energy and seismic affordable renovation solutions

Deliverable 3.1

Report with e-SAFE requirements

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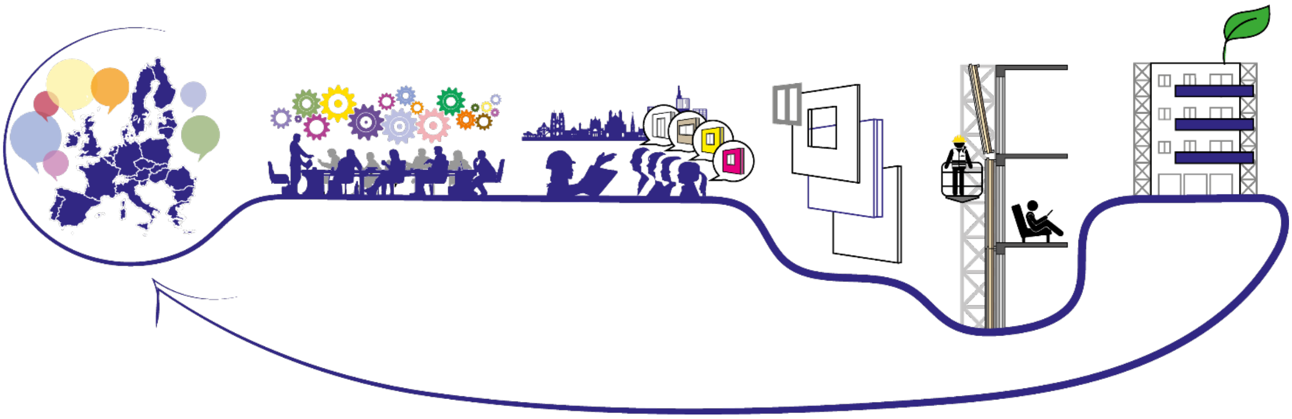

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Executive Summary

The aim of this document is to identify the current thermal, acoustic, seismic, technical, safety and environmental directives, standards and regulations, which apply to the various **e**-SAFE retrofit solutions at European level.

Then, a preliminary analysis of the expected thermo-hygrometric, acoustic, seismic, technological and safety performances of the various solutions and technologies deployed is presented and discussed in detail in order to point out potential issues needing further detailed studies.

The activity has also assessed the relevance of the existing normative framework, both at component and system level, in order to derive specifications for the e-PANEL and e-CLT products development.

Glossary of Terms

Acronym	Description
BEMS	Building Energy Management System
CLT	Cross Laminated Timber
COP	Coefficient of Performance
DF	Daylight Factor
DHW	Domestic Hot Water
EC	Eurocode
EER	Energy Efficiency Ratio
EPC	Energy Performance Certificate
ETICS	External Thermal Insulation Composite System
EU	European Union
GHG	Green House Gas
HDD	Heating Degree Days
IEQ	Indoor Environmental Quality
LCA	Life Cycle Assessment
nZEB	Nearly Zero Energy Building
PEF	Product Environmental Footprint
RC	Reinforced Concrete

1. Introduction

The present document is the deliverable "D3.1 – Preliminary definition of the **e**-SAFE requirements" of the **e**-SAFE project (Grant Agreement No.: 893135), funded by the European Commission under its Horizon 2020 Research and Innovation Programme (H2020).

This report contains a description of the technological solutions proposed in the project for the energy and seismic renovation of the non-historic EU building stock. The report will outline the expected performances of the proposed solutions and the requisites of the components that will be implanted in relation to the technical and normative framework within Europe.

1.1 Purpose and scope of the deliverable

This deliverable is devoted to the identification of the main thermal, energy, comfort, seismic, technological and safety requirements that the various **e**-SAFE components have to satisfy in order to ensure their effectiveness and compliance with relevant EU regulations. Then, a preliminary analysis of the performances expected for each component or technological system is carried out and commented so as to lay the basis for the detailed design stages of the single components (Task 3.3), as well as for the renovation of the pilot buildings (WP5).

1.2 Deliverable structure

After a description of the overall renovation scheme proposed by **e**-SAFE, Section 2 "**e**-SAFE overall concept and components" presents the various building envelope solutions (e-PANEL, e-CLT, e-EXOS), technical systems (e-TANK, e-THERM) and renewable energy sources (photovoltaic panels) proposed in the project.

Section 3, "Requirements and relevant European regulation framework", details the thermal, seismic, technological and safety requirements that **e**-SAFE components and systems must satisfy to comply with the actual European legislation and technical frameworks.

Then, Section 4 "**e**-SAFE response to requirements: expected performances" presents preliminary analyses of the expected performances for each component in order to identify the boundaries for their optimal implementation under the different climates, seismic hazards and technological constraints within the EU.

Finally, conclusions summarize the main outcomes of this report with a particular attention to their use in upcoming related tasks.

1.3 Links with other tasks in the project

The outcomes of this Task will form the key inputs to the detailed design of the **e**-SAFE technologies (Task 3.3), while also defining the constraints to inform the Decision Support System (Task 4.1) before launching the preliminary co-design stage involving the occupants of the real pilot building (Task 5.2).

1.4 Contribution of the partners

UNICT led Task activities by framing the structure of the report and coordinating the contributions from the partners; introduced the project and described this report structure (Section 1); described the main **e**-SAFE technological solutions for the building's envelope (Section 2.1); detailed the requirements and EU regulations concerning thermal, IEQ, acoustic, seismic and technological aspects (Sections 3.1, 3.2, 3.3, 3.4 and 3.5); reported preliminary analyses on how **e**-SAFE responds to such requirements (Sections 4.1, 4.2, 4.3, 4.4 and 4.5); framed the conclusions section.

UNIBO described the overall technical systems concept and architecture, including renewable energy production from photovoltaic panels (Sections 2.2.2 and 2.3); detailed the requirements and EU regulations concerning technical systems and renewable energy production, nearly zero energy buildings and the energy certification scheme (Sections 3.1.4, 3.1.5 and 3.1.6), while also contributing to define the environmental quality of construction materials (Section 3.5.5) and preliminary define the construction products quality performance of **e**-SAFE (Section 4.6).

NMBU detailed the requirements and EU regulations concerning seismic aspects (Section 3.4) and reported preliminary analyses on the **e**-SAFE solutions response to earthquakes (Section 4.4).

PINK described the concept of the decentralized hot water storage tanks (Section 2.2.1) and detailed the requirements and EU regulations concerning them (Section 3.6).

SALFO provided technical support on the definition of the requirements and EU regulations concerning various technological aspects (Section 3.5) and guidance on how **e**-SAFE can respond to them (Section 4.5).

WEBO provided technical support on the definition of the requirements and EU regulations concerning various technological aspects (Section 3.5) and guidance on how **e**-SAFE can respond to them (Section 4.5).

1.5 List of figures

1.6 List of tables

2. e-SAFE overall concept and components

The main scope of **e**-SAFE is to develop a market-ready decarbonising and multi-purpose deep renovation system for non-historic buildings that encompasses technological, functional, aesthetic, financial and economic aspects, while overcoming the most significant barriers faced by deep renovation in EU today.

e-SAFE solutions apply to the whole building: in doing so, they combine energy and structural performances. In terms of energy performances, it can be stated that existing buildings that embed such solutions can meet the current nearly Zero Energy Building (nZEB) standard requirements in force in various European countries. The proposed building envelope solutions make use of pre-fabricated insulating timber-based panels (e-PANEL, section 2.1.1) with embedded glazed components for the minimisation of thermal losses. On the other hand, plug-and-play decentralized small-volume water storage tanks (e-TANK, section 2.2.1) will be installed in each dwelling to store the domestic hot water delivered by a centralized electricity-driven high-efficiency air-to-water heat pump. The latter also covers the energy demand for space heating and cooling, through a system architecture that includes large-volume water-based thermal energy storage devices (e-THERM, section 2.2.2). A significant share of the electric energy needed to feed the heat pumps is covered by photovoltaic panels (section 2.3), according to the logics implemented on a dedicated Building Energy Management System (BEMS).

In terms of seismic performances, **e**-SAFE incudes two alternative components: e-CLT (section 2.1.2) and e-EXOS (section 2.1.3). e-CLT consists of cross laminated timber (CLT) panels to be applied to the outer walls and connected to the existing reinforced concrete (RC) frame via energy dissipation devices (dampers), while e-EXOS consists of a metal exoskeleton made of bi-dimensional bracings equipped with dampers and connected to the existing RC frame. Both structural systems increase lateral stiffness and strength of the building and provide additional energy dissipation capacity. Furthermore, they mitigate the activation of story collapse mechanisms promoting a widespread yielding of the structure in occurrence of strong ground motions. The effect is the reduction of the story drifts caused by the seismic excitation, which in turn reduces damage to non-structural and structural elements improving the seismic performance and seismic resilience of the building. All the materials used for e-CLT and e-EXOS will be selected with the aim of minimizing the environmental impact during the whole life cycle. Finally, e-CLT and e-EXOS can be coupled to e-PANEL according to two innovative plug-in solutions.

2.1 Building envelope solutions

2.1.1 Thermal insulation: e-PANEL

The thermal insulation of the building envelope is the most common practice for an effective energy retrofit of the opaque envelope and for significantly reducing the energy consumption for space heating and cooling in existing low-performing buildings, while also ensuring a suitable level of thermal and acoustic indoor comfort.

In particular, the external thermal insulation composite system (ETICS) is a classical, yet cost-effective, flexible and reliable solution to reach the desired level of thermal insulation for the outer walls. ETICS is also an effective solution to correct thermal bridges, and allows improving the sound insulation provided by the façades. However, in many circumstances, the adoption of ETICS turns out to be time-consuming and disruptive.

According to this premise, the solutions proposed by **e**-SAFE try to conjugate energy savings and the need to minimise occupants' annoyance, implementation costs, and the time needed on-site for installation, while also allowing for renewing the building image and raising its economic and social value. This is accomplished by the development of a customizable, prefabricated, plug-and-play, multifunctional panel (e-PANEL) that is made up of a timber-framed structure combined with local bio-based recyclable (or recycled) insulating materials and finished by customizable cladding material. The e-PANEL is conceived as a versatile "open system" that can be customized, upgraded and easily maintained over time (see Figure 1).

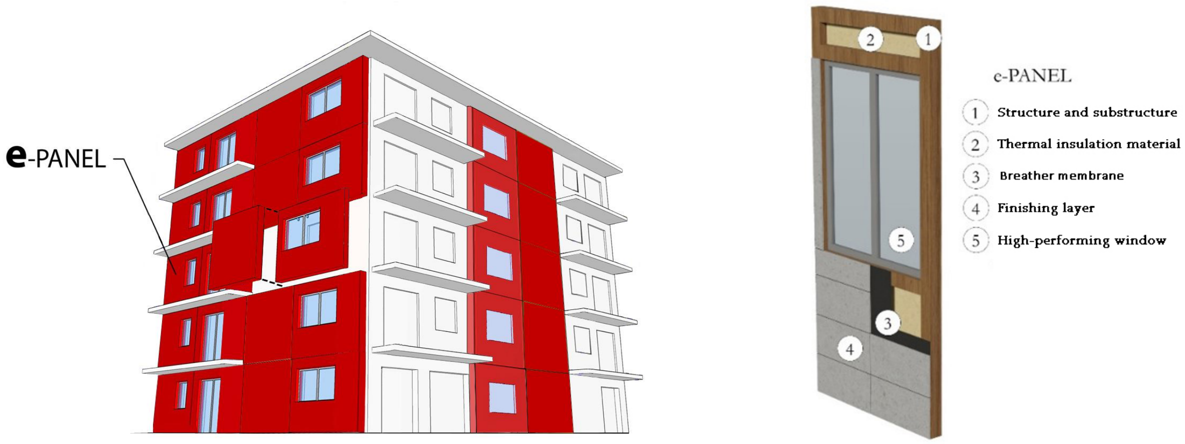


Figure 1. e-PANEL application on the facades and its stratification

In order to reduce the cooling demand in summer, while also facilitating moisture drying in winter, the e-PANEL can also be designed with a ventilated air cavity between the cladding and the insulation layer. The pre-assembled panels also include high-performance, wooden-framed, double-glazing windows, which replace the existing ones. The new windows are thus integrated in the prefabricated e-PANELs and are equipped with solar blinds to reduce indoor overheating in summer, avoid glare risks and enhance visual comfort.

The choice of the insulating material is oriented to locally available low-cost bio-based materials, possibly coming from recycling processes (e.g., hemp, cork, wood fibre, cellulose fibre, sheep wool, etc.), with a consequent reduction of the carbon footprint of the selected solution.

This aspect will be analysed into detail later during the development of the design process, considering the case studies location and the origin of raw or recycled materials. The insulation thickness is set according to the climate, the current state of the building and the desired level of performance. The carbon footprint and the impact of materials are compared considering the same thermal performance, in compliance with actual regulations.

Table 1 shows values of the Embodied Energy and the Embodied Carbon of some insulation materials, from the Inventory of Carbon and Energy ICE, BSRIA [1]. The boundaries of ICE are cradle-to-gate. However, within these boundaries, there are possible variations that might affect the absolute boundaries of the study. More detailed and updated data will be given in the next steps of the research, following the development of the project.

Table 1. Embodied energy and carbon figures for various insulating materials

Insulating material	**Embodied Energy ($MJ \cdot kg^{-1}$)**	**Embodied Carbon ($kgCO_2 \cdot kg^{-1}$)**	**Embodied Carbon (GHG) ($kgCO_{2e} \cdot kg^{-1}$)**
Cork	4	0.19	
Hemp	10		
Cellulose	0.94 - 3.30		
Wool (recycled)	20.90		
Wood wool (board)	20	0.98	
Rockwool (cradle to grave)	16.80	1.05	1.12
Expanded polystyrene (including 46.2 $MJ \cdot kg^{-1}$ of feedstock energy)	88.60	2.55	3.29
Polyurethane rigid foam (including 37.07 $MJ \cdot kg^{-1}$ of feedstock energy)	101.50	3.48	4.26

In general terms, the low density and the high thermal performance of insulating materials from oil industry do not always compensate their embodied energy and carbon coefficient. This issue will be further investigated in Section 4.6. Besides, the ICE database, like other databases, can be used as “proxy data” in the absence of country specific data. For many materials there is a strong influence from international data. It is worth reminding that embodied carbon and embodied footprint are similar terms. The term embodied carbon can only be used in the context of materials, for example all activities related to the construction of a building or production of a power tool, including the production of materials; carbon footprint can also be used to discuss operational carbon requirements, for example heating and lighting of a building, or operation of a power tool.
At very low U-values, the embodied energy can exceed the operational energy; current best practice walls coupled with low building lifetimes mean that this point may be reached. Substantial uncertainty is present in existing embodied energy data. This aspect will be addressed more in detail in the following steps of the research.
Finally, the choice of the cladding material (ceramic, stone, metal, glass, wood, wood-plastic composites, etc.) will be one of the main elements of customization for users during the co-design process, based on their aesthetic preferences.

2.1.2 Structural reinforcement: e-CLT

The e-CLT system consists in the application of customizable prefabricated CLT panels on the outer side of the existing walls, by connecting them to the RC structure through innovative dissipative devices (Figure 2). These devices are basically friction dampers. The use of CLT panels for structural reinforcement of existing buildings has shown great potential, thanks to the high strength and stiffness of this engineered wood product [2]. The e-CLT system is conceived so that in occurrence of moderate ground motions, the dampers rigidly connect CLT panels to the RC structure, thus making available additional lateral stiffness and strength. Conversely, dampers activate in occurrence of stronger ground motions, thus dissipating part of the input seismic energy. Both these effects reduce the drifts demanded by earthquakes, reduce damage to non-structural and structural components, and improve the seismic performance of the RC frame. Furthermore, the activation of the damper defines an upper bound to the force sustained by the CLT panel, thus preventing its failure even under strong ground motions. Strength, stiffness and dissipation capacity provided by the e-CLT system are controlled by modulating the thickness and the number of CLT panels, as well as the damper size.
The damper is basically made by two steel profiles, which connect the CLT panels of two consecutive floors with the existing interposed RC beam. One profile is connected to the RC beam by anchor bolts and to the other by slotted holes and pretensioned high-strength bolts. The shear force is transmitted from the upper to the bottom profile by means of the friction exerted in the contact surface. During an earthquake, when the force transmitted by the damper attains the value of the friction force, the upper profile slides on the bottom one and thus dissipates seismic energy. The final configuration of the damper will be one of the outcomes of **e-**SAFE project.
The e-CLTs, as much as the e-PANELs, integrate both local bio-based recyclable (or recycled) insulating materials and customizable cladding ones. Size and number of CLT (structural) panels applied on the façade are determined based on the initial seismic deficiency of the building and the assumed target performance. Hence, (non-structural) e-PANELs can be coupled to e-CLTs to complete the envelope of the building by retaining an aesthetic uniformity: in this case, they will of course have the same overall thickness. The result is a new performing envelope applied on the existing one, that concurrently improves the energy, seismic and aesthetic performance of the renovated building (Figure 2).

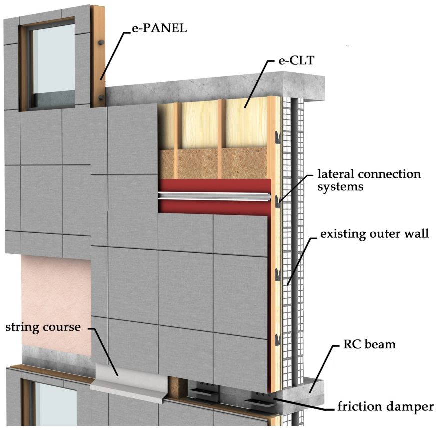


Figure 2. e-CLT application on the facades and its stratification

2.1.3 Structural reinforcement: e-EXOS

The second alternative retrofitting system is constituted by an ensemble of steel bracings equipped with seismic dampers. The bracings are placed with their plane oriented orthogonal to the façade of the existing building and are connected to its perimeter beams. The dampers may be located within the brace members or in the connections between the decks and the bracings. The number of bracings, the length of their span and the size of their members control the additional lateral stiffness provided to the existing structure of the building. Dampers are selected among those already available in the market. Additional strength and energy dissipation capacity are set by tuning the strength capacity of the dampers. Similarly, to the e-CLT, stiffness, strength and energy dissipation capacity provided by e-EXOS can reduce the story drifts demanded by the earthquake excitation below the capacity. e-EXOS is installed on the outside of the existing building and does not interrupt the continuous skin realized by e-PANELs to ensure the proper thermal insulation (Figure 3). The length of the span of the bracings should comply with the urban and legislative constraints on the allowed addition on the building façade. However, small length of the span of the bracings requires an increase in the size of members of e-EXOS. Conversely, the size of members of e-EXOS being fixed, the assumed value of length of the span of the bracings affects the additional stiffness and strength provided to the existing building. Therefore, a limit on the improvement of achievable seismic performance could arise.

Figure 3. Integration of e-EXOS with e-PANEL

2.2 Technical systems

Space Heating and Domestic Hot Water (DHW) services in existing building require water at moderate temperature (50-70 °C). Traditional gas boilers or District Heating Network of first generation (high temperature) generally have low efficiency and require high primary energy consumption. Electric Heat

Pumps (EHP) are today widely used for space heating purposes in buildings thanks to their high efficiency as expressed by the Coefficient of Performance (COP), and for the possibility to be fed also from renewable energy sources. Meanwhile storage systems play an important role in order to reduce peak energy demand and to increase the efficiency of whole production systems. For this reason, the e-THERM concept developed in **e**-SAFE appoints a central role to heat storage systems by deploying innovative integrated technologies that enable effective integration and communication with the heat production devices (see Figure 4).

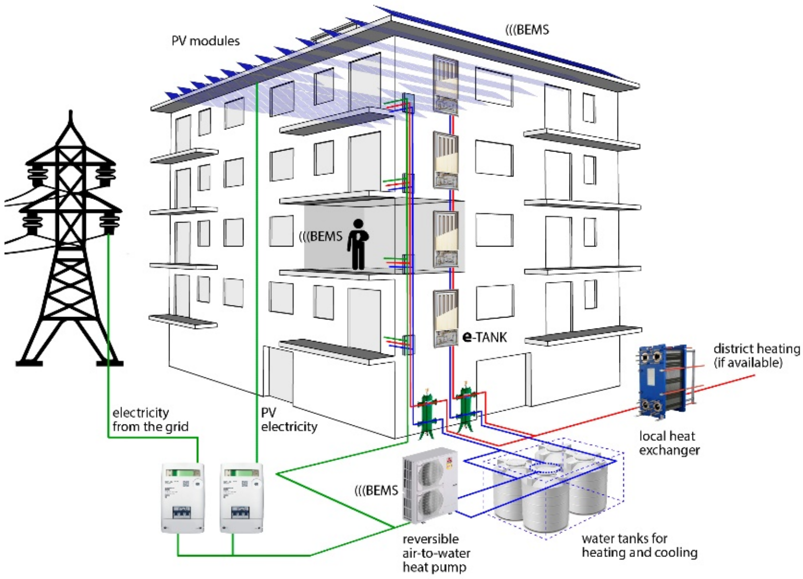


Figure 4. Concept scheme of technical systems integration and operation

The proposed e-THERM solution provides the installation of insulated water tanks to store the thermal energy provided by the reversible air-to-water electric heat pumps (A2W EHP) (or by other systems, like water-to-water HP, existing district heating systems, micro-cogeneration, solar panels, etc.), thus decoupling thermal energy production and demand.

