indoor temperature.

The HDD and CDD calculated on daily basis are subsequently aggregated to provide monthly and annual data, available in Eurostat at the EU-27 level, as well as at different regional levels within each country according to the Nomenclature of Territorial Units for Statistics (NUTS) classification, i.e. NUTS-2 (basic regions), and NUTS-3 (small regions) levels. Specifically, HDD and CDD statistics over the period 1979-2020 can be retrieved at the different NUTS-levels from Eurostat - Energy statistics.

Attention is paid to the HDD average annual values at Member State level (Eurostat, 2020) in order to map the EU-27 territory in climatic zones, since energy consumption per space heating still results the highest share of energy use in buildings. Indeed, in 2019 space heating in EU residential building stock accounted for 64.5 % of the final energy consumption (Eurostat, 2019). Based on the EU 2019 HDD statistics, six climate zones have been identified as a function of specific HDD ranges (Figure 12a), as also defined in Pohoryles et al. (2020): (i) Zone 1 (HDD ≤1200), (ii) Zone 2 (1200<HDD≤2200), (iii) Zone 3 (2200<HDD≤3000), (iv) Zone 4 (3000<HDD≤ 4000), (v) Zone 5 (3000<HDD≤ 4000), and (vi) Zone 6 (5000<HDD≤ 6000).

For sake of clarity and completeness on the climatic conditions of Europe, the EU-27 map based on the 2019 CDD average annual statistics is also depicted in Figure 12b, although an EU classification in climatic zones based on specific CDD ranges is not considered within this study.

Figure 12. EU-27 map based on: (a) 2019 HDD average annual values according to six climatic zones, and (b) 2019 CDD average annual values



Source: Data - Eurostat., 2020

2.3 Simplified prioritisation of EU buildings needing combined seismic and energy retrofit

A simplified analysis on the prioritisation of the EU residential buildings requiring a combined seismic and energy retrofit is carried out according to a two-step framework (Figure 13), briefly summarised as follows:

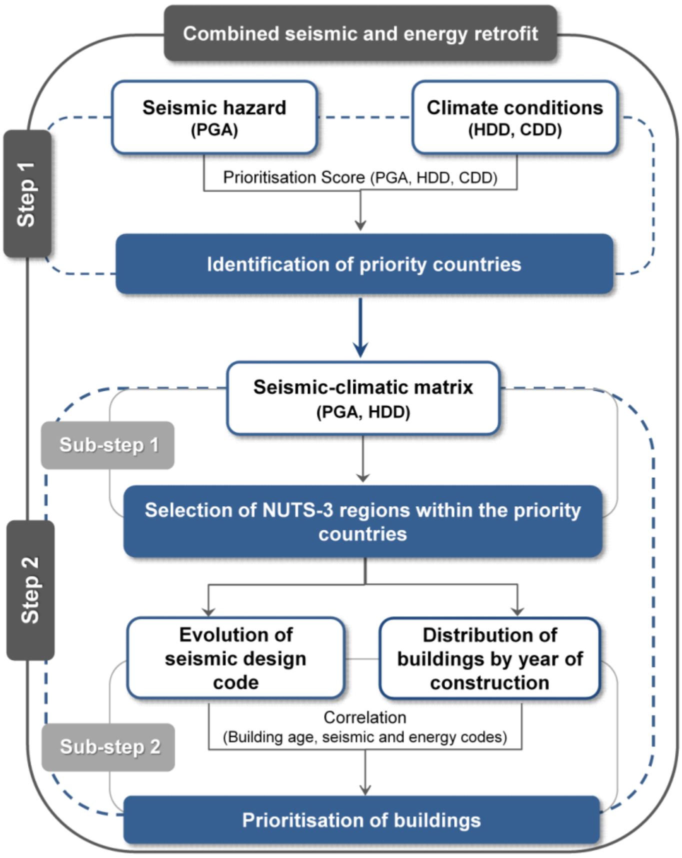
— **Step 1: Priority EU Member States for combined retrofit of buildings** – Step 1 deals with the analysis of the EU-27 in terms of seismic hazard and climatic conditions to identify the priority countries exhibiting the most severe seismic-climatic combination.

— **Step 2: Simplified prioritisation of potential residential buildings needing combined retrofit in the EU priority Member States** – Step 2 deals with two main Sub-steps, as described in the following.

In the *Sub-step 1*, the EU priority countries, selected in Step 1, are further investigated at NUTS-3 level to identify potential regions corresponding to the various possible combinations of seismic hazard and climatic conditions in each country by means of a seismic-climatic matrix based on the three seismic hazard zones and five of the six climatic zones, according to the 2020 ESHM map and the EU climate map in terms of 2019 HDD average annual values, respectively.

In the *Sub-step 2*, the analysis focuses on both the temporal evolution of seismic design code in each selected priority country and the distribution of the number of residential buildings by year of construction in the NUTS-3 regions (identified in Sub-step 1) within each selected priority country, according to the 2011 Census data provided by the corresponding national statistical institutes. The resultant distributions of buildings are superimposed with the year of implementation of both seismic design code and energy regulations in the different countries to identify the number of buildings most needing combined retrofit. Furthermore, indications on the distribution of building typologies in terms of construction material are also considered, based on national statistical data, when available, or on data provided by the NERA project.

Figure 13. Framework for simplified prioritisation of EU buildings needing combined seismic and energy retrofit



The application of Step 1 and Step 2 is described in the following. However, a detailed analysis on regional prioritisation for building renovation, based on seismic risk, energy efficiency, and socioeconomic vulnerability is presented in Gkatzogias et al. (2022).

2.3.1 Step 1: Identification of EU priority countries for combined seismic and energy retrofit

The first step of the proposed framework refers to the identification of the EU priority Member States, where combined seismic and energy retrofit of buildings is most needed. This investigation is carried out according to a score-based approach dealing with the calculation of a Prioritisation Score (PS_i) for each EU Member State i by referring to both its specific seismic hazard in terms of PGA and its climatic conditions in terms of HDD and CDD, according to Equation (3).

$$PS_i = \frac{PGA_i}{Max\ (PGA)} * \frac{HDD_i + CDD_i}{Max\ (HDD + CDD)} * 100 \tag{3}$$

Where:

PGA_i is the maximum reference PGA value on type A ground (i.e. uniform rock site condition) for each EU Member State i, as specified in the corresponding seismic zonation maps included in the National Annexes to Eurocode 8 (CEN, 2004).

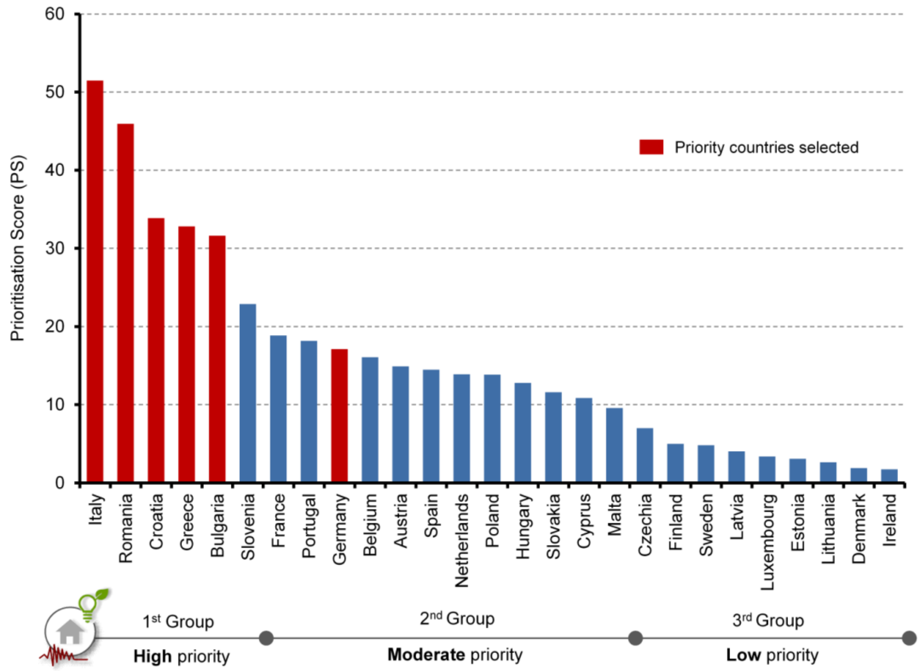
Max (PGA) is assumed equal to 0.5g, indicating very high seismic hazard level.

HDD_i and CDD_i are the 2019 HDD and CDD highest average annual values at the NUTS-3 regions level (Eurostat, 2020) for each EU Member State i.

The distribution of the EU-27 by the corresponding PS, ranging from the highest to the lowest result, is depicted in Figure 14. According to the PS results, the EU-27 can be aggregated into three main groups, depending on the level of priority. The first group, i.e. high priority countries, refers to southern and eastern EU

Member States encompassing geographical areas with the most adverse conditions when EU-27 seismic hazard and climatic conditions are considered simultaneously, thus becoming the most relevant countries where combined seismic and energy retrofit of buildings is needed. Indeed, some EU Member States, from Italy to Slovenia, exhibit the highest values of PS, followed by a second group of Member States, i.e. moderate priority countries, from France to Malta, which correspond to low-to-moderate seismic hazard level. It is worth noting that Cyprus resulted in the moderate priority group, although it exhibits a moderate-to-high seismic hazard level; this output essentially depends on the combination of the seismic hazard with no severe climate conditions in terms of HDD characterising this country. Finally, the third group, i.e. low priority countries, includes mainly northern Europe countries, such as Sweden, Finland, Estonia, accounting for very low values of PS, which indicate a very low seismic hazard level, although the climate is characterised by adverse conditions in terms of HDD. Based on these results, Bulgaria, Croatia, Greece, Italy, and Romania were selected within the first group as high priority countries characterised by moderate-to-high seismic hazard and significant climatic conditions. Germany was also selected within the second group as a moderate priority country in order to provide a more detailed and comprehensive analysis by including a western European country with low-to-moderate seismic hazard. Furthermore, Germany resulted the EU country with the highest number of dwellings in both residential and non-residential buildings (i.e. more than 40 million, as analysed in Section 2.1).

Figure 14. EU-27 distribution by prioritisation score based on the combination of seismic hazard and climatic conditions



2.3.2 Step 2: Identification of EU buildings needing combined seismic and energy retrofit

The second step of the proposed framework refers to a simplified prioritisation of the EU buildings needing combined seismic and energy retrofit in the EU priority countries, identified in Step 1. This investigation is carried out according to the two following main Sub-steps.

The ***Sub-step 1*** concerns the selection of potential regions representative of the various seismic-climatic scenarios in each of the six identified priority countries. Different seismic hazard levels in terms of PGA and climatic conditions in terms of HHD and CDD can coexist in each EU Member State, depending on the specific regions (i.e. NUTS-3 regions) considered. The possible combinations among the three seismic hazard zones in terms of PGA (low, moderate, and high) and five of the six climate zones in terms of HDD (from Zone 1 to 5) (see Section 2.2) were identified in each selected priority country. A synthesis of this investigation is provided in a unique combination matrix (Table 1), also indicating indicative NUTS-3 regions located in the seismic-climatic scenarios identified in each EU priority country, as follows:

- **Bulgaria** - The possible seismic-climatic scenarios identified in Bulgaria correlate the Zone 2 and Zone 3 in terms of climatic zones based on HDD values with moderate to high seismic hazard zones. The following NUTS-3 regions were considered: Pleven (Moderate - Zone 2), Plovdiv (High - Zone 2), Sofia (Moderate - Zone 3), and Blagoevgrad (High - Zone 3).

- **Croatia** - The potential seismic-climatic scenarios characterising Croatian counties combine the following climatic zones, namely Zone 2 and Zone 3, with low, moderate, and high seismic hazard zones. The following NUTS-3 regions (i.e. counties) were selected: Zadar (Low - Zone 2), Split (Moderate - Zone 2), Dubrovnik (High - Zone 2), Osijek (Low – Zone 3), Primorje-Gorski kotar (Moderate - Zone 3), and City of Zagreb (High - Zone 3).
- **Germany** – The regions of Germany are characterised by Zone 3 and Zone 4 in terms of climatic zones combined with low and moderate seismic hazard zones. The following NUTS-3 regions are identified as representative of the possible seismic-climatic scenarios, as reported into the combination matrix: Munich (Low – Zone 3), Aachen (Moderate – Zone 3), and Lindau (Low – Zone 4).
- **Greece** - The regions of Greece are mainly included in Zone 1 and Zone 2 in terms of climatic zones based on HDD values, even if some regions belong to Zone 3. Furthermore, moderate and high seismic hazard levels identify Greek regions. The following NUTS-3 regions are selected as examples of the possible combinations within the seismic-climatic matrix: Andros (Moderate - Zone 1), Central Athens (High - Zone 1), Kozani (Moderate - Zone 2), Preveza (High - Zone 2), and Kastoria (Moderate - Zone 3).
- **Italy** - A particular case is represented by Italy, since this country includes the majority of all possible seismic-climatic scenarios identified in the combination matrix. Italy consists of various climatic zones - from Zone 1 to Zone 5, thus covering all the five climatic zones considered within the matrix, and present low, moderate, and high seismic hazard levels. The following NUTS-3 regions (i.e. provinces) are selected: Trapani (Low – Zone 1), Napoli (Moderate - Zone 1), Reggio Calabria (High - Zone 1), Bari (Low - Zone 2), Pisa (Moderate - Zone 2), Cosenza (High - Zone 2), Como (Low - Zone 3), Vicenza (Moderate - Zone 3), L'Aquila (High - Zone 3), Trento (Low - Zone 4), Belluno (Moderate - Zone 4), and Aosta (Low - Zone 5).
- **Romania** - Romania is characterised by various climatic zones, from Zone 2 to Zone 4, correlated with low, moderate, and high seismic hazard levels, as reported in the seismic-climatic matrix. The following NUTS-3 regions (i.e. districts) are selected as exemplary of the potential seismic-climatic scenarios: Bucharest (Moderate - Zone 2), Cluj (Low - Zone 3), Satu Mare (Moderate - Zone 3), Vrancea (High - Zone 3), Hargita (Moderate - Zone 4), and Covasna (High – Zone 4).

Table 1. Seismic-climatic matrix for the selected EU priority countries

CLIMATIC ZONE (HDD)	SEISMIC HAZARD ZONE			EU Country
	Low ($PGA \leq 0.1g$)	Moderate ($0.1g < PGA < 0.25g$)	High ($PGA \geq 0.25g$)	
Zone 1 ($HDD \leq 1200$)		Andros	Athens	GR
	Trapani	Napoli	Reggio Calabria	IT
Zone 2 ($1200 \leq HDD<2200$)		Pleven	Plovdiv	BG
		Split	Dubrovnik	HR
		Kozani	Preveza	GR
	Bari	Pisa	Cosenza	IT
		Bucharest		RO
Zone 3 ($2200 \leq HDD<3000$)		Sofia	Blagoevgrad	BG
	Osijek	Primorje-Gorski kotar	Zagreb	HR
		Kastoria		GR
	Munich	Aachen		DE
	Como	Vicenza	L'Aquila	IT
	Cluj	Satu Mare	Vrancea	RO

Cont.

CLIMATIC ZONE (HDD)	SEISMIC HAZARD ZONE			EU Country
	Low (PGA ≤ 0.1g)	Moderate (0.1g < PGA < 0.25g)	High (PGA ≥ 0.25g)	
Zone 4 (3000 ≤ HDD<4000)	Lindau			DE
	Trento	Belluno		IT
	Bistrita	Hargita	Covasna	RO
Zone 5 (4000 ≤ HDD<5000)	Aosta			IT

The *Sub-step 2* deals with the identification of buildings needing combined seismic and energy retrofit in all the NUTS-3 regions selected within each EU priority country.

First, the temporal evolution of the seismic design code related to the selected priority countries (Table 2) is investigated. To this end, a study carried out by Crowley et al. (2021) is considered as reference. It provides a detailed analysis of the spatial and temporal evolution of seismic design code in the EU-27 by identifying four main categories of seismic design in order to consider a harmonised classification of seismic code across Europe: (i) no code, which indicates building code only regulating the structural design for gravity loads, (ii) low code, referring to allowable stress design, (iii) moderate code, based on limit state design, and (iv) high code, including capacity design and local ductility criteria.

In general, it is worth noting that no seismic design provisions were introduced before the end of '50s – early '60s in all the selected EU priority countries, except for Italy. The adoption of moderate seismic design code was issued only three decades later in the 80's, although in Italy it was introduced even later in 1996. The introduction of modern seismic design code in line with the Eurocode 8 (CEN, 2004) is quite recent, corresponding to the first years of the 21th century for all the EU priority countries, except for Greece, where it was issued in the middle of '90s.

Table 2. Temporal evolution of seismic design code for the selected EU priority countries

EU country	SEISMIC DESIGN CODE LEVEL		
	Low	Moderate	High
BG	1947	1987	2012 (Eurocode 8)
	1957		
	1961		
	1964		
HR	1948	1981	2006
	1964		
DE	1957	1981	2005
GR	1959	1984	1995
IT	1915	1996	2008
	1935		
RO	1963	1978	2006 (Eurocode 8)
	1970	1981	

Source: Data and seismic design code references - Crowley et al., 2021.

Subsequently, the correlation of the seismic-climatic scenarios (identified in Sub-step 1) with the building stock in terms of age of construction was examined for each EU priority country. Hence, the distribution of the number of residential buildings or dwellings (depending on data availability) by year of construction in all the

NUTS-3 regions selected within each EU priority country (see Table 1) is analysed, according to data provided by the 2011 Census of the corresponding national statistical institutes or the ESS, and correlated with the year of implementation of both seismic design code and energy efficiency regulations. Specifically, as for the seismic design code, the year corresponding to the introduction of the moderate seismic design code is considered for each EU priority country, according to data in Table 2. As for energy efficiency regulations, generally the '70s is recognised as the decade when the first thermal regulations of buildings were introduced to respond to the worldwide energy crisis in 1973, although they were often neglected. Hence, a general simplified assumption indicating 1980 as the year of implementation of more stringent energy efficiency provisions (Bournas, 2018) was considered for all the EU priority countries. However, it is worth noting that a country-by-country analysis on the evolution of the energy efficiency regulations could provide more precise indications of the energy retrofit need for each EU priority country. Furthermore, investigations on the distribution of buildings by material of construction are also carried out to provide indicative remarks on the simplified prioritisation of the EU existing building stock.

The main results of these investigations for each EU priority country are reported in the following.

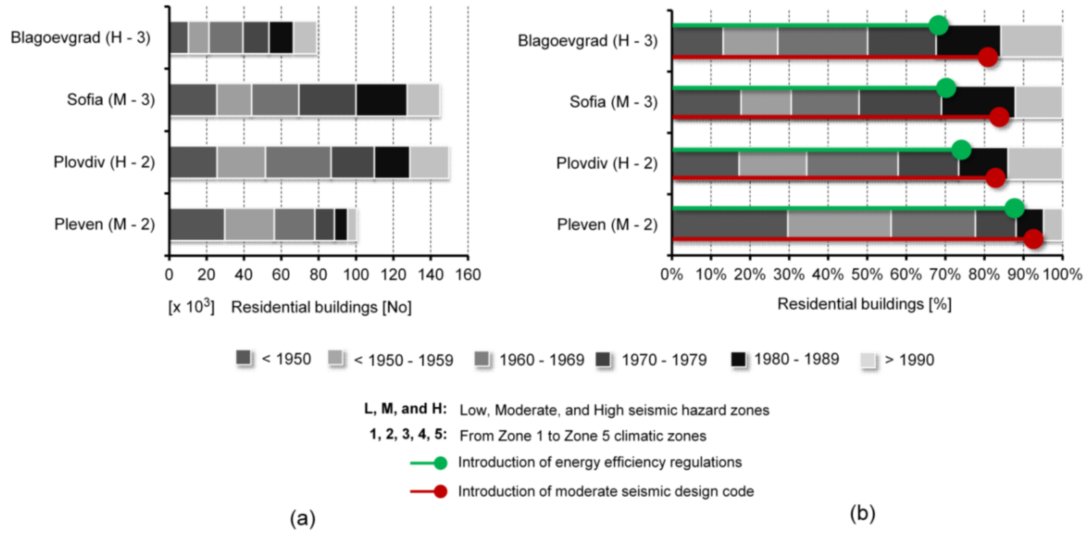
2.3.2.1 Bulgaria

The distribution of residential buildings by year of construction in the selected NUTS-3 regions identifying the seismic-climatic scenarios in Bulgaria (see Table 1) is depicted in Figure 15, also indicating the introduction of both the moderate seismic design code in 1987 (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of buildings needing combined seismic and energy retrofit.

Plovdiv and Sofia result the regions with the highest number of residential buildings (i.e. 145000-150000), followed by Pleven (i.e. about 100000 buildings) and Blagoevgrad with the less number of residential buildings equal to nearly 80000 (Figure 15a) (NSI, 2011).

Based on the year of implementation of both moderate seismic design code and energy efficiency regulations, data analysis in Figure 15b shows that more than 80 % of the residential building stock located in Sofia, Plovdiv, and Blagoevgrad was erected before 1990, whereas this percentage arises to more than 90 % in Pleven. Thus, these building shares potentially require seismic retrofit. Similarly, more than 70 % of residential buildings in all the selected Bulgarian regions was constructed before 1980, thus needing energy upgrading. Buildings erected in the overlapping period resulting from both no or low seismic design code and the absence of energy efficiency regulations are indicative of a potential combined retrofit. Specifically, 70 % of residential buildings in Sofia (Moderate – Zone 3) and Blagoevgrad (High - Zone 3) would benefit from combined seismic and energy retrofit, whereas the percentages of residential buildings in Plovdiv (High – Zone 2) and Pleven (Moderate - Zone 2) exhibiting the potential need for a combined retrofit are equal to more than 80 % and 90 %, respectively.

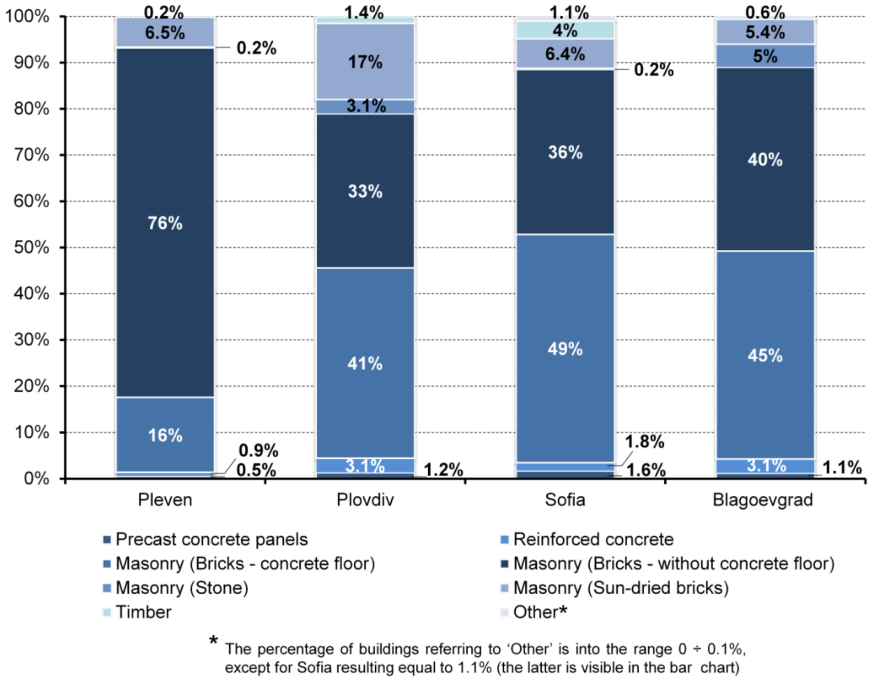
Figure 15. Distribution of residential buildings by year of construction in the selected NUTS-3 regions in Bulgaria in terms of (a) number of buildings, and (b) percentage of buildings along with indications of seismic and energy regulations



Source: Data – National Statistical Institute (NSI) Bulgaria, 2011

The nearly totality of residential building stock in Bulgaria accounts for masonry buildings (i.e. 95 %), mainly consisting of constructions with brick masonry walls with flexible floors (i.e. about 45.8 %), followed by brick masonry buildings with concrete floors (i.e. 34.3 %), adobe brick masonry buildings (i.e. 11.2 %), and masonry stone buildings (i.e. 3.8 %). Very low shares of RC buildings (i.e. 2.4 %), timber buildings (i.e. 1.2 %), precast concrete panels buildings (i.e. 1.1 %), and buildings with other not specified construction materials (i.e. 0.4 %) complete the Bulgarian residential building stock (NSI, 2011). The four selected Bulgarian regions follow similar trends to the above national distribution (Figure 16): masonry buildings are highly predominant in all the four regions, with Pleven accounting for 76 % and 16 % of brick masonry buildings without and with concrete slabs, respectively. These shares are followed by adobe masonry bricks (i.e. 6.5 %) and masonry stone (i.e. 0.2 %) buildings. However, the other three regions account for a higher percentage of brick masonry buildings with concrete slabs into a range equal to 41-49 %, followed by brick masonry buildings without concrete slabs resulting into a range equal to 33-40 % (NSI, 2011).

Figure 16. Distribution of residential buildings by construction material in the selected NUTS-3 regions in Bulgaria



Source: Data – National Statistical Institute (NSI) Bulgaria, 2011

Blagoevgrad represents the Bulgarian region with high seismic hazard level and quite severe climatic conditions (High – Zone 3) among the four selected districts, thus the combined retrofit of its residential building stock, mainly focusing on masonry bricks buildings with or without concrete floors, acquires high priority. However, attention needs to be also paid to the brick masonry residential building shares of the other three Bulgarian districts, since these regions exhibit moderate to high seismic hazard levels combined with quite severe climatic conditions, i.e. Zone 2 to 3, as well as they accounts for high extents of buildings, mainly Plovdid (High – Zone 2) and Sofia (Moderate – Zone 3).