The A2W EHP connected to solar PV panels produce thermal energy mainly during the hours of good availability of solar radiation, then the hot water stored in the water tanks is used in the hours with high thermal energy demand. A specific control system, tailored to real energy needs of occupants and external climate conditions, will be defined with numerical simulations and developed in order to maximize the efficiency of EHP and the PV self-consumption rate.

2.2.1 Plug-and-play decentralized hot water storage: e-TANK

e-TANK is primarily devoted to Domestic Hot Water (DHW) storage for every dwelling renovated through **e**-SAFE and is implemented via a 2-pipe network, which is very easy and inexpensive to install. The distribution network is operated at a low temperature level during heating operation, and the temperature of the feed line is only briefly raised to a higher level while the hot water storage tank is being charged. This results in low heat losses in the pipes. In addition, this creates ideal conditions for efficient operation of low-temperature heat sources such as heat pumps, as it is planned within **e**-SAFE through the e-THERM concept (see next Section). The water content of the storage tank will be determined so as to provide a certain degree of autonomy to the heat pumps while also keeping the tank’s size reasonable. As part of the **e**-SAFE project, two different types of modular water storage tanks produced by PINK GmbH will be deployed (see Figure 5):

- the first type is a storage tank with a very flat design that gives the possibility of the direct integration into (or at least tight fitted to) the walls of a dwelling. Despite the reduced size of the storage tank (1.75 x 0.82 x 0.25 m3), the volume capacity amounts to 140 litres and is deemed sufficient to reliably supply the dwelling with the amount of hot water needed by a typical family of four people.

- the second type is a conventional cylindrical storage tank of dimensions 1.23 x 0.52 x 0.55 m3, resulting in a volume capacity of 150 liters. This solution comes with the advantage of lower production costs if compared to the flat wall storage tank, while retaining the same operation mode. In case there is enough space for integration in the renovated dwelling, this storage variant would be then preferred to the flat one.

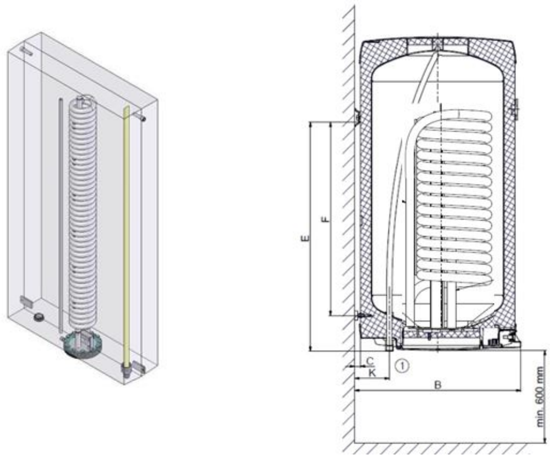


Figure 5. Flat (on the left) and cylindrical (on the right) e-TANK solutions

Both devices include plug-and-play hydraulic connections and integrated electronic control that reduce the number of hydraulic components located inside each dwelling.
In order to manage also the hot water supply for space heating, as well as the fresh water supply for domestic purposes and space cooling, a prefabricated hydraulic module is installed as part of the e-TANK system. In the case of the flat storage tank, this hydraulic module can be installed directly below the storage tank, while the hydraulic unit for the cylindrical tank can be installed in a flush-mounted cabinet below the storage tank. A main advantage of the prefabricated hydraulic unit is its flexibility with regard to the fulfillment of different requirements that can arise in various renovation projects, such as the connection with existing heating systems of different typologies (e.g., radiators and underfloor heating systems).
The integration of additional components for the control and monitoring system is also possible thanks to adapters for heat and cold-water meters with the corresponding thermowells (see Figure 6).
In addition to the design of the e-TANK storage system, another key point addressed is the definition of a control strategy that ensures the supply of the individual apartments with hot water as well as heating energy and possibly also cooling energy.
One innovative control strategy that will be studied in detail in other tasks of the project consists in charging the storage tanks in sequential order in order to ensure more stable conditions with regard to the charging power of the heat source (heat pump). In this way, the constant availability of hot water is guaranteed and a simultaneous operation of the supply network is not always necessary. The possibility of hot water withdrawal with simultaneous standby of the supply lines in summer results in minor heat losses of the pipe network, which can reach up to 70% of the total energy demand in systems without decentralized water heating due to continuous operation. During the heating season the system can, if a low-temperature heating system such as underfloor heating is installed, be operated at far lower temperatures, which can further reduce losses in the pipelines. High feeding temperatures of ~60 °C are only required during the periods of the domestic hot water preparation, which typically occurs only twice a day for 2-3 hours each.

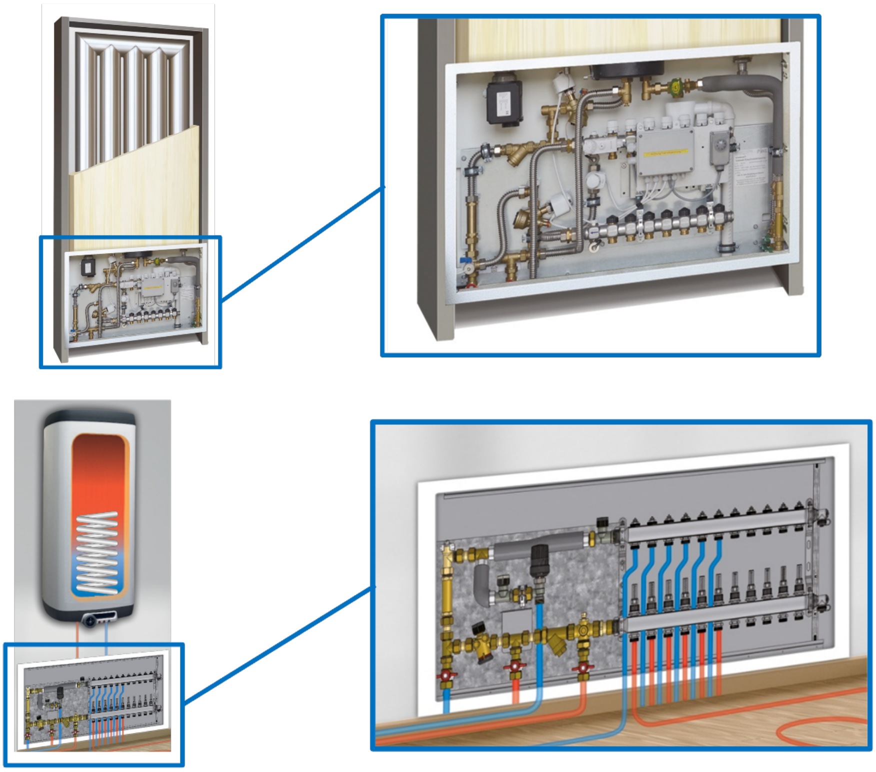


Figure 6. Prefabricated hydraulic units for different e-TANK configurations (flat on top and cylindrical at bottom)

2.2.2 Air-to-water heat pump and thermal energy storage: e-THERM

Air-to-water heat pumps transfer heat from the outside air to the water-based system with the aim of providing space heating and cooling as well as for DHW production. They are amongst the most efficient heat generators in the retrofit market, though they are also very well-suited to new constructions. New generation of A2W EHPs of medium size for residential use offers many advantages: COP values greater than five, use of new refrigerants with low Greenhous Gas (GHG) emission and reduced noise emission.

The proposed e-THERM solution takes advantage from high performance A2W EHP coupled to insulated water tanks to store the thermal energy. In order to avoid excessive upfront investments, air-to-water heat pumps will be preferred, unless local conditions will make it possible to conveniently use water or ground-source heat pumps. In the **e**-SAFE project, the old inefficient thermal systems are replaced with high performance centralized electricity-driven heat pumps in order to satisfy both space heating/cooling needs and DHW needs. Indeed, the most important advantage is that electricity-driven heat pumps can make full profit of PV-based electricity production.

Limits of these EHP are generally related to production of water at high temperature (> 50 °C) and the reduction of COP at low external temperatures. Consequently, for both space heating applications and DHW production, such level of the temperature output will greatly improve the system's COP (provided that the output temperature is still sufficient to fulfil the service, [3][4]).

The proposed solution includes two A2W EHP for outdoor installation, equipped with Full DC Inverter technology and capacity of modulation from 30% to 100%. The R32 refrigerant gas is A2L class (low flammability) and presents an Ozone Depletion Potential (ODP) equal to zero and a Global Warming Potential (GWP) of 675. The efficiency of the chosen EHP comply with min A++ class according to EU Regulation 811/2013 [5] with low water temperature (LWT 35 °C). Seasonal heating performance SCOP is greater than four and seasonal cooling Energy Efficiency ratio (SEER) is greater than six.

The heat pump will be equipped with a programmable control system in order to optimize energy performances for different thermal loads and outdoor climate conditions. The best set up of operational water temperatures will be defined through the help of dynamic thermal simulations and afterwards tuned in real operational conditions with the e-BEMS system developed within the **e**-SAFE project.

2.3 Renewable energy production from photovoltaic panels

A PV power system can be identified with the following main components: the photovoltaic module (composed by PV solar interconnected cells of various types), the mounting structure for the module or array, the inverter (essential for grid-connected systems), and the storage battery and charge controller (for off-grid systems but even more importantly for grid-connected ones).

Cells can be classified as either wafer-based crystalline silicon c-Si (mono- and multi-crystalline, accounting for more than 95% of the overall cell production), compound semiconductor (thin-film) or organic.

Thin-film materials have recently increased in market production. They are formed by depositing thin layers of photovoltaic semiconductor materials onto a backing material such as glass, stainless steel or plastic. The commercially used are cadmium telluride (CdTe) and copper indium-(gallium)-diselenide (CIGS and CIS).

A further technology under development in the PV market concerns the organic thin-film PV (OPV) cells that use dye or organic semiconductors as the light-harvesting active layer.

Focusing on wafer-based crystalline silicon PV panel, their efficiency is determined by two main factors: the cell efficiency, based on the cell design and silicon type, and the total panel efficiency, based on the cell layout, configuration and panel size.

Cell efficiency is determined by the cell structure and base silicon material used which is generally either P-type or N-type. Cell efficiency is calculated by what is known as the fill factor (FF), which is the maximum conversion efficiency of a PV cell at the optimum operating voltage and current. The cell design plays a significant role in panel efficiency. Key features include silicon type, multiple bus bars (MBB), and passivation type (PERC). The high-cost IBC cells are currently the most efficient (20-22%), due to the high purity N-type silicon cell base and no losses from bus bar/finger shading. Nonetheless, recent mono PERC cells with MBB and the latest heterojunction (HJT) cells have achieved efficiency levels well above 20% [6].

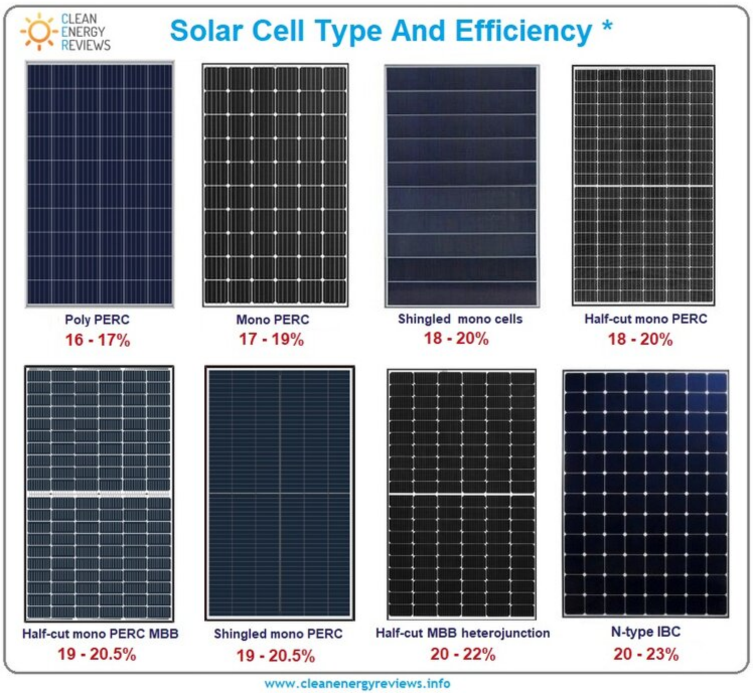


Figure 7. Typical solar cell typologies and their efficiency at STC [6]

Total Panel efficiency (%) is calculated as the ratio between the maximum power output (W) and the total panel area in meters and is referred to Standard Test Conditions (STC), i.e. assuming a cell temperature of 25 °C, a solar irradiance of 1000 W·m^{-2} and air mass of 1.5 (see Figure 7).

However, in real conditions, the efficiency of PV panels is dependent on many external factors. Depending on the local environmental conditions these various factors can reduce the panel efficiency and the overall system performance. The main factors which affect solar panel efficiency are irradiance, shading, panel orientation, temperature, location (latitude), time of year, dust and dirt.

Temperature is one of the most important factors that should be taken into account. Cell temperature generally rises well above 25 °C, depending on the ambient air temperature, wind speed, time of day and amount of solar irradiance. During sunny weather, the internal cell temperature is often 20-30 °C higher than the ambient air temperature, which results in 8-12% reduction in total power output - depending on the type of solar cell and its temperature coefficient. Conversely, extremely cold temperatures will result in an increase in power generation as PV cell voltages increases at lower temperatures below STC.

Higher or lower cell temperature will either reduce or increase the power output by a specific amount for every degree above or below 25 °C (STC). This is known as the power temperature coefficient which is measured in %/°C. Monocrystalline panels have an average temperature coefficient of -0.38% /°C, while polycrystalline panels are slightly higher at -0.40% /°C. Monocrystalline IBC cells have a much better (lower) temperature coefficient of around -0.30%/°C while the best performing cells at high temperatures are HJT (heterojunction) cells which are as low as -0.26% /°C.

Beside considering the cost and lifespan of PV panels, the discussed technical aspects will allow making the best decision for choosing an appropriate PV module.

The **e-**SAFE project envisages the integration of PV panels in the building envelope for on-site electricity generation. Firstly, PV modules will be placed on sloped roofs since the surface of PV modules that can be installed on suitably oriented pitches is sufficient in many cases to produce enough electric energy to cover a high share of the electricity bill. If needed, additional PV modules can be either integrated in the new skin – such as e-PANEL or e-CLT – or placed in a dedicated photovoltaic shelter (in case of flat roofs). In addition, the possibility of adoption an electric storage device to partially support thermal storage will be considered.

3. Requirements and relevant European regulation framework

Directives represent the instrument EU adopts to achieve specific results in a variety of fields without imposing the means for achieving such results. These legal acts are therefore of higher-order than national regulations; these last ones adopt the main principles outlined in European Directives and prescribe the operative ways to achieve them. With reference to the European targets set for the building sector, the following sections report on the thermal and energy requirements (Section 3.1), indoor comfort requirements (Section 3.2), seismic requirements (Section 3.3) and other technological requirements (Section 3.4) actually in force. The design of the e-SAFE technological solution will be inspired by the need to fulfil all these requirements.

3.1 Thermal and energy requirements

The main EU regulatory framework for thermal and energy requirements in buildings is given by the following Directives:

- Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings (recast) [7];
- Directive 2012/27/EU of 25 October 2012 on energy efficiency [8], amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC;
- Directive 2018/844/EU of 30 May 2018 [9], amending both Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.

The following subsections will detail the main requirements that come from such regulations and have to be complied with when existing buildings undergo major renovations.

3.1.1 Thermal transmittance and dynamic thermal parameters

The thermal transmittance coefficient of a building component – also known as overall heat transfer coefficient or U-value – is defined as the amount of heat that flows through a square meter of the component under a temperature difference of one degree Kelvin ($W \cdot m^{-2} \cdot K^{-1}$) between the environment separated by the component itself.

The U-value accounts for the combined effects of thermal radiation, convection and conduction under steady state conditions, i.e. when a thermal equilibrium between the component and the environment is reached. The U-value can be calculated for every building element through the well-known mathematical relation reported in the EN ISO Standard 6946:2017 [10]. This relation accounts for the various material layers composing the element, their thermo-physical properties (e.g., thermal conductivity) and thickness, as well as the environmental boundary conditions the element is exposed to.

The U-value of the various building envelope elements plays a key role in determining buildings' energy efficiency and performance, since they measure the heat losses and gains through the buildings shell: according to its definition, it is easy to infer that the lower is the U-value, the lower is the heat transferred through the component. Hence, the U-values significantly contribute to the calculation of the energy demand for space heating and cooling, and are particularly relevant in the heating season, i.e. when the role played by the solar gains is less important than in the cooling season.

Given its relevance on the energy balance of a building, national and European regulations concerning the energy performance commonly provide specific requirements for the U-value. The following Table 2 reports the maximum admissible U-values for the outer envelope components in different EU countries when subject to major renovations and/or energy upgrading, which are specifically defined by national regulations. As an example, Italy distinguishes amongst energy upgrading when less than 25% of the outer envelope is renovated, important renovation of 2nd level when at least 25% of the outer envelope is renovated and/or the technical systems are renovated, and important renovation of 1st level when at least 50% of the outer envelope is renovated along with the renovation of the technical systems. On the other hand, Norway discriminates only between renovations, when the total cost of the various interventions is below 50% of the technical value of the building, and major renovations when this cost exceeds 50% of the technical value of the building. In case national regulations do not prescribe specific thresholds for renovations or energy upgrading, the values reported in Table 2 refer to new buildings.

It is worth noting that some of these countries do specify different thresholds according to their peculiar climate classification, typically imposing lower U-values for colder conditions.

Table 2. Maximum allowed U-values ($W \cdot m^{-2} \cdot K^{-1}$) for various building components in different EU countries after renovation

Country	Climate zone	Max U-value (walls)	Max U-value (roofs)	Max U-value (windows)
Austria [11]	All	0.35	0.20	1.40
Belgium [12]	All	0.24	0.24	1.50
Cyprus [13]	All	0.40	0.40	2.25
England [14]	All	0.28	Pitched roof with insulation at ceiling level: 0.16 Pitched roof with insulation at rafter level: 0.18 Flat roof: 0.18	1.60
Germany [15]	All	0.24 (outer insulation) 0.35 (inner insulation)	0.20 (flat roof) 0.24 (pitched roof)	1.30
Greece [16]	A	0.60	0.50	3.20
	B	0.50	0.45	3.00
	C	0.45	0.40	2.80
	D	0.40	0.35	2.60
Italy [17]	A	0.40	0.32	3.00
	B	0.40	0.32	3.00
	C	0.36	0.32	2.00
	D	0.32	0.26	1.80
	E	0.28	0.24	1.40
	F	0.26	0.22	1.00
Netherlands [18]	All	0.21	0.15	1.65
Norway [19]	All	0.22	0.18	1.20
Turkey [20]	A	0.70	0.45	2.40
	B	0.60	0.40	2.40
	C	0.50	0.30	2.40
	D	0.40	0.25	2.40

For the sake of assessing the performance of the **e**-SAFE envelope solutions under different climate conditions, various locations in Italy – ranging from warm to cold – have been investigated according to their Heating Degree Days (HDD). In fact, HDD provide a simple yet effective measure of the severity of a specific climate, and as such different locations within the EU context can be preliminarily clustered according to the similarity in their HDD. Mathematically speaking, HDD are defined as the summation of all the positive differences between a conventional indoor set point temperature (T_i) and the average daily outdoor air temperature (T_o) over a defined period whose duration is Δτ (in this case, this is the conventional heating period):

$$HDD = \sum_{j=1}^{N} \left[(T_i - T_{o,j}) \cdot \Delta\tau_j \right] \quad (°C \cdot day) \qquad (1)$$

In Italy, the conventional indoor set point temperature is fixed to 20 °C, while the national territory is classified into six climate zones ranging from A (warmest) to F (coldest) according to their HDD (see Figure 8). This classification is dictated by the Presidential Decree n. 412 of the 26th August 1993 [21] and also determines the conventional heating period of buildings, as reported in Table 3.