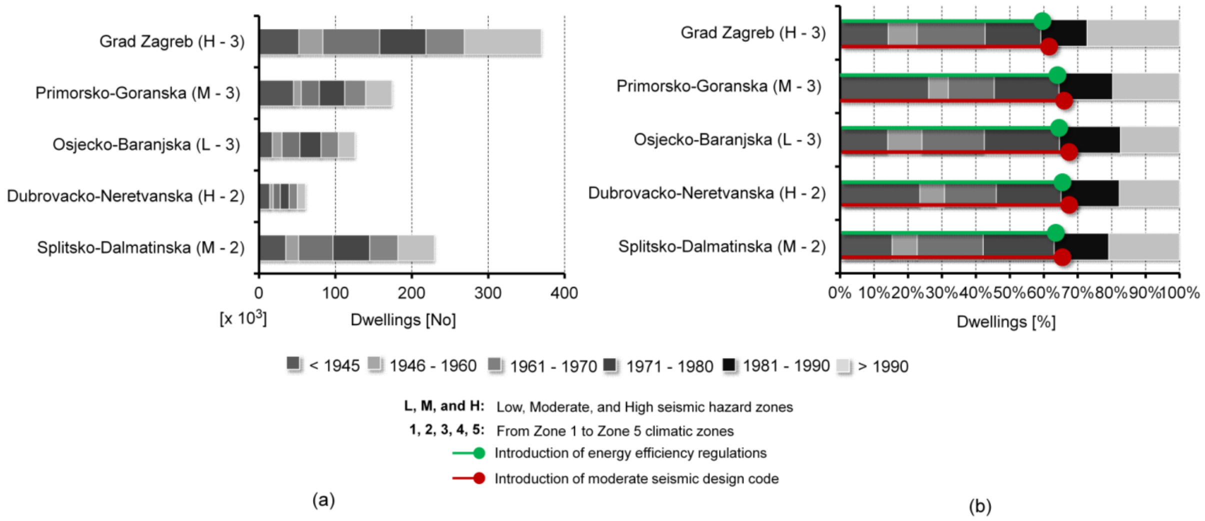
2.3.2.2 Croatia

The distribution of dwellings in residential buildings by year of construction in the selected NUTS-3 regions in Croatia (see Table 1) is depicted in Figure 17, also indicating the introduction of the moderate seismic design code in 1981 (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of dwellings potentially needing combined seismic and energy retrofit.

The city of Zagreb results into the selected NUTS 3 region with the highest number of dwellings in residential buildings (i.e. more than 300000), followed by Split with a share of dwellings higher than 200000. The remaining Croatian counties exhibit a number of dwellings less than 100000 with Dubrovnik accounting for a very low extent of dwellings slightly higher than 60000 (Figure 17a).

Based on the years of implementation of both moderate seismic design code and energy efficiency regulations in Croatia, data analysis in Figure 17b shows that buildings erected in the overlapping period resulting from both no or low seismic design codes and the absence of energy regulations are indicative of a potential combined retrofit. Specifically, all the selected regions account for a percentage of dwellings into a range equal to 60-65 % erected before 1980, thus potentially needing combined seismic and energy retrofit. Particular attention has to be drawn on the building stock located into the areas representative of the seismic-climatic scenarios characterised by moderate-to-high seismic hazard level and severe climatic conditions.

Figure 17. Distribution of dwellings in residential buildings by year of construction in the selected NUTS-3 regions in Croatia in terms of (a) number of buildings, and (b) percentage of buildings along with indications of year of implementation of seismic and energy regulations



Source: Data – ESS, EU Population and Housing Census, 2011

No statistical data related to the distribution of residential buildings by construction material in Croatia are available by the corresponding national statistical institute. Hence, reference is made to the NERA project, providing these data collected according to both questionnaire and field surveys on the Croatian building stock (Crowley et al., 2014). Results of this investigation pointed out that the majority of Croatian dwellings in both urban and rural areas consists of masonry constructions, mainly composed by brick, concrete block or natural stone masonry walls with reinforced concrete floors, followed by a significant share of reinforced or confined masonry dwellings and masonry dwellings with timber floors. A considerable number of RC wall buildings, erected both before and after 1981, also characterises the Croatian residential building stock, mainly in urban areas, where dwellings in pre-1981 and post-1981 buildings consisting of RC framed structures also accounts for a significant portion.

Seismic-climatic scenarios characterised by low seismic hazard zones are excluded from data analysis for the prioritisation of the Croatian building typologies, since an urgent seismic retrofit is not required. However, a potential energy retrofit can be considered in case of quite severe climatic conditions. The city of Zagreb represents the Croatian regions with high seismic hazard level and quite severe climatic conditions (High – Zone 3), among the five selected counties. Hence, the residential building stock, erected in Croatian areas exhibiting the same seismic-climatic scenario, acquires high priority with particular relevance to masonry buildings with timber floors, as well as pre-1981 RC wall and framed structures, resulting more vulnerable to seismic events. However, attention should be also drawn to the existing dwelling stock located in areas characterised by moderate seismic hazard level and quite severe climatic conditions (Zone 2 and Zone 3).

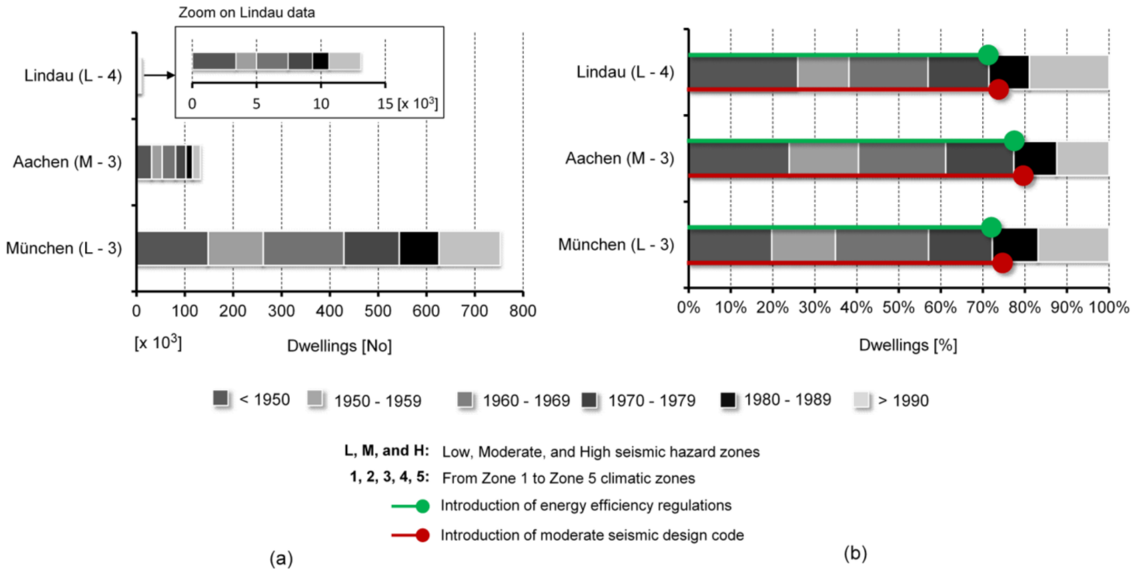
2.3.2.3 Germany

The distribution of dwellings in residential buildings by year of construction in the selected NUTS-3 regions indicative of the seismic-climatic scenarios in Germany (see Table 1) is depicted in Figure 18, also indicating the introduction of the moderate seismic design code in 1981 (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of buildings needing combined seismic and energy retrofit.

München represents the selected region with the highest number of dwellings equal to more than 750000, followed by Aachen with a low number equal to nearly 133000 dwellings. Lindau accounts for an even lower number of dwellings equal to more than 13000 (Figure 18a). In Aachen and Lindau the highest number of dwellings was erected before 1950, although huge shares of buildings were also constructed during the period 1950-1979. München is characterised by the highest number of dwellings built during the decade 1960-1969 with significant shares also constructed before 1950. These figures indicate that the majority of the German existing building stock in the selected regions is ageing (Destatis, 2011).

Based on the years of introduction of both moderate seismic design code and energy efficiency regulations in Germany, data analysis in Figure 18b shows that dwellings erected in the overlapping period resulting from both no or low seismic design codes and the absence of energy efficiency regulations are indicative of the potential need of a combined retrofit. Specifically, a percentage slightly higher than 70 % of the residential building stock located in both Lindau (Low-Zone 4) and München (Low – Zone 3) was erected before 1980, whereas this percentage arise to nearly 80 % for Aachen (Moderate - Zone 3). Hence, these building shares could benefit from a combined seismic and energy retrofit.

Figure 18. Distribution of residential buildings by year of construction in the selected NUTS-3 regions in Germany in terms of (a) number, and (b) percentage along with indications of the years of implementation of seismic and energy regulations



Source: Data – Federal Statistical Office of Germany (Destatis), 2011

No statistical data related to the distribution of residential buildings by construction material in Germany are available in the corresponding national statistical institute. However, generic national data can be retrieved from the NERA project: more than 50 % of the German building stock consists of masonry buildings, followed by RC constructions, and a small percentage of timber buildings (Ozcebe et al., 2014). Hence, focusing on the seismic-climatic scenario characterised by moderate seismic hazard combined with quite severe climatic conditions, represented by Aachen (Moderate – Zone 3), a combined seismic and energy retrofit of its building stock is needed, giving priority to both RC and masonry buildings. Although the seismic–climatic scenarios characterised by low seismic hazard do not draw urgent attention to seismic strengthening interventions for the building stock located in those areas, an energy retrofit alone can be beneficial to face severe (Zone 4) and quite severe (Zone 3) climatic conditions.

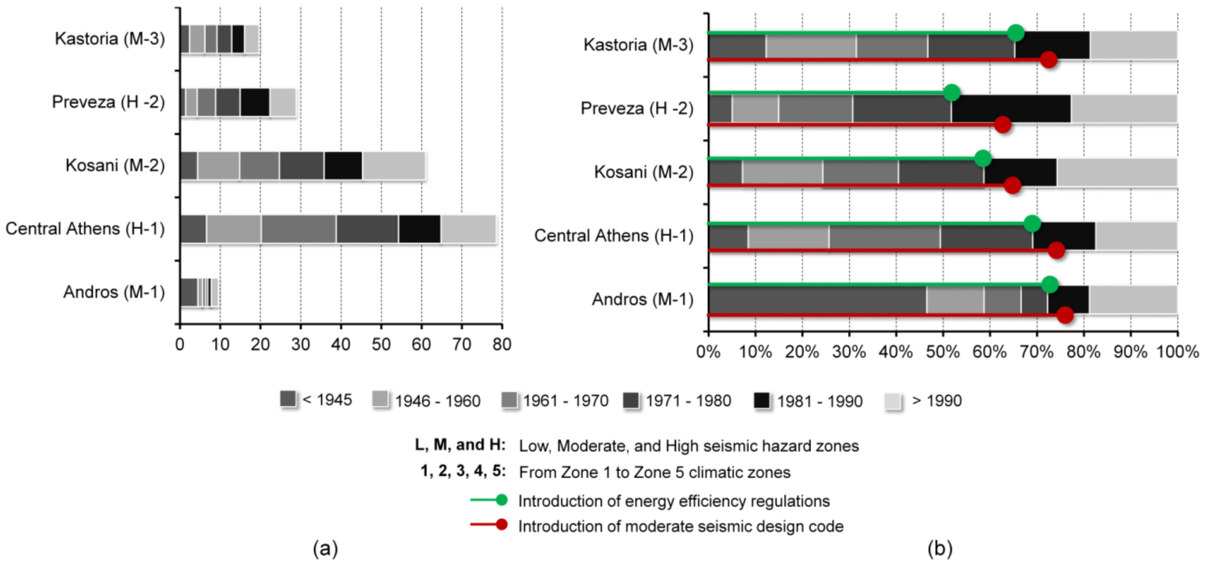
2.3.2.4 Greece

The distribution of the residential buildings by year of construction in the selected NUTS-3 regions in Greece (see Table 1) is depicted in Figure 19, also indicating the introduction of the moderate seismic design code in 1984 (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of buildings needing combined seismic and energy retrofit.

The region of Attiki accounts for the highest percentage of buildings in Greece, thus it is not surprising that Central Athens results into the selected NUTS-3 region with the highest number of residential buildings (i.e. nearly 80000). This figure is followed by Kozani with about 60000 residential buildings, whereas the three remaining selected NUTS-3 regions account for a lower number of buildings, with Andros including less than 10000 buildings (Figure 19a) (ELSTAT, 2011).

Based on the year of implementation of the moderate seismic design code in Greece, data analysis in Figure 19b shows that more than 70 % of the existing building stock in Central Athens, Andros, and Kastoria was erected before 1984, followed by more than 60 % in Kozani and Preveza. Hence, these shares of residential buildings potentially need seismic strengthening interventions. Similarly, a percentage of residential buildings fluctuating between 50 % and 70 % was constructed before 1980 in the selected NUTS-3 Greek regions, thus these buildings shares potentially need interventions to improve their energy efficiency. Buildings erected in the overlapping period resulting from both no or low seismic design code and the absence of energy efficiency regulations are indicative of a potential combined retrofit. Specifically, more than 70 % of residential buildings in Central Athens and Andros, exhibiting high and moderate seismic hazard, respectively, could benefit from a combined retrofit, although these regions are characterised by less severe climatic conditions (i.e. Zone 1). These percentages result lower, being into a range equal to more than 50-65 %, for the building stock located in all the other three selected Greek regions, representative of moderate-to-high seismic hazard level combined with quite severe climatic conditions (i.e. Zone 2 and Zone 3).

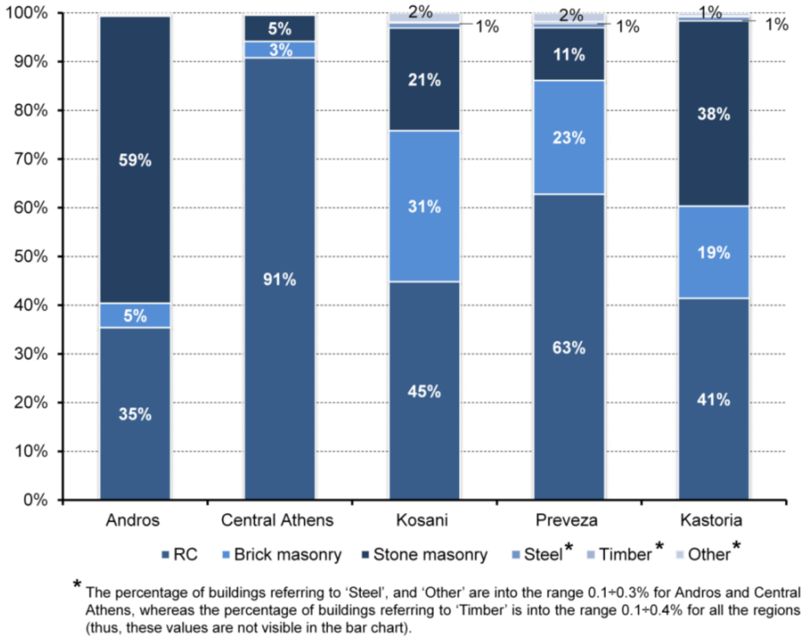
Figure 19. Distribution of residential buildings by year of construction in the selected NUTS-3 regions in Greece in terms of (a) number, and (b) percentage along with indications of the years of implementation of seismic and energy regulations



Source: Data - Hellenic Statistical Authority (ELSTAT), 2011

Greek buildings mainly consist of RC structures with a share of buildings equal to nearly 60 % of the entire building stock. This figure is not particularly surprising since the majority of buildings in Greece was erected during the two decades 1961-1980, when the boom of RC buildings occurred in several EU countries. However, masonry buildings are also quite spread, accounting for a percentage of nearly 40 %, including brick (i.e. 21 %) and stone (i.e. 18 %) masonry buildings, mainly erected before 1945. Finally, low percentages of steel (i.e. 0.8 %), timber (i.e.0.5 %), and other material (i.e. nearly 2 %) buildings complete the distribution of the Greek existing building stock by construction material (ELSTAT, 2011). This national trend reflects the selected Greek NUTS-3 regions (Figure 20): RC buildings are predominant in Central Athens and Preveza, whereas Kozani and Kastoria accounts for significant shares of masonry buildings (brick, plus stone masonry buildings), beyond the RC ones. Conversely, Andros accounts for a very high percentage of masonry buildings, also resulting the maximum share of stone masonry buildings (i.e. 59 %) constructed in all Greece. However, 35 % of the residential building stock erected in Andros consists of RC buildings. The highest number of RC residential buildings refers to Central Athens, accounting for 91 %, followed by Preveza (63 %), Kozani (45 %), and Kastoria (41 %). Masonry buildings shares result into the range 8-57 % (brick, plus stone masonry typologies) with Kozani, Preveza, and Kastoria exhibiting major percentages of brick masonry buildings, whereas Central Athens accounts for a slightly higher percentage of stone masonry buildings compared to the brick one (ELSTAT, 2011).

Figure 20. Distribution of residential buildings by construction material in the selected NUTS-3 regions in Greece.



Source: Data - Hellenic Statistical Authority (ELSTAT), 2011

Preveza represents the Greek region with high seismic hazard level and quite severe climatic conditions (High – Zone 2) among the five selected NUTS-3 regions, thus the combined retrofit of its residential building stock, mainly focusing on RC buildings acquires high priority. Similar remarks can be underlined for the RC building stock in Central Athens (High – Zone 1), although the climatic conditions do not result severe in this region. As for the region representative of moderate seismic hazard level combined with quite severe climatic conditions, i.e. Kastoria (Zone 3) and Kozani (Zone 2), a combined retrofit of their building stocks, prioritising both RC and masonry buildings, is also required. Finally, a combined retrofit of the building stock located in the Greek region representative of the seismic-climatic scenario (Moderate – Zone 1) is potentially beneficial, although no severe climatic conditions characterise this region. However, a seismic strengthening becomes highly important, mainly prioritising stone masonry buildings.

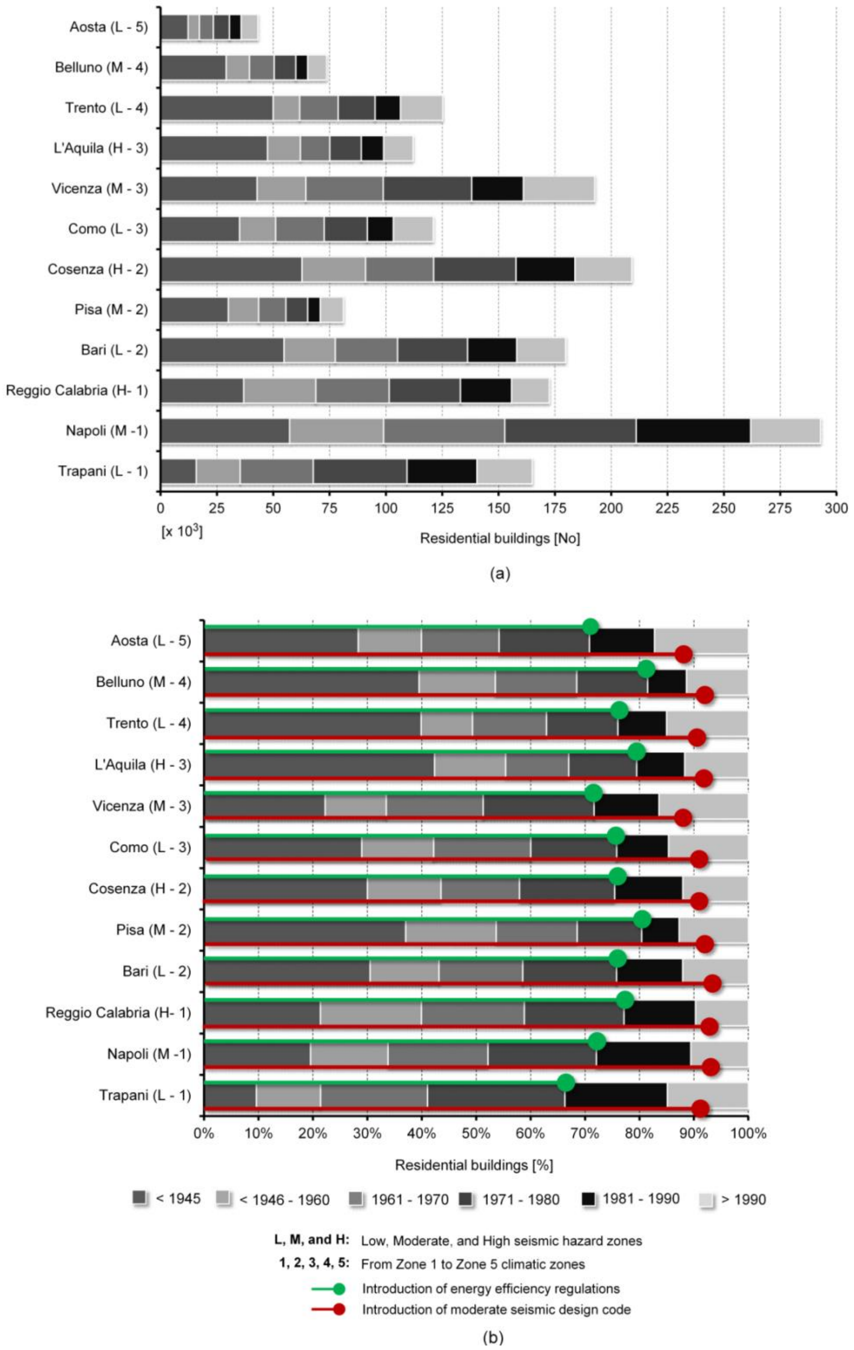
2.3.2.5 Italy

The distribution of the residential buildings by year of construction in the selected NUTS-3 regions (i.e. provinces) representative of the seismic-climatic scenarios in Italy (see Table 1) is depicted in Figure 21, also indicating the introduction of the moderate seismic design code in 1996 (Ministerial Decree (DM) 16/01/1996) (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of buildings needing combined seismic and energy retrofit.

Naples results into the province with the highest number of residential buildings (i.e. nearly 300000), followed by Cosenza and the group of the provinces Vicenza, Bari, Reggio Calabria, and Trapani with more than 200000 and 150000 residential buildings, respectively. Trento, L'Aquila, and Como have more than 100000 residential buildings, whereas Pisa, Belluno, and Aosta accounts for a lower number of residential buildings equal to less than 100000, with Aosta accounting for less than 50000 buildings (Figure 21a) (ISTAT, 2011).

Based on the year of implementation of the moderate seismic design code in Italy, data analysis in Figure 21b shows that more than 80 % of the residential building stock located in all the selected regions was erected before 1990, thus seismic strengthening is extensively required. Similarly, more than 70 % of residential buildings in all regions was constructed before 1980 (assumed as year of implementation of energy efficiency regulations, although more stringent energy provisions were introduced in Italy only in 1991), except for Trapani with a percentage decreasing to more than 60 %. Hence, an energy retrofit is extremely beneficial to improve the energy performance of these huge fractions of buildings. Buildings erected in the overlapping period resulting from both no or low seismic design code and the absence of energy efficiency regulations are indicative of a potential combined retrofit. Specifically, 70-80 % of residential buildings in the provinces of Aosta, Belluno, and Trento need combined seismic and energy retrofit. This trend is also similar to the Italian provinces representative of the low, moderate, and high seismic hazard levels combined with the climatic zones Zone 2 and 3. As for the provinces characterised by less severe climatic conditions, (i.e. Zone 1), Reggio Calabria and Naples accounts for more than 70 % of their residential buildings stocks needing combined retrofit, whereas this percentage is further reduced to more than 60 % for the existing residential building stock in Trapani.

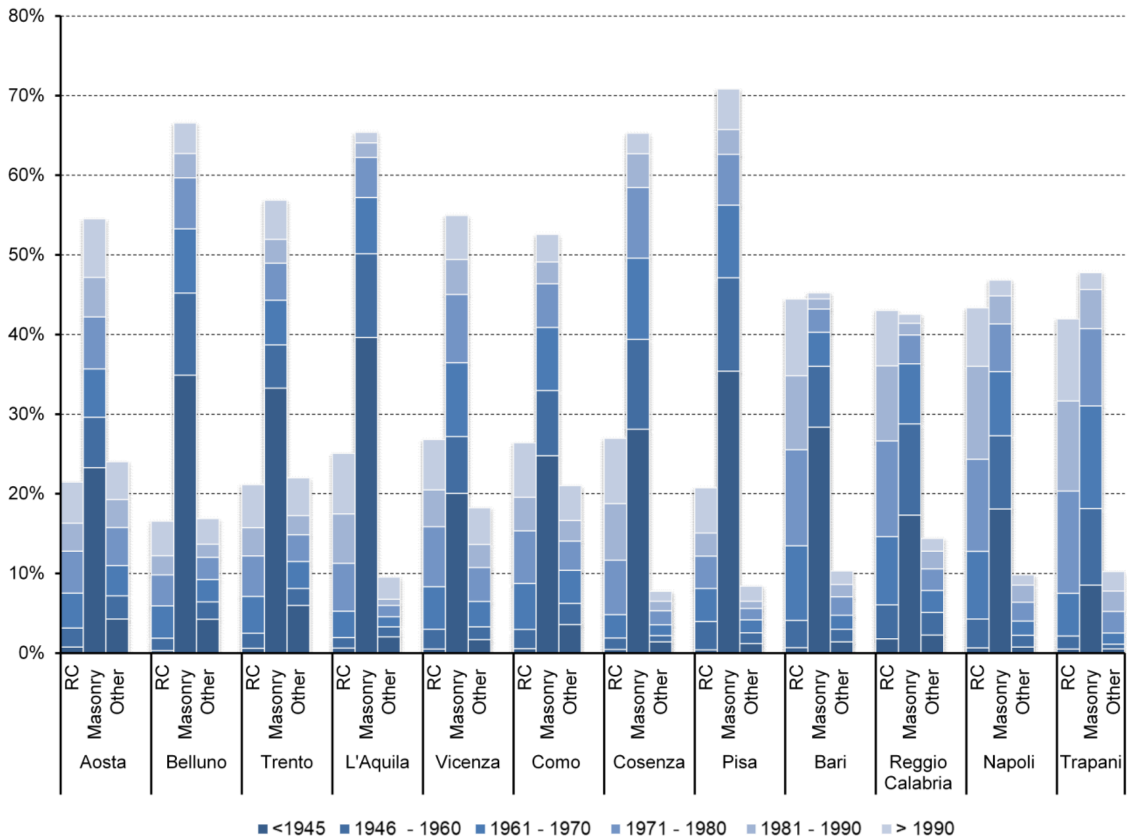
Figure 21. Distribution of residential buildings by year of construction in the selected NUTS-3 regions in Italy in terms of (a) number, and (b) percentage along with indications of seismic and energy regulations



Source: Data – Italian National Statistical Institute (ISTAT), 2011

The Italian residential building stock mainly consists of masonry structures with a share of buildings equal to 57 % of the entire residential building segment, followed by RC structures and buildings characterised by other not specified construction materials (e.g. steel, timber, etc.), accounting for 30 % and 13 % of the total number of Italian residential buildings, respectively (ISTAT, 2011). Generally, the largest extent of masonry buildings was erected pre-1919 with significant shares until 1945, when the construction of RC structures arose to provide more rapid housing after the 2nd World War. These trends are perfectly visible in all the selected Italian NUTS-3 regions (Figure 22): masonry buildings represent the most spread segment in all the selected provinces, except for Reggio Calabria, where the RC residential building stock is slightly higher than the masonry one. Specifically, the masonry residential building stock is highly predominant in Aosta, Belluno, Trento, L'Aquila, Vicenza, Como, Cosenza, and Pisa with a range equal to 52-70 % of the total number of residential buildings for each region, whereas the RC residential building stock results equal to less than 30 %. However, Bari, Reggio Calabria, Napoli, and Trapani are characterised by comparable total shares of masonry and RC buildings, resulting into a percentage range equal to 42-48 %. The major amounts of masonry residential buildings refer to the period pre-1945 in all the selected provinces with L'Aquila accounting for the highest number of buildings erected in that period, i.e. 40 % of the entire residential building stock constructed in that province. The highest number of RC residential buildings was instead erected during the period 1960-1990 in all the selected provinces, with Bari, Reggio Calabria, Napoli, and Trapani accounting for the most significant shares equal to 30 % of the entire residential building stock erected in these provinces (ISTAT, 2011).

Figure 22. Distribution of residential buildings by construction material and year of construction in the selected NUTS-3 regions in Italy



Source: Data – Italian National Statistical Institute (ISTAT), 2011

Seismic-climatic scenarios characterised by low seismic hazard zones are excluded from data analysis for the prioritisation of Italian building typologies, since an urgent seismic retrofit is not required. However, an energy retrofit alone could be appropriate mainly for the existing building stock located in regions with severe climatic conditions (i.e. Zone 4 and Zone 5), such as Aosta and Trento. Focusing on the remaining ones, L'Aquila is representative of the seismic-climatic scenario characterised by high seismic hazard and quite severe climatic conditions (High – Zone 3) among the selected Italian NUTS-3 regions, thus a combined seismic and energy retrofit of its building stock is potentially highly needed, mainly prioritising masonry buildings, although the RC ones should not be neglected. Similar remarks also refer to the other Italian NUTS-3 regions indicative of the moderate-to-high seismic zones and quite severe climatic conditions (i.e. Zone 2 and Zone 3). However, a combined retrofit is potentially beneficial also for the existing building stock located in high-to–moderate seismic zones with not severe climatic conditions (Zone 1), as well as moderate seismic zones with severe climatic conditions (Zone 4). Specifically, both masonry and RC buildings require priority for a combined retrofit in Reggio Calabria and Naples, also considering that the latter accounts for a very high number of buildings, whereas the prioritisation of masonry buildings in Belluno is recommended.

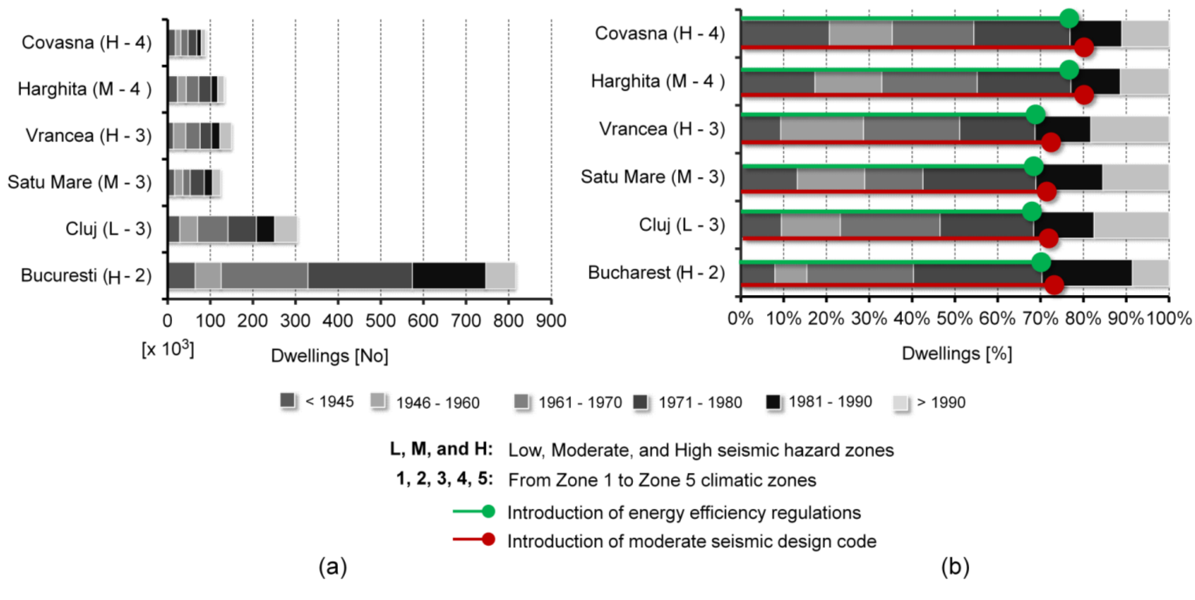
2.3.2.6 Romania

The distribution of residential buildings by year of construction in the selected NUTS-3 regions representative of the seismic-climatic scenarios in Romania (see Table 1) is depicted in Figure 23, also indicating the implementation of the moderate seismic design code in 1981 (see Table 2) and the energy efficiency provisions in 1980 in order to identify the share of buildings needing combined seismic and energy retrofit.

Bucharest represents the region with the highest number of dwellings (i.e. more than 800000), followed by Cluji with about 300000 dwellings. The remaining four selected NUTS 3 regions account for lower shares of dwellings resulting into the range of 90000-150000 (Figure 23a).

Based on the year of implementation of both moderate seismic design code and energy efficiency regulations, data analysis in Figure 23b shows that buildings erected in the overlapping period resulting from both no or low seismic design code and the absence of energy efficiency regulations are indicative of a potential combined retrofit. Specifically, nearly 80 % of the dwellings in the residential buildings in Cosvana (High – Zone 4) and Harghita (Moderate –Zone 4) were erected before 1980, thus a combined seismic and energy retrofit is highly needed. Slightly more than 70 % of the dwelling stock located in each of the other selected Romanian NUTS 3 regions, was constructed before 1980. It is clear that these fractions of buildings could also benefit from a combined seismic and energy retrofit.

Figure 23. Distribution of residential buildings by year of construction in the selected NUTS-3 regions in Romania in terms of percentage along with indications of seismic and energy regulations



Source: Data - ESS, EU Population and Housing Census, 2011

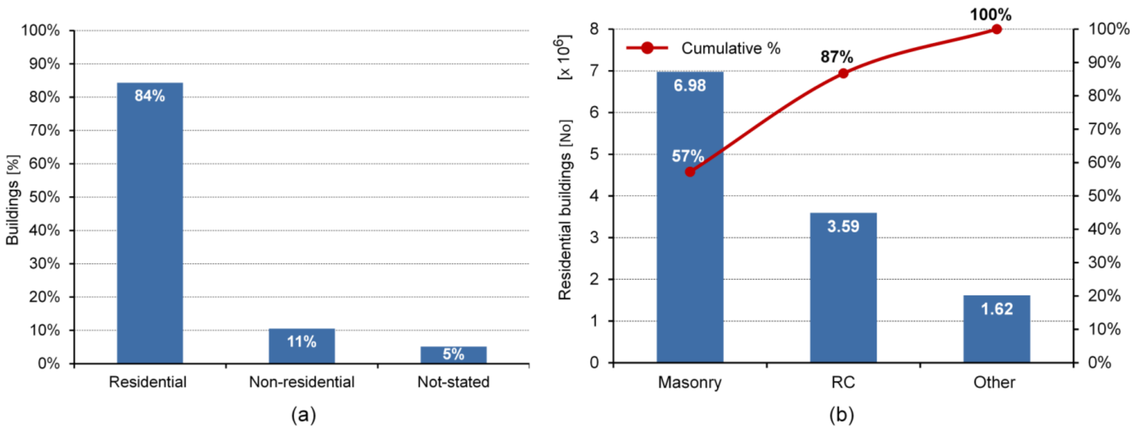
3 A focus on the Italian building typologies most needing combined seismic and energy retrofit

Italy results one of the EU-27 high priority country, where combined seismic and energy retrofit of its existing building stock is deeply needed (see Section 2.3.1). Italy also represents a particular case-study due to the huge variability of its buildings in terms of construction technologies. Indeed, Italian buildings are extremely diversified by typology not only from a morphological point of view, but also for both materials of structural components, mainly with regard to masonry buildings, and construction techniques.

The significant variability of the Italian building stock typically depends on different local factors related to material supply, technical skills of the workers, and availability of economic resources at the time of construction. For instance, as for masonry buildings, both monumental constructions and small dwellings in residential buildings made of natural blocks (e.g. rocks) account for a large amount in areas where a huge availability of this material was provided, while artificial elements (e.g. clay bricks) were mainly used where natural rocks were not available. Thus, buildings located in towns along the Adriatic coast are mostly made by clay bricks due to the unavailability of natural rocks. Conversely, masonry buildings in the small towns located along the Apennine mountain chain are frequently made of limestone blocks. Moreover, the historical evolution of seismic design codes and seismic zonation at national level can increase the complexity of the identification of building typologies due to different structural details, dissimilar size in terms of floor area and volume by year of construction and geographical distribution depending on seismic and energy requirements in force at the time of construction. Another essential aspect which affects the significant diversification of the building typologies is represented by non-structural elements, mainly regarding RC buildings. Indeed, the building envelope assumes a fundamental role for the assessment of both seismic and energy performances of buildings. As an example, infill walls of RC framed buildings represent one of the main sources of heat loss, beyond their effects on the seismic behaviour of buildings due to frame–to–masonry infill interaction. A large number of different infill walls can be identified into the existing Italian RC building stock, mainly due to the evolution of energy efficiency regulations over time.

These concerns makes Italy an interesting case study to be further analysed in order to carry out a simplified prioritisation of the Italian building typologies needing combined seismic and energy retrofit, focusing on residential building stock. Indeed, the latter represents the Italian construction segment with the highest number of buildings. According to the statistics provided by the 2011 Population and Housing Census (hereinafter, indicated as 2011 Census) of the Italian Statistical Institute (ISTAT), the whole Italian building stock accounts for more than 14 million of constructions, of which more than 12 million (i.e. 84 %) are residential buildings, followed by 1.5 million (i.e. 11 %) of non-residential buildings. The remaining extent equal to more than 0.7 million (i.e. 5 %) refers to not-stated buildings (Figure 24a).

Figure 24. (a) Distribution of the Italian building stock by use, and (b) distribution of the Italian residential building stock by construction material



Source: Data – Italian National Statistical Institute (ISTAT), 2011

The distribution of the 12 million residential buildings by construction material (Figure 24b) points out that the number of masonry and RC buildings is equal to nearly 7 million and nearly 3.6 million, respectively. The remaining extent equal to 1.6 million includes the residential buildings referring to other not specified construction materials (e.g. steel, timber, etc.). Hence, masonry and RC buildings globally account for 87 % of the Italian entire residential building stock. Furthermore, the prevalence of masonry structures becomes one of the potential motivations for the wide spread of low-rise buildings in Italy: nearly half of the Italian constructions are two-storey buildings, although significant town-by-town differences of the building inventory in terms of number of storeys can emerge (Masi et al., 2021).

The evolution of both the seismic design code and energy efficiency regulations in Italy is briefly summarised as a preliminary step in the perspective of the simplified prioritisation of the Italian building typologies (Section 3.1). This overview may provide a general indicative figure of the seismic vulnerability and energy performance of the Italian existing residential building stock by comparing the periods of time when significant legislation developments were issued with the periods of construction of buildings. Based on this synthesis, a research focus investigating the Italian masonry (Section 3.2) and RC (Section 3.3) residential building typologies needing combined seismic and energy retrofit is presented in the following.

3.1 Evolution of seismic design code and energy efficiency regulations in Italy

3.1.1 Evolution of the Italian seismic design code

Italy exhibits a long history of strong seismic activity (Paz, 1994); the evolution of the Italian seismic design code, since its roots at the end of the 18th century, has reflected the occurrence of severe seismic events (Boschi et al., 2000), leading to direct and indirect losses mainly in terms of collapsed/extensively damaged buildings and fatalities. Indeed, the catastrophic consequences of these natural disasters over time have provided the corresponding impulses for the introduction of the first generation of seismic design code in 1909, after the 1908 Reggio Calabria and Messina earthquake, until the adoption of the modern seismic design code, as arose in the last two decades in the aftermath of both the 2002 Molise and the 2009 L'Aquila earthquakes.

The temporal evolution of the Italian seismic design code can be summarised into four main phases: (i) Phase I - pre-code phase, (ii) Phase II - first generation of seismic design code, (iii) Phase III - second generation of seismic design code, (iv) Phase IV - modern generation of seismic design code. Each phase corresponds to different categories of seismic design, according to the classification provided in Crowley at al. (2021) and adapted to the Italian context: (i) Phase I: no code (pre-1909), (ii) Phase II: low code (1909-1995), (iii) Phase III: moderate code (1996 – 2002), and (iv) Phase IV: high code (2003 –to date). Specifically, Phase I refers to building codes only regulating structural design for gravity load, although practical rules for seismic-resistant constructions were introduced in Italy already in the 18th century following catastrophic seismic events. Low code (Phase II) and moderate code (Phase III) indicate seismic design based on allowable stress method and limit state method, respectively. Finally, high code (Phase IV) indicates the modern seismic design code prescribing capacity design and local ductility criteria. The most significant legislative developments for each phase are provided in the following.

- **Phase I** (No code) – The phase I represents a pre-code phase during which practical seismic design rules for safe constructions were introduced, setting a remarkable qualitative step towards quantitative studiesfor the future development of the first generation of Italian seismic design code in the 20th century (Marotta et al., 2019). The first Italian seismic design rules dates back to 1784, following the 1783 sequence of earthquakes in the South Calabria area, part of the Kingdom of Naples at that time, which caused catastrophic effects also in the North-East Sicily area. The damages and fatalities accounted for about 30000 deaths in Calabria and hundreds of human victims in Sicily, mainly in Messina, along with the complete destruction of nearly two hundred towns and villages. Further to this event, the Bourbon government, under Ferdinando IV, introduced the first Italian 'seismic design rules', named 'Istruzioni Reali', providing two main types of design requirements for the seismic risk reduction: (i) criteria to select the sites for the entire reconstruction of destroyed towns and villages, and (ii) indications on structural typologies and construction details for new buildings, leading to the introduction of a primordial earthquake-resistant construction (Vivenzio, 1788). The latter is the so-called 'Baraccata' system building (Ruggieri, 2017), based on a timber framing system embedded in rubble masonry constructions. Afterwards, the 1859 Norcia earthquake (Central Italy) led to the development of a new set of practical 'seismic design rules', which specified the maximum heights of buildings, construction criteria, and material properties, followed by the Royal Decree (RD) 2600/1884 (RD 2600/1884), issued after the 1883 Ischia earthquake (in Southern Italy). The latter indicated rules related to the maximum height of new buildings, also providing comprehensive detailed indications about masonry construction, and a qualitative understanding of the role of site response. A detailed review of both regulations is provided in Marotta et al. (2019).

— **Phase II and III** (From low to moderate code) – The phase II initiated with the introduction of the first seismic design code in 1909 and its following evolution of low seismic design code until the adoption of the moderate seismic design code in 1996 (Ministerial Decree (DM) 16/01/1996), which marked the beginning of the Phase III. In the following, only the main legislative changes related to this temporal evolution are briefly summarised by two overviews dedicated to masonry and RC structures separately. Hence, it is recommended to refer to Di Pasquale et al. (1999a, b) for a more comprehensive review.

The Reggio Calabria and Messina earthquake, that occurred on 28th December 1908 with an estimated loss of 80000 lives, marked the beginning of the history of the Italian seismic design code by issuing the Royal Decree 193/1909 (RD 193/1909). This decree contained provisions for the strengthening and reconstruction of existing buildings and the design of new buildings in the area affected by the earthquake. The decree also introduced the concept of the seismic zonation of the Italian territory by classifying as seismic nearly 454 municipalities in Calabria and Sicily regions, providing the corresponding seismic design provisions for these areas.

Following this decree, the development of the Italian low seismic design code in the first decades of the 20th century was essentially devoted to masonry buildings, with a fundamental step provided by the Royal Decree 573/1915 (RD 573/1915), which explicitly introduced the first provision regarding the value of the horizontal seismic base shear. An important change in the Italian seismic code was enforced in 1975 with the Ministerial Decree of 3 March 1975 (DM 3/3/1975), through the introduction of the response spectrum in seismic design. However, the first harmonised seismic design code for masonry buildings was issued only in 1987. The substantial changes related to the seismic design of masonry buildings from 1909 to 1996 are described in Table 3.

Table 3. Evolution of the Italian structural/seismic design code from 1909 to 1996 referring to masonry buildings.

Phase	Legislative document/ Year	Main provisions
Phase II (Low code)	**RD 193/1909** - Royal Decree No 193 of 18 April 1909.	Introduction of instructions to be applied to seismic areas: • Choice of building sites, avoiding sliding soils, transition zones between geo-morphologically different soils. • As for structural typologies, masonry bearing walls provided with a steel or timber frame (bracing masonry); plain masonry allowed only if constructed by bricks or square stones and mortar. Plain masonry allowed only for one-storey buildings. • Maximum building height equal to 10 m and number of floors limited to 2 floors + 1 basement floor for braced masonry vertical structures and 1 floor + 1 basement floor for bricks, square stones masonry vertical structures. • Provision of a State Building Office for building works, indicating instructions for seismic checks.
	DL 1526/1916 - Decree-Law No 1526 of 5 November 1916.	Definition of gravity and seismic loads, as follows: • Vertical loads prescribed as the sum of dead loads and live loads. • Mass-proportional forces in two perpendicular directions in order to consider inertia effects.

Cont.

Phase	Legislative document/ Year	Main provisions
Phase II (Low code)	**RD 640/1935** - Royal Decree No 640 of 25 March 1935, 'Technical building rules with particular prescriptions for earthquake struck zones'.	Important rules were issued regarding masonry buildings, as follows: • Prescription of (i) bricks or RC bordering for plain masonry consisting of irregular stones and mortar, and (ii) perimeter beams for bearing walls. • Introduction of wind action in structural design. • Thrusting structures (roof) forbidden.
	L 1684/1962 - Law No 1684 of 25 November 1962.	Only plain and bordered masonry was allowed and new height limits were released.
	L 64/1974 - Law No 64 of 2 February 1974.	This law served as basis for the recent Italian building codes, stating that the modernisation of building codes was entrusted to Ministerial Decrees.
	DM 3/3/1975 – Ministerial Decree of 3 March 1975, 'Approval of the technical standards for buildings in seismic areas'.	• Definition of new height standards based on the seismic category of the building site. • Provisions of rules such as the need of a perimeter beam at the top of bearing walls of each storey, maximum distance between bearing walls equal to 7 m, minimum wall thickness depending on material, etc. • Definition of the method for calculating seismic loads, but no indication for safety checks of masonry structures.
	DM 20/11/1987 – Ministerial Decree of 20 November 1987, 'Technical standards for the design, execution and testing of masonry buildings and for their consolidation'.	First harmonised building code exclusively devoted to masonry buildings, stating that load-bearing masonry buildings needed to be conceived as three-dimensional structures. The following aspects were considered: • Rules about the structural concept of the building, detailed indications on the types of mortar. • Design and verification methods for gravity and horizontal loads.
Phase III (Moderate code)	**DM 16/01/1996** – Ministerial Decree of 16 January 1996, 'Technical standards for constructions in seismic areas'	Some additional specifications to the DM 20/11/1987 were considered such as: • Building regular and compact plan arrangement. • Openings distance from corners not less than 1m. • Maximum height of first storey limited to 5 m. • Possibility of adopting plain masonry foundations if a RC ring beam is placed above the foundation layer.

DM: Ministerial Decree; DL: Decree-Law; L.: Law; RD: Royal Decree.

The first structural design code focused on RC buildings dates back to 1939 (RD 2229/1939), although no seismic design provisions were defined. The first few provisions in terms of seismic design for RC buildings were introduced at the beginning of '60s, when the Law (L) 1684/1962 (L 1684/1962) was issued. The temporal evolution of the seismic design code leading to substantial changes to the seismic design of RC buildings from 1939 to 1996 is reported in Table 4.

Table 4. Evolution of the Italian seismic design code from 1939 to 1996 referring to RC buildings

Phase	Legislative document/ Year	Main provisions
Phase II (Low code)	**RD 2229/1939** - Royal Decree No 2229 of 16 November 1939.	This decree was not a seismic code, but it introduced important provisions for RC structures related to quality of materials (concrete and steel), minimum amount of steel reinforcing, as well as some design indications, as follows: • Detailed indications on each component of concrete such as quality of aggregates, water. and cement. • Concrete strength to be determined by compressive test on cubic specimens; steel reinforcement strength to be determined by tensile tests.
	L 1684/1962 - Law No 1684 of 25 November 1962, 'Provisions for buildings with specific prescriptions for seismic zones'.	Some rules for seismic design of RC buildings were provided: • Maximum heights for RC framed buildings depending on seismic zone, i.e. 21 m or 6 floors + basement for the seismic (zone) Category I (high seismicity), and 24.5 m or 7 floors + basement for the seismic (zone) Category II. • Lateral forces equal to 0.1 and 0.07 times the weight of each storey in the seismic (zone) Category I and II, respectively.
	L 1086/1971 - Law No 1086 of 5 November 1971, 'Rules for reinforced concrete, normal and pre-stressed concrete, and steel structures'.	This law did not include any seismic provisions, but it was the basis for an important improvement of the quality of RC structures by introducing the following provisions: • Assessment of mechanical properties of concrete and steel during the construction works by specific laboratory tests. • Responsibilities of structural designer and submission of structural design to the Civil Engineering Office.
	L 64/1974 - Law No 64 of 2 February 1974.	This law represents the basis of the recent Italian Building codes, stating that the modernisation of building codes was entrusted to Ministerial Decrees.
	DM 3/3/1975 – Ministerial Decree of 3 March 1975, 'Approval of the technical standards for buildings in seismic areas'.	The following rules were recognised: • Definition of seismic action through a response spectrum. • Possibility that the structure could exceed a strictly elastic behaviour. • Removal of rules about the maximum height for RC frame structures.
	DM 02/07/1981 – Ministerial Decree of 2 July 1981, 'Provisions for repairing and strengthening of buildings damaged by the earthquake in the regions Basilicata, Campania and Puglia'.	This decree provided rules for performing structural design for the rehabilitation of buildings damaged by the catastrophic earthquake of 23 November 1980.

Cont.

Phase	Legislative document/ Year	Main provisions
Phase III (Moderate code)	**DM 16/01/1996** – Ministerial Decree of 16 January 1996, 'Technical standards for constructions in seismic areas'.	Some important changes were introduced, as follows: • Possibility of performing, also in seismic zones, safety verifications based on the ultimate limit state method, along with the allowable stress design method. • Provisions for the limitation of damage to non-structural elements, by limiting the maximum interstorey drift

DM: Ministerial Decree; DL: Decree-Law; L.: Law; RD: Royal Decree.

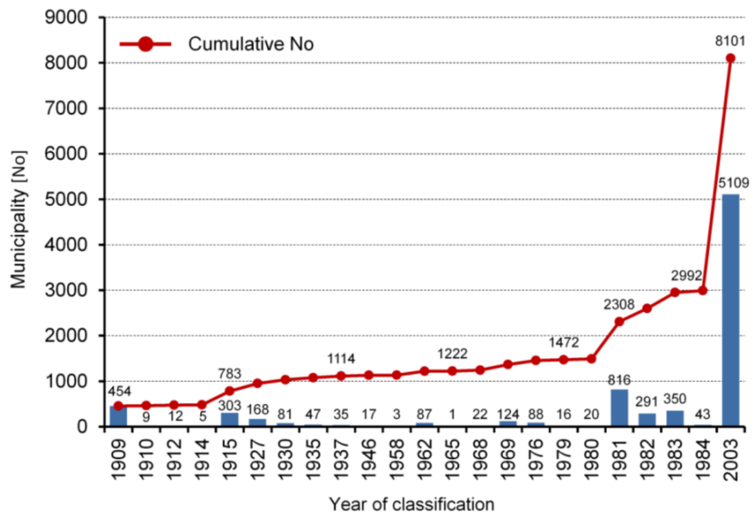
— **Phase IV** (High code) - The 2002 Molise earthquake, which caused the tragic loss of 27 pupils and a teacher due to the collapse of a masonry primary school, led to the beginning of the modern seismic design code wave with the adoption of the Ordinance of the President of the Council of Ministers (OPCM) 3274/2003 (OPCM 3274/2003). The latter was completely different from the previous standard (i.e. DM 16/01/1996, in conjunction with DM 20/11/1987) due to the introduction of the limit states method for the design and retrofit of buildings in line with the Eurocode 8 (CEN 2004).