Table 3. Climate conditions with representative cities and Heating Degree Days (HDD) in Italy

Climate zone with HDD range (°C·day)	Representative city	Heating period
A (HDD < 600)	Lampedusa (568 °C·day)	From December 1st to March 15th
B (600 ≤ HDD ≤ 900)	Catania (833 °C·day)	From December 1st to March 31st
C (901 ≤ HDD ≤ 1400)	Naples (1034 °C·day)	From November 15th to March 31st
D (1401 ≤ HDD ≤ 2100)	Rome (1415 °C·day)	From November 1st to April 15th
E (2101 ≤ HDD ≤ 3000)	Bologna (2259 °C·day)	From October 15th to April 15th
F (HDD > 3000)	Cuneo (3012 °C·day)	Throughout the year when needed

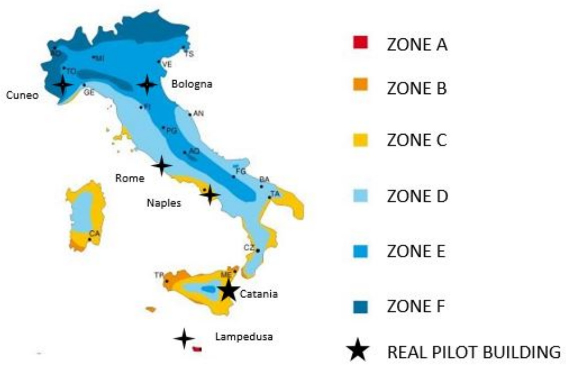


Figure 8. Climate zoning in Italy with the location of the real pilot building highlighted (Catania, Zone B)

Along with the stationary thermal transmittance (or U-value), this report considers also the periodic thermal transmittance Y_{IE} ($W \cdot m^{-2} \cdot K^{-1}$) and other dynamic parameters such as the attenuation factor f_a (non-dimensional, also known as decrement factor), the phase shift φ (h) and the specific internal heat capacity κ_i ($kJ \cdot m^{-2} \cdot K^{-1}$) defined in the EN ISO Standard 13786:2017 [22].
In fact, such parameters are useful for describing the thermal behaviour of the various building components when they are subject to periodic boundary conditions, i.e. variable heat flow rate or temperature profiles on one or both of their boundaries. This issue is particularly relevant in summer because of the combined action of variable solar radiation and air temperature values exerted on the wall.
Actually, when a cyclic temperature excitation acts on the outer side of a wall, this induces the release of cyclic heat flux into the indoor environment. In this case, it is possible to define the periodic thermal transmittance (Y_{IE}) as the ratio between the amplitude of the two cyclic functions describing the transferred heat flux and the temperature excitation, respectively. The calculation of the periodic thermal transmittance involves the use of complex numbers, according to the algorithms reported in EN ISO 13786:2017 Standard.
A national regulation in Italy states that external walls must have $Y_{IE} < 0.10\ W \cdot m^{-2} \cdot K^{-1}$ [17]: this condition applies to new buildings and in case of important renovation (1st level), that is to say when more than 50% of the building envelope is renovated. However, this condition does not apply to walls exposed to North and in those locations with low horizontal solar irradiance (below 290 $W \cdot m^{-2}$ on average during the month with highest insolation).
The decrement factor is the ratio between the periodic and the steady thermal transmittance ($f_a = Y_{IE}/U$): the lower it is, the higher the attitude of the wall to damp the periodic heat wave transferred in dynamic conditions.
The phase shift is the time lag between the peak outdoor temperature and the peak heat flux transferred indoors under dynamic conditions. Walls with good dynamic thermal performance have a high phase shift (φ > 10 h, or even φ > 12 h in case of excellent performance), whereas φ < 6 h means poor dynamic thermal performance.
Finally, the internal areal heat capacity (κ_i) describes the ability of a wall to accumulate heat when a periodic heat wave acts on its inner side. A wall with high internal areal heat capacity has a high potential for thermal storage, which helps to attenuate the indoor overheating produced by intense heat gains and to improve the indoor thermal comfort in summer. As an example, according to some studies, $\kappa_i > 50\ kJ \cdot m^{-2} \cdot K^{-1}$ can be

regarded as a good performance [23], while a recent Italian regulation [24] states that all new public buildings must have $\kappa_i > 40$ kJ·m^{-2}·K^{-1}.

3.1.2 Thermal bridges

Thermal bridges are those parts of the building envelope where heat transfer does not follow the traditional one-dimensional pattern between the external and internal faces, because the otherwise uniform thermal resistance is significantly altered. Examples can be as follows:

- full or partial penetration of the building envelope by materials with different thermal conductivity;
- local change in the thickness of the fabric;
- difference between the internal and external surface areas of the same component (e.g., in the case of junctions between a wall with the floor and the ceiling).

The main effects of a thermal bridge are:

- the local increase in the thermal losses, which in turn increases the building's energy demand;
- the reduced indoor surface temperatures, which may lead to thermal discomfort and/or vapour condensation and mould growth risks (see next section).

The EN ISO Standard 7345:2018 [25] differentiates linear and point thermal bridges: a linear thermal bridge has a uniform cross section along one of the three orthogonal axes, while a point one identifies a localised thermal discontinuity.

The heat transfer through thermal bridges is measured by the linear thermal transmittance (Ψ, expressed in W·m^{-1}·K^{-1}) or the punctual thermal transmittance (χ, expressed in W·K^{-1}).

Detailed numerical calculation approaches to assess these parameters are described in the EN ISO 10211:2017 Standard [26], including the rules to define suitable 3D or 2D geometric models, the boundary conditions and the thermophysical properties in the calculation of the heat fluxes. Further information about linear thermal transmittance values for a wide variety of building details can be found in books and abacuses, even if case-by-case evaluation through numerical simulation tools is always recommended. Designers might also resort to the EN ISO Standard 14683:2017 [27], where an abacus of various common linear thermal bridges is presented along with their suggested Ψ-values. However, the validity of these tabular values is limited to a specific range of the most relevant parameters describing the envelope components (thickness, U-value and thermal conductivity of the insulation material if present), hence the reported Ψ-values might severely underestimate the actual heat losses.

The regulations in force in the EU countries seldom prescribe specific requirements for the Ψ-values of thermal bridges. In France, for instance, the only relevant limitation refers to the linear thermal bridge constituted by the façade and the intermediate floors, which must have Ψ < 0.60 W·m^{-1}·K^{-1} [28].

Much more frequently, the regulations include thermal bridges in the calculation of an overall heat transfer coefficient for the entire building envelope (H'$_T$), defined as in Equation (2):

$$H_T^{'} = \frac{\sum_k U_k \cdot A_k + \sum_j \psi_j \cdot L_j}{\sum_k A_k} \qquad (W \cdot m^{-2} \cdot K^{-1}) \qquad (2)$$

Here, the subscript "k" refers to all the surfaces separating heated spaces from unheated spaces (and the outdoors, of course), whereas the subscript "j" refers to all the thermal bridges that can be identified, whose respective length is L_j. In Italy, H'$_T$ must not exceed the threshold values reported in Table 4, depending on the climate zone and the surface-to-volume ratio (S/V).

Table 4. Maximum allowed values for H'T (W·m^{-2}·K^{-1}) after renovation in Italy [17]

Climate zone	S/V ≥ 0.7	0.7 ≥ S/V ≥ 0.4	S/V < 0.4
A – B	0.58	0.63	0.80
C	0.55	0.60	0.80
D	0.53	0.58	0.80
E	0.50	0.55	0.75
F	0.48	0.53	0.70

The application of the e-SAFE technologies basically removes most of the existing thermal bridges in RC framed buildings (e.g., outer wall edges, uninsulated beams and pillars exposed to the outdoors, floor supports, window to wall junctions) thanks to the continuous external insulation provided by the e-PANEL and the ad-hoc connections to existing openings. However, in the case of e-CLT and e-EXOS, point thermal bridges occur at the anchorage of the seismic dampers with the existing RC frame: these items will be dealt with in detail in Task 3.3 (Designing the e-SAFE components) and are not tackled here. The verification of the above regulations concerning thermal bridges cannot be generalized, as it must be tackled case by case as a function of the building geometry.

3.1.3 Condensation and mould growth risks

Surface condensation and mould growth on the internal surface of building components is directly linked with their surface temperature; this in turn depends on the U-value of the components and the presence of thermal bridges, but also on the psychrometric conditions of indoor air.
The standard approach employed to assess the risk of surface condensation and mould growth is defined in the European Standard EN ISO 13788 [29]. Here, the so called "*temperature factor*" (otherwise known as f-factor), is defined as a bulk index that describes the thermal quality of an envelope component in terms of surface condensation and mould formation avoidance, and can be calculated as follows:

$$f_{RSI} = \frac{T_{si} - T_o}{T_{op} - T_o} \quad (-) \qquad (3)$$

Here, T_{si} and T_o are the internal surface and outdoor air temperature values respectively, while T_{op} is the indoor operative temperature calculated as the arithmetic mean of the air temperature and the mean radiant temperature of the room.
Operatively speaking, the f-factor calculated for the analysed component is then compared with a minimum allowable temperature factor $f_{RSI,min}$, derived by imposing a threshold condition for the surface relative humidity. The critical relative humidity values considered by the EU national regulations range from 75% in Sweden to 100% in Bulgaria, most frequently being 80% as prescribed in Germany, Italy and Spain. In other countries, such as in Denmark and UK, the surface condensation and mould growth risks are instead taken into account indirectly through the prescription of a maximum allowed U-value (please see Section 3.1.1).
However, condensation can also take place in the inner layers of a building component, and as such, it would not be visible from the outside. It is the case of interstitial condensation, which can be triggered by various complex physical phenomena like vapour convection and vapour diffusion when the water is in its gaseous state, and by capillary transport or surface diffusion when the water is in its liquid state. These mechanisms are strictly intertwined, and cannot be easily separated because moisture carries heat with it and temperature differences impact upon the way moisture moves.
Notwithstanding such a complexity, the approach prescribed by the EN ISO 13788 Standard only considers the vapour diffusion mechanism generated by the difference in partial vapour pressure between the indoors and the outdoors. The specific flux of water vapour through a material layer of a building component can then be appraised through the Glaser's method based on the Fick's law (moisture diffusion equation):

$$g = \delta_o \cdot \frac{p_I - p_O}{s_D} \quad (kg \cdot m^{-2} \cdot s^{-1}) \qquad (4)$$

Here, δ_O is the water vapour permeability of air ($187.5 \cdot 10^{-12}$ $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$), p_I and p_O are the indoor and outdoor water vapour partial pressure (Pa) respectively, and s_D is the equivalent air layer thickness (m) for water vapour diffusion. The equivalent air layer thickness is defined as the product of a layer's material thickness (m) by its vapour resistance factor μ, the latter being a non-dimensional quantity that expresses the resistance opposed to water vapour diffusion by a material compared to that opposed by still air (the higher the value, the higher the resistance to the flow).
The equivalent air layer thickness s_D is commonly used for classifying the construction materials, and in particular membranes and sheets, according to their attitude to vapour diffusion. This is for example the case of the Italian Technical Standard UNI 11470:2015 [30] that classifies such materials as follows:

- Highly-breathable membranes: $s_D \leq 0.1$ m;
- Breathable membranes: $0.1 < s_D \leq 0.3$ m;
- Vapour screens: $2 < s_D \leq 20$ m;
- Vapour barriers: $s_D \geq 100$ m.

The water vapour contained in the air and flowing through a square meter of a building material can eventually condensate, i.e. changing its state from vapour to liquid, if its partial vapour pressure reaches the corresponding saturation pressure p_S (Pa), a quantity that depends only on the material's temperature.
For a multi-layer construction assembly, the Glaser's method thus prescribes to first set reference conditions indoors and outdoors either relying on the EN ISO 15927-1:2004 Standard [31] or on other specific national regulations. Then, the temperature profile through the envelope component is calculated under the assumptions of mono-dimensional heat flux and steady-state conditions, and is eventually used to estimate the saturation pressure profile. Finally, the vapour partial pressure profile p_v is calculated and compared to the saturation pressure profile p_S: condensation occurs in those points where $p_v \geq p_S$. The amount of condensate can thus remain in its liquid state – and in this case national regulations usually introduce maximum threshold values – or evaporate again thanks to the drying capability of the assembly.
Results obtained through such an analysis are generally conservative when dealing with vapour diffusion only, and can be safely used during the preliminary design phase of the various **e**-SAFE envelope components. Nonetheless, as anticipated above, they neglect other condensation mechanisms that can be relevant under certain circumstances (e.g., climates characterised by frequent rain events or particular constructions exposed to the ground where rising damp can take place because of the materials' capillarity). These mechanisms will be dealt with in detail within Task 3.3 activities by using a dedicated transient hygrothermal software tool that performs the detailed analyses reported in the EN 15026 Standard [32].

3.1.4 Technical systems and renewable energy production

All technical systems have to comply with the requirements set by the European legislation concerning industrial products (for example, the CE marking and subsequent implementations). They must be designed and installed in order to ensure good energy performance and low thermal losses. General requirements of technical systems can regard the efficiency of a single subsystem (e.g., emission, distribution, storage, control system, generation) of the service plant (heating, cooling, DHW) or rather a global efficiency value.
In particular, because of their high-energy efficiency and of the possibility of integration with renewable energy sources, the use of heat pumps has been promoted widely in last years. In order to be installed, heat pumps must guarantee minimum efficiency values in both heating (Coefficient of Performance, COP) and cooling (Energy Efficiency Ratio, EER) modes. As an example, the Italian legislation [17] prescribes the minimum efficiency values reported in
Table 5 for electrical heat pumps as a function of the heat source and of the hot (T_H) and cold (T_C) sources temperature.

Table 5. Minimum energy performances of electrical heat pumps in Italy for specific operational temperatures T_H (hot source) and T_C (cold source) [17]

Type	**Heating mode working temperatures (°C)**	**COP (-)**	**Cooling mode working temperatures (°C)**	**EER (-)**
Air/air	T_c = 7 °C; T_h = 20 °C	3.5	T_c = 27 °C; T_h = 35 °C	3
Air/water (P< 35 kW)	T_c = 7 °C; T_h = 30 °C	3.8	T_c = 23 °C; T_h = 35 °C	3.5
Air/water (P≥ 35 kW)	T_c = 7 °C; T_h = 30 °C	3.5	T_c = 23 °C; T_h = 35 °C	3
Brine/air	T_c = 0 °C; T_h = 20 °C	4	T_c = 27 °C; T_h = 30 °C	4
Brine/water	T_c = 0 °C; T_h = 30 °C	4	T_c = 27 °C; T_h = 30 °C	4
Water/air	T_c = 15 °C; T_h = 20 °C	4.2	T_c = 27 °C; T_h = 30 °C	4
Water/water	T_c = 10 °C; T_h = 30 °C	4.2	T_c = 23 °C; T_h = 30 °C	4.2

The Directive 2009/28/EC [35] required the EU member states to fulfil at least 20% of its total energy needs with renewables by 2020 and specified national renewable energy targets for 2020 for each country, taking into account their initial condition and overall potential for renewables. For instance, these targets range from 10% for Malta to 49% for Sweden. EU countries also set out how they plan to meet these 2020 targets and the general course of their renewable energy policy in national renewable energy action plans.
The Directive 2009/28/EC was recently revised in December 2018 with the Renewable Energy Directive (2018/2001/EC) [36] that requires EU countries to fulfil at least 32% of their total energy needs with renewables by 2030.
EU Countries have different minimum requirements to use renewable energy sources for building thermal end electrical energy use. In Italy, the use of renewable energy sources is currently mandatory for thermal energy production in new and renovated buildings (the latter case only if the net floor area exceeds 1000 m^2), and have to cover at least the 50% of DHW production and 50% of the Heating, Cooling and DHW demand altogether. Furthermore, the peak electrical power of plants powered by renewable sources must be greater than or equal to the ratio S/50 (in kW), where S is the footprint area of the building.

3.1.5 Nearly Zero Energy Buildings (nZEB)

According to Directive 2010/31/EU, new buildings occupied by public authorities and properties have to be classified as nearly Zero Energy Buildings (nZEBs) from the 31st December 2018 while all other new buildings should comply with the nZEB standard starting from 31st December 2020. A nZEB is defined as a very high energy performing building, with a very low amount of energy required for its operation that should be covered to a very significant extent by energy from renewable sources. Each Member State shall define indicators and values concerning the building's primary energy use ($kWh \cdot m^{-2}$) and amount of renewable energy to be produced in order to reach a cost-optimal performance, defined as the energy performance that leads to the lowest cost during the estimated economic lifecycle.
In order to take into account for the impact of climate conditions on heating and cooling needs, the European Commission set benchmarks for nZEB primary energy use in four climate zones for new office buildings and single-family houses as shown in Table 6.

Table 6. Recommendations for nZEBs level of performance (Energy Performance Global Index, EPgl, $kWh \cdot m^{-2} \cdot year^{-1}$) per building type in different climate zones [37].

Building Type	Climatic Zone			
	Mediterranean Catania (others: Athens, Larnaca, Luga, Seville, Palermo)	**Oceanic** Paris (others: Amsterdam, Berlin, Brussels, London Copenhagen, Prague, Warszawa)	**Continental** Budapest (others: Bratislava, Ljubljana, Milan, Vienna)	**Nordic** Stockholm (others: Helsinki, Tallin, Riga, Gdansk, Tovarene)
Offices	Level of performance ($kWh \cdot m^{-2} \cdot year^{-1}$)			
net primary energy	20-30	40-55	40-55	55-70
primary energy	80-90	85-100	85-100	85-100
on-site renewable energy source primary energy	60	45	45	30
New single-family house	Level of performance ($kWh \cdot m^{-2} \cdot year^{-1}$)			
net primary energy	0-15	15-30	20-40	40-65
primary energy	50-65	50-65	50-70	65-90
on-site renewable energy source primary energy	50	35	30	25

Usually, calculations for the Energy Performance Index are performed in relation to a reference building. Therefore, the achievement of the nZEB target is expressed in comparison to a benchmark, the Energy Performance Global Index EPgl (kWh·m^{-2}·year^{-1}), and not in absolute terms.
Besides, the coefficients for the transformation of a certain secondary energy source to primary energy vary according to the various energy production systems of different countries.
According to the European Directives recalled at the beginning of Section 3.1, Member States have developed national definitions of nZEBs and reference values for the different relevant parameters. The Concerted Action of the European Community, which supports the development of national applications of nZEB definitions, continuously reports on the status of national nZEBs [12].
As shown in Figure 9, the definition of a nZEB is not always followed by legally binding documents, which definitely represents a drawback in the definition of the concept but not an obstacle in the development of the **e**-SAFE concept that can be adapted to different national contexts also in relation to the specific nZEB standard.

Main points of the national NZEB definition (as reported by the CA EPBD delegates)			Austria	Belgium: Brussels	Belgium: Flanders	Belgium: Walloon	Bulgaria	Croatia	Cyprus	Czech Republic	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy	Latvia	Lithuania	Luxembourg *	Malta	Netherlands	Norway	Poland	Portugal	Romania	Slovak Republic	Slovenia	Spain	Sweden	United Kingdom
Detailed definition	Included in a legal document	Governmental decree/law		■	■	■	■		■				■				■		■	■		■	■			■			■	■		■	
		Technical regulation						■		■	■	■		■				■	■		■								■				
		National NZEB plan	■					■																				■		■			
	Not yet included in a legal document														■	■						■		■	■		■				■		■
	Draft available														x							x		x							x		
Very high energy performance	Tighter requirements compared to current values for	General												■												■					x		
		Mean U-value of building envelope								■																							
		Reference technologies								■																		■					
		Heating energy demand																												■			
		Final energy	■																														
		Primary energy				■	■	■		■			■						■									■	■	■			
		(Primary) energy performance coefficient			■	■																		x									
	Top building class						■		■			■					■	■		■	■	■ x	■						■				x
	Specific new building class										■																						
	Passive house (building envelope) level			■																													
	KfW efficiency house 55/70														x																		
Nearly zero or very low amount of energy required. Limits on:	Component U-values				■	■			■								■	■	■					x		■			■	■	x		
	Thermal bridges																	■															
	Mean U-value of building envelope				■	■	■			■					x									x						■		■	
	Heat transfer coefficient/heat loss of building envelope																		■		■												
	Air permeability																	■															
	(Net) heat demand		■	■					■						x		■					■ x											
	Installed lighting power								■																								
	System efficiencies						■										■	■	■														
	Heating energy demand																		■	■										■	x		
	Cooling energy demand																		■												x		
	Total energy efficiency		■																														
	Electrical input																															■	
	Final energy (total or divided into energy uses)		■							■																■			■				x
	Primary energy			■	■	■	■	■	■	■	■	■	■	■	x		■	■	■	■	■	■ x	■	x		■		■	■	■	x	■	
	CO_2 emissions		■															■										■					x
	Summer overheating																■		■														
Very significant extent of renewable energy	Direct	Minimum share in %	■		■		■	■	■						x		■	■	■	■	■		■					■	■	■			
		Minimum contribution in kWh/m².year			■									■				■															
		(Choice of) exemplary RES measures	■		■						■								■														
	Indirect **			■		■				■	■	■	■									■ x		x		■					x	■	x
Primary energy indicator in kWh/m².year	Included		■	■		■	■	■	■	■	■	■	■	■	x		■		■	■	■	■ x	■			■		■	■	■	x	■	
	Other main indicator, but PE as additional/interim result. Main indicator:	CO_2																															x
		Primary EP coefficient			■	■												■						x									

* At the time of the factsheet Luxembourg had a national NZEB definition for residential buildings in place, but not yet a NZEB definition for non-residential buildings.
** Indirect: RES contribution required in order to achieve the minimum energy performance requirements.