  The OPCM 3274/2003 was followed by the 'Italian Technical Code for Constructions' in 2008 (NTC 2008), according to the Ministerial Decree of 14 January 2008 (DM 14/01/2008), which enforced the performance-based design approach with the introduction of specific limit states devoted to operation, damage limitation, life safety, and collapse prevention of structures. Furthermore, capacity design and local ductility criteria were prescribed. The Italian building code NTC 2008 entered in force after the 2009 L'Aquila earthquake (Abruzzo region) and it was updated in 2018 (NTC 2018) according to the Ministerial Decree of 17 January 2018 (DM 17/01/2018).

3.1.1.1 Evolution of the seismic zonation of Italian territory

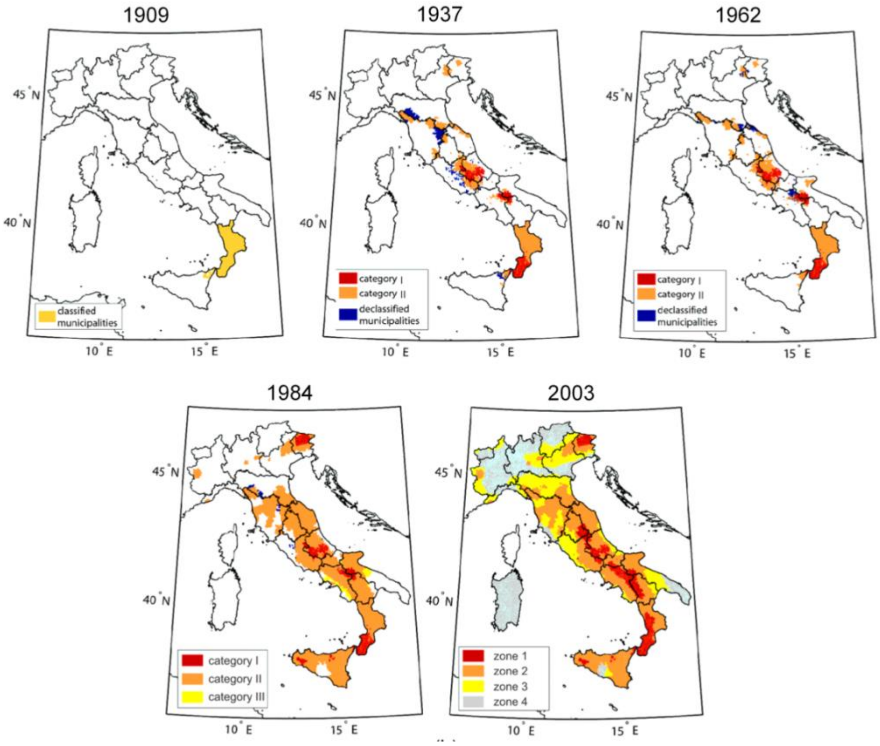
The evolution of the seismic zonation of the Italian territory reflects the development of specific legislative steps related to the evolution of the Italian seismic design code, as well as the occurrence of severe earthquakes. The distribution of the number of new municipalities classified as seismic over time, from the first Italian seismic design code (RD 193/1909) to the adoption of the first modern seismic design code (OPCM 3274/2003) is depicted in Figure 25, along with the evolution of the seismic zonation maps of the Italian territory (Figure 26). The most significant evolution steps are presented in the following, but a comprehensive review is reported in Di Pasquale e al. (1999a, b).

Figure 25. Distribution of the number of Italian municipalities classified as seismic by year (1909 - 2003)



Source: Data – Di Pasquale et al., 1999b, OPCM 3274/2003

Figure 26. Evolution of the seismic zonation maps of the Italian territory (1909 - 2003)



Source: ©Petruzzelli and Iervolino, 2021 (CC BY 4.0)

After the first seismic zonation by classifying 454 Italian municipalities as seismic in the regions Calabria and Sicily according to the Royal Decrees 193/1909 (RD, 193/1909) and 542/1909 (RD 542/1909), following the 1908 Messina earthquake, a series of legislative acts were issued in the following two decades in order to update the lists of municipalities classified as seismic based on the earthquakes occurred in those years. The most relevant legislative steps refer to the Royal Decree 573/1915 (RD 573/1915) leading to the addition of municipalities in Lazio and Abruzzo regions after the 1915 Avezzano earthquake in Abruzzo, followed by the Royal Decree 431/1927 (RD 431/1927), which introduced two seismic zones, named Category I (high seismicity) and Category II (moderate seismicity).

During the period 1937 - 1962, the evolution of the seismic zonation was characterised by the absence of significant steps with the main changes essentially addressing the seismic de-classification of Italian municipalities, which changed their status from seismically to non-seismically prone areas. A crucial aspect was underlined by the Law 1684/1962 (L 1684/1962), which claimed that seismic codes should have been applied not only to municipalities hit by an earthquake, but also to the ones subjected to intense seismic activity. However, this prescription remained substantially void until the early '80s (Petruzzelli and Iervolino, 2021).

After the 1976 Friuli earthquake, a research project (i.e. the so-called Progetto Finalizzato Geodinamica – in Italian) was promoted by the Italian National Research Council leading to the development of a new approach, partially based on probabilistic criteria, to update the seismic zonation of the Italian territory in macroseismic intensity maps. Thanks to this pioneering project, new significant improvements in the Italian seismic zonation were pointed out during '80s by means of the Ministerial Decrees of 3 June 1981 (DM515/1981) and 19 June 1984 (DM 19/06/1984), issued after the 1980 Irpinia-Basilicata earthquake. These decrees introduced a third seismic zone, named Category III, and for the first time the seismic zonation involved additional geographical areas not recently affected by an earthquake. The period 1981-1984 was characterised by a significant increase of the number of new Italian municipalities classified as seismic, reaching an extent of more than 1500. Hence, a cumulative number of nearly 3000 Italian municipalities (Meletti et al., 2014) was indicated as seismic prone in 1984, thus 45 % of the Italian territory was classified as seismic.

Afterwards, the seismic zonation of the Italian territory remained unchanged for the following two decades. The lack of updates related to the seismic zonation of the Italian territory dramatically emerged at the beginning of the 21th century, after the 2002 Molise earthquake, which hit a geographical area not classified as seismic at that time. This tragic event provided the major impulse related to the seismic zonation of Italian territory by issuing the OPCM 3274/2003, which introduced a seismic zonation based on probabilistic values of the expected PGA. The entire Italian territory was classified as seismic prone by considering four seismic zones (SZ), from SZ1 to SZ4, characterised by decreasing seismic hazard levels, identified by specific values of PGA on stiff soil (rock) with an exceeding probability of 10 % in 50 years (corresponding to a return period of 475 years). Consequently, more than 5100 municipalities were further classified as seismic to cover the entire Italian territory, leading to a cumulative number of more than 8000 municipalities recognised as seismic in 2003. According to the following 2006 Ordinance of the President of the Council of Ministers (OPCM 3519/2006), the four SZs were identified by four ranges of PGA values with a 10 % probability of exceedance in 50 years: (i) ZS1 - PGA > 0.25g, (ii) ZS2 - 0.15g <PGA $\leq$ 0.25g, (iii) ZS3 - 0.05g <PGA $\leq$ 0.15g, and (iv) ZS4 - PGA $\leq$ 0.05g.

The introduction of the modern seismic design code significantly modified the role of the seismic zonation for structural design purposes. In fact, according to the Italian building code NTC 2008 (DM 14/01/2008), design values of seismic actions refer to seismic hazard, expressed as local PGA values depending on geographical coordinates of the project area instead of seismic zones.

Based on the brief overviews related to the evolution of Italian seismic design code and seismic zonation of the Italian territory, it is evident that the majority of Italian existing masonry and RC buildings may be subjected to seismic vulnerability, since they do not comply with the modern seismic requirements provided in the NTC 2008 and in its updated version NTC 2018. Indeed, both standards have a poor influence on seismic performance of existing residential masonry and RC buildings since a very low extent of new constructions have been erected after their entry in force (as demonstrated in Section 3.2.1 and Section 3.3.1 related to residential masonry and RC buildings, respectively). Furthermore, only 25 % of the Italian territory was classified as seismic until 1980, when more than 80 % of the Italian residential buildings were already constructed, thus seismic strengthening interventions are extensively needed to enhance the structural performance of the Italian existing building stock.

3.1.2 Evolution of the Italian legislation on energy efficiency of buildings

The evolution of the Italian legislation on energy efficiency of buildings can be subdivided into two main eras, whose reference time was marked by the introduction of the EU EPBD (Directive 2002/91/EU) in 2002. The pre-2002 era refers to the first generation of the national legislation on energy efficiency adopted into the period 1970-2001, whereas the post-2002 era includes the second generation of national regulations on energy efficiency to implement the EU EPBD requirements, according to their evolution over time. The two main eras are presented in the following, indicating their main legislative developments.

3.1.2.1 The pre-2002 Italian legislation on energy efficiency of buildings

The first Middle East oil embargo in 1973 against countries supporting Israel during the Fourth Arab-Israel War, led to a worldwide energy crisis, causing United States and Western European countries to reassess their dependence upon Middle Eastern oil and posing great emphasis on improving energy efficiency. The Italian response to this crisis resulted into the first Italian legislative step on energy efficiency in 1976 by issuing the Law 373/1976, aimed to reduce the energy consumption of buildings. The most relevant provision introduced by this law addressed thermal insulation criteria in building design by providing stringent threshold values of the thermal capacity of the building envelope to reduce heat loss and, consequently, the energy demand.

The Law 373/1976 was repealed in 1991, when the Italian Law 10/1991 was issued to implement the National Energy Plan for the energy use, energy saving, and renewable energy use. The Law 10/1991, which is currently recognised as the first energy efficiency standard in Italy, introduced requirements for the reduction of the energy consumption of buildings along with new thermal criteria for the design and management of building envelope/energy consumption systems. The application of this law was implemented by two following Decrees of the President of the Italian Republic (DPR), i.e. DPR 412/1993 and DPR 551/1999, regulating the calculation method of the annual energy demand for space heating of a building based on the HDD parameter and the volume of the building. Hence, the DPR 412/1993 introduced the classification of the Italian territory in six climatic zones, from A to F (i.e. from the warmest to the coldest zone), as a function of the HDD (setting a baseline temperature equal to 20°C), thus corresponding to increasing energy demand for space heating.

3.1.2.2 The post-2002 Italian legislation on energy efficiency of buildings

Since the beginning of the 21th century, the temporal evolution of the Italian legislation on energy efficiency of buildings has reflected the national implementation of the EU EPBD, from its first adoption (Directive 2002/91/EU), via its recast (Directive 2010/31/EU), to its revision (Directive (EU) 2018/844) – hereinafter indicated as EPBD I, EPBD II, and EPBD III, respectively - leading to three main evolution phases, as follows:

— **EBPD I implementation in Italy** (2005-2009) - The first EU legislative step related to energy efficiency in the construction sector dates back to the beginning of 90's with the adoption of the directive 1993/76/EEC, also known as SAVE, aimed at tackling the issue of climate change by reducing CO_2 emissions. The EU impulse to deal with the energy performance of buildings was achieved one decade later by the adoption of the 2002 EPBD (Directive 2002/91/EU) to meet the 1997 Kyoto protocol objectives. The main provisions introduced by the EPBD I refer to the following areas: (i) the calculation method of the energy performance of buildings by considering all the energy use (e.g. heating, cooling, domestic hot water, lighting, etc.), (ii) the minimum requirements on the energy performance of new and existing buildings under major renovation, (iii) the release of energy performance certificates (EPCs) for new and existing buildings, representing a sort of energy passport of buildings, and (iv) regular inspections of heating and air-conditioning systems.

  The implementation of the EPBD in Italy is a shared task between the State, the Regions and the Autonomous Provinces, and it is applied at three levels: (i) national level, devoted to monitoring of the energy policy, (ii) regional level, focused on technical guidelines, rules and general inspections, (iii) local level (province, municipality), dedicated to inspections (Salvalai et al., 2015). Specifically, the Legislative Decree (DLgs) 192/2005, amended by the DLgs 311/2006, set the basis for the EPBD I implementation in Italy (Costanzo et al., 2016). According to the transposition of the EPBD I provisions, these two Italian decrees provided threshold values for both the annual energy demand for space heating and thermal transmittance (U-values) of opaque and transparent components of building envelope (Annex C of the DLgs 192/2005) depending on the Italian climatic zones (as classified in the DPR 412/1993). This initial step of implementation was followed by a series of complementary legal acts in 2009. Specifically, the DPR 59/2009 was adopted to update the calculation method and the minimum energy requirements provided by the DLgs 192/2005, also introducing threshold values for the annual energy demand for space cooling. At the same time, the Ministerial Decree of 26 June 2009 (DM 26/06/2009) provided the national guidelines, specifying the procedures, the performance classes and elements for certification, to carry out the compulsory EPC of buildings by an independent assessor, as required in the EPBD I. Specifically, eight energy performance classes, from A+ to G corresponding to decreasing level of the energy efficiency of a building, were identified, and the selection of the energy class for a specific building depends on the assessment of the global energy performance index (EP_{gl}) including heating, cooling, and domestic hot water, along with lighting in case of non-residential buildings and expressed in KWh/m^2y.

— **EBPD II implementation in Italy** (2013 - 2015) - The first version of the EU EPBD was followed by its recast in 2010, leading to the adoption of the EPBD 2010/31/EU, which added several new or strengthened requirements to overcome the fragmented framework related to energy issues in the construction sector and extend the scope of the 2002 EPBD. Key changes were related to the following points: (i) development of a comparative methodology for calculating cost-optimal levels of minimum energy performance requirements, (ii) all new buildings to be nearly zero energy by December 2020 (December 2018 for public buildings), (iii) Member States to list fiscal incentives to enable the transition to energy efficiency of buildings, (iv) mandatory EPCs for all properties constructed, sold or rented out, and (v) enhanced heating and cooling system inspections and reporting requirements.

  In Italy, the Law 90/2013, converting the Decree-Law 63/2013 into law to implement the EPBD II at national level, provided significant changes to the first 2005 implementation (Dlgs 192/2005). One of the main novelty included in the new law refers to the nZEBs by both introducing the nZEB definition and setting new criteria and energy performance requirements of buildings, with the energy demand needing to also be covered by renewable energy source. The implementation of the EPBD II was completed with the adoption of the Ministerial Decree of 26 June 2015 (DM 26/06/2015), consisting of three inter-ministerial decrees focused on (i) minimum energy performance requirements of buildings (DM 26/06/2015 (15A05198)), (ii) technical report on building project attesting the minimum energy performance requirements (DM 26/06/2015 (15A05199)), and (iii) EPC guidelines (DM 26/06/2015 (15A05200)). Attention is briefly paid to the first and third inter-ministerial decrees, since they provide significant changes to the legislation on energy efficiency of buildings. The first decree included an updated energy performance calculation methodology, new stricter minimum energy performance requirements for buildings, building systems and building components, as well as primary energy conversion factors. The third decree introduced a new EPC system, harmonised on national territory, and established a new energy rating system based on the assessment of the global energy performance (including heating, cooling, domestic hot water, and ventilation, plus lighting and transport for non-residential buildings) in non-renewable primary energy ($EP_{gl,nren}$), expressed in KWh/m^2y. The resulted $EP_{gl,nren}$ index of the analysed building enables its energy performance class to be identified among ten energy classes, from A (the most efficient), subdivided in 4 classes (from A4 to A1), to G (the least efficient). The energy classes are defined by means of the $EP_{gl,nren}$ index of the reference building, equipped with the envelope components and energy systems compliant with the minimum energy performance requirements in force from 2019/2021 ($EP_{gl,nren,rif,standard(2019/21)}$), according to the DM 26/06/2015. This index indicates the threshold value between the A1 and B classes. The ranges defining the other classes are obtained by multiplying the $EP_{gl,nren,rif,standard(2019/21}$ by specific reduction or incremental coefficients.

— **EBPD III implementation in Italy** (2020 to date) **–** The EPBD 2010/31/EU along with the Energy Efficiency Directive (EED) were revised in 2018 (Directive 2018/844), as part of the 2016 Clean Energy for All Europeans package, to ensure that buildings play their part in achieving the overall EU Climate and Energy goals to 2030 and 2050. The main amendments aimed to modernise the EU's building sector and to increase the renovation rate of the existing buildings. A significant change concerned the establishment of strong long-term renovation strategies (LTRS) (moved from the 2012 EED) for a fully decarbonised European building stock by 2050, also mobilising national financing and investments to improve the energy efficiency of buildings. Furthermore, measures related to seismic risk and fire safety were encouraged for planning LTRS. The introduction of smart readiness indicator was also indicated and the requirement of nZEBs for all new buildings as of 2021 was enforced. The directive also required EU Member States to set cost-optimal minimum energy performance requirements for new buildings, existing buildings under major renovation, and replacement of building envelope components and/or energy system by applying a harmonised calculation methodology.

  In Italy, the DLgs 48/2020 transposed the EU EPBD III at national level, with the main objectives to foster the energy upgrading of existing buildings and integrate the LTRS to mobilise fiscal resources for the construction of nZEB buildings by 2050. Main amendments refer to the EPCs, inspections of energy systems, and revision of criteria for fiscal incentives to boost the energy renovation of buildings. To this end, it is worth mentioning the 'Ecobonus' mechanism, first introduced in Italy in 2007, updated over the years and currently regulated by the Law 234/2021, to foster the energy retrofit of existing buildings by achieving substantial tax deductions (e.g. up to 75 % of the total expenses as for interventions to block of flats). Furthermore, energy efficiency interventions can be combined with seismic strengthening ones (i.e. 'Sismabonus' mechanism) increasing the limit of maximum tax deduction up to 110 % according to the so-called 'Superbonus' mechanism introduced as part of the measures for the Italian economic relaunch after the Covid-19 pandemic (DL 34/2020).

This synopsis underlines that the Italian legislation on energy efficiency of buildings is quite recent with stringent requirements adopted only in the last three decades. Hence, the energy retrofit of the existing buildings becomes a high-priority issue, also considering that the European Commission has recently proposed the revision of the EPBD (Proposal COM (2021)802) as an essential element of the Renovation Wave strategy (COM (2020)662) to set out how Europe can achieve a zero-emission and fully decarbonised building stock by 2050. The proposed measures aim to increase the renovation rate of existing buildings with particular reference to the worst-performing ones in each Member State.

3.2 Prioritisation of Italian masonry buildings needing seismic strengthening and reduction of energy inefficiency

A simplified prioritisation of the Italian masonry residential buildings aimed at identifying the related building typologies most needing combined seismic and energy retrofit is based on a three-step procedure, briefly described as follows:

1. **Analysis of statistics related to the Italian masonry residential building stock** – This step deals with the investigation of the Italian masonry residential building stock in order to collect data on its age and its geographical distribution, according to the 2011 Census of the Italian Statistical Institute (ISTAT).

2. **Combination of seismic and climatic zones** – This step focuses on the identification of the Italian geographical areas where the combined seismic and energy retrofit demand results high, also defining the corresponding distribution of masonry buildings.
3. **Identification of masonry building typologies needing combined seismic and energy retrofit** – Based on the combination of the outcomes of Step 1 and 2, two routes of investigation, namely a seismic-driven and an energy-driven investigation, are carried out in order to identify potential Italian masonry building typologies most needing combined retrofit. The seismic-driven investigation focuses on a detailed analysis of the database on post-earthquake damage and compliance with safety requirements to collect further data on structural typology, size, and age of the Italian existing masonry building stock, whereas the energy-driven investigation aims to provide data on building envelope and its corresponding thermal properties.

A detailed description of each above-mentioned step is provided in the following.

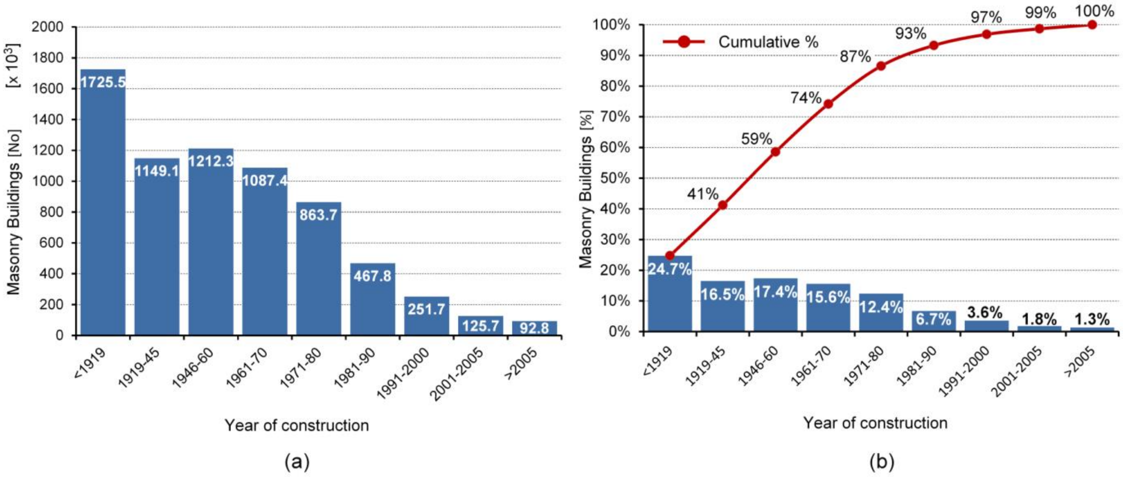
3.2.1 The Italian masonry residential building stock

The Italian masonry residential buildings are nearly 7 million, accounting for about 57 % of the entire Italian residential building stock, which consists of a total number of buildings equal to more than 12 million. A detailed analysis of the Italian masonry residential building stock by year of construction and its geographical distribution has been carried out according to the statistics provided by the 2011 Census of the Italian Statistical Institute (ISTAT, 2011). The main outcomes of this twofold investigation are described in the following.

3.2.1.1 Distribution of Italian masonry buildings by year of construction

The distribution of the Italian masonry residential building stock by year of construction (Figure 27a) shows that the oldest buildings date back to 1919 and early decades, thus data also include historical masonry residential buildings erected during the 19th century. It is not surprising that the period before 1919 accounts for the highest number of masonry buildings equal to 1.7 million. Indeed, they become widespread in Italy in the past centuries due to the availability of natural blocks (e.g. rocks) in several regions substituted by artificial blocks (e.g. clay bricks) in locations where the raw material supply was absent. Hence, the use of masonry as main construction material was undisputed in Italy until the 2nd World War, when the requirement of rapid constructions with less architectural restraints arose to meet the need of housing a large extent of people in short time. RC buildings initiated to gain a great consensus to effectively achieve this objective. Regardless the growing popularity of RC buildings, the construction rate of masonry residential buildings continued to increase, nearly constantly, with an average extent equal to about 1 million of new constructions per decade until 1980. However, the following decades were characterised by the decline of the construction of new masonry buildings accounting for negligible shares.

Figure 27. Distribution of the Italian masonry residential buildings by year of construction, expressed in terms of: (a) number of buildings, and (b) percentage of buildings and its corresponding cumulative percentage



Source: Data - Italian National Statistical Institute (ISTAT), 2011

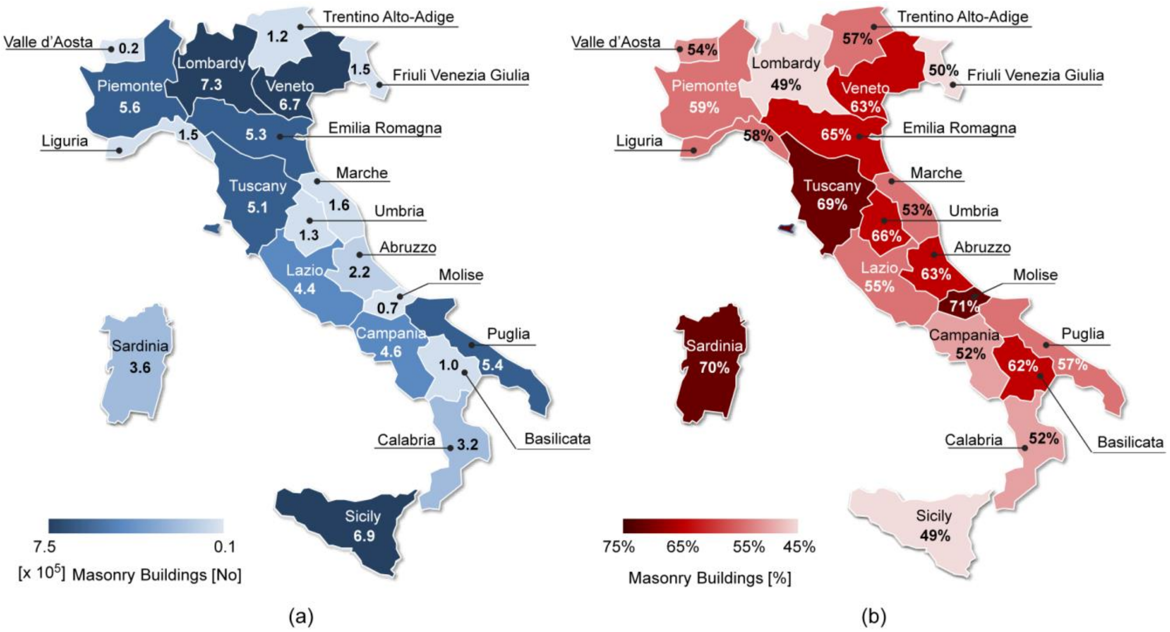
The analysis of these figures (Figure 27b) points out that nearly 60 % of the entire Italian masonry residential building stock is more than 60 years old and 87 % of it was erected before 1980. Hence, nearly the total share of the existing masonry residential buildings in Italy is compliant neither with the provisions issued by the 1987 first harmonised seismic design code of masonry buildings (DM 20/11/1987) in conjunction with the 1996 moderate seismic design code (DM 16/01/1996), nor with the energy efficiency requirements provided by the 1991 first Italian regulation (Law 10/1991). These remarks make evident that an extensive combined retrofit of the existing Italian masonry building stock is highly required.

3.2.1.2 Geographical distribution of Italian masonry buildings

The geographical distribution of the Italian masonry residential building stock has been investigated according to two main levels: (i) by region (i.e. NUTS-2 level) and (ii) by municipality.

As for the analysis at regional level, Lombardy results the Italian region with the highest number of masonry residential buildings (0.73 million), followed by Sicily (0.69 million) and Veneto (0.67 million) based on the total extent of the Italian masonry residential buildings (Figure 28a). Furthermore, the investigation of the single residential building stocks of each Italian region enables to estimate the corresponding percentage distribution of masonry residential buildings per region (Figure 28b), identifying the Italian locations where the use of masonry was more prevalent than other construction materials (e.g. RC, timber, steel). Molise and Sardinia account for the largest shares of masonry residential buildings with a percentage equal to more than 70 % of the entire number of residential buildings erected in either regions, followed by Tuscany, Umbria, and Emilia Romagna with shares of masonry buildings ranging into a high percentage equal to 69-65 %. Abruzzo and Basilicata also account for relevant percentages equal to 63 % and 62 %, respectively.

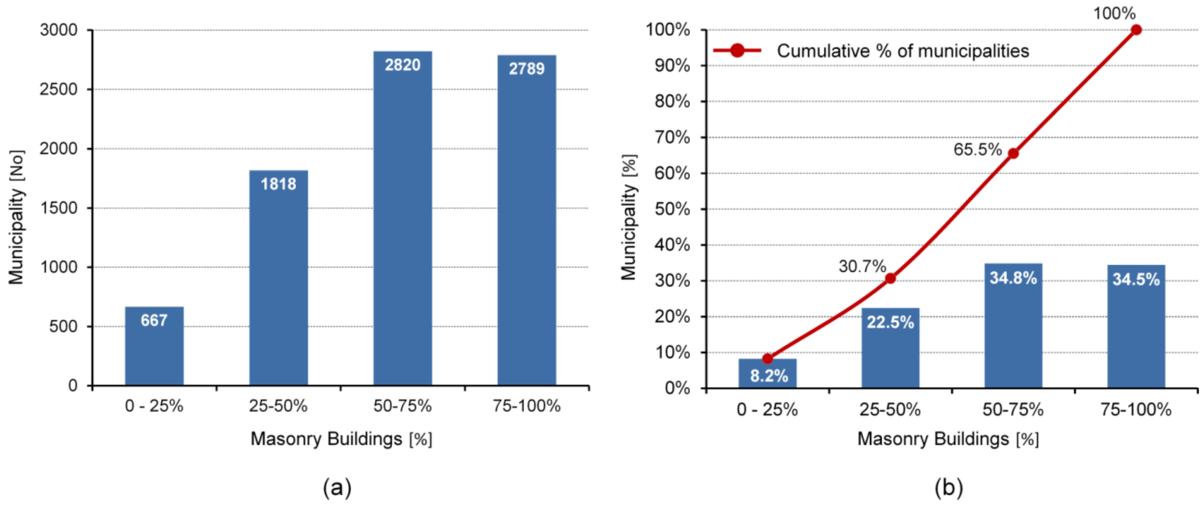
Figure 28. Geographical distribution of Italian masonry residential buildings at regional level: (a) number of masonry buildings by region, and (b) percentage of masonry buildings over the total number of buildings in each region.



Source: Data - Italian National Statistical Institute (ISTAT), 2011

As for the analysis at municipality level, the distribution of a total number of 8094 Italian municipalities was carried out by percentage range of masonry buildings (Figure 29a). Statistical data show that one third (i.e. nearly 35 %) of Italian municipalities (i.e. more than 2700) accounts for at least 75 % of the whole masonry residential building stock, and at least 50 % of the entire number of Italian masonry residential buildings are located in nearly 70 % of municipalities (i.e. the sum of the percentages in the third and fourth bars of the chart in Figure 29b).

Figure 29. Distribution of Italian municipalities by percentage range of masonry buildings, expressed in terms of (a) number of municipalities and (b) percentage of municipalities and its corresponding cumulative percentage



Source: Data - Italian National Statistical Institute (ISTAT), 2011

3.2.2 Combination of Italian seismic hazard zones and climatic zones

The analysis of the Italian territory in terms of seismic hazard and climatic conditions is needed to provide useful information on the Italian geographical areas where the combined retrofit of the existing masonry building stock is most required based on the most severe seismic-energy demand.

This investigation is carried out according to a simplified-to-detailed approach leading to a two levels of analysis identifying Italian seismic-climatic zones (SCZs): (i) Level 1 – Simplified analysis, and (ii) Level 2 – Detailed analysis – hereinafter indicated as Level 1 analysis and Level 2 analysis, respectively. The Level 1 analysis is first carried out by combining the Italian seismic zones and climatic zones, according to the OPCM 3519/2006 and the DPR 412/1993, respectively, in order to achieve a preliminary rapid outcome on priority areas, also identifying the corresponding number of masonry residential buildings. Subsequently, a more detailed analysis relying on more accurate data to analyse the combined seismic and climatic severity of the Italian territory is considered. Specifically, the local values of HDD (instead of the climatic zones) and PGA (instead of the seismic zones) are considered at municipality level in order to overcome the limitation of an excessive aggregation of data as in the Level 1 analysis. Both analyses are presented in the following.

3.2.2.1 Level 1 - Simplified analysis combining seismic zones and climatic zones

The simplified analysis for combining seismic hazard and climatic conditions in Italy relies on the national territory mapping in seismic zones and climatic zones. Specifically, four seismic zones (SZ), defined as a function of the PGA having an exceedance probability of 10 % in 50 years, were considered according to the OPCM 3519/2006: (i) SZ1 (PGA > 0.25g), (ii) SZ2 (0.15g < PGA ≤ 0.25g), (iii) SZ3 (0.05g < PGA ≤ 0.15g), and (iv) SZ4 (PGA ≤ 0.05g). Six climatic zones (CZ), corresponding to the classification provided by the DPR 412/1993, were defined, ranging from A to F for increasing heating energy demands based on HDD: (i) CZ1=A (HDD ≤ 600), (ii) CZ2=B (600 < HDD ≤ 900), (iii) CZ3=C (900 < HDD ≤ 1400), (iv) CZ4=D (1400 < HDD ≤ 2100), (v) CZ5=E (2100 < HDD ≤ 3000), and (vi) CZ6=F (HDD > 3000).

The four seismic and six climatic zones were combined into a 24-cell matrix, showing the number of the Italian masonry residential buildings corresponding to each of the 24 potential combinations of SCZs, as reported in Table 5. Specifically, the number of buildings was aggregated at municipality level (a total number of 8100 Italian municipalities was considered) and distributed by the combined SCZs. The distributions of the total number of masonry buildings by seismic zone or climatic zone are also provided in Table 5.

Table 5. Seismic-climatic matrix and distribution of the Italian masonry residential buildings by seismic-climatic zones, according to the Level 1 – Simplified analysis

Climatic zone (CZ)	Seismic zone (SZ)				Total
	1	2	3	4	
A		1315	1336		**2651**
B	62687	77657	51350	103869	**295563**
C	130781	541547	327456	440634	**1440418**
D	200141	569568	435088	448264	**1653061**
E	361191	965459	829201	985250	**3141101**
F	52078	127659	126665	136781	**443183**
Total	**806878**	**2283205**	**1771096**	**2114798**	**6975977**

Source: Data – OPCM 3274/2003; Annex A of the DPR 412/1993; ISTAT, 2011

The 24 seismic-climatic combinations can be reduced to four main SCZs by correlating the aggregated seismic zones 1-2, and 3-4 with the aggregated climatic zones A-B-C and D-E-F, in order to achieve four different severity levels of combined seismic-energy demand. The four SCZs are depicted in Table 6, where the total number of masonry buildings per SCZ is also indicated. The SCZ1 (seismic zones 1-2 with the climatic zones D-E-F) is characterised by high seismic hazard and severe climatic conditions. It was estimated that one third of the Italian masonry residential building stock is located in the SCZ1, thus potentially requiring a high demand for combined retrofit. The SCZ3 (seismic zones 3-4 with the climatic zones A-B-C), is the less severe SCZ in terms of both seismic hazard and climatic conditions, thus requiring a low demand for combined retrofit. The remaining two SCZs, i.e. SCZ2a (seismic zone 1-2 with the climatic zones A-B-C) and SCZ2b (seismic zone 3-4 with the climatic zones D-E-F) require a moderate demand for combined retrofit with the SCZ2a potentially characterised by a prevalent demand for seismic retrofit, whereas the SCZ2b driven by a predominant demand for energy retrofit. It is worth noting that 54 % of the Italian masonry residential buildings is concentrated in the moderate SCZ (i.e. SCZ2a plus SCZ2b).

Table 6. Identification of four combined seismic-climatic zones and distribution of the corresponding masonry residential buildings, according to the Level 1 – Simplified analysis.

SCZ	Seismic zone (SZ)	Climatic zone (CZ)	Combined demand	Masonry buildings [No]	Masonry buildings [%]
1	**1-2**	**D-E-F**	High	2276095	32.6
2a	**1-2**	**A-B-C**	Moderate	813987	11.6
2b	**3-4**	**D-E-F**	Moderate	2961850	42.5
3	**3-4**	**A-B-C**	Low	924695	13.3
Total				**6975977**	**100.0**

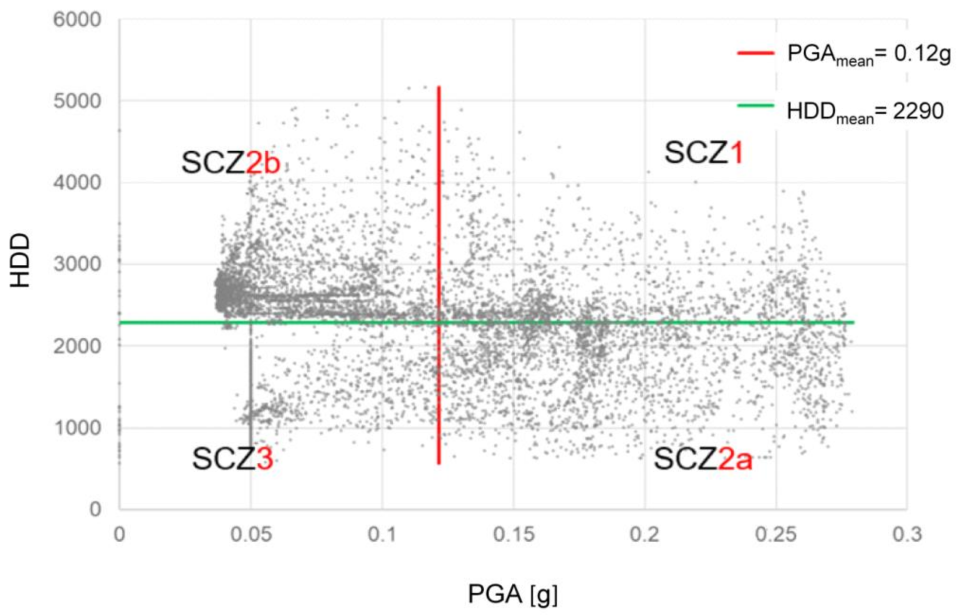
Source: Data – OPCM 3274/2003; Annex A of the DPR 412/1993; ISTAT, 2011

3.2.2.2 Level 2 – Detailed analysis combining PGA and HDD values at local level

The simplified combination of the seismic-climatic zones carried out in the Level 1 analysis needs to be detailed at municipality level by considering local values of both the PGA with 10 % of probability exceedance in 50 years and the HDD, expressing the seismic hazard level and the climatic conditions, respectively. Indeed, the ranges of PGA and HDD values defining the four seismic and six climatic zones used in the simplified analysis indicate a wide variability of seismic hazard and climatic conditions.

Based on these remarks, a detailed analysis for the identification of the SCZs needs to be carried out by considering specific PGA and HDD values for each Italian municipality. Specifically, each of the 8100 Italian municipalities was identified by a pair of values, i.e. local values of PGA and HDD, representing the coordinates of a point. All points as a whole define a point cloud distribution of the Italian municipalities in the PGA-HDD Cartesian plane (Figure 30). The SCZs are obtained by dividing the point cloud distribution in four quadrants by means of two straight lines, representing two constant functions corresponding to the mean values of HDD and PGA, equal to 2290 and 0.12g, respectively. Similarly to the previous simplified analysis, each quadrant identifies one of the four following SCZs: (i) SCZ1 (PGA>0.12, HDD>2290), (ii) SCZ2a (PGA>0.12, HDD<2290), SCZ2b (PGA $\leq$ 0.12, HDD>2290), and (iv) SCZ3 (PGA $\leq$ 0.12, HDD<2290).

Figure 30. Identification of four combined seismic-climatic zones according to local values of PGA and HDD, identifying about 8100 Italian municipalities



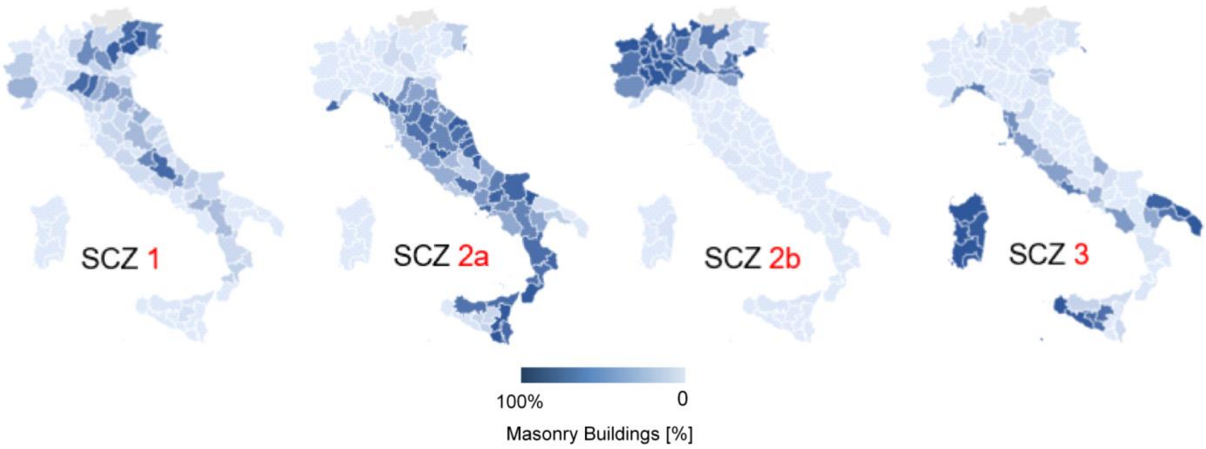
The four SCZs based on local values of PGA and HDD indicate various levels of combined seismic and energy demand, i.e. SCZ1 (high demand), SCZ2a and SCZ2b (moderate demand, with SCZ2a characterised by a seismic-driven demand and SCZ2b by energy-driven demand), and SCZ3 (low demand), similarly to the Level 1 analysis. However, the corresponding distribution of the total number of masonry residential buildings by SCZ (Table 7) differs from the results achieved by the Level 1 analysis. The variability between the two analyses mainly depends on the threshold values of PGA and HDD identifying the four SCZs into the Level 2 analysis. The main difference refers to the lower percentage of masonry buildings concentrated into the SCZ1, equal to 18 %, compared to the extent of buildings equal to 32.6 % related to the simplified analysis.

Table 7. Distribution of masonry residential buildings by seismic-climatic zone, according to local values of PGA and HDD (Level 2 – Detailed analysis)

SCZ	PGA [g]	HDD	Combined demand	Masonry buildings [%]
1	> 0.12	> 2290	High	18
2a	> 0.12	< 2290	Moderate	36
2b	≤ 0.12	> 2290	Moderate	24
3	≤ 0.12	< 2290	Low	22

The distribution of the total number of masonry buildings located in each SCZ by Italian province (i.e. corresponding to the NUTS 3 regions) is depicted in Figure 31.

Figure 31. Distribution of Italian masonry residential buildings in each SCZ by Italian province, according to local values of PGA and HDD (Level 2 – Detailed analysis)



Source: Data - ISTAT, 2011

As for the SCZ1, the highest number of masonry buildings is concentrated in the Italian provinces located along the Apennine areas, mainly in Abruzzo region, requiring a high combined seismic-energy demand. Furthermore, some provinces of Emilia region and northern–eastern Italian areas also result into the SCZ1 with a high percentage of masonry buildings, due to the threshold value of PGA triggering the high level of seismic hazard (PGA > 0.12g), which is lower than the corresponding one considered in the Level 1 – Simplified analysis (PGA > 0.15g, according to the minimum PGA value of the range identifying the SZ2 in OPCM 3519/2006). The majority of masonry buildings concentrated in the SCZ2a are located in the provinces of central and southern Italy, where the seismic hazard is moderate-to-high and the climatic conditions are not so severe, followed by a lower percentage of buildings (about 25 %) concentrated along the Tyrrhenian cost. Conversely, the majority of masonry buildings resulting into the SCZ2b mainly refer to northern-western Italian regions, which are energy-driven areas since they exhibit significant climate conditions in terms of HDD, but a moderate-to-low level of seismic hazard. Finally, the SCZ3 includes Sardinia and southern Puglia regions accounting for the highest percentage of masonry buildings requiring low seismic-energy demand, followed by a lower percentage of buildings (about 25 %) mainly concentrated along the Tyrrhenian cost.

3.2.3 Identification of Italian masonry building typologies needing combined seismic and energy retrofit

A potential method for the identification of potential Italian masonry residential building typologies needing combined seismic and energy retrofit refers to two routes of investigation, as follows:

1. **Seismic-driven investigation** – This analysis deals with the identification of the building typology in terms of structural characteristics, period of construction, number of floors, and average floor area, based on data related to the Italian post-earthquake safety and damage assessment surveys to ordinary buildings, according to the AeDES (Agibilità e Danno nell'Emergenza Sismica, in Italian) forms (Baggio et al., 2007).

   The use of post-earthquake surveys in Italy has became a crucial need for the emergency management and the following recovery phase since the 1976 Friuli earthquake, which also marked the beginning of the development of different inspection operational tools over time, as briefly reviewed in Dolce et al. (2019). The first generation of the Italian post-earthquake surveys was based on vulnerability forms with their own peculiarities depending on reference earthquake (e.g. 1976 Friuli, 1980 Irpinia-Basilicata, 1984 Abruzzo, 1990 Basilicata), thus lacking of data uniformity among the different emergency campaigns. The era of the second generation of the Italian post-earthquake surveys dates back to 1996-1997 with the introduction of a specific tool, the AeDES form, for damage assessment, short term countermeasures for damage limitation and evaluation of the post-earthquake compliance with safety requirements of ordinary buildings (Baggio et al., 2007). The occurrence of the 1997 Umbria-Marche earthquake accelerated the implementation process of this new type of form, which was used into its preliminary version (i.e. AeDES 09/97) after this seismic event to inspect buildings located in Marche region. A different inspection tool was used for the post-earthquake survey of buildings located in Umbria. In the following years, the AeDES form was subjected to some modifications to reach an optimised version in 2000, becoming, since 2002, the official operational tool recognised by the Italian Civil Protection Department (DPC) for the technical management of post-earthquake emergencies. The national use of the AeDES form was also enforced at the Italian legislation level in 2011 through the Decree of the President of the Council of Ministers (DPCM), issued on 5 May 2011 (DPCM 5/05/2011). This outcome represented an essential step in the field of post-earthquake surveys by ensuring a harmonised collection of data since the post-2002 Italian earthquakes. The current version of the AeDES form (i.e. AeDES 07/13) consists of nine sections related to different aspects: (i) *Section 1 - Building identification*, (ii) *Section 2 - Building description*, (iii) *Section 3 - Building typology*, (iv) *Section 4 - Damage to structural components*, (v) *Section 5 - Damage to non-structural components*, (vi) *Section 6 - External damage due to other constructions*, (vii) *Section 7 – Soil and foundations*, (viii) *Section 8 – Judgment of compliance with safety requirements to use the building*, and (ix) *Section 9 – Other observations*. A detailed illustration of each section is provided in Baggio et al. (2007).

   The huge amount of data collected since 1976 represent an invaluable scientific heritage to improve the reliability of seismic risk models. However, the dissimilarities among the various pre-AeDES forms, as well their differences with the post-AeDES ones led to the impossibility of creating a unique dataset for more than 40 years. This issue was faced in 2014 by means of a scientific project conducted by the Italian Civil Protection Department (DPC) with the technological support of Eucentre Foundation leading to the development of a WebGIS platform, named Database of Observed Damage (Da.O.D) to collect, catalogue and compare data on structural characteristics and seismic damage of ordinary buildings inspected after the severe seismic events occurred in Italy since the 1976 Friuli earthquake (Dolce et al., 2019). Data from both pre-AeDES and post-AeDES survey forms were included. However, the limitation of their dissimilarities was faced by keeping the various datasets separate from each other, but providing them to users in both the original and decoded format, in order to enable some comparison among corresponding fields. Moreover, homogenisation processes related to vulnerability classes and damage levels have been implemented in the platform (Dolce et al., 2019). Currently, the Da.O.D includes 11 databases on seismic events, i.e. Friuli 1976, Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise and Puglia 2002, Emilia 2003, L'Aquila 2009, Emilia 2012, Garfagnana-Lunigiana 2013, and Mugello 2019.

2. **Energy-driven investigation** is focused on the analysis of the thermal characteristics of the building envelope, referring to the structural typologies identified in the previous investigation.

   The energy-driven investigation relies on data collected within the 2009-2012 Intelligent Energy Europe (IEE) project 'Typology Approach for Building Stock Energy Assessment' (TABULA), which led to the development of a series of databases of the national building typologies representing the residential building stock of 21 European countries, implemented into a dedicated web-based tool, named TABULA WebTool. Each national building typology consists of a classification scheme grouping buildings according to their size, age and further parameters and a set of exemplary buildings representing the building type. Furthermore, the tool provides statistical data for buildings and supply systems, and enables an online calculation of typical values of both the energy consumption and the energy saving potentials.

The implementation of the two above-mentioned routes is separately described in the following.

3.2.3.1 Seismic-driven investigation

The seismic-driven investigation to identify potential Italian masonry building typologies most needing seismic retrofit relies on the analysis of the outcomes of the Italian post-earthquake damage and usability surveys to ordinary buildings according to the AeDES forms related to the 2012 Emilia earthquake and retrieved from the Da.O.D platform in their original version. The choice of the 2012 Emilia database depends on two main factors, as follows:

- A high percentage (i.e. 65 %) of the existing residential building stock of this region accounts for masonry buildings (Section 3.2.1).
- According to the Level 2 analysis for the simplified prioritisation of regions where combined seismic and energy retrofit of buildings is needed, provinces of Emilia region result into both the SCZ1 and SCZ2a, identified by a high and moderate seismic-energy demand, respectively (Section 3.2.2.2)

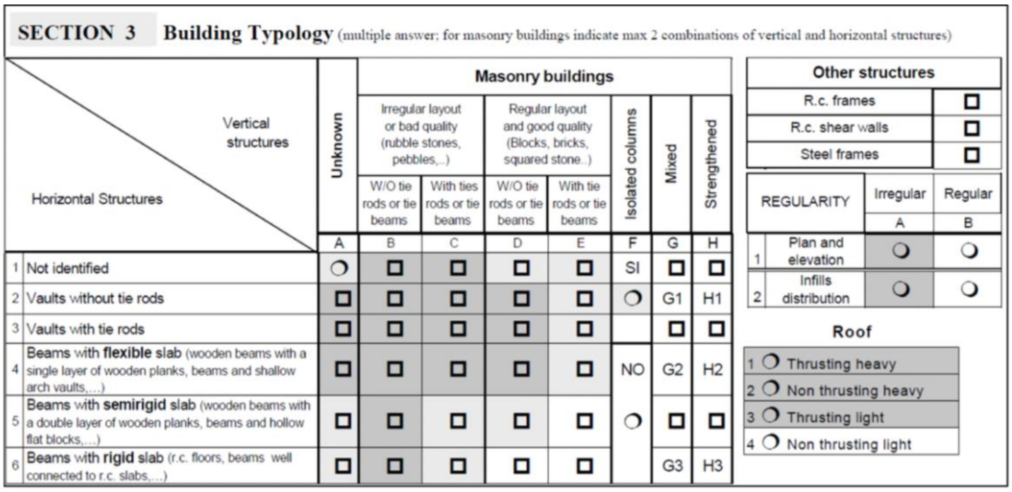
Hence, the following investigation is related to Italian masonry building typologies representative of the Emilia region, and potentially also indicative of the existing masonry building stock located in the north-eastern Italian areas.