Figure 9. Status of nZEB definition in different European countries at February 2018 [12]

3.1.6 Energy certification scheme

The Energy Performance Certificate (EPC) is a document recognised by a Member State, or by a legal person designated by it, which indicates the energy performance of a building or building unit calculated according to a methodology adopted in accordance with Article 3 of Directive 2010/31/EU. The Directive sets several general requirements to be adopted in the EPC scheme but allows enough flexibility for Member States to adjust these requirements in order to appropriately fit with their national context. This results in a wide range of differences in the implementation of specific aspects of the Directive 2010/31/EU amongst Member States, among which the calculation methods, the registration procedures, promotional activities undertaken, quality control mechanisms and enforcement systems, and financial issues.

Therefore, the **e**-SAFE system will help achieving the best performing classes displayed in the certificates according to the specific country where the building to be retrofitted is located.

In Italy, where the real pilot building is located, a big difference in the certification procedure depends on the percentage of the envelope that is considered for renovation: if more than 50% of the total envelope surface is considered for retrofitting, then the standard level must be equated to the one requested for new buildings (nZEB, class A building). This means that the buildings retrofitted with the **e**-SAFE system will become net-ZEBs.

3.2 Requirements for Indoor Environmental Quality (IEQ)

The most recent European Standard dealing with indoor comfort and indoor air quality – which can be combined under the more general term "Indoor Environmental Quality (IEQ)" – is the EN Standard 16798-1:2019 [33]. This Standard has replaced the previous EN Standard 15251:2007 that for more than a decade has regulated every aspect of Indoor Environmental Quality in buildings [34].
Both Standards have introduced four different categories of Indoor Environmental Quality, related to the level of expectation the occupants may have (Table 7). It is good practice that Category II (medium or normal expectation) is ensured in all buildings, even if Category I may be selected for occupants with special needs (children, elderly, persons with disabilities).

Table 7. Indoor Environmental Quality categories according to EN 16798-1:2019 [33]

IEQ Category	Expectation
I	High
II	Medium
III	Moderate
IV	Low

The Standard then provides further tables with the values of the different indoor parameters that must be complied with in order to ensure the different IEQ categories in relation to indoor air quality, thermal comfort, acoustic comfort and visual comfort.

3.2.1 Indoor air quality

As a general rule, in order to ensure suitable indoor air quality, the EN Standard 16798-1:2019 states that the incoming fresh airflow rate during occupancy should never be below 4 $l \cdot s^{-1}$ per person.
In office buildings, the recommended design ventilation airflow rate can be calculated as a function of either the number of occupants or the room surface area (the higher value resulting from the two approaches should be used). Alternatively, designers can just ensure that CO_2 concentration in office buildings does not exceed a suitable threshold, assigned as a maximum difference above outdoor concentration (Table 8).
In residential buildings, lower polluting emissions from people and other sources are normally observed. However, stricter requirements are introduced in bedrooms, as highlighted in Table 9. Please consider that the outdoor CO_2 concentration nowadays approaches 400 ppm on average, but in dense and polluted urban areas it can be considerably higher.

Table 8. Design ventilation rates and required CO_2 concentration for office buildings

IEQ Category	$l \cdot s^{-1}$ per person	$l \cdot s^{-1}$ per m^2	Design CO_2 concentration (ppm above outdoor levels)
I	20	2	550
II	14	1.4	800
III	8	0.8	1350
IV	5.5	0.55	1350

Table 9. Design ventilation rates and required CO_2 concentration for residential buildings

IEQ Category	Total ventilation (including air infiltration)		Design CO_2 concentration (ppm above outdoor levels)	
	$l \cdot s^{-1}$ per m^2	ACH	Living rooms	Bedrooms
I	0.49	0.7	550	380
II	0.42	0.6	800	550
III	0.35	0.5	1350	950
IV	0.23	0.4	1350	950

3.2.2 Thermal comfort

In mechanically heated or cooled spaces, thermal comfort can be assessed on the basis of the Fanger's theory, which introduced the concept of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [38]. Recommended PMV and PPD ranges are reported in Table 10.

Accordingly, suitable design values for the indoor operative temperature are recommended (see Table 11). These values hold under RH = 50% and low indoor air velocity ($v_a < 0.1$ $m \cdot s^{-1}$), and assume common clothing habits.

In the summer, artificially increased air velocity can be used to compensate for increased air temperatures, but only if the increased air velocity is under personal control. For instance, with $v_a = 0.6$ $m \cdot s^{-1}$ the indoor operative temperature can be increased by 1.2 °C, whereas an increase by 2.2 °C is allowed under $v_a = 1.2$ $m \cdot s^{-1}$.

Table 10. Recommended PPD and PMV values for indoor thermal comfort [33]

IEQ Category	PPD	PMV
I	< 6%	- 0.2 < PMV < + 0.2
II	< 10%	- 0.5 < PMV < + 0.5
III	< 15%	- 0.7 < PMV < + 0.7
IV	< 25%	- 1.0 < PMV < + 1.0

Table 11. Recommended design values for the indoor operative temperatures in buildings with mechanical heating/cooling systems [33]

	IEQ Category	Heating season	Cooling season
Residential buildings (with sedentary activity)	I	21.0 °C	25.5 °C
	II	20.0 °C	26.0 °C
	III	18.0 °C	27.0 °C
	IV	16.0 °C	28.0 °C
Residential buildings (with standing or walking activity)	I	18.0 °C	-
	II	16.0 °C	-
	III	14.0 °C	-
	IV	-	-
Offices, classrooms, restaurants, auditorium (sedentary activity)	I	21.0 °C	25.5 °C
	II	20.0 °C	26.0 °C
	III	19.0 °C	27.0 °C
	IV	17.0 °C	28.0 °C

3.2.3 Acoustic comfort

In order to ensure indoor acoustic comfort, suitable values for the indoor Equivalent Continuous Sound Level are recommended by the EN Standard 16798-1:2019 (

Table 12). However, these values just refer to noise generated by building service systems.

Table 12. Recommended values for indoor Equivalent Continuous Sound Level [33]

Building	Type of space	Equivalent Continuous Sound Level		
		I	II	III
Residential	Living rooms	≤ 30 dB	≤ 35 dB	≤ 40 dB
	Bedrooms	≤ 25 dB	≤ 30 dB	≤ 35 dB
Offices	Small offices	≤ 30 dB	≤ 35 dB	≤ 40 dB
	Landscape offices	≤ 35 dB	≤ 40 dB	≤ 45 dB
	Conference rooms	≤ 30 dB	≤ 35 dB	≤ 40 dB
Schools	Classrooms	≤ 30 dB	≤ 34 dB	≤ 38 dB
	Gymnasiums	≤ 35 dB	≤ 40 dB	≤ 45 dB

3.2.4 Visual comfort and daylight

Daylighting is the practice linked to the access and illumination of interior spaces by natural light. It is an established component of good building design and is in close relationship with visual comfort, improved health and task performance of building occupants.

Daylight requirements in buildings are presented in the EN 17037 Standard [39], which defines the quantity and quality of daylight building occupants should experience for visual comfort and health conditions. This standard is applicable to all rooms occupied on a regular basis, except for rooms with functions that are incompatible with daylight and for the illumination of workspaces that fall under the provisions of EN 12464-1 Standard [40]. The other European Standard linked to daylight in buildings is EN 15193 [41] that defines a methodology for determining the contribution of daylight in buildings in terms of energy requirements and energy consumption for electric lighting.

Back to the EN 17037 Standard, this sets minimum requirements for each room within a building and establishes performance levels for four daylighting criteria. These criteria can be addressed either via detailed hourly or sub-hourly simulations that account for detailed geometry and local climate conditions through specific weather files (e.g. from the EnergyPlus or Meteonorm databases), or through simplified calculations detailed in the same standard. The four daylighting criteria to address are daylight, views, exposition to sunlight and glare. Despite the EN 17037 Standard does rigorously apply to new designs only, **e**-SAFE envelope solutions that may negatively affect daylighting (e-PANEL and e-CLT namely) will be investigated through a simplified assessment of the daylight criterion only. In fact, the assessment of the exposition to sunlight, views and glare criteria heavily depend on the context around the existing building and its internal layout, and as such are outside of the scopes of **e**-SAFE.

The daylight provision requires that adequate natural lighting should be present for building occupants to perform their regular tasks. A space is deemed compliant if it is calculated to achieve a minimum amount of natural light as reported in Table 13 for spaces with minimum, average and high performances respectively. The reference illuminance E_T (lx) values should be guaranteed over at least 50% of a fictitious workplane placed at 0.85 m from the floor, while the minimum reference illuminance $E_{T,min}$ (lx) should be guaranteed over at least 95% of such a workplane. Further, these minimum daylight provisions have to be achieved for more than half of daylight hours in the year (i.e., for more than 2190 hours).

Table 13. Daylight performance levels through vertical and sloped windows [39]

Performance level	Reference illuminance E_T (lx)	Fraction of the workplane on which E_T should be guaranteed	Minimum reference illuminance $E_{T,min}$ (lx)	Fraction of the workplane on which $E_{T,min}$ should be guaranteed
Minimum	300	50%	100	95%
Average	500	50%	300	95%
High	750	50%	500	95%

Alternatively, the Standard allows calculating the Daylight Factor (DF) of the room, in order to compare it against minimum equivalent DF values. These minimum DF values are given in a tabular format for various EU capital cities, and range from 2.6 % of Mediterranean countries such as Italy and Greece to 4.3 % of Iceland for guaranteeing average daylight performance.

3.3 Acoustic requirements for the building envelope

This section aims to resume the content of the main national building regulations in force in the EU countries and dealing with the acoustic performance of the building elements. Generally, these regulations address many different aspects of the acoustic performance of buildings, but in this section only those aspects that are relevant to the **e**-SAFE solutions will be considered. This is the case of the sound insulation of the building façade; on the contrary, this section does not deal with the sound insulation between dwellings and the impact sound insulation of floors.

At a first glance, it is possible to observe that building acoustic regulations normally apply to new buildings only, including buildings converted to other uses, but most often they do not apply to renovated buildings, if uses are unchanged. However, in case of important building refurbishment, some local regulations may require the same level of acoustic quality as for a new building. Furthermore, many European countries introduced a voluntary classification scheme for the acoustic performance of buildings, where the top classes imply that the acoustic performance is well beyond the limit values holding for new buildings.

In this framework, the authors of this report believe that the minimum legal acoustic performance applied to the facades of new buildings is a relevant reference also in case of renovation through the **e**-SAFE envelope solutions.

When dealing with the sound insulation of the building façades, the national building regulations in force in the EU countries make use of many different descriptors. These can be divided into two main categories:

- Descriptors directly measuring the sound insulation capacity of the façade, such as the apparent weighted sound reduction index (R'w) or the weighted standardized level difference (DnT,w);
- Descriptors indirectly measuring the sound insulation capacity of the façade, based on the sound pressure level ensured indoors.

While in the first case the numerical value of the descriptor only depends on the composition of the facade, in the second case it also depends on the outdoor noise level occurring in the specific context, meaning that a given façade solution can turn out to be unsuitable in noisy urban areas while being acceptable in quiet suburban areas.

Table 14 resumes the descriptors used to measure the façade sound insulation in the main EU national regulations, while also providing some basic information about their meaning.

Table 14. Descriptors for façade sound insulation used in national regulations across EU countries [42]

Symbol	Descriptor
R'_w	Weighted apparent sound reduction index
$R'_w + C_{tr}$ (1)	Weighted apparent sound reduction index with spectrum adaptation term for traffic noise
$D_{2m,nT,w}$ (2)	Weighted standardized level difference
$D_{nT,w} + C_{tr}$ (3)	Weighted standardized level difference with spectrum adaptation term for traffic noise
$L_{AF,max}$	A-weighted maximum indoor sound pressure level (measured with Fast time weighting)
L_{Aeq} (4)	A-weighted equivalent indoor sound pressure level
L_{den}	A-weighted day–evening–night (den) indoor noise level

(1) Also indicated as ($R'_{res,w} + C_{tr}$) in Austria and (R_A) in Poland
(2) The subscript "2m" means that the outdoor noise level is measured at a distance of 2 m from the façade
(3) Also indicated as ($D_{A,tr}$) in Belgium
(4) The equivalent sound pressure level is usually measured over specific time intervals (e.g. $L_{Aeq,7-22}$ or $L_{Aeq,24h}$)

All descriptors are measured in dB, and they must be verified on-site after the building construction (or renovation); the measurements must be performed according to the procedures described in the EN ISO 16283-3 Standard [43].
Table 15 reports the threshold values adopted by the regulations in the different European countries. Please observe that the descriptors directly measuring the sound insulation capacity (R'_{w}, $D'_{2m,nT.w}$) must comply with a lower threshold (minimum value), whereas the descriptors indirectly measuring the sound insulation capacity (L_{Aeq}, L_{den}) must comply with a higher threshold (maximum value).

Table 15. Requirements for façade sound insulation in the main EU Countries

Country	Descriptor	Ref.	Requirement
Austria	$R'_{res,w} + C_{tr}$	[45]	It must keep above a threshold value, depending on the outdoor noise level measured in front of the façade (Table 16)
Belgium	$D_{A,tr}$	[46]	$D_{A,tr} \geq (L_{A(outdoor)} - 34$ dB) and $D_{A,tr} \geq 26$ dB (≥ 34 dB for bedrooms near airports and railways)
Croatia	$L_{Aeq,day}$ (indoor)	[47]	Dwellings: $L_{Aeq,day} \leq 40$ dB ; Offices: $L_{Aeq,day} \leq 35$ dB
	$L_{Aeq,night}$ (indoor)	[47]	Dwellings: $L_{Aeq,night} \leq 30$ dB ; Offices: $L_{Aeq,night} \leq 25$ dB
Denmark	$L_{Aeq,24h}$ (indoor)	[48]	$L_{Aeq,24h} \leq 30$ dB
Finland	$L_{Aeq,7\text{-}22}$ (indoor)	[48]	$L_{Aeq,7\text{-}22} \leq 35$ dB
	$L_{Aeq,22\text{-}7}$ (indoor)	[48]	$L_{Aeq,22\text{-}7} \leq 30$ dB
France	$D_{nT,w} + C_{tr}$	[47]	$(D_{nT,w} + C_{tr}) \geq 30$ dB
Germany	$L_{Aeq,day}$ (indoor)	[49]	$L_{Aeq,day} \leq 35$ dB
	$L_{Aeq,night}$ (indoor)	[49]	$L_{Aeq,night} \leq 25$ dB
Greece	L_{Aeq} (indoor)	[42]	$L_{Aeq} \leq 35$ dB (during public quiet hours)
Iceland	$L_{Aeq,24h}$ (indoor)	[42]	$L_{Aeq,24h} \leq 30$ dB
	$L_{AFmax,22\text{-}6}$ (indoor)	[42]	$L_{Amax,22\text{-}6} \leq 45$ dB
Italy	$D_{2m,nT,w}$	[50]	Dwellings: $D_{2m,nT,w} \geq 40$ dB ; Offices: $D_{2m,nT,w} \geq 42$ dB Hospitals: $D_{2m,nT,w} \geq 45$ dB ; Schools: $D_{2m,nT,w} \geq 48$ dB
Netherlands	$D_{2m,nT,w} + C_{tr}$	[42]	$(D_{2m,nT,w} + C_{tr}) \geq 23$ dB
	L_{den} (indoor)	[42]	$L_{den} \leq 30$ dB
Norway	$L_{Aeq,24h}$ (indoor)	[42]	$L_{Aeq,24h} \leq 30$ dB
	$L_{AFmax,23\text{-}7}$ (indoor)	[42]	$L_{Amax,23\text{-}7} \leq 45$ dB
Poland	R_A	[47]	It must keep above a threshold value
Portugal	$D_{2m,nT,w}$	[51]	Dwellings: $D_{2m,nT,w} \geq 33$ dB; Offices: $D_{2m,nT,w} \geq 30$ dB
Spain	$D_{2m,nT,w} + C_{tr}$	[47]	It must keep above a threshold value
Sweden	$L_{Aeq,24h}$ (indoor)	[42]	$L_{Aeq,24h} \leq 30$ dB
	$L_{AFmax,22\text{-}6}$ (indoor)	[42]	$L_{Amax,22\text{-}6} \leq 45$ dB
Turkey	$D_{2m,nT,w} + C_{tr}$	[52]	It must keep above a threshold value, depending on the outdoor noise level measured in front of the façade (Table 17)
	L_{Aeq} (indoor)	[52]	$L_{Aeq} \leq 30$ dB (during occupancy, new buildings) $L_{Aeq} \leq 34$ dB (during occupancy, existing buildings)

Table 16. Requirements for the sound insulation of the façades in Austria according to ONORM B 8115-2 [45]

L_{Aeq} (in front of the façade)	Day	≤ 50 dB	51-55 dB	56-60 dB	61-65 dB	66-70 dB	71-75 dB	76-80 dB
	Night	≤ 40 dB	41-45 dB	46-50 dB	51-55 dB	56-60 dB	61-65 dB	66-70 dB
$R'_{res,w} + C_{tr}$		≥ 28 dB	≥ 33 dB	≥ 33 dB	≥ 38 dB	≥ 38 dB	≥ 43 dB	≥ 48 dB

Table 17. Requirements for the sound insulation of the façades in Turkey [52]

Outdoor L_{den}	$D_{2m,nT,w} + C_{tr}$	
	New buildings	Existing buildings
55-60 dB	≥ 28 dB	≥ 24 dB
61-65 dB	≥ 34 dB	≥ 30 dB
66-70 dB	≥ 39 dB	≥ 35 dB
71-75 dB	≥ 44 dB	≥ 40 dB
76-80 dB	≥ 49 dB	≥ 45 dB
> 80 dB	≥ 53 dB	≥ 49 dB

3.4 Seismic requirements

The European seismic code, Eurocode 8 (EC8) [55][56], stipulates the performance objectives that buildings in seismic area have to fulfil and provides rules to define the expected seismic excitation, methods of analysis to estimate the seismic demand and capacity criteria to assess the achievement of the performance objectives. In particular, EC8 – part 1-3 [56] defines three performance objectives for existing buildings. Each performance objective is achieved if the specified limit state is not exceeded for the corresponding seismic excitation level. The three limit states are defined as follows:

1. *Limit state of Near Collapse (NC)*: the structure is heavily damaged, with low residual lateral strength and stiffness, and it would probably not survive another earthquake, even of moderate intensity;
2. *Limit state of Significant Damage (SD)*: the structure is significantly damaged, with some residual lateral strength and stiffness, it can sustain after-shocks of moderate intensity but it is likely to be uneconomic to repair;
3. *Limit state of Damage Limitation (DL)*: the structure is only lightly damaged, with structural elements retaining their strength and stiffness properties, while partitions and infills may show distributed cracking but the damage could be economically repaired.

The three seismic excitation levels are those with probability of exceedance of 2%, 10% and 20% in 50 years corresponding to return periods of 2475, 475 and 225 years, respectively. Hence, according to EC8 the three performance objectives are achieved if the NC, SD and DL limit states are not exceeded for seismic excitations with probability of exceedance of 2%, 10% and 20% in 50 years.

As stipulated in EC8 – part 1-1 [55], the seismic excitation corresponding to each seismic excitation level can be defined by the elastic spectrum response or by a spectrum-compatible set of accelerograms. The NC and SD limit states are related to the structural safety of the buildings and the fulfilment of the corresponding performance objectives. The exceedance of the limit state of DL is detrimental to the functionality of the building but it does not jeopardize the human life.

The two seismic upgrading systems (e-CLT and e-EXOS) will be designed aiming at improving the seismic performance of the existing RC framed structure. The three performance objectives defined in the European seismic code for existing buildings will be assumed as benchmark. However, since the National Authorities may decide whether all the three Limit States shall be checked (or two of them, or just one of them), may stipulate more permissive values of probability of exceedance, and may allow also a partial seismic upgrading of the building, lower performance objectives compatible with the national regulations may be assumed to design e-CLT and e-EXOS. The main target of the seismic retrofit intervention is the achievement of NC and SD performance objectives, which are devoted to safeguard the human life. Instead, the fulfilment of the DL performance objective, which is difficult to be achieved in presence of brittle non-structural elements, is considered optional.

The achievement of the performance objectives will be checked by the compliance criteria stipulated in Eurocode 8 and resumed in the following sections.