In 2012, the north-eastern geographical area of the Emilia region (i.e. part of the provinces of Modena, Ferrara, and Bologna) was hit by a severe earthquake sequence, characterised by two main shocks and thousands of aftershocks. The first main shock displaying a local magnitude M_L 5.9 (M_w 5.86) occurred on 20 May 2012; its epicenter was located in Emilia region, about 30 km to the West of Ferrara (Dolce and Di Bucci, 2014). A second severe shock with a M_L 5.8 (M_w 5.66) occurred on 29 May 2012, about 20 km to the West of the previous one, also affecting the southern portion of the province of Mantova in Lombardy and some municipalities of the province of Rovigo in Veneto. The overall seismic sequence caused 27 victims, 400 injured and tens of thousands evacuees, as well as damages to historical and ordinary buildings, and to local farms and industrial buildings leading to an estimation of the overall economic loss equal to of about 13 billion Euro (Meroni et al., 2017). The majority of casualties was due to the unprecedented number of extensively damaged and collapsed precast concrete industrial buildings (Bournas et al., 2014). However, monumental and rural masonry buildings were also significantly damaged (Parisi and Augenti, 2013, Dolce and Di Bucci, 2014), as well as old ordinary masonry buildings, consisting of solid clay bricks, which showed typical defects and lack of proper detailing with a consequent high level of seismic vulnerability (Penna et al., 2014). One of the most recurrent cause of vulnerability refers to the presence of thrusting or unstable timber roofs leading to partial out-of-plane collapses in residential and farm buildings (Sorrentino et al., 2014, Penna et al., 2014).

The 2012 Emilia database within the Da.O.D. platform includes a total number of 22554 records of ordinary buildings inspected according to the corresponding AeDES forms. An extent equal to nearly 20000 records refers to masonry buildings, which were analysed to collect data on the following aspects:

- **Structural characteristics** – Out of the nine sections of the AeDES form, data on the structural characteristics of inspected buildings are reported in *Section 3 - Structural typology* (Figure 32). The framework of the Section 3 related to masonry buildings is structured as a matrix combining vertical (indicated by capital letters – from A to E) and horizontal (indicated by numbers – from 1 to 6) structural components, which define 30 different masonry structural typologies. As for the vertical structural components, i.e. masonry walls, two types of masonry are considered: (i) irregular layout or bad quality (i.e. columns B and C), and (ii) regular layout and good quality (columns D and E). Furthermore, both types can be characterised by the presence or absence of tie rods/tie beams. The use of these strengthening measures allows an effective connection between walls and floors to reduce the potential out-of-plane collapse of walls. As for the horizontal structural components, various typologies of floor slabs are indicated: vaults with (Row 2) or without (Row 3) tie rods, and floors with beams and flexible (Row 4), semi-rigid (Row 5), or rigid (Row 6) slab. A separate framework refers to four roof typologies distinguished among thrusting heavy or light and non-thrusting heavy or light. It is worth noting that the two shades of grey (i.e. from light to dark) in the various frameworks of the Section 3 of the AeDES form indicate increasing levels of vulnerability.

Figure 32. Framework of the Section 3 of the AeDES form.



SECTION 3 Building Typology (multiple answer; for masonry buildings indicate max 2 combinations of vertical and horizontal structures)

Horizontal Structures / Vertical structures	Unknown	Masonry buildings: Irregular layout or bad quality (rubble stones, pebbles,..) – W/O tie rods or tie beams	Irregular layout or bad quality – With ties rods or tie beams	Regular layout and good quality (Blocks, bricks, squared stone..) – W/O tie rods or tie beams	Regular layout and good quality – With tie rods or tie beams	Isolated columns	Mixed	Strengthened
	A	B	C	D	E	F	G	H
1 Not identified	○	□	□	□	□	SI	□	□
2 Vaults without tie rods	□	□	□	□	□	○	G1	H1
3 Vaults with tie rods	□	□	□	□	□		□	□
4 Beams with **flexible slab** (wooden beams with a single layer of wooden planks, beams and shallow arch vaults,...)	□	□	□	□	□	NO	G2	H2
5 Beams with **semirigid slab** (wooden beams with a double layer of wooden planks, beams and hollow flat blocks,...)	□	□	□	□	□	○	□	□
6 Beams with **rigid slab** (r.c. floors, beams well connected to r.c. slabs,...)	□	□	□	□	□		G3	H3

Other structures	
R.c. frames	□
R.c. shear walls	□
Steel frames	□

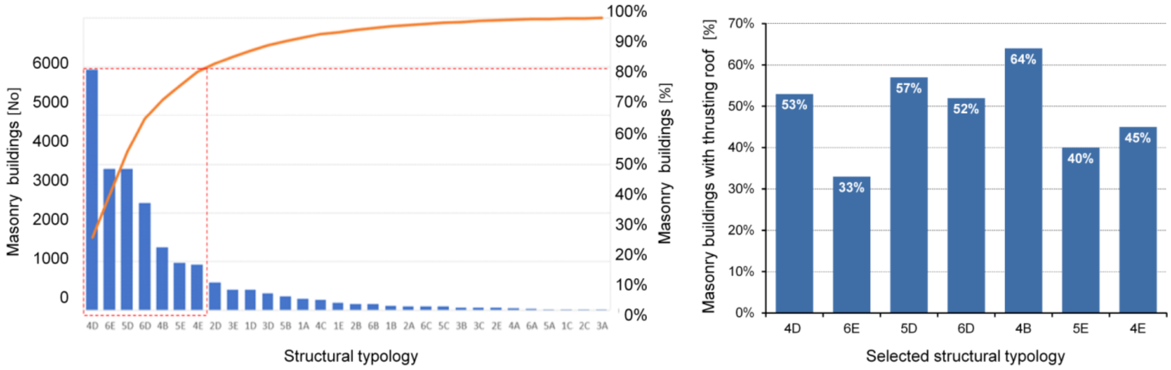
REGULARITY	Irregular	Regular
	A	B
1 Plan and elevation	○	○
2 Infills distribution	○	○

Roof
1 ○ Thrusting heavy
2 ○ Non thrusting heavy
3 ○ Thrusting light
4 ○ Non thrusting light

Source: Baggio et al, 2007

Based on data provided by the Section 3 of the AeDES forms related to the nearly 20000 masonry buildings inspected in the aftermaths of the 2012 Emilia earthquake, the distribution of the investigated buildings by structural typology, according to the 30 potential options, is depicted in Figure 33a. Results point out that the structural typology 4D, consisting of masonry walls with regular layout without tie rods and floors with beams and flexible slab, is the most widespread one characterising nearly 5000 inspected buildings. It is followed by six structural typologies, i.e. 6E, 5D, 6D, 4B, 5E, and 4E, which also account for a wide extent of masonry buildings resulting into a range equal to nearly 3000-1000 buildings. Hence, the seven above-mentioned structural typologies, i.e. from 4D to 4E in Figure 32a, are selected as the prevalent ones since they globally characterise 80 % of inspected buildings.

Figure 33. Analysis of structural characteristics of the inspected masonry buildings: (a) distribution of buildings by structural typology, and (b) distribution of buildings with thrusting roof by the seven selected structural typologies



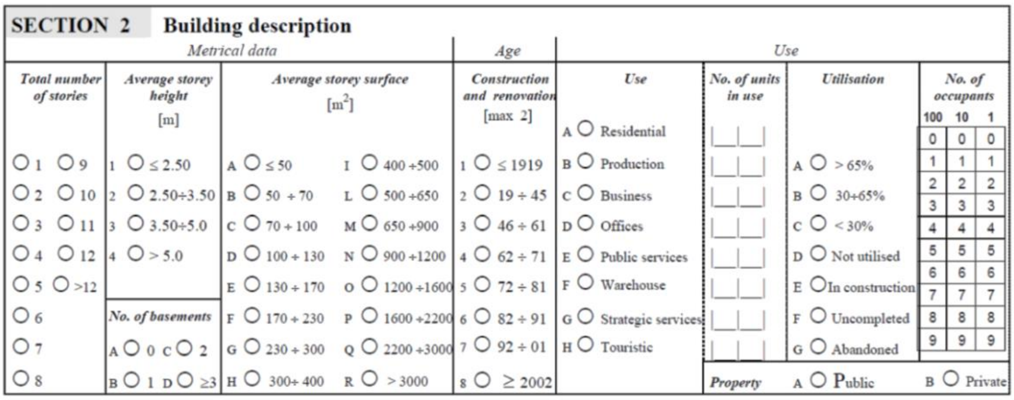
(a) (b)

Source: Data – Da.O.D, 2012 Emilia database (AeDES form).

Hereinafter, data analysis will be restricted to inspected buildings with the structural typologies referring to the seven selected ones. Specifically, the structural typologies consisting of vertical structural components B and D are more vulnerable than the E ones due to the absence of tie rods. However, the B ones exhibit a higher level of vulnerability compared to the D ones since the former are also characterised by irregular layout or bad quality of masonry. The presence of thrusting roofs in masonry buildings increases their seismic vulnerability, thus the distribution of buildings with this roof type by the seven selected structural typologies is provided in Figure 33b in order to carry out a comprehensive analysis on the structural system of the inspected buildings. It is pointed out that 64 % of buildings with the structural typology 4B have thrusting roofs. Buildings with the structural typologies 5D, 4D, and 6D having thrusting roofs also account for significant percentages equal to more than 50 % each. The buildings characterised by the remaining structural typologies having thrusting roofs resulted into a lower percentage range equal to 30-40 %.

— **Age and size** – Data related to age based on the year of construction, as well as metrical data related to size in terms of number of stories and average floor area, among others, of the inspected masonry buildings are provided in the *Section 2 - Building description* of the AeDES form (Figure 34).

Figure 34. Framework of the Section 2 of the AeDES form.


SECTION 2 Building description

Metrical data | *Age* | *Use*

Total number of stories: ○1 ○9; ○2 ○10; ○3 ○11; ○4 ○12; ○5 ○>12; ○6; ○7; ○8

Average storey height [m]: 1 ○ ≤ 2.50; 2 ○ 2.50÷3.50; 3 ○ 3.50÷5.0; 4 ○ > 5.0

No. of basements: A ○ 0 C ○ 2; B ○ 1 D ○ ≥3

Average storey surface [m²]: A ○ ≤ 50; B ○ 50 ÷ 70; C ○ 70 ÷ 100; D ○ 100 ÷ 130; E ○ 130 ÷ 170; F ○ 170 ÷ 230; G ○ 230 ÷ 300; H ○ 300÷ 400; I ○ 400 ÷500; L ○ 500 ÷650; M ○ 650 ÷900; N ○ 900 ÷1200; O ○ 1200 ÷1600; P ○ 1600 ÷2200; Q ○ 2200 ÷3000; R ○ > 3000

Construction and renovation [max 2]: 1 ○ ≤ 1919; 2 ○ 19 ÷ 45; 3 ○ 46 ÷ 61; 4 ○ 62 ÷ 71; 5 ○ 72 ÷ 81; 6 ○ 82 ÷ 91; 7 ○ 92 ÷ 01; 8 ○ ≥ 2002

Use: A ○ Residential; B ○ Production; C ○ Business; D ○ Offices; E ○ Public services; F ○ Warehouse; G ○ Strategic services; H ○ Touristic

No. of units in use

Utilisation: A ○ > 65%; B ○ 30÷65%; C ○ < 30%; D ○ Not utilised; E ○ In construction; F ○ Uncompleted; G ○ Abandoned

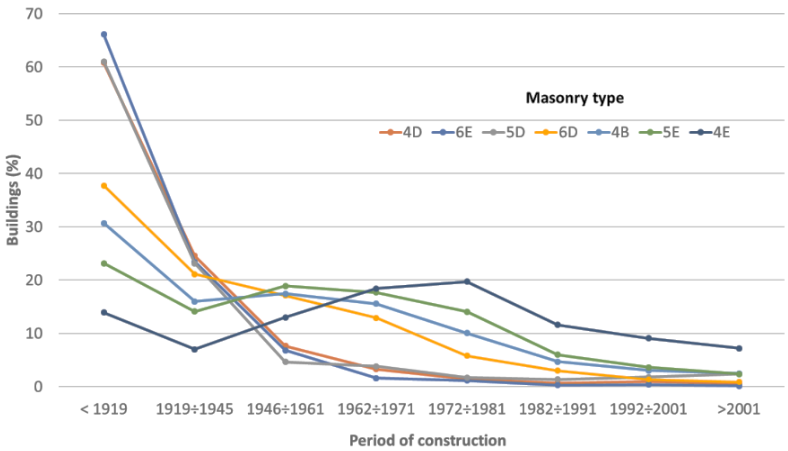
No. of occupants: 100 10 1; 0 0 0; 1 1 1; 2 2 2; 3 3 3; 4 4 4; 5 5 5; 6 6 6; 7 7 7; 8 8 8; 9 9 9

Property: A ○ Public B ○ Private

Source: Baggio et al, 2007

As for the building age investigation, the percentage distribution of the buildings consisting of the seven selected structural typologies by year of construction is depicted in Figure 35. In general, results indicate that the majority of the investigated masonry buildings are old constructions since the highest number of these buildings was erected before 1919, except for the buildings with structural typology 4E with its highest percentage referring to the period 1972-1981. The latter result related to the 4E buildings underlines that the use of flexible slabs was widespread also for constructions erected in quite recent years. The masonry buildings with the structural typologies 6E, 4D, and 5D follow the same trends with the highest percentages of their masonry building stocks erected before 1945 (i.e. cumulative percentage resulting into the range 80-90 % related to the periods pre-1919 and 1919-1945). The extents of these buildings erected in the following periods are very low, thus becoming nearly negligible. Similarly, masonry buildings with the structural typology 6D exhibit their highest percentage of constructions, i.e. nearly 60 %, before 1945, although an extent of 6D masonry buildings equal to nearly 30 % was constructed into the period 1946-1971. The buildings with the structural typologies 4B and 5E follow a very similar trend of the 6D masonry buildings.

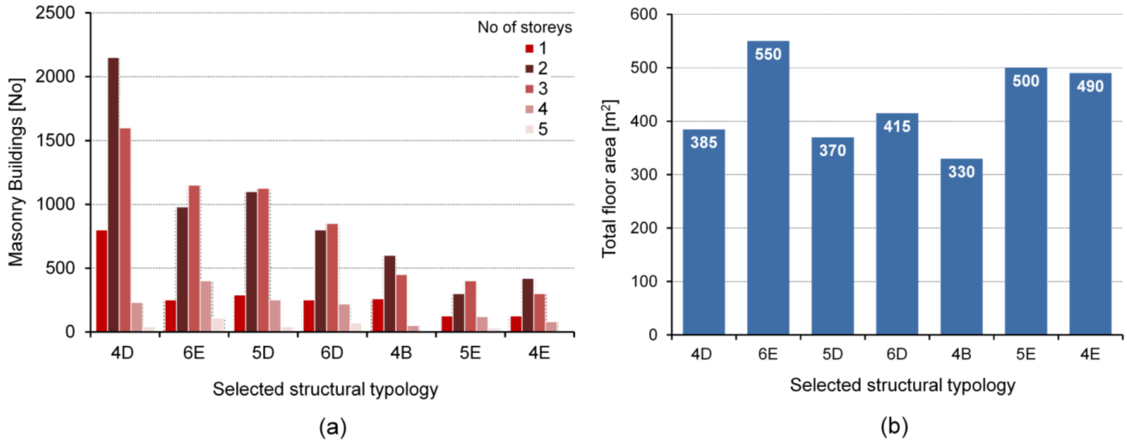
Figure 35. Analysis of building age: distribution of the inspected masonry buildings (considering the seven selected structural typologies) by year of construction



Source: Data –Da.O.D, 2012 Emilia database (AeDES form).

As for the geometric and metrical data, the distribution of masonry buildings in terms of number of storeys by the seven selected structural typologies is depicted in Figure 36a. Results of these analyses underline that the majority of the inspected masonry buildings are low-storey constructions composed by 2 or 3 storeys, followed by one-storey buildings, for all the seven selected structural typologies. Furthermore, these data served for the computation of the total floor area of the masonry buildings by the seven selected structural typologies, based on the data related to the average floor area according to the Section 2 of the AeDES form. Results of this estimation reported in Figure 36b provides an overview of the global size of the investigated masonry buildings. In general, the total floor area resulted into the range 300-550 m^2 for all the seven selected structural typologies, thus the investigated masonry buildings mostly exhibit a small size. Specifically, masonry buildings with the structural typologies 4B, 5D, and 4D account for a total floor area a bit higher than 300 m^2, whereas the total floor area for buildings with the structural typologies 6D, 4E, and 5E resulted into the range 400-500 m^2. Buildings with structural typology 6E are the unique ones with a total floor area higher than 500 m^2, thus exhibiting a larger size compared to the common trend.

Figure 36. Analysis of geometric and metrical data of the inspected masonry buildings: (a) distribution of buildings per number of storey, and (b) total floor area of masonry buildings by the seven selected structural typologies.



Source: Data – Da.O.D, 2012 Emilia database (AeDES form).

The combination of the main outcomes of the previous analyses enables the identification of masonry building typologies most needing seismic retrofit within the group of the seven selected structural typologies, representative of the Emilia region, and potentially also indicative of the existing masonry building stock located in the north-eastern Italian areas. Based on the investigations related to the structural characteristics and age, the priority structural typologies result 4D, 5D, and 6D. Indeed, they account for the highest number of buildings, resulting very old since their largest extents were erected before 1945. However, an additional discrete number of buildings with the structural typology 6D was constructed until 1971. Although the buildings with the structural typology 6E present the same characteristics described for the three structural typologies above, they have been excluded from the prioritisation since their seismic performance is enhanced by both the presence of tie rods/tie beams and the use of rigid slabs for the horizontal structural components.

The structural typologies 4D and 5D differ only for the horizontal structural components consisting of flexible and semi-rigid slabs, respectively. Hence, they can be merged into a unique typology, i.e. 4-5D, leading to the final simplified prioritisation of the two following representative Italian masonry residential building typologies, (i) **4-5D**, and (ii) **6D**, needing seismic retrofit to be combined with the energy one, according to the energy driven investigation. A synthesis of the main characteristics of the two selected building typologies in terms of structural typology, size, and age is provided in Table 8.

Table 8. Identification of the selected Italian masonry building typologies needing seismic retrofit in Emilia region (potentially applicable also to North-East Italy)

Masonry building typologies			
Main characteristics		4D-5D	6D
Structural Typology	Vertical structural components	Walls with regular layout and good quality of masonry	Walls with regular layout and good quality of masonry
	Tie rods/tie beams	Missing	Missing
	Horizontal structural components	**4D**: Flexible (e.g. timber planks, beams and shallow arch vaults, etc.) **5D**: Semirigid (e.g. beams and flat hollow clay bricks, etc.)	Rigid (e.g. RC slab)
	Roof	Thrusting	Thrusting
Building size	Number of stories	2 or 3	2 or 3
	Total floor area [m^2]	300-400	400-450
Building age	Period of construction	<1945	<1971

Source: Data – Da.O.D, 2012 Emilia database (AeDES form)

3.2.3.2 Energy-driven investigation

The energy-driven investigation intends to identify the building envelope and the main thermal properties of its components related to the building typologies 4-5D and 6D, selected by means of the previous seismic-driven investigation, with the objective to finalise the identification of Italian masonry building typologies needing combined seismic and energy retrofit.

The energy-driven investigation relies on the outcomes of the IEE project TABULA. Specifically, the TABULA WebTool - hereinafter, indicated as Tool - was examined with reference to the database of the Italian building stock (Loga et al., 2012). The selection of the building types in the Tool is addressed by the combination of different size (i.e. single-family house, terraced house, multi-family house, and apartment block), and age classes, resulting into a so-called 'Building Type Matrix'. Specifically, the combination of the multi-family house category and the period of construction 1900-1920 was considered in the Tool to select a building type compliant with the size and age of the buildings typologies 4-5D and 6D, leading to the identification of the exemplary building indicated with the code 'IT.MidClim.MFH.02.Gen' - hereinafter, referred to as exemplary building.

The exemplary building results compliant with the building typology 4-5D with flexible floors. Indeed, according to the building data retrieved by the Tool, it is representative of a three-storey multi-family masonry building with timber roof, floors consisting of beams and shallow arch vaults, and two types of masonry walls. One type is a 38 cm-thick masonry wall made of solid clay bricks, whereas the other type is a 60 cm-thick masonry wall consisting of stones listed with solid clay bricks. As for the transparent vertical components, single-glass windows with timber frames are considered.

The Tool assumes that the exemplary building is located in an Italian region with climatic zone E (the Emilia region, which the building typology 4-5D is referred to, is characterised by the same climatic zone), and provides values of the thermal transmittance (i.e. U-values) of either vertical and horizontal components above. Table 9 shows the comparison of these values, indicating the 'as is' scenario of the existing exemplary building, with the corresponding threshold values required for existing buildings in case of energy renovation by the DM 26/06/2015 for the climatic zone E. The U-values of the building envelope components related to the 'as is' scenario result much higher that the corresponding threshold ones, thus demonstrating the poor thermal properties of the envelope components of the selected building type in the 'as is' scenario.

Furthermore, according to the data provided by the Tool, the total non-renewable primary energy demand results equal to 213 kW/m^{2}y, which yields an energy class G according to the DM 26/06/2015 classification. Hence, these outputs underline that the building type, represented by the exemplary building and compliant with the building typology 4-5D, urgently needs an energy retrofit, beyond the seismic one.

Table 9. Thermal transmittance (U-value) of the envelope components of the selected building type in the 'as is' scenario and threshold values required by the DM 26/06/2015.

Building envelope component		U-value [W/m^{2}K]	
		Building type [(1)] (IT.MidClim.MFH.02.Gen)	Threshold values for existing buildings under renovation [(2)]
Opaque vertical components	Wall (60cm-thick)	1.19	0.28
Horizontal components	Roof	1.54	0.24
	Floor	1.20	0.29
Transparent vertical components	Window	4.90	1.40

(1) Data retrieved from TABULA WebTool.
(2) Threshold U-values (climatic zone E) in force from 1st January 2021 for existing building subjected to energy renovation (Appendix B of DM 26/06/2015).

3.3 Prioritisation of Italian RC buildings needing combined seismic and energy retrofit

The prioritisation of the Italian RC residential buildings aimed at identifying the related building typologies most needing combined seismic and energy retrofit, is based on a three-step procedure, similar to the one carried out for the masonry buildings, as follows:

1. **Analysis of statistics related to the Italian RC residential building stock** – The first step deals with the investigation of the Italian RC residential building stock in order to collect data on its age and its geographical distribution, according to the 2011 Census of the Italian Statistical Institute.
2. **Combination of seismic and climatic zones** – The second step focuses on the identification of the Italian geographical areas where the combined seismic and energy retrofit demand result high, also defining the corresponding distribution of RC residential buildings.
3. **Identification of RC building typologies needing combined seismic and energy retrofit** – Based on the combination of the outcomes of Step 1 and 2, two routes of investigation, namely a seismic-driven and an energy-driven investigation, are carried out in order to identify potential RC building typologies most needing combined retrofit. The seismic-driven investigation focuses on research studies on seismic vulnerability to collect further data on structural typology and details, age, size, infill walls configuration of the Italian existing RC building stock, whereas the energy-driven investigation aims to provide data on building envelope components referring to infill walls and the corresponding thermal properties.

A detailed description of each above-mentioned step is provided in the following.

3.3.1 The Italian RC residential building stock

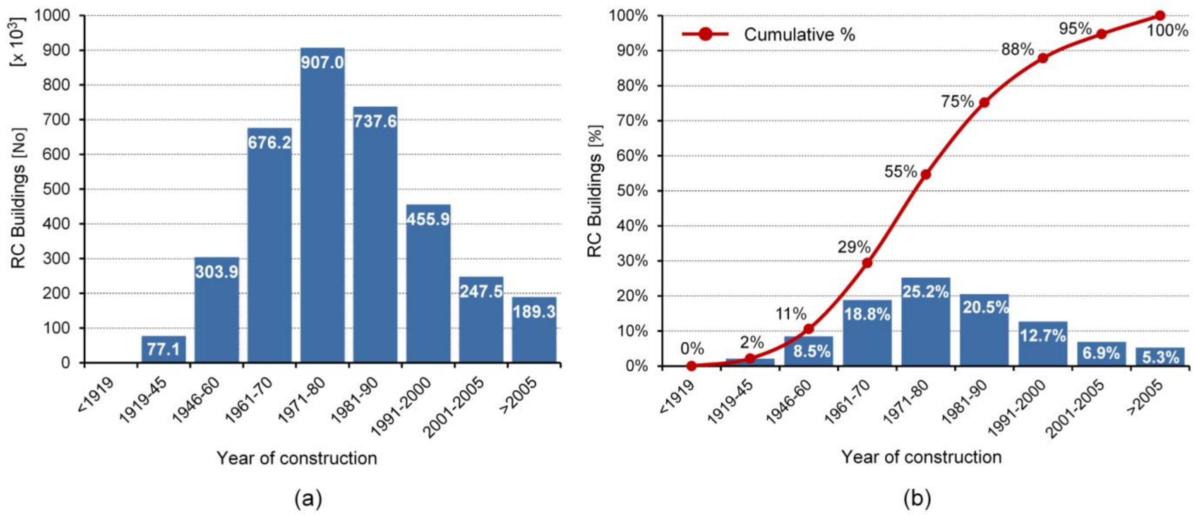
The Italian RC residential buildings are nearly 3.6 million, accounting for nearly 30 % of the entire Italian residential building stock, which consists of a total number of buildings equal to more than 12 million. A detailed analysis of the Italian RC residential building stock by both year of construction and its geographical distribution have been carried out according to the statistics provided by the 2011 Census of the Italian Statistical Institute (ISTAT, 2011). The main outcomes of this twofold investigation are described in the following.

3.3.1.1 *Distribution of Italian RC buildings by year of construction*

The distribution of the Italian RC residential building stock by year of construction (Figure 37a) shows that no RC building was constructed pre-1919. The first RC buildings were erected between 1919 and 1946, but a crucial impulse to their construction occurred only after the 2nd World War by leading to a final extent of more than 300000 RC residential buildings at the end of 60's. However, the most consistent rise of RC buildings share refers to the three following decades by reaching a peak of more than 900000 RC buildings erected during the decade 1971-1980. The analysis of these statistics points out that 75 % of Italian RC residential buildings was constructed before 1990 and only 12 % in the decade 1990-2000 with a further decrease in the two following decades (Figure 37b).

These results demonstrate that 75 % of the Italian RC residential building stock was constructed before the adoption of the first Italian regulation on energy efficiency in 1991 (Law 10/1991). Furthermore, more than 75 % of the existing RC buildings is not compliant with the requirements of the 1996 moderate seismic design code (DM 16/01/1996) and the modern seismic design code first introduced in 2003 (OPCM 3274/2003). In addition, most of the Italian territory was not classified as seismic until 1980, when 55 % of RC residential buildings was already erected. Based on these figures, the combined seismic and energy retrofit of the Italian existing RC residential building stock emerges as a crucial need to enhance its structural and energy performances.

Figure 37. Distribution of the Italian RC residential buildings by year of construction, expressed in terms of: (a) number of buildings, and (b) percentage of buildings and its corresponding cumulative percentage



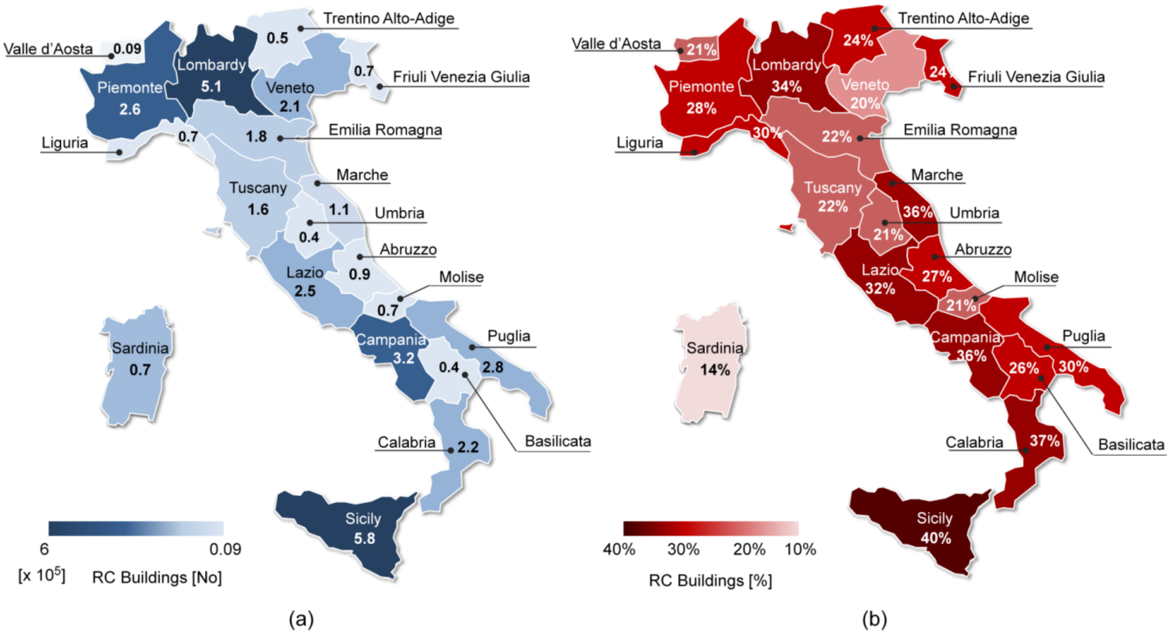
Source: Data - ISTAT, 2011

3.3.1.2 *Geographical distribution of Italian RC buildings*

The geographical distribution of the Italian RC residential building stock has been investigated according to two main levels: (i) by region (i.e. NUTS-2 level) and (ii) by municipality.

As for the analysis at regional level, based on the total extent of the Italian RC residential buildings, Sicily results the Italian region with the highest number of RC residential buildings (nearly 580000) (Figure 38a). Furthermore, the investigation of the single residential building stocks of each Italian region enables to estimate the corresponding percentage distribution of RC residential buildings per region (Figure 38b), identifying the Italian locations where the use of RC was more diffused than other construction materials (e.g. masonry, timber, steel). Sicily accounts for the largest share of RC residential buildings with a percentage equal to 40 % of the total number of residential buildings constructed in this region, followed by Calabria, Campania, Marche, Lombardy, and Lazio with shares varying into a percentage range equal to 37-32 %.

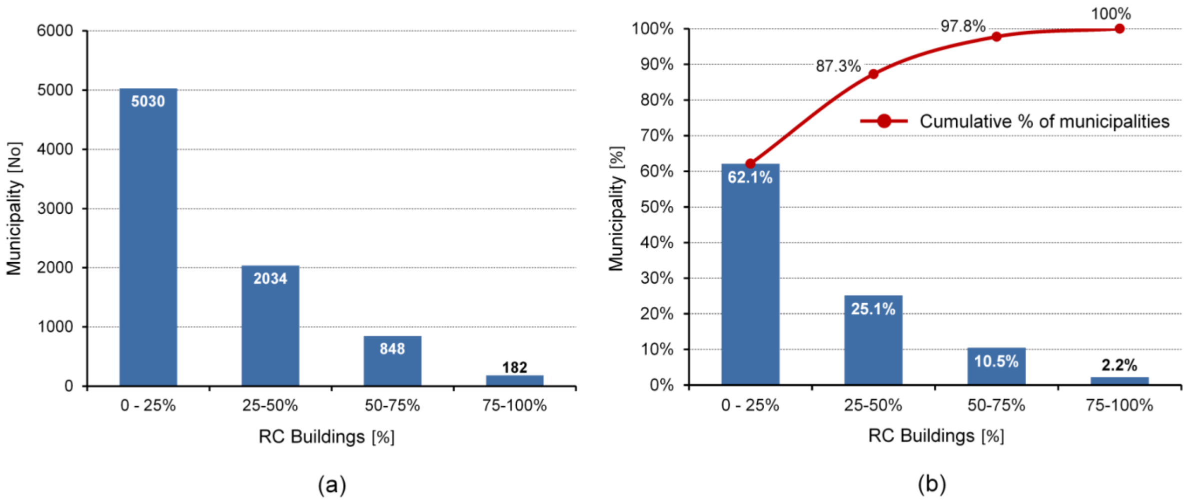
Figure 38. Geographical distribution of Italian RC residential buildings at regional level: (a) number of RC buildings by region, and (b) percentage of RC buildings over the total number of buildings in each region



Source: Data - ISTAT, 2011

As for the analysis at municipality level, the distribution of a total number of 8094 Italian municipalities has been investigated by percentage range of RC buildings (Figure 39a). Statistics show that more than 60 % of Italian municipalities (i.e. more than 5000) accounts for no more than 25 % of RC buildings and less than 50 % of RC buildings is located in nearly 88 % of Italian municipalities (Figure 39b).

Figure 39. Distribution of Italian municipalities by percentage range of RC residential buildings in terms of: (a) number of municipalities, and (b) percentage of municipalities and its corresponding cumulative percentage



Source: Data - ISTAT, 2011

3.3.2 Combination of seismic hazard and climatic zones

The analysis of the Italian territory in terms of seismic hazard and climatic conditions is needed to provide useful information on the Italian geographical areas where the combined retrofit of the existing RC building stock may be most required based on the most severe seismic-energy demand.

Similar observations carried out for the analysis related to the Italian masonry residential building stock are also valid for the RC buildings. Hence, two levels of investigations are considered for the combination of SCZs:

(i) Level 1 – Simplified analysis, and (ii) Level 2 – Detailed analysis, which are both described in the following. It is worth noting that the information common to the investigation related to the masonry residential building stock will not be replicated in this section, thus it is recommended to refer to Section 3.2.2 for a detailed explanation, as well as to Section 3.2.2.1 and Section 3.2.2.2 for details related to the application of Level 1 and Level 2 analyses, respectively.

3.3.2.1 Level 1 - Simplified analysis combining seismic zones and climatic zones

The four seismic and six climatic zones, according to the OPCM 3519/2006 and the DPR 412/1993, respectively, were combined into a 24-cell matrix, showing the number of the Italian masonry residential buildings corresponding to each of the 24 potential combinations of SCZs, as reported in Table 10. Specifically, the buildings were aggregated at municipality level and distributed by the combined SCZs. The distributions of the total number of RC buildings by seismic zone or climatic zone are also provided in Table 10.

Table 10. Seismic-climatic matrix and distribution of the Italian RC residential building stock by seismic-climatic zones, according to the Level 1 – Simplified analysis

Climatic zone (CZ)	Seismic zone (SZ)				Total
	1	2	3	4	
A		919	97		**1016**
B	68277	81353	49882	122168	**321680**
C	76630	323211	233073	276012	**908926**
D	78184	326338	211122	212532	**828176**
E	170117	425886	365634	465287	**1426924**
F	13553	29167	34729	30524	**10793**
Total	**406761**	**1186874**	**894537**	**1106523**	**3594695**

Source: Data – OPCM 3274/2003; Annex A of the DPR 412/1993; ISTAT, 2011

The 24 seismic-climatic combinations can be reduced to four main SCZs in order to achieve four different severity levels of combined seismic-energy demand, as depicted in Table 11, where the total number of RC buildings per SCZ is also indicated. Nearly one third of the Italian RC residential building stock is located in the SCZ1, thus potentially requiring a high demand for combined retrofit, whereas 52 % of the Italian RC residential buildings is concentrated in the moderate SCZ (i.e. SCZ2a, characterised by a prevalent seismic demand, plus SCZ2b, driven by a predominant energy demand). The SCZ3, characterised by a low demand for combined retrofit, account for 19 % of the Italian RC residential buildings.

Table 11. Identification of four combined seismic-climatic zones and distribution of the corresponding RC buildings, according to the Level 1 – Simplified analysis.

SCZ	Seismic zone (SZ)	Climatic Zone (CZ)	Combined demand	RC buildings [No]	RC buildings [%]
1	1-2	D-E-F	High	1043245	29.02
2a	1-2	A-B-C	Moderate	550389	15.31
2b	3-4	D-E-F	Moderate	1319828	36.2
3	3-4	A-B-C	Low	681232	18.95
Total				**3594695**	**100.0**

Source: Data – OPCM 3274/2003, Annex A of the DPR 412/1993, ISTAT, 2011

3.3.2.2 Level 2 – Detailed analysis combining PGA and HDD values at local level

The simplified combination of the seismic-climatic zones carried out in the Level 1 analysis needs to be detailed at municipality level by considering local values of both PGA with 10% of probability exceedance in 50 years and HDD, expressing the seismic hazard level and the climatic conditions, respectively.

The resulting point cloud distribution of the 8100 Italian municipalities on the PGA-HDD Cartesian plane (Figure 15 in Section 3.2.2.2) enables to identify four SCZs, indicating various levels of combined seismic and energy demand, similarly to the to the Level 1 analysis. However, the corresponding distribution of the total number of RC residential buildings by SCZ (Table 12) differs from the results achieved in the Level 1 analysis. The main difference refers to the lower percentage of RC buildings concentrated in the SCZ1.

Table 12. Distribution of RC residential buildings by seismic-climatic zone, according to local values of PGA and HDD (Level 2 – Detailed analysis)

SCZ	PGA [g]	HDD	Combined demand	RC buildings [%]
1	> 0.12	> 2290	High	14
2a	> 0.12	< 2290	Moderate	43
2b	≤ 0.12	> 2290	Moderate	22
3	≤ 0.12	< 2290	Low	21

The distribution of the total number of RC buildings located in each SCZ by Italian province (i.e. corresponding to the NUTS 3 regions) is depicted in Figure 40.

Figure 40. Distribution of Italian RC residential buildings in each SCZ by Italian province, according to local values of PGA and HDD (Level 2 – Detailed analysis)

Source: Data - ISTAT, 2011

Similarly to the investigation related to masonry buildings, the highest number of RC buildings in the SCZ1 is concentrated in the Italian provinces located along the Apennine areas, mainly in Abruzzo region, where a high combined seismic-energy demand is required. Furthermore, some provinces of Emilia region and north–eastern Italian areas also result into the SCZ1 with a high percentage of masonry buildings. The inclusion of these geographical areas in the SCZ1 related to the Level 2 analysis is due to the threshold value of PGA triggering the high level of seismic hazard (PGA > 0.12g), which is lower than the corresponding one considered in the Level 1 analysis (PGA > 0.15g, according to the minimum PGA value of the range identifying the SZ2 in OPCM 3519/2006). The majority of RC buildings concentrated in the SCZ2a are located in the provinces of central and southern Italy, where the seismic hazard is moderate-to-high and the climatic conditions are quite severe, followed by a lower percentage of buildings (about 25 %) concentrated along the Tyrrhenian coast. Conversely, the majority of RC buildings resulting into the SCZ2b mainly refer to north-western Italian regions, which are energy-driven areas since they exhibit significant climate conditions in terms of HDD, but a moderate-to-low level of seismic hazard. Finally, the SCZ3 includes Sardinia and southern Puglia regions accounting for the highest percentage of RC buildings requiring low seismic-energy demand, followed by a lower percentage of buildings (about 40 %) mainly concentrated along the Tyrrhenian cost.

3.3.3 Identification of Italian RC building typologies needing combined seismic and energy retrofit

A potential method for the identification of the Italian RC residential building typologies needing combined seismic and energy retrofit refers to two routes of investigation, as follows:

1. **Seismic-driven investigation** – This analysis deals with the identification of potential Italian RC building typologies most needing seismic retrofit, based on literature data related to period of construction, number of floors, structural details, mechanical properties of constitutive materials (i.e. concrete and steel), and infill masonry walls arrangement, which are provided in several research studies devoted to the assessment of seismic vulnerability and seismic risk of the Italian building stock (e.g. Lagomarsino and Giovinazzi, 2006, Masi and Vona, 2012, Masi et al., 2015, Dolce et al., 2020, Masi et al., 2021).
2. **Energy-driven investigation** is focused on the analysis of the thermal characteristics of the building envelope components related to the structural typologies identified in the previous investigation and based on literature data.

The application of these two routes is separately described in the following.

3.3.3.1 Seismic-driven investigation

The seismic-driven investigation to identify potential Italian RC building typologies most needing seismic retrofit relies on the analysis of data provided in Masi and Vona (2012), Masi et al. (2015), Manfredi and Masi (2017), and Masi et al. (2021), mainly devoted to assess the seismic vulnerability of existing Italian RC buildings, as a development of previous studies relevant to plane frames extracted from real RC buildings (Masi, 2003).

RC buildings are typically distinguished into three main structural typologies: (i) RC frame structure, (ii) RC walls, and (iii) dual systems. According to the studies above, most of the Italian existing RC residential buildings have been designed only for gravity loads, by implementing one-way RC moment-resisting frame structures representing the most widespread RC structural typology in Italy until '90s (Masi et al., 2021). Hence, these RC structural typologies, representative of the Italian RC building stock erected during the period 1950-1980, are particularly subject to seismic vulnerability, since they were conceived without earthquake-resistant design (ERD), thus most needing seismic retrofit.

Conversely from the prioritisation of Italian masonry building typologies, the Italian residential buildings consisting of RC framed structures without ERD – hereinafter indicated as no-ERD RC framed structures - can be considered representative of the existing RC building stock located in the majority of the Italian regions, since no huge variability due to the use of local raw materials exists in case of RC buildings. However, different infill wall typologies characterise the existing RC framed structures, significantly affecting both their seismic and energy performances, thus the diversity of infill walls typologies needs to be taken into account. In the perspective of identifying the Italian RC building typologies most needing seismic retrofit (to be combined with the energy upgrading), RC residential buildings consisting of no-ERD RC framed structures are further investigated to collect data on various aspects, as follows:

- **Age and size -** Data related to the age based on the year of construction, as well as data related to the size in terms of number of stories and average floor area are analysed.

  The year of construction of existing buildings represents an essential aspect serving as a crucial indication to collect data on structural details. According to the analysis on the distribution of the Italian RC residential building stock by year of construction (see Section 3.3.1), RC buildings were mainly spread after the 2nd World War, with the highest number of building erected during the three decades from 1960 to 1990, with the peak of constructions reached during the '70s. To this end, two main periods of construction can be considered, identifying the two following structural typologies: (i) Case 1 - no-ERD RC framed structures, erected before 1971 (pre-1971), and (ii) Case 2 - no-ERD RC framed structures, erected after 1971 (post-1971), which also corresponds to a significant development in the evolution of the structural design code of the RC structures with the issue of the Law 1086/1971 (see Table 4).

  As for the building size, the most widespread no-ERD RC framed structures generally exhibit regularity both in plan and in elevation (Masi and Vona, 2012, Masi et al., 2015). Specifically, these structures have a rectangular symmetric plan distinguishing between two main sizes of the floor area: (i) small floor area, consisting of three bays along the longitudinal direction, or (ii) large floor area, characterised by five bays along the longitudinal direction. Two bays are typically found along the transversal direction in both cases. The bays can be assumed equal to 5 m in both directions to provide an indicative measure of the floor area (i.e. 150 m^2 and 250 m^2 in case of small and large size, respectively). As for the building size in elevation, the analysis of the existing RC buildings in terms of number of storeys leads to the identification of three main types, differentiated among two-storey, four-storey and eight-storey buildings, representative of low-, mid-, and high-rise buildings, compliant with the classification provided in the 2001-2004 European project RISK-UE (Milutinovic and Trendafiloski, 2003). Furthermore, an inter-storey height equal to 3 m is considered for all levels. The geometrical data above are considered valid for both the pre-71 and post-71 structural typologies.

- **Structural details** – Both the pre-71 and the post-71 no-ERD RC framed structures typically consists of frames only in one direction, generally the longer one (i.e. longitudinal direction), whilst solely external frames are present along the orthogonal direction.

  The analysis of structural details is essential to assess the seismic vulnerability of a building. However, the assessment of existing RC buildings is a complex task compared to the design of new buildings, since a limited knowledge of the structure can be obtained. Main issues refer to the difficulty of effectively determining current constitutive material properties and possible deterioration conditions. Other important issues concerns the possibility of obtaining sufficiently accurate knowledge of some structural data (e.g. amount and location of longitudinal and transversal steel reinforcement) as appropriate technical documentation is rarely available (Masi, 2003). To overcome this issue, data related to structural details can be obtained by simulated design according to design practice and seismic codes at the time of construction (Masi, 2003). Specifically, the structural design codes in force for the design of the pre-1971 and post-1971 no-ERD RC framed structures were the Royal Decree 2229/1939 and the Law 1086/1971 (see Table 4), respectively. No substantial changes in terms of seismic safety exist between the two codes, since the Law 1086/1971 was not a seismic code, but it was mainly devoted to define quality of materials and responsibilities. In both codes, the allowable stress method was prescribed in the safety verifications for the design of structural elements. Hence, the main difference to consider between the pre-71 and post-71 structural typologies essentially regards the typical mechanical properties of the RC constitutive materials (i.e. concrete and steel). The pre-1971 and the post-1971 typologies can be considered representative of RC framed buildings with poor and medium construction quality, respectively. Specifically, as for the pre-1971 typology a low quality concrete C10/12 (mean compressive strength, f_{cm} = 16 MPa), and smooth steel reinforcement AQ42 (mean yielding strength F_{ym} = 250MPa) can be assumed (Masi and Vona, 2012, Puppio et al., 2017) compliant with the requirements of the codes in force. Similarly, as for the post-71 typology a medium quality concrete C20/25 (mean compressive strength, f_{cm} = 28 MPa), and ribbed steel reinforcement Feb38k (mean yielding strength F_{ym} = 400MPa) are considered according to the Law 1086/1971 provisions.

- **Infill wall configuration** – The external masonry infill walls, although considered as non-structural elements, play a key role in RC framed structures in terms of seismic performance due to the frame-infill interaction. Indeed, regularly distributed infills may behave as structural elements contributing to withstand the seismic actions, mainly in case of RC buildings designed only for gravity loads. If the infill walls are rigidly connected to the RC frames, they can increase the strength of the structure, acting as additional equivalent struts collaborating with the RC structural members. However, this behaviour typically leads to infill damage due to in-plane deformations and the possibility of out-of-plane collapse when the infill-frame connection is poor or deteriorates after seismic damage. Conversely, irregular arrangement of infills may be strongly detrimental, producing unfavourable distribution of plastic hinges, high demand of inelastic deformations, brittle failures, reduction of the global dissipation capacity.

  Based on these observations, the different configuration of masonry infills is an essential aspect to consider for the prioritisation of the RC framed structures. Hence, three main cases can be identified to include in the seismic vulnerability assessment of both pre-1971 and post-1971 structural typologies: (i) bare frames (BF), indicating ineffective infills, having many and/or very large openings or badly connected to the structure (ii) regularly infilled-frame (IF), referring to frames with regular and effective frames, and (iii) pilotis-frame (PF), representative of frames without masonry infill walls at the ground floor.

A synthesis of the main characteristics of the two identified building typologies in terms of age, structural typology, and size is provided in Table 13.

Table 13. Identification of the Italian RC building typologies needing seismic retrofit

RC building typology			
Main characteristics		Case 1	Case 2
Building age	Period of construction	Pre-1971	Post-1971
Structural details	Structural typology	No-ERD framed structure	No-ERD framed structure
	Beam [dimension]	Rigid: 30 x 50 cm Flexible: 70 x 22 cm	Rigid: 30 x 50 cm Flexible: 70 x 22cm
	Column [dimension]	30 x 30 cm (4-storey building)	30 x 30 cm (4-storey building)
Materials	Concrete	C 10/12	C 20/25
	Steel	AQ42	FeB38k
Building size	Floor area [m^2]	Small floor area: 150 Large floor area: 250	Small floor area: 150 Large floor area: 250
	Number of stories	2 (Small floor area) 4-8 (Large floor area)	2 (Small floor area) 4-8 (Large floor area)
Infill walls	Configuration	Bare frame Regularly infilled frame Pilotis frames	Bare frame Regularly infilled frame Pilotis frames

Source: Data – Masi, 2003, Masi and Vona, 2012, Masi et al., 2015.

Parametric studies carried out in Masi (2003) and Masi and Vona (2012) varying concrete strength, infill distribution, and building height of the pre-71 and post-71 building typologies to assess their seismic vulnerability demonstrated that infill distribution has the greatest influence on seismic response. Post-71 typologies generally show better performances than pre-71 typologies. Globally, by comparing the seismic behaviour of the examined typologies, a high vulnerability can be expected for the buildings with pilotis frames, as confirmed in past earthquakes, e.g. the 2009 L'Aquila earthquake (Ricci et al., 2011). Conversely, a low vulnerability can be assigned to the buildings with regularly arranged masonry infills. An intermediate behaviour, although closer to PF than IF types, is shown by the building typologies with ineffective infills. Furthermore, drift values are always higher in structures with lower concrete strength with differences decreasing with building height.

It is evident that both pre-71 and post-71 RC framed structures designed without seismic-resistant requirements and presenting ineffective infills or pilotis frames most need seismic retrofit to be combined with the energy one, according to the energy driven investigation.

3.3.3.2 Energy-driven investigation

The energy-driven investigation is intended to identify the masonry infill wall typologies and their main thermal properties in relation to the RC framed building typologies selected by means of the previous seismic-driven investigation, with the objective to finalise the identification of Italian RC building typologies needing combined seismic and energy retrofit. In fact, the infill wall represents the main building envelope component of RC framed structures, extensively influencing the energy performance of buildings, beyond the seismic one. Different infill typologies can be found in Italy, as well as in other European countries (e.g. D'Ayala et al., 2004, Brzev et al., 2004, Hak et al., 2012, Vicente et al., 2012, Lamego et al., 2017)

Manfredi and Masi (2018) provide an overview of different infill wall typologies used in RC buildings from 1930 to date, also based on a field survey conducted in the aftermath of the 2009 L'Aquila earthquake to assess the seismic damages on masonry infills and partitions of the RC buildings, as reported in Braga et al.

(2011). Those two studies are considered as references to provide the synthesis on the evolution of the configuration of infill walls over time, along with their thermal properties, leading to the identification of five infill wall typologies, indicated as (a), (b), (c), (d), and (e) in Figure 41, and briefly described in the following.

Wall (a) - In the ‘30s–‘40s, infill walls were typically single leaf masonry walls, generally consisting of solid brick masonry or, less frequently, stone masonry with a wall thickness into the range 30-60 cm (Figure 41a). The thermal transmittance value (U-value) of this infill wall typology is around 1.88 W/m^{2}K in case of solid brick wall (Campioli et al., 2006a).

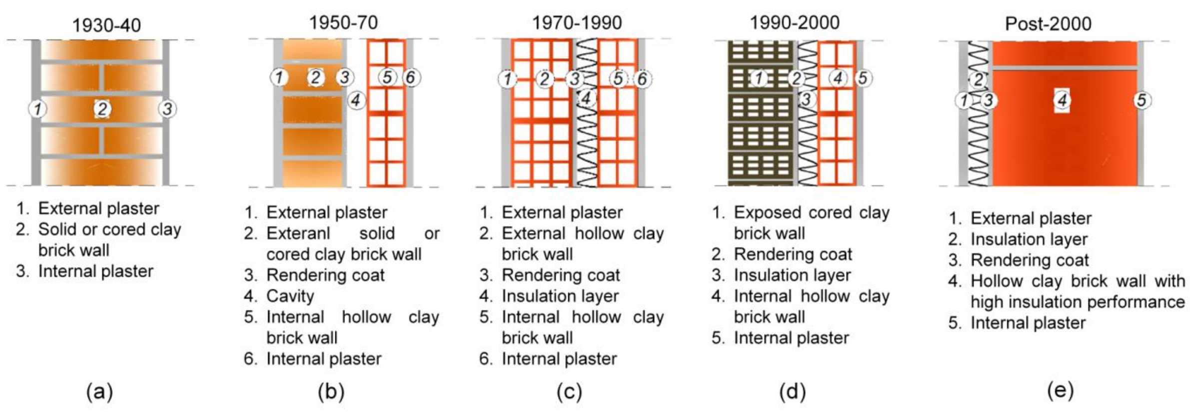
Wall (b) - At the beginning of the ‘50s, the cavity walls consisting of two single leaf masonry walls, one external with solid or hollow clay bricks and the other internal with hollow clay bricks, separated by a cavity, became the most widespread infill typology. The external and the internal walls are typically 12 cm and 8 cm thick, respectively. The cavity is usually 5-10 cm thick, thus the wall has an overall thickness equal to maximum 30 cm (Figure 41b). The use of hollow clay bricks for the external wall enhances the thermal insulation properties of this infill typology, exhibiting thermal transmittance values into the range 1.59-1.30 W/m^{2}K, depending on the use of solid or hollow clay bricks for the external wall, respectively (Campioli et al., 2006b).