3.4.1 Performance of the RC framed structure

The limit states of RC beams and columns may be exceeded because the maximum deformation demand recorded during the earthquake exhausts the deformation capacity or the force demand overcomes the resistance. The deformation demand is expressed in terms of chord rotation θ, i.e., of the angle between the

tangent to the axis at the yielding end and the chord connecting that end with the point of contraflexure (end of the shear span). Instead, the force demand is expressed in terms shear force.
The value of the total chord rotation capacity (elastic plus inelastic part) at ultimate, θ_u, of concrete members under earthquake loading may be calculated from the following expression:

$$\theta_u = \frac{1}{\gamma_{el}} 0.016\left(0.3^{\upsilon}\right)\cdot\left[\frac{\max(0.01,\omega')}{\max(0.01,\omega)} f_c\right]^{0.225}\cdot\left(\frac{L_V}{h}\right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c}\right)}\left(1.25^{100\rho_d}\right) \quad (5)$$

Where:
γ_{el} is element safety coefficient;
h is the depth of cross-section;
L_V is the ratio moment/shear at the end section;
ν is the element axial force normalized with respect the axial resistance of the concrete cross section,
ω, ω' are the mechanical reinforcement ratio of the tension and compression longitudinal reinforcement,
f_c and f_{yw} are the concrete compressive strength and the stirrup yield strength (MPa),
ρ_{sx} is the ratio of transverse steel parallel to the direction x of loading,
ρ_d is the steel ratio of diagonal reinforcement (if any), in each diagonal direction,
α is the confinement effectiveness factor.
The chord rotation capacity corresponding to NC limit state θ_{NC} is assumed equal to θ_u, while the chord rotation capacity corresponding to SD limit state θ_{SD} may be assumed to be 3/4 of the ultimate chord rotation θ_u. Finally, the capacity for the DL limit state is the yielding bending moment under the design value of the axial load or, in case the verification is carried out in terms of deformations, the corresponding capacity θ_{DL} is given by the chord rotation at yielding θ_y.
The shear resistance V_{Rd} is the same for the verification of all the limit states and is calculated according to Eurocode 2 (EC2) [57]. It is assumed equal to minimum value calculated by the following expressions:

$$V_{Rd,max} = 0.9\cdot d\cdot b_w\cdot\alpha_c\cdot f_c'\cdot\frac{\cot\theta}{1+\cot^2\theta} \quad (6)$$

$$V_{Rd,s} = 0.9\cdot d\cdot\frac{A_{sw}}{s}\cdot f_{yw}\cdot\cot\theta \quad (7)$$

where:

d	is the effective depth of the cross-section
b_w	is the width of the web cross-section
f_c'	is concrete compressive strength reduced because of shear cracking
f_{yw}	is the stirrup yield strength
α_c	is a coefficient that takes into account the effect of axial force
A_{sw}	is the area of shear reinforcement
s	is the step of shear reinforcement
$\cot\theta$	ranges from 1.0 to 2.5 and is assumed so as to maximize the shear resistance V_{Rd}.

3.4.2 Performance of friction dampers and CLT panels

Friction dampers

The friction dampers must satisfy constructive, installation and safety limit state requirements.
The constructive requirements comprise the geometrical features and structural arrangement of the Asymmetric Friction Connection. The AFC may be composed of five elements, characterized by the following mechanical and geometrical features: one of the two profiles should present an elongated hole, to allow for the sliding movement; the other profile should have normal holes, for the insertion of the bolts; a secondary cap plate should be used to close the system and obtain the friction connection [58]. The aforementioned elements should be made of steel. In addition to the three steel plates, the AFC comprises two intermediate

shim layer plates: these plates are made with a material with a different Brinell hardness than steel, and are used to improve the stability of the friction behaviour (see Figure 10).

Figure 10. Schematic representation of friction damper design

The installation requirements comprise the protocol to be followed in pre-loading the bolts of the AFC and mounting the whole system on the existing building. Pre-loading of the bolts should be carried out in order to obtain the exact amount of preload force needed for the friction connection to work as expected, the methods allowed for preloading bolts are specified in the EN1090-2 [59]. Safety requirements shall be respected during the mounting phase, when CLT panels with friction dampers are lifted and attached to the building adequate restraints are to be provided during the mounting phase, in order to avoid any possible fall of the system prior to definitive fixing to the existing building.
The limit state requirements refer to the fulfilment of the three limit states:

- near collapse;
- significant damage;
- damage limitation.

The displacement capacity of the AFC must be higher than the displacement demand associated to the three limit states:

$$d_R \geq d_D \quad (8)$$

where:

d_R is the displacement capacity equal to the maximum drift tolerable by the AFC
d_D is the displacement demand corresponding to a given limit state

The displacement demand descends from suitable structural analysis, where the AFC may be modelled using a Coulomb-like hysteresis model:

$$F_{R,S} = n_s \cdot n_b \cdot \mu(e) \cdot F_P \quad (9)$$

Where:

$F_{R,S}$ is the slip force
n_s is the number of shear planes
n_b is the number of preloaded bolts
$\mu(e)$ is the friction coefficient
F_P the preload force

According to literature, the slip force is not constant [60]. Therefore, the definition of the friction coefficient may be considered as dependent to the dissipated hysteretic energy e.

Cross laminated timber (CLT) panels

The cross laminated timber (CLT) panels must satisfy the standard requisite according to EN16351 [61], or the producer European technical approval.

According to EN16351 Standard, CLT is structural timber consisting of at least three layers of which a minimum of three are orthogonally bonded, which always comprise timber layers and may also comprise wood-based panel layers.

The limit state requirements refer to the fulfilment of the limit states in different design situations:

- Tension parallel to the grain;
- Tension perpendicular to the grain;
- Compression parallel to the grain;
- Compression perpendicular to the grain;
- Bending and shear out of plane;
- Bending and shear and in plane;
- Stability.

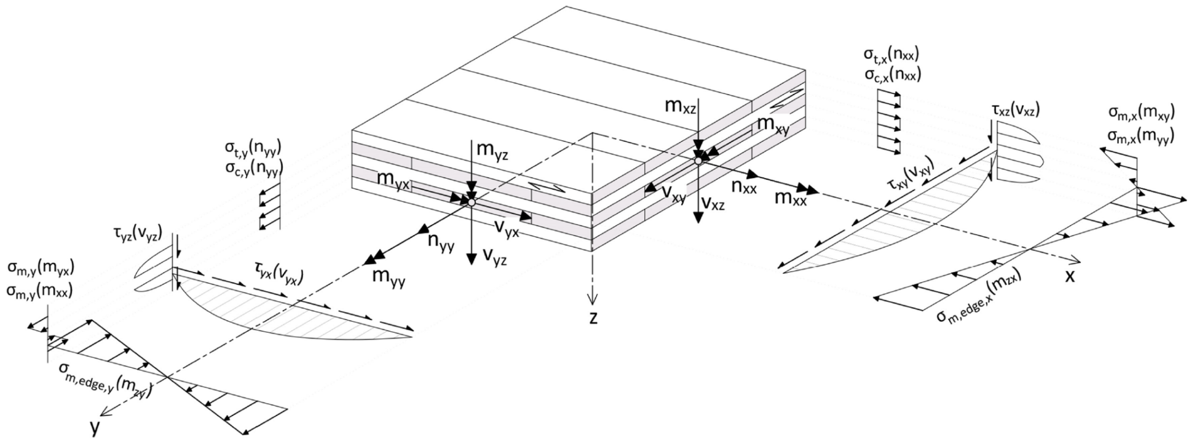


Figure 11. Different possible stresses acting on a CLT element [62]

The verification rules are set according to the producer technical approval or relative literature [63].

In the **e**-SAFE application, the most decisive requirement is in plane shear resistance of the panel. Cross laminated timber diaphragms or walls subjected to shear stresses in plane shall fulfil the following requirements. The cross laminated timber may comprise non-edge glued layers and cracks.

Verifications shall be done with the effective net cross-section. For the determination of the effective cross-section $A_{ef,x}$ or $A_{ef,y}$ comprising the outermost layers, the thickness of the outermost layers shall be reduced by 20%.

For ratios of the lamination width or distance between the edge and a groove or spacing between grooves within a lamination b_l and the lamination thickness t_l of $b_l/t_l \leq 4$, the shear stresses in the glue lines between laminations of adjacent orthogonal layers, shall be verified according to the following formula:

$$\tau_{tor,node,d} = \frac{3}{2} \cdot \tau_{v,xy,d} \cdot \left(\frac{t_l}{b_l}\right) \leq f_{tor,node,d} \quad (10)$$

Where:

$\tau_{tor,node,d}$	is the design torsional shear stress due to shear force in plane;
$\tau_{v,xy,d}$	is the design shear stress in plane of the effective net cross-section;
t_l	is the lamination thickness;
b_l	is the lamination width or distance between the edge and a groove or spacing between grooves within a lamination;
$f_{tor,node,d}$	is the design torsional shear strength.

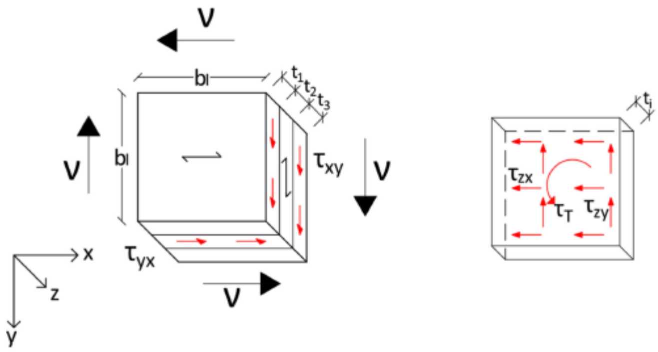


Figure 12. Representation of shear stresses on an infinitesimal CLT element [62]

For verifications in the other main direction, the design shear stress $\tau_{v,xy,d}$ x shall be replaced by $\tau_{v,yx,d}$. If the cross laminated timber comprises different lamination thicknesses and lamination widths or distance between the edge and a groove or spacing between grooves within a lamination, t_l shall be taken as $t_{l,max}$ and b_l , shall be taken as $b_{l,mean}$.
For the determination of the ratio b_l/t_l the presence of grooves in laminations shall be considered.

Steel-to-timber connections

For the verification of the connection between the friction damper and the CLT panel the verification rules are set according to the Eurocode 5 [64], the producer technical approval or relative literature [65].
The product requirement of the dowel type connectors are according to EN 14592 [66] or producer technical approval. According to EN1995, for the determination of the characteristic load-carrying capacity of connections with metal dowel type fasteners the contributions of the yield strength, the embedment strength and the withdrawal strength of the fastener shall be considered. The embedment strength for Cross laminated Timber should be derived in accordance with the CLT producer technical approval.
The characteristic load-carrying capacity of a steel-to-timber connection depends on the thickness of the steel plates d (see Figure 13). Steel plates of thickness less than or equal to 0.5 d are classified as thin plates and steel plates of thickness greater than or equal to d with the tolerance on hole diameters being less than 0.1 d are classified as thick plates. The characteristic load-carrying capacity of connections with steel plate thickness between a thin and a thick plate should be calculated by linear interpolation between the limiting thin and thick plate values.

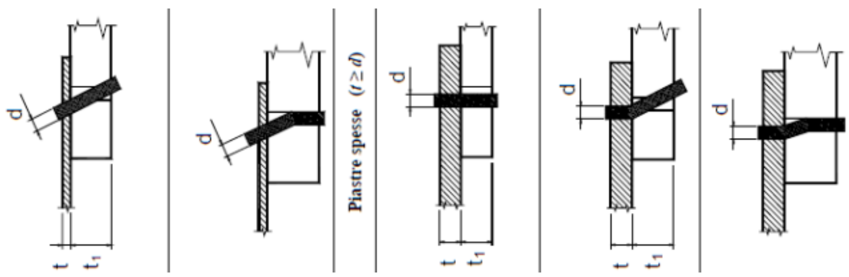


Figure 13. Failure modes for steel-to-timber connections

3.4.3 Performance of the steel exoskeleton and dampers

The e-EXOS is constituted by an ensemble of steel bracings equipped with seismic dampers. The steel bracings have to provide stiffness and strength to ensure an almost uniform distribution of the drift demand along the height of the structure. For this reason, yielding and buckling of these members have to be prevented under the axial forces developed at the achievement of the NC limit state. The plastic axial resistance $N_{pl,Rd}$ and the buckling resistance $N_{b,Rd}$ of steel bracings are calculated according to Eurocode 3 (EC3) [67]:

$$N_{pl,Rd} = \frac{A\, f_y}{\gamma_{M0}} \tag{11}$$

$$N_{b,Rd} = \chi \frac{A\, f_y}{\gamma_{M1}} \tag{12}$$

Where:

A is the area of the cross-section;
f_y is the yield stress of the adopted steel;
γ_{m0} is the partial factor for resistance of cross-sections to instability;
γ_{m1} is the partial factor for resistance of members to instability;
χ is the reduction factor for the relevant buckling mode calculated as a function of the non-dimensional slenderness of the element and of the imperfection factor corresponding to the appropriate buckling curve for the selected cross-section shape.

Internal forces on vertical members of the exoskeleton should not cause their instability or yielding. Because these members are subjected to axial force *N* and (low) bending moment *M* about one of the principal axes of the cross-section, instability is avoided when the following requirements are satisfied for bending about the strong (y) axis:

$$\max \begin{cases} \dfrac{N}{N_{b,Rd,y}} + k_{yy} \dfrac{M}{M_{Rd,y}} \\ \dfrac{N}{N_{b,Rd,z}} \end{cases} \leq 1 \tag{13}$$

And for bending about the weak (z) axis:

$$\frac{N}{N_{b,Rd,z}} + k_{zz} \frac{M}{M_{Rd,z}} \leq 1 \tag{14}$$

In Equations (13) and (14), $N_{b,Rd,y}$, $N_{b,Rd,z}$, $M_{Rd,y}$ and $M_{Rd,z}$ are the buckling and the moment resistances about the strong and the weak axis, while k_{yy} and k_{zz} are the interaction factors calculated according to Method 2 given in Annex B of EC3 [67]. Similarly, yielding of these members is avoided when the following conditions are met for bending about the strong (y) axis:

$$\begin{cases} \dfrac{M}{M_{Rd,y}} \leq 1 & : \text{for } \dfrac{N}{N_{pl,Rd}} \leq 0.5\, a_w \\ \dfrac{N}{N_{pl,Rd}} + \left(1 - 0.5\, a_w\right) \dfrac{M}{M_{Rd,y}} \leq 1 & : \text{for } \dfrac{N}{N_{pl,Rd}} > 0.5\, a_w \end{cases} \tag{15}$$

and for bending about the weak (z) axis:

$$\begin{cases} \dfrac{M}{M_{Rd,z}} \leq 1 & : \text{for } \dfrac{N}{N_{pl,Rd}} \leq a_f \\ \dfrac{N}{N_{pl,Rd}} + \left(1 - 0.5\, a_f\right) \dfrac{M}{M_{Rd,z}} \leq 1 & : \text{for } \dfrac{N}{N_{pl,Rd}} > a_f \end{cases} \tag{16}$$

In Equations (15) and (16), which are derived from the resistance criteria stipulated by EC3 for the verification of wide-flange cross-sections subjected to combined bending and axial force, N_{Rd} is plastic resistance to normal forces and a is the ratio of web area to gross area of the cross-section.
The resistances N_{Rd}, $N_{b,Rd,y}$, $N_{b,Rd,z}$, $M_{Rd,y}$ and $M_{Rd,z}$ are calculated according to the relevant provisions of EC3.

The dampers included in e-EXOS have to provide energy dissipation to reduce the drift demand below the drift capacity. Out of the dampers available in the market, buckling restrained braces (BRBs) are selected. The BRB basically consists of a ductile steel core that is restrained from buckling and thus forced to yield both in tension and in compression. No deformation capacity of BRBs is stipulated in European seismic code; however, experimental test carried out on these members [68][69][70][71] have pointed out that two types of ductility capacity can be defined and calculated: the maximum ductility capacity and the cumulative ductility capacity. The ductility demand μ_d is defined as the ratio of the maximum elongation or shortening of the BRB to the elongation at yielding. Based on the results of the above-mentioned experimental tests, the maximum ductility μ_{max} that BRBs can accommodate (ductility capacity) is in the range from 10 to 25, based on the BRB technology. This ductility capacity is assumed as target value at the NC limit state (μ_{NC}). Consistently with the assumptions made for the chord rotation capacity of members belonging to the RC framed structure, the ductility capacity corresponding to SD limit state μ_{SD} is assumed to be 3/4 of the maximum ductility capacity.

3.5 Technological and safety requirements

The **e-**SAFE prefabricated components (e-PANEL and e-CLT) have to be designed and produced according to the European standards in order to ensure a high level of quality and safety for the consumer. The main technological and safety requirements that must be followed in the design stage are presented in the following subsections, regarding both the pre-assembled panels and the windows to be integrated into.

3.5.1 Fire reaction and fire resistance

The Regulation (EU) No. 305/2011 of the European Parliament lays down the harmonised conditions for the marketing of construction products, considering safety in the event of fire as one of the essential requirements that construction products must have. The European classification system for the fire performance of construction products involves different Euroclasses, related both to the fire reaction and fire resistance requirements (Figure 14).

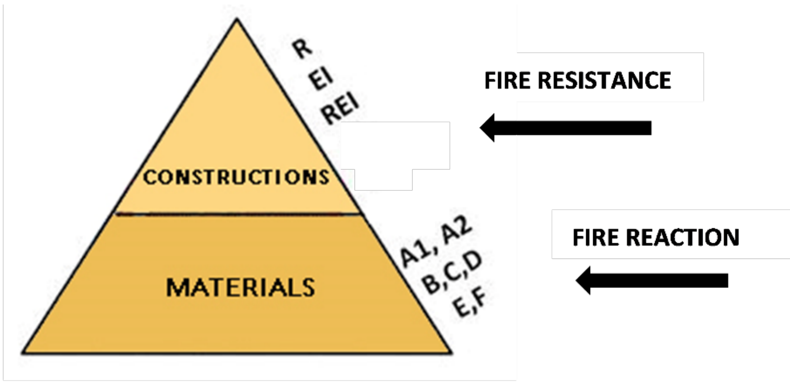


Figure 14. Fire reaction and fire resistance classification according to EN 13501-1 and EN 13501-2

The *fire reaction* parameter is specific to materials and represents their response in contributing by their own decomposition to a fire which are exposed to. The European fire reaction classification is set out in EN 13501-1 [72]. Specifically, construction products are classified into seven Euroclasses (A1, A2, B, C, D, E, F) based on their reaction-to-fire performance, which are reported in technical specifications or derived from specific fire tests (

Table 18). The taxonomy used in terms of fire behaviour considers non-combustible materials (A1, A2), very limited to medium contribution to fire (B, C, D) and high contribution to fire (E, F) materials. The European harmonisation of fire classifications also addresses the smoke class (classes *s*1, s2, s3) and the burning droplets one (classes d0, d1, d2), as reported in

Table 18. In terms of smoke development, the classes considered are little or no smoke (s1), medium smoke (s2) and heavy smoke (s3). As regard the formation of flaming droplets/particles, the classes are d0 (no

droplets within 600 seconds), d1 (droplet form within 600 seconds but do not burn for more than 10 seconds) and d2 (not as d0 or d1).

Table 18. Fire reaction classification of construction products excluding floorings according to EN 13501-1 [72]

Definition	Construction products		
non-combustible materials	A1		
	A2-s1, d0	A2-s1, d1	A2-s1, d2
	A2-s2, d0	A2-s2, d1	A2-s2, d2
	A2-s3, d0	A2-s3 d1	A2-s3, d2
combustible materials- very limited contribution to fire	B-s1, d0	B-s1, d1	B-s1, d2
	B-s2, d0	B-s2, d1	B-s2, d2
	B-s3, d0	B-s3, d1	B-s3, d2
combustible materials- limited contribution to fire	C-s1, d0	C-s1, d1	C-s1, d2
	C-s2, d0	C-s2, d1	C-s2, d2
	C-s3, d0	C-s3, d1	C-s3, d2
combustible materials- medium contribution to fire	D-s1, d0	D-s1, d1	D-s1, d2
	D-s2, d0	D-s2, d1	D-s2, d2
	D-s3, d0	D-s3, d1	D-s3, d2
combustible materials - highly contribution to fire	E | E-d2		
combustible materials - easily flammable	F		

The *fire resistance* of construction elements represents the fire exposure time, expressed in minutes, during which they ensure specific functional performance. In accordance with the European standard EN 13501-2 [73], the fire resistance classification system is based mainly on three performance criteria (R, E, I), or their combination, which are tested by means of specific fire test methods. The tested performance criteria are the following:

- *Criterion R – load bearing capacity*. The ability of a construction product to preserve its mechanical characteristics and relevant load capacity under fire;
- *Criterion E – integrity*. The ability of a construction product to not allow the passage or production of gases, flames or smokes to areas not exposed to fire;
- *Criterion I – insulation*. The ability of a construction product to prevent the temperature increase in the areas non directly exposed to fire.