Wall (c) - Since the ‘70s, cavity walls, consisting of external and internal walls made of hollow clay bricks, have been characterised by the cavity infilled with insulation materials (e.g. glass wool, mineral wool, etc.) to increase the thermal insulation properties of the entire wall, as a consequence of the first provisions on energy saving and energy efficiency of buildings (Figure 41c). As an example, the introduction of a 4 cm-thick glass wool insulation layer leads to a U-value of the wall equal to 0.71 W/m^{2}K (Manfredi and Masi, 2018), hence exhibiting a better thermal performance, if compared with the cavity wall used during the ’50s-‘60s.

Wall (d) - The infill wall typology used for more recent RC framed buildings erected in the decade 1990-2000 differs from the cavity wall used in the two previous decades mainly for a larger thickness of the external and internal walls to improve the thermal performance of the overall cavity wall, in line with the requirements of the first stringent Italian standard on the energy efficiency of buildings (Law 10/1991). Indeed, the use of 16-30 cm thick cored bricks usually without external plaster is introduced, leading to a reduced U-value of the wall equal to 0.3 W/m^{2}K (Monticelli, 2008).

Wall (e) - One of the most recent infill wall typology was introduced at the beginning of the 21th century due to the need to shorten the execution time of works. This infill typology consists of a single leaf hollow brick, having high insulation performance, combined with an insulation layer to further decrease the thermal transmittance value, which results equal to a very low value, i.e. 0.25 W/m^{2}K, (Campioli et al., 2006b) in case of an infill made of 30 cm thick bricks and 6 cm thick glass wool insulation.

Figure 41. Infill walls typologies used in Italian RC buildings (1930-post-2000)



Source: © Manfredi and Masi, 2018 (CC BY 4.0)

Table 14 shows the comparison of the U-values of the five infill wall typologies, i.e. (a), (b), (c), (d), and (e), with the threshold value required for opaque vertical components, i.e. walls, of existing buildings in case of energy renovation, according to the DM 26/06/2015 for the climatic zone E (i.e. 1400 < HDD < 2100) representative of the majority of the Italian regions and indicative of quite severe climate conditions. Focus is paid to the infill wall typologies (b), (c), and (d), since they result the most suitable ones for the RC structural typologies identified according to the seismic driven investigation. It is evident that these infill walls provide a poor thermal performance. Indeed, their U-values are higher that the threshold ones, mainly as for the wall typology (b) and (c), which refer to RC buildings erected before 1990. These remarks underline the need of an urgent energy retrofit of the Italian RC framed residential buildings constructed during 1950-1990 to be combined with the seismic one.

Table 14. Thermal transmittance (U-value) of the five investigated infill walls typologies and threshold value required by the Ministerial Decree 26/06/2015

Building envelope component		U-value [W/m²K]	
		Infill wall typology	Threshold values for existing buildings under renovation (2)
Opaque vertical components	Wall **(a)** (1)	1.88	0.28
	Wall **(b)** (1)	1.30 -1.59	
	Wall **(c)** (1)	0.71	
	Wall **(d)** (1)	0.30	
	Wall **(e)** (1)	0.25	

(1) The infill wall typologies, from (a) to (e), are illustrated in Figure 41.

(2) Threshold U-value of opaque vertical components (climatic zone E) in force from 1st January 2021 for existing buildings subjected to energy renovation (Appendix B of DM 26/06/2015).

4 Conclusions

A wide renovation of the EU existing building stock is a key-priority as emphasised by the European Green Deal to meet the climate-neutrality by 2050. The analysis of the EU existing building typologies needing an integrated renovation to simultaneously reduce their seismic vulnerability and improve their energy efficiency represents a crucial step towards the identification of technology options for an effective combined seismic and energy retrofit intervention.

In this context, **a simplified prioritisation** of the **EU buildings** most needing combined upgrading was carried out according to a three-step approach.

The residential building stock, consisting of SFHs and MFHs, represents the most widespread construction segment in Europe. Its main characteristics in terms of age, building type, i.e. one-dwelling (SFHs), two-dwelling, and three- or more-dwelling (MFHs) buildings, size, and construction material were first analysed, according to data provided by both the 2011 Population and Housing Census of the European Statistic System, and relevant research European projects, such as ENTRANZE and NERA. Results related to the year of construction during the period pre-1919-2011 indicates that the highest share of dwellings in both residential and non-residential buildings in Europe (i.e. EU-27, Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) was built between 1946 and 1980, accounting for a percentage equal to 44 % of the entire number of dwellings. More than 20 % and nearly 79 % of the European dwellings were built before 1945 and 1990, respectively. Hence, the majority of the European existing dwellings are compliant neither with modern energy efficiency provisions, nor with modern seismic design requirements. Nearly the total segment of dwellings in Europe is located in residential buildings, accounting for 98.5 % in the EU-27, with the highest share (i.e. more than 50 %) of dwellings located in three- or more-dwelling buildings, followed by 40 % of dwelling in one-dwelling buildings. Only 9 % of the EU dwellings is located in two-dwelling buildings. Hence, both SFHs and MFHs need to be considered in the modernisation of the EU building stock. Estonia, Latvia, Spain, Italy are the EU countries exhibiting the highest number of dwellings in MFHs, whereas Ireland accounts for the highest share of dwelling in SFHs, followed by Belgium and the Netherlands with significant fractions. Another important characteristic to take into account is the size of the EU buildings; generally SFHs accounts for higher average floor area than MFHs. The mean value of the EU average floor area per dwelling is equal to 100 m^2 and 68 m^2 for SFHs and MFHs, respectively. General indications on the distribution of EU buildings by construction materials point out that the majority of the EU building stock consists of masonry buildings, followed by RC constructions. However, some countries, such as Portugal, Greece, accounts for higher fractions of RC buildings. Furthermore, low but no negligible shares of timber buildings are concentrated in few Member States including Germany and North European countries.

Secondly, the EU territory is mapped in seismic hazard and climatic zones. To this end, maps of low, moderate and high seismic hazard zones depending on specific peak ground acceleration (PGA) ranges, according to the European Seismic Hazard Model 2020 (ESHM20) and of six climatic zones in terms of HDD based on the 2019 annual average HDD values related to the EU-27 were presented.

Thirdly, the main outcomes of the two previous investigations are correlated in order to identify the European buildings most requiring combined upgrading. To this end, a methodology based on a two-step framework is considered. The first step allows the identification of EU priority countries exhibiting the most severe seismic-climatic combination. Bulgaria, Croatia, Greece, Italy, and Romania were selected as representative countries characterised by high seismic and severe climatic conditions. Furthermore, Germany was also considered to include in the analysis a country exhibiting a low-to–moderate seismic hazard. The second step deals with the selection of potential NUTS 3 regions representative of the various seismic-climatic scenarios in each of the six identified priority countries. Subsequently, ad-hoc analyses correlating residential building age, year of implementation of moderate seismic deign code and initial energy efficiency regulations, and building type in terms of construction material were carried out in the different regions within the selected countries. Main results point out a **potential to apply combined upgrading** to at **least 60–70 %** of the existing residential building stock in examined regions of the selected EU priority countries, mainly referring to scenarios characterised by high-to-moderate seismic hazard and severe climatic conditions. However, attention needs to be also drawn to the buildings located in low-to-moderate seismic hazard regions. Furthermore, both masonry and RC buildings in all the selected priority countries needs a combined retrofit, prioritising stone and bricks masonry buildings, mainly in Bulgaria and Croatia, as well as RC wall and framed structures, mainly in Greece, and Romania. A focus on the **Italian building typologies most needing combined seismic and energy retrofit** was also carried out, due to the huge variability of the Italian building stock in terms of construction technologies, structural details, envelope components, typically depending by local raw material supply, workmanship, evolution of the seismic and energy regulations over time.

The existing residential building stock, composed of 57 % and 30 % of masonry and RC buildings, respectively, represents the most widespread construction segment in Italy. The investigation on the distributions of residential buildings by period of construction and the evolution of both the Italian seismic design code and seismic zonation was carried out. It was pointed out that more than 90 % and 55 % of existing Italian masonry and RC residential buildings were constructed without seismic provisions, respectively. The first building code for masonry structures was issued in 1987, while seismic provisions for RC buildings were issued after the catastrophic Irpinia-Basilicata earthquake in 1980. However, the seismic design code based on the limit state method was introduced in Italy only one decade later in 1996, when nearly the entire masonry building stock and 75 % of RC buildings were already constructed. Moreover, 88 % of the existing Italian residential buildings are not compliant with modern energy performance requirements since a stringent code on the energy efficiency of buildings was issued in Italy solely in 1991. These figures underlined the urgent need for a combined seismic and energy retrofit of both Italian masonry and RC residential buildings.

Investigations on the masonry and reinforced concrete building stocks by year of construction, geographical distribution at regional and municipality level, and severity of combined seismic and energy demands were carried out. These analyses served as basis for the prioritisation of Italian masonry and RC building typologies most needing combined retrofit.

As for **Italian masonry buildings**, data on structural typologies, age, and size, which were collected within the AeDES forms for damage and safety assessment survey of ordinary buildings in post-earthquake emergency related to the 2012 Emilia earthquake, were examined. Two masonry building typologies, mainly varying by period of construction, floor area, and horizontal structural elements (i.e. floors), were identified as the constructions most suffering from seismic vulnerability. One building typology consist of a regular layout and good quality masonry walls without tie rods/tie beams supporting (i) flexible (e.g. timber), or (ii) semi-rigid (e.g. double layer timber panels) floors. This typology is indicative of low-rise buildings erected before 1945, with 2 o 3 floors and a total floor area equal to 300-400 m^2. The other identified building typology differs from the previous one by the use of rigid floors (e.g. RC floors), the period of construction referring to buildings erected before 1971, with a total floor area equal to 400-450 m^2. Thrusting roofs are present in both building typologies, representing a recurrent cause of seismic vulnerability for masonry buildings. It is worth noting that the masonry building typologies above are representative of the Emilia region, and potentially also indicative of the existing masonry building stock located in the north-eastern Italian areas. Beyond seismic vulnerability, these building typologies also exhibit an inadequate energy performance, as demonstrated by the U-values of the building envelope components, resulting much higher than the corresponding threshold values required by the Italian regulations on energy efficiency of buildings currently in force.

As for the **Italian RC buildings**, research studies on seismic vulnerability assessment of the Italian existing buildings, providing details on typical residential RC buildings, were analysed. RC framed structures designed only for gravity loads resulted into the most widespread RC structural typology in Italy, generally consisting of one-way moment resisting frames until the '90s. Two buildings typologies most needing seismic retrofit to be combined with the energy one were identified based on the period of construction: (i) pre-1971 RC framed structures and (ii) post-1971 RC framed structures, mainly varying for the constitutive material properties. Both typologies are regular in plan and elevation, differentiated between small and large floor area, as well as among two-storey, four-storey and eight-storey buildings. Masonry infills play a crucial role in the seismic performance of RC framed structures, thus various configurations of infill walls were considered: bare frame (ineffective infills), regularly infilled-frame, and pilotis-frame. Both pre-1971 and post1971 building typologies exhibited the highest seismic vulnerability in case of pilotis-frames. However, the infill walls assume a fundamental role also for the energy performance of framed structures, thus the evolution of infill typologies from '40s to '90s was investigated. Similarly to Italian masonry building typologies, a poor thermal performance of the infill walls was pointed out. Indeed, the U-values of infill used during the period 1950-1990 were higher than the threshold values required by the Italian regulations on energy efficiency of buildings currently in force.

Further developments and improvements to extend the investigation on the EU building typologies that could benefit from the combined seismic and energy retrofit need to be considered to provide a fine-tuned inventory. As examples, regarding seismic investigations, a more comprehensive overview of the Italian masonry building typologies suffering from seismic vulnerability could be achieved by analysing databases related to other post-earthquake surveys due to the region-by-region diversity of the Italian masonry buildings, mainly depending on local material supply and quality of masonry. In relation to the RC building typologies, more accurate data related to the concrete strength of the existing structures can be achieved by referring to in-situ and laboratory testing, beyond the design values provided by the codes in force at the time of construction. Moreover, regarding energy investigations, it is worth noting that during the last 20 years of the 21th century the effect of the climate change is drastically contributing to the increase of unusually hot days, known as extreme heatwaves, in all Europe (Basarin et al., 2020, Lhotka and Kyselý, 2022). Beyond the impacts produced on human health, regional economies, forest ecosystems, the demand for cooling is expected to increase with a consequent increase of electricity consumption due to air conditioning systems. Based on this, further research on two main routes of investigation are needed: (i) analysis on the energy demands of buildings in the framework of climate change for the future decades, e.g. a study by Ciancio et al. (2020) focused on the investigation across Europe for the future years 2050 and 2080); (ii) study on thermal insulation as an effective retrofit strategy for existing building to tackle overheating, mainly in southern Europe (e.g. Calama-Gonzales et al., 2023).

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List of abbreviations and definitions

AeDES	Safety and damage assessment survey form of ordinary buildings in post-earthquake emergency (Agibilità e Danno nell'Emergenza Sismica), in Italian
BF	Bare frames
BPIE	Building Performance Institute Europe
CDD	Cooling Degree Days
CO_2	Carbon dioxide
CZ	Climatic zones
Da.O.D	Database of Observed Damage
DL	Decree-Law (according to Italian legislation)
DLgs	Legislative Decree (according to Italian legislation)
DM	Ministerial Decree (according to Italian legislation)
DPC	Italian Civil Protection Department (Dipartimento di Protezione Civile, in Italian)
DPCM	Decree of the President of the Council of Ministers (according to Italian legislation)
DPR	Decree of the President of the (Italian) Republic (according to Italian legislation)
EED	Energy Efficiency Directive
ELSTAT	Hellenic Statistical Authority
ENTRANZE	Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe
EP_{gl}	Global Energy Performance index
$EP_{gl,nren}$	Non-renewable Global Energy Performance index
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ERD	Earthquake-resistant design
ESHM	European Seismic Hazard Model
ESS	European Statistic System
EU	European Union
EU-27	27 EU Member States
GHG	Greenhouse gas
HDD	Heating Degree Days
IEE	Intelligent Energy Europe
IF	Regularly Infilled-frame
ISTAT	Italian National Statistics Institute
L	Law
LCT	Life Cycle Thinking
LTRS	Long-term renovation strategies
M_L	Local magnitude
MFH	Multi-Family House
NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
NSI	National Statistical Institute Bulgaria

NTC	Italian Technical Code for Constructions (Norme Techniche per le Costruzioni, in Italian)
NUTS	Nomenclature of Territorial Units for Statistics
nZEB	Nearly Zero-Energy Building
OPCM	Ordinance of the President of the Council of Ministers (according to Italian legislation)
PF	Pilotis frame
PGA	Peak Ground Acceleration
PS_i	Prioritisation score for each EU Member State *i*
RC	Reinforced concrete
RD	Royal Decree
SCZ	Seismic-climatic zone
SZ	Seismic zone
SFH	Single Family House
TABULA	Typology Approach for BUiLding Stock Energy Assessment
UN	United Nations
U-value	Thermal transmittance value
f_{cm}	Mean compressive strength (concrete)
F_{ym}	Mean yielding strength (steel)

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Annex 1

Annex 1 - Table 1. Data related to the distribution of number of dwellings in Europe by year of construction.

Country	Pre-1919	1919 – 1945	1946 – 1960	1961 – 1970	1971 – 1980	1981 – 1990	1991 – 2000	2001 – 2005	Post-2006	Not stated	Total (by country)
EU-27 Member States											
Austria	791264	341264	492249	624730	663001	522565	487725	256931	261679	0	4441408
Belgium	1254727	715491	640034	643584	742173	391726	483773	205384	228692	3362	5308946
Bulgaria	58136	347773	655278	665865	829343	724129	265414	95009	239787	2076	3882810
Croatia	181522	123046	188278	354849	412858	335264	195871	112842	133738	208642	2246910
Cyprus	3968	9129	20343	24255	61247	85503	70094	54897	92117	9506	431059
Czechia	374654	529758	364925	577688	822621	615104	359204	158258	206075	748285	4756572
Denmark	524694	456245	356556	455384	469960	257764	143513	99909	107787	1553	2873365
Estonia	39899	70547	57101	116654	132597	122526	25777	20033	41320(e)	23292	608426
Finland	43020	226037	377532	389604	598793	514309	320885	157044	143626	36655	2807505
France	6170401	3469278	4660624	3110649	4626459	4625624	3381869	1690801	1808237	0	33543942
Germany	5683647	4169081	6423880	6341340	6082648	4075319	5293217	1472715	1021466	0	40563313
Greece	163759	318372	605693	1002902	1437424	1049931	806977	539009	447834	0	6371901
Hungary	377336	514866	530957	653376	934214	673405	280091	239225	186832	0	4390302
Ireland	150516	115153	127987	114796	214663	172929	239565	267311	172102	419946	1994968
Italy	3656542	2799407	4268838	5986048	5770951	3874961	2311576	1348445	1121510	0	31138278
Latvia	105390	126004	93297	170822	210439	200056	47187	15169	36322	13846	1018532
Lithuania	45612	139489	132496	237070	311622	300861	96014	29556	55877	25636	1374233
Luxembourg	22557	26053	24942	19766	25435	20038	28078	14228	17083	24766	222946
Malta	15755	13330	15640	13865	22485	28886	23386	10820	8603	71080	223850
Netherlands	546580	865751	850734	1069878	1205509	1084910	884260	348187	360375	243510	7459694
Poland	1037200	1439905	1123847	1802952	2646895	1781684	1161225	662854	810025	499009	12965596
Portugal	251619	373893	539060	648488	983645	1011960	1098329	581718	370828	0	5859540
Romania	298142	680934	1371011	2054242	1730409	1186525	469868	249535	447084	234648	8722398
Slovenia	121955	57973	80827	122353	176521	146825	64743	31500	41959	0	844656
Slovakia	43015	117010	259667	331411	430301	322343	94976	50168	62926	229359	1941176
Spain	1575395	1230460	2246490	3573200	5011355	3137195	3084000	2217825	2443790	686820	25206530
Sweden	365836	805780	772274	816988	713354	386117	205649	85567	138417	534245	4824227
Sub-Total EU-27 (by year)	23903141	20082029	27280560	31922759	37266922	27648459	21923266	11014940	10964771	4016236	**216023083**
Other contries in Europe											
Iceland	2651	11867	16495	16898	22755	16990	14636	13543	10337	39	126211
Liechtenstein	880	913	1404	2356	3243	2481	3623	1611	1339	584	18434
Norway	224953	179785	325896	291093	380846	330282	230172	138849	168956	145028	2415860
Switzerland	675016	423664	511143	613617	574153	468251	418916	169912	276670	0	4131342
United Kingdom	5771870	4610900	4194100	3836220	2871780	2341690	1936280	1021875	884710	0	27469425
Sub-Total Other countries (by year)	6675370	5227129	5049038	4760184	3852777	3159694	2603627	1345790	1342012	145651	**34161272**
TOTAL	30578511	25309158	32329598	36682943	41119699	30808153	24526893	12360730	12306783	4161887	**250184355**

Source: European Statistical System – 2011 Population and Housing Census

Annex 1 – Table 2. Data related to the distribution of number of dwellings in Europe by building type.

Country	Dwellings in one-dwelling buildings	Dwellings in two-dwelling buildings	Dwellings in three- or more- dwelling buildings	Sub-total (Dwellings in residential buildings)	Dwellings in non-residential buildings	Not stated	Total (by country)
EU-27 Member States							
Austria	1442066	570126	2287857	4300049	141359	0	4441408
Belgium	3464147	257822	1481522	5203491	105455	0	5308946
Bulgaria	1745586	271185	1866039	3882810	0	0	3882810
Czechia	1227376	538606	2299909	4065891	38744	651937	4756572
Denmark	1382818	105038	1114154	2602010	268328	3027	2873365
Germany	12003404	6353787	21869873	40227064	336249	0	40563313
Estonia	185547	12606	450105	648258	1488	0	649746
Ireland	1686393	23119	249279	1958791	15222	20955	1994968
Greece	2457437	1049001	2846083	6352521	19380	0	6371901
Spain	7709205	1145520	15664980	24519705	440340	246480	25206525
France	18043541	1208943	14291457	33543941	0	0	33543942
Croatia	1119594	294922	827172	2241688	5222	0	2246910
Italy	6114853	5314546	19708879	31138278	69883	0	31208161
Cyprus	181937	59050	156450	397437	32530	1092	431059
Latvia	270226	19738	712125	1002089	1357	15086	1018532
Lithuania	496963	55043	819434	1371440	2793	0	1374233
Luxembourg	118840	11328	91909	222077	869	0	222946
Hungary	2498706	141378	1723670	4363754	26548	0	4390302
Malta	82577	21298	48895	152770	0	71080	223850
Netherlands	4726666	250607	2062066	7039339	105568	314787	7459694
Poland	4992920	529956	7403228	12926104	38355	1139	12965598
Portugal	3049752	335729	2433663	5819144	40396	0	5859540
Romania	5063653	155708	3436998	8656359	8567	57472	8722398
Slovenia	452016	58984	307201	818201	26455	0	844656
Slovakia	925482	71990	942928	1940400	776	0	1941176
Finland	1002434	120696	1630240	2753370	52557	1578	2807505
Sweden	2440411	17390	2280076	4737877	79436	6914	4824227
Other countries in Europe							
Iceland	35024	14908	74940	124872	1305	34	126211
Liechtenstein	7045	3109	7790	17944	490	0	18434
Norway	1214550	365947	768499	2348996	66864	0	2415860
Switzerland	1040895	386838	2551088	3978821	152521	0	4131342
United Kingdom	6336100	8268240	12579140	27183480	285945	0	27469425

Source: European Statistical System – 2011 Population and Housing Census

Annex 1 – Table 3. Data related to the distribution of number of dwellings in Europe by useful floor area.

Country	Floor area < 30 m²	30 m² ≤ Floor area < 40 m²	40 m² ≤ Floor area < 50 m²	50 m² ≤ Floor area < 60 m²	60 m² ≤ Floor area < 80 m²	80 m² ≤ Floor area < 100 m²	100 m² ≤Floor area < 120 m²	120 m² ≤ Floor area < 150 m²	Floor area ≥ 150 m²	Not stated	Total (by country)
EU-27 Member States											
Austria	51543	154016	232681	355790	822226	691005	418536	551964	367197	0	3644958
Belgium	/	/	/	/	/	/	/	/	/	/	4563651
Bulgaria	/	/	/	/	/	/	/	/	/	/	2665941
Czechia	241435	226323	374586	458345	727824	416886	245681	462766	530419	420370	4104635
Denmark	14431	33218	63214	156749	455871	479553	349129	437963	515478	3244	2508850
Germany	549116	1202011	2471108	3919396	8695258	6406749	4599036	5251623	3825178	/	36919475
Estonia	23496	67036	111438	75400	137757	37301	28306	24420	39188	625	544967
Ireland	/	/	/	/	/	/	/	/	/	/	1649112
Greece	55593	126587	212701	359488	971186	1047247	674547	429026	245713	0	4122088
Spain	50425	158865	495745	988265	4560825	5859485	2458145	1696320	1813515	0	18081595
France	/	/	/	/	/	/	/	/	/	/	27913047
Croatia	33285	86347	126725	202131	391665	268509	176984	102543	108369	0	1496558
Italy	32343	459987	1121167	1618310	4993602	6081472	4192549	2897122	2738625	0	24135177
Cyprus	/	/	/	/	/	/	/	/	/	/	297122
Latvia	67712	108042	184913	127852	148372	49200	29680	26615	54277	11148	807811
Lithuania	51767	131026	190742	209823	299872	106507	61351	43666	57977	16239	1168970
Luxembourg	3138	3017	4083	6375	19239	25953	19824	32529	53278	39432	206868
Hungary	71856	217576	332544	679298	865378	797494	518635	277643	152005	0	3912429
Malta	/	/	/	/	/	/	/	/	/	/	152770
Netherlands	22875	61492	158768	305568	1009835	1374186	1434679	1245001	1244723	82360	6939487
Poland	463814	1496796	2213906	1864975	2342015	1126287	1070791	843485	1216226	3622	12641916
Portugal	77946	114405	202659	263692	599075	793883	688015	571298	680139	0	3991112
Romania	1584317	1600692	1438787	823819	1078238	406937	177030	92398	92770	0	7294988
Slovenia	27954	47185	65495	93589	158436	98068	67016	63313	49071	0	670127
Slovakia	/	/	/	/	/	/	/	/	/	/	1669903
Finland	/	/	/	/	/	/	/	/	/	/	/
Sweden	50117	126487	203973	375803	967505	695792	568217	592020	422091	0	4002005
Other countries in Europe											
Iceland	977	2264	4750	7910	21305	24423	18646	18660	18995	4	117934
Liechtenstein	222	277	467	614	1539	2330	2880	3550	3533	0	15412
Norway	30114	49054	81000	127322	320233	254054	244611	305672	724529	68601	2205190
Switzerland	/	/	/	/	/	/	/	/	/	/	3534508
United Kingdom	/	/	/	/	/	/	/	/	/	/	26292055

/ data not available

Source: European Statistical System – 2011 Population and Housing Census

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