The test results are obtained in form of a time stamp (i.e., 15, 20, 30, 45, 60 etc.) that shows how many minutes the construction element resists the fire before the threshold for each criterion is exceeded.
The e-PANEL and e-CLT components are designed to be installed on the existing buildings envelope from the outside, and as such they can be considered as façade elements. The fire safety requirements of façades have a key role in preventing the spread of a fire that can break out inside or outside the building. In fact, façade spread is one of the fastest ways in which a fire can travel through the building. Furthermore, the damage of façade elements in case of fire can be dangerous both for the exodus of occupants and for the safety of rescue workers. However, currently there is no European harmonised approach to the fire performance assessment and classification for façade systems, but there is a methodological proposal that was developed within the framework of the EU project "Development of a European approach to assess the fire performance of facades" [74] and is currently under definition in response to the EU Tender ref 761/PP/GRO/IMA/19/1133/11140 "Finalisation of the European approach to assess the fire performance of façades". Examples of typical products and systems covered by this proposal include exterior thermal insulation composite systems (ETICS), metal composite material cladding systems (MCM), structural insulation panel systems (SIPS), insulated sandwich panel systems, rain screen cladding or ventilated facades, wooden façades, etc.

Therefore, at present each EU member countries have national regulations or guidance governing the fire performance of façades. These regulations are mainly covered by the existing European system on fire reaction and fire resistance, except for some countries that establish additional requirements not covered by the EN 13501-1 [72] and EN 13501-2 [73] Standards. In Italy, where the **e**-SAFE real pilot building is located, the normative reference to determining the fire safety requirements of façades is the Technical Guidance on "Fire safety requirements for facades (facings) on civil buildings" [75] (reference to the circulars DCPST No 5643 of 31st March 2010 and DCPST No 5043 of 15th April 2013). This guide is a normative document of voluntary application referring to buildings with a "fire height" greater than 12 m, and is currently under update and transposition into Vertical Technical Rule (VTR) concerning "Civil buildings closures" and related to the Italian Technical Fire Prevention Standards. According to the Ministerial Decree of 16th January 2019, the application of these guidelines is required in residential buildings falling into the above-mentioned category (i.e. "fire height" > 12 m).

As regards fire reaction requirements, the main guidelines are summarized as follows:

- the façade insulation products must have a minimum fire reaction class equal to B-s3,d0; in the event that the façade insulating function is provided by a set of components jointly marketed as a kit, the minimum class B-s3,d0 must be referred to it in its final operating conditions; other specific lower classes are also allowed if insulation products are protected by non-combustible materials;
- the gaskets, sealants and sealing materials must have the same fire reaction requirements of insulation ones if they occupy a total area greater than 10% of the entire façade surface;
- all the other façade components must have the same fire reaction requirements of insulation ones if they occupy a total area greater than 40% of the entire façade surface.

Regarding fire resistance requirements, no measures are prescribed if the façades elements belong to compartments with low specific fire load (qf ≤ 200 MJ / m^2) or if the compartments are equipped with fire control measures, regardless of the specific fire load value.

Otherwise, specific fire resistance requirements are identified based on the type of building façades. In particular, as concerns "simple façades" or "curtain walls", the technical guide provides the design of a fire-resistant band, with class E60-ef (o→i), between the compartmentation elements of the building (wall or floor) and the external façade (Figure 15), in order to prevent or delay the spread of fire along the building compartments.

As specified above, the Italian Technical Guidance on "Fire safety requirements for facades (facings) on civil buildings" are currently under update and transposition into Vertical Technical Rule (VTR) concerning "Civil buildings closures", with the aim to provide more prescriptive fire safety requirements based on both the building fire height and the type of building façade.

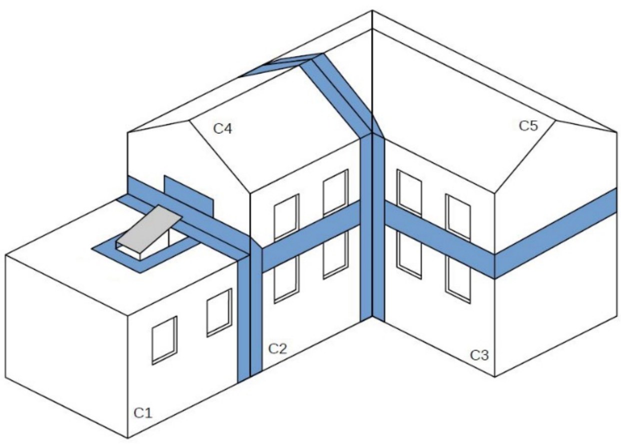


Figure 15. Example of separating fire-resistant façade bands between building compartments

3.5.2 Impact resistance

The impact resistance of construction works is part of the requirements of safety in use.
Building façades must cope with different load conditions during their lifetime, from self-weight and wind loads to everyday bumps and scrapes. Consequently, the façades components (e-PANEL and e-CLT) have to accommodate these loading without risk to the safety of those around the building. At the same time, façade damage has to be minimised in order to ensure its serviceability. The main two types of façade impact are the *soft body* and the *hard body* impact. The first one results primarily from people falling or thrown against the façade and results in its general bending. The second one results from the collision of rigid objects to the façade, tending to cause localised punching (e.g. bumps from vehicles and malicious damage from objects such as hammers etc.).
According to ETAG 007 [76] concerning timber building kits, timber walls with well-known internal lining materials, such as standard gypsum boards, wood-based panel products and solid timber boards with suitable thickness and stud spacings, shall generally be accepted to have a satisfactory impact resistance for normal use in residential housing, office buildings, etc. as long as the deemed to-satisfy conditions are met:

- stud spacing ≤ 0,65 m
- minimum thickness of internal board lining:
  - Particleboard type P2-7: t ≥ 10 mm
  - Plywood: t ≥ 8 mm
  - OSB/2-4: t ≥ 10 mm
  - Gypsum plasterboard: t ≥ 10 mm
  - Solid wood lining: t ≥ 10 mm
  - MDF: t ≥ 10 mm

Otherwise, the impact resistance of timber wall shall be tested according to EOTA TR 001 “Determination of impact resistance of panels and panel assemblies”.
Considering e-CLT and e-PANEL components as wall elements, the minimum accepted impact resistance for walls should normally be 100 Nm for soft body impact and 10 Nm for hard body impact, when the intended use is for residential housing, office buildings, etc.

3.5.3 Wind load resistance

Building façades are exposed to wind action. Consequently, each component installed on them (both e-PANEL and e-CLT) must be properly designed to resist to specific design wind pressure, which is generally calculated according to EN 1991-2-4 [77] or national regulations.
Equivalently, the windows to integrate into the e-PANEL must respond to specific wind load resistance requirements. In detail, wind-load resistance of windows refers to their ability to resist to wind pressure without any damages (e.g., cracking, local yield, bonding failure, etc.) and functional impairment, such as loose hardware and opening difficulties. According to the product standard EN 14351-1 [78], the wind load resistance tests must be carried out according to the EU standards EN 12211 [79] and the results must be expressed in accordance with EN 12210 [80]. The standard EN 12211 defines the test method to determine the resistance to wind load for completely assembled windows and pedestrian doorsets of any materials, when submitted to positive or negative test pressures. The strength of the glass is not evaluated in this standard. The test method consists in three different pressure tests (P1, P2, P3), each performed by applying on the test specimen the pressure (Pa) of the class for which the test is doing (Table 19). Specifically:

- Test P1 measures the maximum deformation of the window in the most critical points, when subjected to pressure or depression;
- Test P2 verifies the overall resistance of the window subjected to 50 cycles of negative and positive pressures;
- Test P3 verifies the ability of the window to not become dangerous after the application of a very strong pressure, both negative and positive, for a short period of time.

The wind load class is assigned when the specimen passes all the three pressure tests for that class.

Then, the deformation class of the test specimen is also evaluated, based on the maximum frontal deflection established during the deformation test P1 (Table 20).
Finally, the global classification of wind resistance of the specimen is obtained by combining both the wind load and deformation classes (Table 21).

Table 19. Resistance to wind load classes according to EN 12211 [79]

Class	P1 [Pa]	P2 = 0.5 P1 [Pa]	P3 = 1.5 P1 [Pa]
0	not tested		
1	400	200	600
2	800	400	1200
3	1200	600	1800
4	1600	800	2400
5	2000	1000	3000
E xxxx[a]	xxxx		

a Test specimen tested with wind loading above class 5, where xxxx is the actual test pressure P1 expressed in Pa (e.g. 2350).

Table 20. Classification of relative frontal deflection according to EN 12210 [80]

Class	Relative frontal deflection
A	< 1/150
B	< 1/200
C	< 1/300

Table 21. Classification of resistance to wind load of windows and pedestrian doorsets according to EN 12210 [80]

Wind load class	Relative frontal deflection		
	A	B	C
1	A1	B1	C1
2	A2	B2	C2
3	A3	B3	C3
4	A4	B4	C4
5	A5	B5	C5
Exxxx	AExxxx	BExxxx	CExxxx

3.5.4 Water tightness

According to [76], the e-SAFE prefabricated timber-based components must be sufficiently watertight in in relation to water from rain and melting snow under normal climatic conditions, including driving rain and snow penetration. Therefore, both e-PANEL and e-CLT must be watertight without any geographical area limitations. For this purpose, they must include appropriate watertight layers that may vary for type and number.

As regards windows components, the EU standard EN 1027 [81] defines the test methods to measure their capacity to resist to water penetration, while the windows classification based on the water penetration capacity is in accordance with the EU standard EN 12208 [82] (Table 22), as reported in the product standard EN 14351-1 [78]. The principle of the test procedure consists of constantly spraying a specified quantity of water on the external surface of the test specimen through many nozzles, while positive increments of test pressure are applied at regular intervals till the water flows to the inner surface. Firstly, the specimen is sprayed just with water for 15 minutes. Then, every 5 minutes, pressure is increased in 50 Pa steps until it reaches 300 Pa. Once there, the steps increase by 150 Pa reaching 450 Pa after one hour of test. There are two test methods (A and B). Method A is appropriate for products that are fully exposed while method B is appropriate for partially shielded products.

Table 22. Water tightness classification of windows and doors according to EN 12208 [82]

Test pressure	**Classification**		**Specifications**
P_{max} (Pa)	**Test method A**	**Test method B**	
-	0	0	No requirement
0	1A	1B	Water spray for 15 min
50	2A	2B	As class 1 + 5 min
100	3A	3B	As class 2 + 5 min
150	4A	4B	As class 3 + 5 min
200	5A	5B	As class 4 + 5 min
250	6A	6B	As class 5 + 5 min
300	7A	7B	As class 6 + 5 min
450	8A	-	As class 7 + 5 min

3.5.5 Environmental quality of materials

The construction and operation of buildings in the EU account for about half of all extracted materials and energy consumption and about a third of water consumption. The sector also generates about one third of all waste and is associated with environmental pressures that arise at different stages of a building's life-cycle including the manufacturing of construction products, building construction, use, renovation and the management of building waste.

Resource use is determined in large part by design decisions and choices over construction materials. To help bringing resource efficiency gains, designers, manufacturers, contractors, authorities and users need useable and reliable information to inform their decision-making.

The recycling or reuse of materials or even whole products is increasingly important as a means to improve the efficient use of materials and to avoid negative impacts associated with the use of virgin materials. However, the overall balance depends to a large extent on the existence of an efficient recycling system at

local, regional or national level which presents an attractive and cost-efficient alternative to landfill. The attractiveness of recycling alternatives is governed by the length of transport distances to recycling sites, achieving the necessary level of purity of the recycled materials and recycling and production processes.
The Product Environmental Footprint (PEF) is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle. PEF information is produced for the overarching purpose of helping to reduce the environmental impacts of goods and services.
Based on a life-cycle approach, the PEF Guide provides a method for modelling the environmental impacts of the flows of material/energy and resulting emissions and waste streams associated with a product from a supply chain perspective (from extraction of raw materials, through use, to final waste management). A life cycle approach refers to take into consideration the spectrum of resource flows and environmental interventions associated with a product or organisation from a supply chain perspective. It includes all stages from raw material acquisition through processing, distribution, use, end-of-life processes and all relevant related environmental impacts, health effects, resource-related threats and burdens for the society.
Each requirement specified in the PEF Guide is chosen taking into consideration the recommendations of similar, widely recognised product environmental accounting methods and guidance documents. Specifically, the methodology guides considered are:

- ISO standards, in particular: ISO 14044(2006) [83], ISO/DIS 14067(2012) [84], ISO 14025(2006) [85], ISO 14020(2000) [86];
- EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method [87];
- EN 15804:2012+A2:2019 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products [88];
- ILCD (International Reference Life Cycle Data System) Handbook [89];
- Product Environmental Footprint: Commission Recommendations 2013/179/EU [90];
- Greenhouse Gas Protocol (WRI/ WBCSD) [91];
- General principles for an environmental communication on mass market products BPX 30-323-0 (ADEME) [92];
- Specification for the assessment of the life cycle greenhouse gas emissions of goods and services [93].

3.6 Hot water storage tanks

3.6.1 Domestic potable water installations

The main European standard concerning the installation of domestic potable water systems is the EN 806 Standard [94] [95]. It provides requirements for installations inside buildings conveying water for human consumption and applies to new installations, alterations, extensions and repairs.
The main objectives of this standard, which are listed in the general part (EN 806-1, [94]), are to ensure that the deterioration of water quality within the installation is avoided, the required flow of water and pressure is available at the draw-off points and at the connection points of appliances (e. g. water heaters, washing machines). Furthermore, it should be guaranteed that potable water meets the standards for physical, chemical and microbiological quality at the draw-off points. Finally, all the various components must not cause danger to health and must not damage property within the expected lifetime, while the maintenance of the installation have to meet the functional requirements during the expected lifetime.
The second part of the Standard (EN 806-2, [95]) regulates, among other things, what requirements shall be met by each component with regard to pressure, temperature and lifetime. In particular, to ensure adequate strength, all the components shall be designed to meet the pressure test requirements of local and national laws and regulations. The test pressure shall be at least 1.5 times the allowable maximum operating pressure (PMA) reported in Table 23. All pipes and joints of a potable water installation shall be designed for a service life of 50 years taking into account appropriate maintenance and specific operating conditions. Unless otherwise specified in National Standards, the materials, components and appliances for hot drinking water installations shall be capable of resisting water temperatures up to 95 °C under fault conditions for a certain period as reported in Table 24.

Table 23. Maximum allowed operating pressure classes [95]

Maximum allowable operating pressure (PMA) class	Pressure (kPa)
PMA 1.0	1000
PMA 0.6	600
PMA 0.25	250

Table 24. Classification of service conditions for plastic pipe systems [95]

Application class	Design temperature T_D (°C)	Service life operating at T_D (years)	Maximum temperature T_{max} (°C)	Service life operating at T_{max} (years)	Fault condition temperature T_{fault} (°C)	Service life operating at T_{fault} (hours)	Typical field of application
1	60	49	80	1	95	100	Hot water supply at 60 °C
2	70	49	80	1	95	100	Hot water supply at 70 °C

3.6.2 Expansion groups of storage tanks

The European standard EN 1488 [96] specifies the dimensions, materials and performance requirements (including test methods) for expansion groups of nominal sizes ranging from DN 15 to DN 40 and with working pressures ranging from 0.1 MPa (1 bar) to 1.0 MPa (10 bar). Expansion groups are intended for fitting to the cold water supply of storage tanks with a maximum distribution temperature of 95 °C. Expansion groups act by limiting the increasing pressure inside the water heater produced by the thermal expansion of water.

In accordance with the EN 1488 Standard, both the **e**-SAFE storage tanks (flat and cylindrical types) will adopt an expansion group integrated into the prefabricated hydraulic system. Such expansion group is mounted in the supply line of the cold water and serves to protect closed DHW preparator while also preventing from overpressure issues. The expansion group is installed close to the heat exchanger of the storage tanks according to the manufacturer's recommendations. In addition, in order to correctly evacuate the water that may escape during the loading process of the storage tank, a connection to the drain system of the building must also be provided, whereby a siphon is installed in the system.

3.6.3 Heat losses from the storage tanks

The labeling of the heat losses of the hot water storage tank used in the **e**-SAFE project is regulated within the Delegated Regulation (EU) No 812/2013 [97].

Among other things, this regulation lists the maximum heat loss that is permitted for hot water storage tanks under certain measurement conditions, so that it can be labeled with the specified energy label.

Both the flat and cylindrical tanks meet the requirements for energy label B, i.e. a maximum energy loss ranging from 940.3 to 1315.3 Wh·day^{-1}.

4. e-SAFE response to requirements: expected performances

4.1 Thermal and energy performance

4.1.1 Typical wall structures and appraisal of their thermo-hygrometric performances

This section reports the thermo-hygrometric analysis of typical European wall structures under a variety of climate conditions. The overarching aim is to get a preliminary – yet sound – knowledge of how different walls respond to a range of hygrothermal conditions. Such a response is then compared to that obtainable when the same walls are renovated through e-CLT and e-PANEL. For the sake of conciseness, detailed results are presented only for e-CLT; nevertheless, these results are briefly compared in the text against those achieved when applying e-PANEL under the same boundary conditions, in order to understand the different hygrometric behaviour of the two retrofit solutions.

To address potential hygrothermal issues, the steady-state calculation procedures described in the European Standard EN ISO 13788 [29] have been followed to evaluate:

- the risk of mould growth and surface condensation on the inner surface of the walls;
- the risk of interstitial condensation due to vapour diffusion only, i.e. neglecting phenomena such as wind driven rain, capillary water transport and water absorption due in hygroscopic materials;
- the time needed for the water to completely evaporate in case of interstitial condensation.

The same European Standard reports that when vapour diffusion is the main driving force for water vapour migration through a building component, the results of this kind of assessment are generally conservative, and more detailed analyses may be reserved for worst cases. For this reason, the current report considers this vapour migration mechanism only; Task 3.3 will include detailed thermo-hygrometric analyses of the most critical configurations.

The wall structures here included are some of those listed in the final report of the EU Tabula project [98], which are considered representative of a large share of existing walls for the non-historic EU residential building stock, being this the target of the **e**-SAFE renovation strategy. In detail, the investigated walls have been tagged as follows:

- Wall structure ID1: solid brick wall with no insulation;
- Wall structure ID2: solid brick wall with poor external insulation;
- Wall structure ID3: hollow clay bricks cavity wall with no insulation;
- Wall structure ID4: concrete wall with no insulation;
- Wall structure ID5: hollow clay bricks cavity wall with poor insulation in the air gap;
- Wall structure ID6: concrete wall with poor external insulation;
- Wall structure ID7: hollow clay bricks cavity wall with average insulation in the air gap.

The materials used in these wall assemblies, along with their thermophysical properties, are listed in Table 25 and are gathered from the EN ISO 10456:2007 Standard [99]. Tables 24-30 describe in detail their stratigraphy and stationary and dynamic thermal parameters calculated according to the Standards EN ISO 6946:2017 [10] and EN ISO 13786:2017 [22].

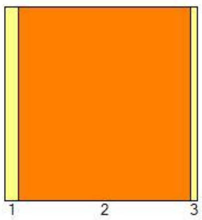
To this aim, the values of the internal and external surface thermal resistance are set to 0.13 $m^2 \cdot K \cdot W^{-1}$ and 0.04 $m^2 \cdot K \cdot W^{-1}$ respectively. Given the wide variety of construction techniques found throughout Europe, these Tables are only indicative of likely construction assemblies found in various non-historic residential buildings in EU countries. As such, they do not aim to cover all the possible existing configurations, but rather to provide an abacus of target walls for the application of the **e**-SAFE envelope solutions.

Table 25. Thermophysical properties of wall construction materials

Material	Density ρ (kg·m^{-3})	Thermal conductivity λ (W·m^{-1}·K^{-1})	Specific heat C_p (J·kg^{-1}·K^{-1})	Water vapour resistance μ (-)
External plaster	1800	0.90	1000	10
Internal plaster	1400	0.70	1000	10
Solid brick	1800	0.72	1000	10
Insulating layer	50	0.038	2100	1
Hollow clay brick	800	0.40	1000	10
Still air gap (vertical, 2 cm)	1	0.11*	1004	1
Still air gap (vertical, 3 cm)	1	0.16*	1004	1
Still air gap (vertical, 7 cm)	1	0.38*	1004	1
Reinforced concrete	2400	2.00	1000	80
Ext. wooden cladding	1350	0.28	1674	110
CLT panel	420	0.12	1600	60

*this is the equivalent thermal conductivity corresponding to a thermal resistance of 0.18 m^2·K·W^{-1}

Table 26. Thermal parameters of wall structure ID1 (solid brick wall with no insulation)

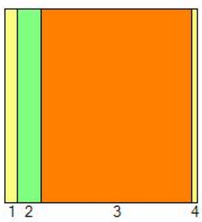


ID	Description	Stratigraphy
1	Solid brick wall with no insulation – overall thickness 28 cm	1. External plaster (2 cm) 2. Solid brick (25 cm) 3. Internal plaster (1 cm)

Uninsulated solid brick walls are typical of single-family houses and terraced houses built throughout Europe, and in particular in Northern Europe, approximately up to 1980

Stationary parameters	
Superficial mass (plasters included)	500 kg·m^{-2}
U-value	1.81 W·m^{-2}·K^{-1}
Dynamic parameters	
Y_{IE}	0.43 W·m^{-2}·K^{-1}
Attenuation factor	0.25
Phase shift	10 h
Areal internal heat capacity	70.2 kJ·m^{-2}·K^{-1}

Table 27. Thermal parameters of wall structure ID2 (brick wall with poor insulation)



ID	Description	Stratigraphy
2	Solid brick wall with poor insulation – overall thickness 32 cm	1. External plaster (2 cm) 2. Insulation layer (4 cm) 3. Solid brick (25 cm) 4. Internal plaster (1 cm)

Solid brick walls with poor exterior insulation have been mostly used in single-family houses, terraced houses and multi-family houses built in continental Europe approximately from 1945 to 1980

Stationary parameters	
Superficial mass (plasters included)	501.2 kg·m^{-2}
U-value	1.09 W·m^{-2}·K^{-1}
Dynamic parameters	
Y_{IE}	0.15 W·m^{-2}·K^{-1}
Attenuation factor	0.14
Phase shift	11 h
Areal internal heat capacity	66.2 kJ·m^{-2}·K^{-1}

Table 28. Thermal parameters of wall structure ID3 (cavity wall with no insulation)

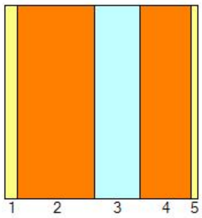
	ID	Description	Stratigraphy
	3	Cavity wall with air gap and no insulation – overall thickness 30 cm	1. External plaster (2 cm) 2. Hollow clay brick (12 cm) 3. Air gap (7 cm) 4. Hollow clay brick (8 cm) 5. Internal plaster (1 cm)
Uninsulated cavity walls made up of two leaves of hollow clay bricks are peculiar of multi-family houses and apartment blocks built in warmer Mediterranean countries approximately from 1945 to 1980		**Stationary parameters**	
		Superficial mass (plasters included)	210.1 kg·m^{-2}
		U-value	1.11 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.59 W·m^{-2}·K^{-1}
		Attenuation factor	0.53
		Phase shift	7.1 h
		Areal internal heat capacity	54.2 kJ·m^{-2}·K^{-1}

Table 29. Thermal parameters of wall structure ID4 (concrete wall with no insulation)

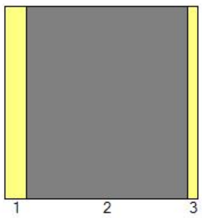
	ID	Description	Stratigraphy
	4	Concrete wall – overall thickness 18 cm	1. External plaster (2 cm) 2. Reinforced concrete (15 cm) 3. Internal plaster (1 cm)
Uninsulated concrete walls have been employed mostly throughout Europe especially in multi-family houses and apartment blocks built approximately between 1945 and 1980		**Stationary parameters**	
		Superficial mass (plasters included)	410 kg·m^{-2}
		U-value	3.55 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	1.52 W·m^{-2}·K^{-1}
		Attenuation factor	0.47
		Phase shift	5.3 h
		Areal internal heat capacity	83.1 kJ·m^{-2}·K^{-1}

Table 30. Thermal parameters of wall structure ID5 (cavity wall with poor insulation)

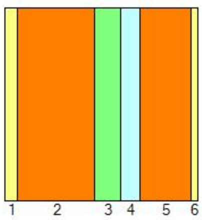
	ID	Description	Stratigraphy
	5	Cavity wall with air gap and poor insulation – overall thickness 30 cm	1. External plaster (2 cm) 2. Hollow clay brick (12 cm) 3. Insulation layer (4 cm) 4. Air gap (3 cm) 5. Hollow clay brick (8 cm) 6. Internal plaster (1 cm)
Cavity walls with infill insulation represent an evolution of uninsulated cavity walls (ID 3) and have been employed widely for single-family houses, terraced houses, multi-family houses and apartment blocks namely built approximately between 1980 and 2000		**Stationary parameters**	
		Superficial mass (plasters included)	211.2 kg·m^{-2}
		U-value	0.72 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.32 W·m^{-2}·K^{-1}
		Attenuation factor	0.44
		Phase shift	8.4 h
		Areal internal heat capacity	53 kJ·m^{-2}·K^{-1}

Table 31. Thermal parameters of wall structure ID6 (concrete wall with poor insulation)

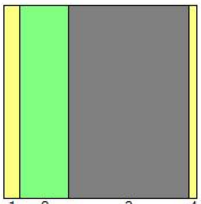
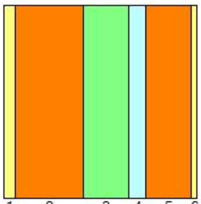
	ID	Description	Stratigraphy
	6	Concrete wall with poor insulation – overall thickness 24 cm	1. External plaster (2 cm) 2. Insulation layer (6 cm) 3. Reinforced concrete (15 cm) 4. Internal plaster (1 cm)
Concrete walls with external insulation represent an evolution of uninsulated concrete walls (ID 4) and have been mostly used in single-family houses, terraced houses, multi-family houses and apartment blocks namely approximately built between 1980 and 2000		**Stationary parameters**	
		Superficial mass (plasters included)	411.8 kg·m^{-2}
		U-value	1.20 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.31 W·m^{-2}·K^{-1}
		Attenuation factor	0.27
		Phase shift	7.1 h
		Areal internal heat capacity	83.5 kJ·m^{-2}·K^{-1}

Table 32. Thermal parameters of wall structure ID7 (cavity wall with average insulation)

	ID	Description	Stratigraphy
	7	Cavity wall with air gap and average insulation – overall thickness 34 cm	1. External plaster (2 cm) 2. Hollow clay brick (12 cm) 3. Insulation layer (8 cm) 4. Air gap (3 cm) 5. Hollow clay brick (8 cm) 6. Internal plaster (1 cm)
This wall typology represents an improvement of cavity walls with infill insulation (ID 5) for all residential buildings built approximately after 2000		**Stationary parameters**	
		Superficial mass (plasters included)	212.4 kg·m^{-2}
		U-value	0.61 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.27 W·m^{-2}·K^{-1}
		Attenuation factor	0.44
		Phase shift	8.2 h
		Areal internal heat capacity	53 kJ·m^{-2}·K^{-1}

4.1.2 Climate data for thermo-hygrometric simulations

For each city representative of the Italian climate zones described in Section 3.1.1, the average monthly climate conditions gathered from the Italian Standard series UNI 10349:2016 [100] are used to derive the corresponding indoor conditions as dictated by the EN ISO 13788 Standard [29] for walls exposed to outdoor conditions.

The assessment of indoor conditions is carried out considering a worst-case scenario, i.e. supposing a heating system able to provide sensible heating only and not to manage latent heat. This means that indoor relative humidity is expected to rise, especially in case of high occupancy rate and high vapour production from the occupants, which depends on their activity.

More in detail, indoor air temperature is set to 20 °C during the heating periods listed in Table 3, while it coincides with the outdoor air temperature value in the remaining of the year (a lower threshold of 18 °C applies in case of particularly cold outdoor conditions). The indoor vapour content is instead defined as a function of outdoor conditions and internal vapour production rate, which depends on the intended use of the indoor space (e.g., offices, spaces with or without a mechanical ventilation system, kitchens, etc.).

Since internal vapour production can significantly influence the hygrothermal performances of the walls, in this report both the suggested “vapour class production 3” – houses without mechanical ventilation and with unspecified occupancy pattern – and the more demanding “class production 4” – gyms, kitchens and canteens – are taken into account. This allows to perform a sensitivity analysis of mould growth, surface condensation and interstitial condensation risks to indoor humidity values.

4.1.3 Thermo-hygrometric performance of existing wall structures

The hygrothermal risk assessment of the various wall assemblies is carried out through the freeware software PAN v.7.1.0.4, a tool developed by the Italian National Association for Thermal Insulation (ANIT) that complies with all the relevant previously listed European Standards and implements the Glaser's method [101].
The results are presented in
Table 34 and Table 35 for vapour class production 3 and 4, respectively, using a green mark (V) for a positive assessment and a red cross (X) for a negative one. On the other hand, an exclamation mark (!) identifies a positive assessment according to the EN ISO 13788 Standard, but with the presence of some interstitial condensation that is below the maximum accepted thresholds reported in Table 33 depending on the material and its thickness *d* (m), and in any case below the suggested value of 500 g·m^{-2}. In such cases, the assessment is considered positive only if the amount of condensate is able to re-evaporate completely within a year cycle.

Table 33. Maximum tolerable interstitial condensation in various construction materials [29]

Material	**Density ρ (kg·m^{-3})**	**Maximum tolerable condensate (g·m^{-2})**
Clay	600-2000	≤ 500
Concrete	400-2400	≤ 500
Wood and derived materials	500-800	≤ 30·ρ·d
Plasters and mortars	600-2000	≤ 30·ρ·d
Organic fibres with waterproof glue	300-700	≤ 20·ρ·d
Organic fibres with non-waterproof glue	300-700	≤ 5·ρ·d
Mineral fibres	10-150	$\leq 5000 \cdot \rho \cdot d \cdot \lambda \cdot (1 - 1.7 \cdot \lambda)^{-1}$
Cellular plastic materials	10-80	$5000 \cdot \rho \cdot d \cdot \lambda \cdot (1 - 1.7 \cdot \lambda)^{-1}$

If looking at Table 34, it emerges that the most problematic existing wall structures are:

- uninsulated concrete walls (ID 4), for which a risk of surface condensation and mould growth is predicted in all climate zones because of their low thermal resistance (U-value = 3.55 W·m^{-2}·K^{-1})
- uninsulated solid brick walls (U-value = 1.81 W·m^{-2}·K^{-1}) where surface condensation and mould growth can be an issue for climate zones C, D, E and F respectively.

As far as interstitial condensation is concerned, a limited amount of condensate is predicted for uninsulated concrete walls only in the coldest climate zones (E and F) at the interface between the internal plaster and the reinforced concrete layer. However, as shown in Figure 16, the amount of cumulated condensate in the coldest period (November to February) is about 330 g·m^{-2} (below the standard threshold of 500 g·m^{-2}) and completely re-evaporates within the year. As such, interstitial condensation is not considered an issue.
On the other hand, if considering a higher indoor vapour production (vapour class 4, Figure 17), surface condensation and mould growth are now an issue for almost all the different wall assemblies and the climate zones ranging from C to F. This can be easily explained as now indoor relative humidity is typically higher than 80%, which is widely recognized as the activation threshold for the formation of fungi on internal surfaces.
When considering interstitial condensation issues, now also wall ID3 (cavity wall with air gap and no insulation) in climate zone F is subject to some condensation, precisely at the interface between the air gap and the external hollow clay brick, but the amount is negligible (less than 5 g·m^{-2} in December) and completely re-evaporated in a year cycle. Conversely, the amount of cumulated condensate within concrete wall (ID4) in the coldest climate zone F is about 1400 g·m^{-2} at the interface between internal plaster and reinforced concrete. This is considerably higher than the suggested threshold of 500 g·m^{-2} (and more than four times higher than the corresponding case with vapour concentration class 3), and cannot be completely re-evaporated within a year. As such, corrective design actions are required for this kind of wall structure when placed in the coldest climate zones E and F.

Table 34. Hygrothermal risk assessment results for vapour concentration class 3 – Existing wall structures

Climate zone	Risk assessment	Wall ID 1	Wall ID 2	Wall ID 3	Wall ID 4	Wall ID 5	Wall ID 6	Wall ID 7
Climate zone A	Surface condensation and mould growth	✓	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone B	Surface condensation and mould growth	✓	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone C	Surface condensation and mould growth	✗	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone D	Surface condensation and mould growth	✗	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone E	Surface condensation and mould growth	✗	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	!	✓	✓	✓
Climate zone F	Surface condensation and mould growth	✗	✓	✓	✗	✓	✗	✓
	Interstitial Condensation	✓	✓	✓	!	✓	✓	✓

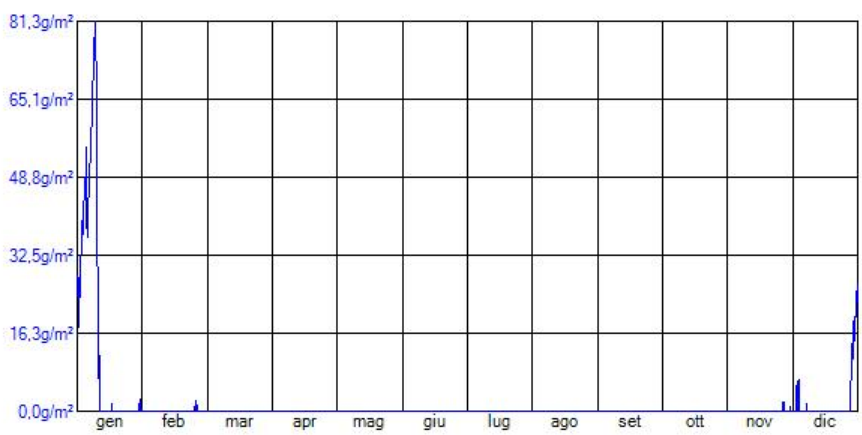


Figure 16. Interstitial condensation for wall ID4 in Climate Zone F – Vapour concentration class 3

Table 35. Hygrothermal risk assessment results for vapour concentration class 4 – Existing wall structures

Climate zone	Risk assessment	Wall ID 1	Wall ID 2	Wall ID 3	Wall ID 4	Wall ID 5	Wall ID 6	Wall ID 7
Climate zone A	Surface condensation and mould growth	✗	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone B	Surface condensation and mould growth	✗	✓	✓	✗	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone C	Surface condensation and mould growth	✗	✗	✗	✗	✓	✗	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone D	Surface condensation and mould growth	✗	✗	✗	✗	✗	✗	✓
	Interstitial Condensation	✓	✓	✓	!	✓	✓	✓
Climate zone E	Surface condensation and mould growth	✗	✗	✗	✗	✗	✗	✓
	Interstitial Condensation	✓	✓	✓	✗	✓	✓	✓
Climate zone F	Surface condensation and mould growth	✗	✗	✗	✗	✗	✗	✗
	Interstitial Condensation	✓	✓	!	✗	✓	✓	✓

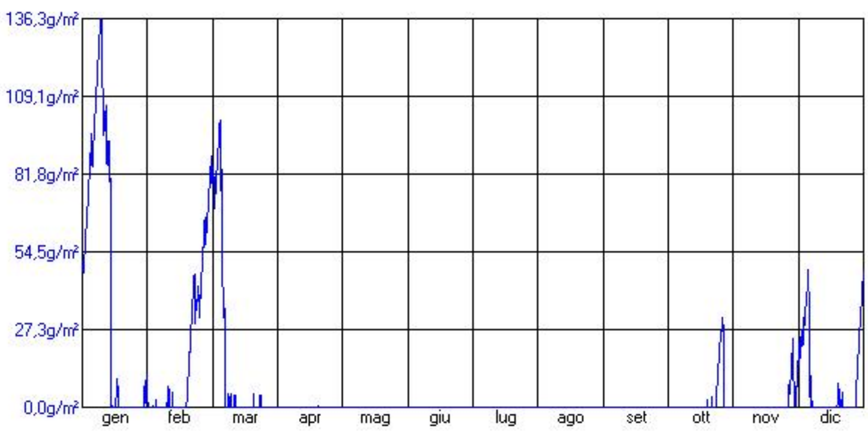


Figure 17. Interstitial condensation for wall ID4 in Climate Zone F – Vapour concentration class 4

4.1.4 Thermo-hygrometric performance with e-CLT and e-PANEL

The stationary and dynamic thermal parameters obtained after the e-CLT renovation for the seven wall structures are reported in detail in Table 36 to Table 42, while Table 43 summarizes the corresponding figures obtained with the use of e-PANEL.

The application of the e-CLT solution to the outer surface of existing walls brings noticeable benefits in terms of improved thermal resistance, thanks to:

- the low thermal conductivity of CLT (λ = 0.12 W·m^{-1}·K^{-1});
- the insulation layer with 6 cm thickness on its outer face (this value is assumed as a reasonable average thickness for different climatic contexts);
- the additional thermal resistance brought by the non-ventilated air gap layer between the external cladding and the insulation layer.

Consequently, e-CLT significantly reduces the U-value of the different wall structures. These values now range between 0.23 W·m^{-2}·K^{-1} (wall ID 7r, cavity wall with air gap and average insulation) and 0.34 W·m^{-2}·K^{-1} (wall ID 4r, concrete wall with no insulation), making this retrofit solution compliant with most of the European countries prescribing maximum U-values after building renovation (see Table 2 in Section 3.1.1). The corresponding values without the e-CLT package are 0.61 W·m^{-2}·K^{-1} (wall ID 7) and 3.55 W·m^{-2}·K^{-1} (wall ID 4) (see Table 26 to Table 32).

The additional thermal mass provided by e-CLT, and the presence of the insulation material, significantly improve the dynamic thermal response as well:

- the attenuation factor ranges between 0.03 (wall ID 2r) and 0.11 (wall ID 4r)
- the dynamic thermal transmittance YIE ranges between 0.01 W·m-2·K-1 and 0.04 W·m-2·K-1, that is to say well below the maximum value of 0.10 W·m-2·K-1 allowed for instance in Italy.
- the phase shift is between 13 h (wall ID 4r) and 19.1 h (wall ID 2r), which classifies all the proposed solutions as “excellent”.

The areal internal heat capacity is the only dynamic parameter that shows a slight worsening if compared with the original wall structures; in any case, the worst case (wall ID 3r, κ_i = 47.4 kJ·m^{-2}·K^{-1}) still satisfies the regulation holding in Italy for public buildings (κ_i > 40 kJ·m^{-2}·K^{-1}).

In order to draw a comparison with the performance ensured by the e-CLT solution, in the case of e-PANEL renovation the wooden fibre thickness has been set to 9 cm, thus obtaining exactly the same U-values as for the corresponding cases with the e-CLT. However, the substitution of the CLT with a lighter insulating material brings about changes in the other static and – most notably – dynamic thermal parameters, as reported in Table 43.

The main effects are a slight worsening of the periodic thermal transmittance Y_{IE}, which now ranges between 0.02 and 0.07 W·m^{-2}·K^{-1}, and of the attenuation factor that spreads from 0.08 to 0.21. Despite this, the attained values are still well satisfactory according to Italian regulations and recommendations from scientific literature.

Table 36. Thermal parameters of wall structure ID1r (retrofitted with e-CLT)

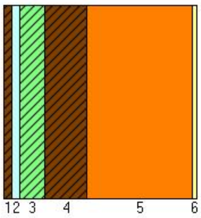
	ID	Description	Stratigraphy
	1r	Solid brick wall with no insulation + e-CLT package – overall thickness 45.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Solid brick (25 cm) 6. Internal plaster (1 cm)
		Stationary parameters	
		Superficial mass (plasters included)	533.3 kg·m^{-2}
		U-value	0.31 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.01 W·m^{-2}·K^{-1}
		Attenuation factor	0.04
		Phase shift	17.5 h
		Areal internal heat capacity	64.1 kJ·m^{-2}·K^{-1}

Table 37. Thermal parameters of wall structure ID2r (retrofitted with e-CLT)

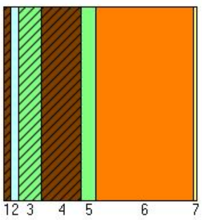
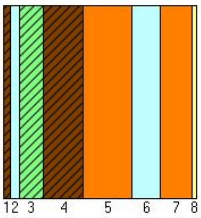
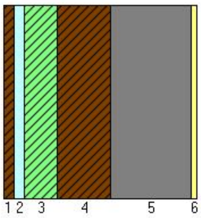
	ID	Description	Stratigraphy
	2r	Solid brick wall with poor insulation + e-CLT package – overall thickness 49.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Insulation layer (4 cm) 6. Solid brick (25 cm) 7. Internal plaster (1 cm)
		Stationary parameters	
		Superficial mass (plasters included)	534.5 kg·m^{-2}
		U-value	0.28 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.01 W·m^{-2}·K^{-1}
		Attenuation factor	0.03
		Phase shift	19.1 h
		Areal internal heat capacity	64.1 kJ·m^{-2}·K^{-1}

Table 38. Thermal parameters of wall structure ID3r (retrofitted with e-CLT)



ID	Description	Stratigraphy
3r	Cavity wall with air gap and no insulation + e-CLT package – overall thickness 47.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Hollow clay brick (12 cm) 6. Air gap (7 cm) 7. Hollow clay brick (8 cm) 8. Internal plaster (1 cm)
	Stationary parameters	
	Superficial mass (plasters included)	243.4 $kg \cdot m^{-2}$
	U-value	0.28 $W \cdot m^{-2} \cdot K^{-1}$
	Dynamic parameters	
	Y_{IE}	0.02 $W \cdot m^{-2} \cdot K^{-1}$
	Attenuation factor	0.08
	Phase shift	15.3 h
	Areal internal heat capacity	47.4 $kJ \cdot m^{-2} \cdot K^{-1}$

Table 39. Thermal parameters of wall structure ID4r (retrofitted with e-CLT)



ID	Description	Stratigraphy
4r	Concrete wall + e-CLT package – overall thickness 35.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Reinforced concrete (15 cm) 6. Internal plaster (1 cm)
	Stationary parameters	
	Superficial mass (plasters included)	443.3 $kg \cdot m^{-2}$
	U-value	0.34 $W \cdot m^{-2} \cdot K^{-1}$
	Dynamic parameters	
	Y_{IE}	0.04 $W \cdot m^{-2} \cdot K^{-1}$
	Attenuation factor	0.11
	Phase shift	13 h
	Areal internal heat capacity	81.8 $kJ \cdot m^{-2} \cdot K^{-1}$

Table 40. Thermal parameters of wall structure ID5r (retrofitted with e-CLT)

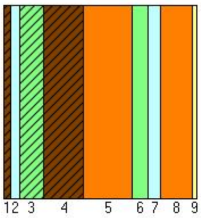
	ID	Description	Stratigraphy
	5r	Cavity wall with air gap and poor insulation + e-CLT package – overall thickness 47.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Hollow clay brick (12 cm) 6. Insulation layer (4 cm) 7. Air gap (3 cm) 8. Hollow clay brick (8 cm) 9. Internal plaster (1 cm)
		Stationary parameters	
		Superficial mass (plasters included)	244.6 kg·m^{-2}
		U-value	0.25 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.01 W·m^{-2}·K^{-1}
		Attenuation factor	0.05
		Phase shift	17 h
		Areal internal heat capacity	48.5 kJ·m^{-2}·K^{-1}

Table 41. Thermal parameters of wall structure ID6r (retrofitted with e-CLT)

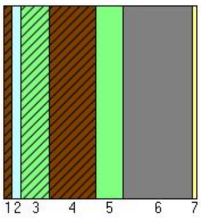
	ID	Description	Stratigraphy
	6r	Concrete wall with poor insulation + e-CLT package – overall thickness 41.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Insulation layer (6 cm) 6. Reinforced concrete (15 cm) 7. Internal plaster (1 cm)
		Stationary parameters	
		Superficial mass (plasters included)	445.1 kg·m^{-2}
		U-value	0.29 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.02 W·m^{-2}·K^{-1}
		Attenuation factor	0.07
		Phase shift	15 h
		Areal internal heat capacity	81.6 kJ·m^{-2}·K^{-1}

Table 42. Thermal parameters of wall structure ID7r (retrofitted with e-CLT)

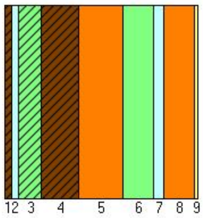
	ID	Description	Stratigraphy
	7r	Cavity wall with air gap and average insulation + e-CLT package – overall thickness 51.8 cm	1. External wooden cladding (1.8 cm) 2. Air gap (2 cm) 3. Insulation layer (6 cm) 4. CLT panel (10 cm) 5. Hollow clay brick (12 cm) 6. Insulation layer (8 cm) 7. Air gap (3 cm) 8. Hollow clay brick (8 cm) 9. Internal plaster (1 cm)
		Stationary parameters	
		Superficial mass (plasters included)	245.8 kg·m^{-2}
		U-value	0.23 W·m^{-2}·K^{-1}
		Dynamic parameters	
		Y_{IE}	0.01 W·m^{-2}·K^{-1}
		Attenuation factor	0.04
		Phase shift	16.5 h
		Areal internal heat capacity	49.4 kJ·m^{-2}·K^{-1}

Table 43. e-PANEL thermal parameters for the various wall assemblies

Thermal parameters	**ID1**	**ID2**	**ID3**	**ID4**	**ID5**	**ID6**	**ID7**
Stationary parameters							
Superficial mass (plasters included, kg·m^{-2})	493	494	203	403	204	405	205
U-value (W·m^{-2}·K^{-1})	0.31	0.28	0.28	0.34	0.25	0.29	0.23
Dynamic parameters							
Y_{IE} (W·m^{-2}·K^{-1})	0.03	0.02	0.06	0.07	0.03	0.06	0.02
Attenuation factor (-)	0.09	0.08	0.19	0.21	0.13	0.20	0.10
Phase shift (h)	13.3	13.5	11.1	8.5	12.4	9.2	12.4
Areal internal heat capacity (kJ·m^{-2}·K^{-1})	64.3	64.3	48.3	83.3	48.8	82.7	49.7

As expected, the improvements in the thermal parameters of the retrofitted walls do positively influence also their hygrometric behaviour, as demonstrated from Table 44. In fact, surface condensation and mould growth risks are now solved for all wall structures and indoor vapour production analysed because of their increased thermal resistance, which raises the temperature of the walls' internal surface and thus reduces the risk of achieving dew point conditions.
In terms of interstitial condensation, some condensate is present at the exterior face of the insulating material for vapour concentration class 3 only in the case of wall ID 3r (cavity wall with air gap and no insulation) in the coldest climate zone F, but the very low amount predicted (2.2 g·m^{-2}) is easily re-evaporated. When considering an increased indoor vapour production (vapour concentration class 4, Table 45), some interstitial condensation may occur in climate zones E and F for five out of the seven wall structures, but once again the amount of condensate is low (below 20 g·m^{-2}) and re-evaporated.

Table 44. Hygrothermal risk assessment results for vapour concentration class 3 – Retrofitted wall structures with e-CLT

Climate zone	Risk assessment	Wall ID 1r	Wall ID 2r	Wall ID 3r	Wall ID 4r	Wall ID 5r	Wall ID 6r	Wall ID 7r
Climate zone A	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone B	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone C	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone D	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone E	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone F	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	!	✓	✓	✓	✓

Table 45. Hygrothermal risk assessment results for vapour concentration class 4 – Retrofitted wall structures with e-CLT

Climate zone	Risk assessment	Wall ID 1r	Wall ID 2r	Wall ID 3r	Wall ID 4r	Wall ID 5r	Wall ID 6r	Wall ID 7r
Climate zone A	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone B	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone C	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone D	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	✓	✓	✓	✓	✓	✓	✓
Climate zone E	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	!	!	!	✓	!	✓	!
Climate zone F	Surface condensation and mould growth	✓	✓	✓	✓	✓	✓	✓
	Interstitial Condensation	!	!	!	✓	!	✓	!

In the case of e-PANEL, mould growth and surface condensation are avoided as well for every wall assembly, climate condition and indoor vapour production class. However, interstitial condensation is predicted on the exterior face of the insulation material for climate zones D, E and F for walls ID 1, 2, 3, 5 and 7, respectively, for both vapour production classes 3 and 4.

Hence, the hygrothermal performance of e-PANEL is slightly worse than e-CLT: this can be attributed to the lower water vapour resistance of the walls retrofitted with e-PANEL, which ease the water vapour to move through and reach the coldest points of the walls, thus eventually condensing. The highest amount of condensate is predicted for wall assembly ID3 (uninsulated cavity wall with two leaves of clay bricks) located in the coldest climate zone F and for indoor vapour production class 4. Under these circumstances, water vapour condensate amounts to around 490 $g \cdot m^{-2}$, a value close to the threshold of 500 $g \cdot m^{-2}$ set by the EN ISO 13788 Standard that may deteriorate the insulating material.

For these reasons, in such extreme conditions the use of a vapour screen/barrier on the internal face of the insulation layer is suggested, while also considering the opportunity to shelter the insulation material from the rain penetrating through the external cladding with a waterproof breathable membrane. These aspects will be addressed in detail during the activities of Task 3.3.

4.2 Indoor Environmental Quality (IEQ) performance

Indoor air quality

As detailed in Section 3.2.1, the EN Standard 16798-1 reports design ventilation rates and indoor CO_2 concentration that must be ensured indoors to comply with different levels of expectation. In residential buildings, medium (normal) expectation can be satisfied by ensuring that indoor CO_2 concentration does not exceed by more than 800 ppm in living rooms – and 550 ppm in bedrooms – the CO_2 concentration measured outdoors.

In **e**-SAFE, no mechanical ventilation systems are envisaged in principle, even if they can be included in the e-THERM solution when required by national regulations. In any case, the Building Energy Management System (e-BEMS) will provide monitoring of indoor air quality: through a dedicated application software tool, the residents will be able to check on their smartphones the CO_2 concentration inside their dwellings, and will be invited to open windows when this exceeds the thresholds set by the EN Standard.

Indoor thermal comfort

In case of buildings equipped with mechanical heating and cooling systems, the EN Standard 16798-1 indicates the minimum (maximum) indoor operative temperatures that can be accepted during the heating (cooling) season. For instance, in residential buildings a medium (normal) level of expectation requires that $T_{op} \geq 20$ °C in the heating season and $T_{op} \leq 26$ °C in the cooling season. These values can be loosened to $T_{op} \geq 18$ °C and $T_{op} \leq 27$ °C, respectively, if moderate satisfaction with thermal comfort is accepted.

e-SAFE will provide heating and cooling systems to all dwellings, and of course they will be sized in order to ensure the required temperature levels. In the real pilot, this is undoubtedly a great improvement in the living conditions of the residents. Indeed, according to a preliminary survey with interviews, in the majority of the apartments there is no heating/cooling system working, and the residents suffer from cold. Most of them try to heat their home with mobile gas stoves that turn out not to be efficient and not to provide sufficient comfort in all rooms.

Indoor acoustic comfort

As explained in Section 3.2.3, according to EN Standard 16798-1 indoor acoustic comfort is ensured if the Equivalent Continuous Sound Level ($L_{A,eq}$) generated by building service systems is sufficiently low. For instance, in residential buildings $L_{A,eq} \leq 35$ dB is required in living rooms, and $L_{A,eq} \leq 30$ dB in bedrooms respectively, in order to satisfy medium (normal) expectation.

In **e**-SAFE, all e-THERM components will be selected by looking also at their noise spectrum, in order to ensure compliance with these requirements based on preliminary calculations. Particular attention will be paid to the selection of the internal units (fan coils) and the heat pump, the latter being installed outdoors in close proximity to the building.

Daylight provision and visual comfort

Daylight provision indoors has been checked with a preliminary analysis based on the calculation of the average Daylight Factor (DF), which represents the ratio of the average indoor illuminance to the outdoor illuminance detected in absence of direct sunlight (i.e., under diffuse radiation only) and without obstructions. As such, the Daylight Factor is a proxy of how much light would fall in a space under overcast sky conditions (worst-case analysis), and cannot account for potential glare issues coming from direct sunlight, as already reported in Section 3.2.4. Nevertheless, it is a good starting point for more detailed analysis that can be performed later on, in the detailed design stage of Task 3.3, based on the outcomes of such calculation.
The DF can be calculated for a room according to Equation (17):

$$DF = \frac{S_w \cdot \tau}{S_{tot} \cdot (1 - \rho_m)} \cdot \varepsilon \cdot \psi \quad (\%) \qquad (17)$$

Here, S_w is the total fenestration area (m^2), τ is the visible transmissivity of the glazing (-) and S_{tot} represents the total surface area of the room including both glazed and opaque surfaces (m^2). On the other hand, ρ_m is the average visible reflectivity of all the surfaces in the room calculated as follows:

$$\rho_m = \frac{\sum_{i=1}^{n} S_i \cdot \rho_i}{S_{tot}} \quad (-) \qquad (18)$$

Finally, ε is the so-called window factor (-) while Ψ is the window reduction factor (-). Both of them are pure numbers that account for the presence of obstructions in proximity of the openings and for the depth of the sill, respectively, and can be determined for a specific geometric configuration by using the graphs reported in [40].

In order to keep this analysis as general as possible, the base case calculation is carried out considering a typical room of dimensions 4 x 4 x 2.7 m^3 equipped with a single-glazed window (τ = 0.85) of 1.3 x 1.6 m^2 extension and a sill depth of 0.1 m. The average indoor reflectivity calculated by setting the reflectivity values of floor, walls and ceiling to 0.3, 0.5 and 0.8 respectively, is of 0.52. No external obstructions are considered. Under these assumptions, the calculation of the DF returns the value of 2.4 %, which is higher than the minimum threshold of 1.6 % suggested by the EN 17037 Standard for Italy in order to guarantee a minimum daylight of 300 lx over the workplane [39].

The calculation for the **e**-SAFE scenario, instead, are carried out assuming the same base case settings except for an increased sill depth of 0.2 m due to the addition of the e-CLT package discussed in Section 4.1, and for the use of more performing double-glazed windows with a visible transmissivity value of 0.7.

Under this new configuration, the DF turns out to be exactly 2%, which is the threshold set by EN 17037 Standard for most EU countries. On the other hand, this value cannot guarantee a minimum daylight level of 300 lx inside buildings located at high latitudes, e.g. Germany, The Netherlands and the UK, for which the amount of glazed surfaces should be higher than the one assumed here.

In the end, the application of a double skin in the form of the e-CLT or e-PANEL solutions to the existing building envelope does not significantly reduce the amount of daylight coming through the windows.

4.3 Acoustic performance of the e-SAFE solutions

In terms of acoustic performance, the **e**-SAFE technologies applied to the building envelope must comply with the national regulations that are in force in the EU countries discussed in Section 3.3. This is particularly relevant for the e-PANEL and the e-CLT, which are expected to modify the stratigraphy of the existing facades. In order to perform this analysis, as well as to provide possible guidelines to ensure the compliance with the regulations, it is necessary to remind that the sound insulation provided by a façade depends not only on the acoustic performance of the opaque components, but also on the features of the glazed components. Indeed, the weighted apparent sound reduction index of a façade can be assessed as in Eq. (19):

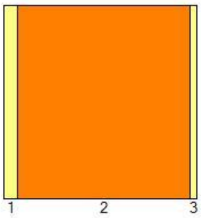
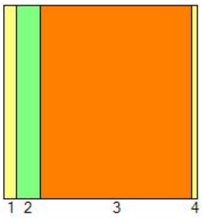
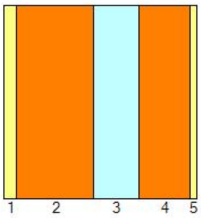
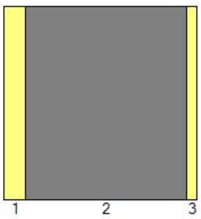
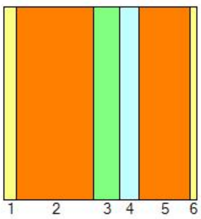
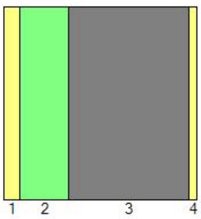
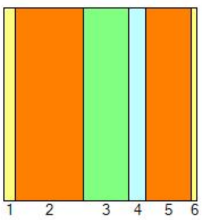
$$R'_w = -10 \cdot \log\left(\frac{\sum_{i=1}^{n} S_i \cdot 10^{-\frac{R_{w,i}}{10}}}{\sum_{i=1}^{n} S_i}\right) - K \qquad (19)$$

Here, S_i is the surface of each component of the facade (walls, windows) and $R_{w,i}$ the respective sound reduction index. K is a term that accounts for the sound transmission through lateral paths; K = 2 dB is the suggested value in buildings with reinforced concrete frames [102]. Equation (19) does not include the role of vents and ventilation grilles, which are not relevant when dealing with **e**-SAFE technologies.

Now, the windows have usually a lower sound reduction index than the walls, and the exponential structure of Eq. (19) makes them able to undermine the acoustic performance of the façade, even if they have a relatively low surface. For instance, a basic low-performance double-glazing with R_w = 32 dB that occupies

15% of the overall façade area implies an overall R_w = 40 dB, whatever is the acoustic performance of the wall above R_w = 50 dB. With an average-performance window (R_w = 37 dB), such an asymptotical behaviour only occurs if the glazed surface is at least 40% of the façade.
Now, let us consider a common geometry for a room in a residential building, with a net floor surface S = 16 m^2, height H = 2.7 m, and a window measuring 2.1 m^2, that is to say around 20% of the overall façade area.
The e-PANEL applied to an existing wall made of uninsulated double-leaf of hollow bricks (e.g. wall ID 3, with R_w = 47-48 dB) can easily ensure R_w = 55-56 dB (even slightly more, depending on the thickness of the insulation to be applied in case of a wool-based material). If one assumes that windows with average performance (R_w = 37 dB) will be installed together with the e-PANEL, the proposed example would yield R'_w = 41.5 dB and $D_{2m,nt,w}$ = 42.5 dB.
This result is encouraging and allows to ensure compliance with law in those countries where the parameter $D_{2m,nt,w}$ is recalled by regulations (Italy, Portugal). In some countries (Turkey, France) the regulations apply to the weighted standardized level difference plus the spectrum adaptation term for traffic noise ($D_{2m,nt,w} + C_{tr}$). It is not easy to foresee the value of C_{tr}, as this can be determined only through on-site measurements: however, common practice suggests that in the worst cases this can reach C_{tr} = –7 dB or even C_{tr} = –9 dB, which implies ($D_{2m,nt,w} + C_{tr}$) ≈ 34-36 dB. This would allow compliance with law in Turkey and France, except for those areas where the outdoor noise level exceeds $L_{Aeq,day}$ = 65 dB.
In any case, improving this performance does not depend on the features of the e-PANEL itself. Indeed, as already highlighted, improving the sound reduction index of the wall well beyond 56 dB would ensure only marginal benefits. This means that in noisy urban contexts, where very high sound insulation levels are required to the facade, better performing windows are needed.
In order to get a wider perspective, Table 46 resumes the results of the above exercise for all wall structures proposed in Section 4.1.1, for an average-performing window (R_w = 37 dB) and a highly performing double-glazing window with stratified external glass (6-16-44.1, R_w = 40 dB).

Table 46. Expected performance of the most common wall structures after e-PANEL application (with 10-cm insulation)

Wall structure	Description	Initial sound reduction index	Façade sound insulation with e-PANEL	
			Average-performance window (R_w = 37 dB)	**High-performance window (R_w = 40 dB)**
	**ID 1** Solid brick wall with no insulation (thickness: 28 cm)	R_w = 52÷53 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB
	**ID 2** Solid brick wall with poor insulation (thickness: 32 cm)	R_w = 56÷57 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB
	**ID 3** Cavity wall with air gap and no insulation (thickness: 30 cm)	R_w = 47÷48 dB	R_w = 43.5 dB R'_w = 41.5 dB $D_{2m,nT,w}$ = 42.5 dB	R_w = 46.5 dB R'_w = 44.5 dB $D_{2m,nT,w}$ = 45.5 dB
	**ID 4** Uninsulated concrete wall (thickness: 18 cm)	R_w = 49÷50 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB
	**ID 5** Cavity wall with air gap and poor insulation (thickness: 30 cm)	R_w = 49÷50 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB
	**ID 6** Concrete wall with poor insulation (thickness: 24 cm)	R_w = 55÷56 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB
	**ID 7** Cavity wall with air gap and average insulation (thickness: 34 cm)	R_w = 51÷52 dB	R_w = 44 dB R'_w = 42 dB $D_{2m,nT,w}$ = 43 dB	R_w = 47 dB R'_w = 45 dB $D_{2m,nT,w}$ = 46 dB

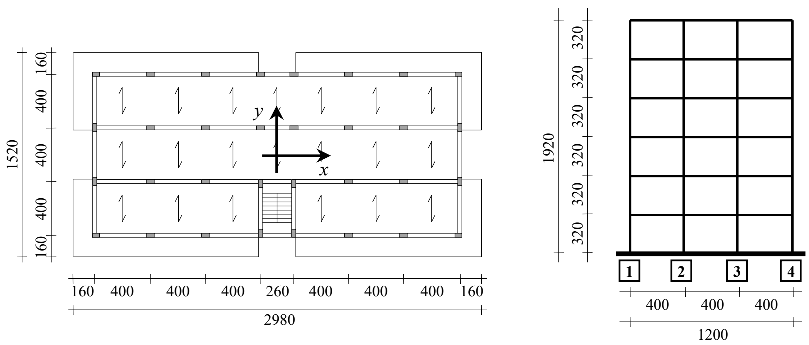
The results reported in Table 46 confirm that, for a given window performance, the overall façade performance keeps constant whatever is the wall structure, provided that this ensures $R_w > 48$ dB. The choice of the window is then a key element in the acoustic design of the e-PANEL renovation system, and must be attentively verified case-by-case in relation to the outdoor noise level and the local regulations. Similar conclusions apply to e-CLT: indeed, e-CLT is expected to ensure better sound insulation than e-PANEL, thanks to the higher mass of the CLT panels, but this section has already demonstrated that further improvement to the sound reduction index of the opaque components has no effect if windows are not improved.

4.4 Seismic performance

A case study RC frame is analysed to show the typical seismic deficiencies of old existing buildings with RC framed structure in seismic area. The building is assumed to be located in high seismicity region on soft soil (type C defined in EC8). In order to quantify the need for seismic upgrading, the seismic capacity of the frame is determined and compared to the minimum capacity required by EC8 [103] as implemented in Italy by means of the relevant National Annex [104]. The capacity of the frame is defined as the maximum PGA that can be sustained before the exceedance of the target limit state and it is evaluated by Incremental nonlinear Dynamic Analysis (IDA) carried out by means of the OpenSees program [105]. The minimum required capacity is the PGA stipulated in the Italian National Annex of EC8 for the verification of the target limit state depending on the seismicity of the region. The NC limit state is considered as target. For the verification of this limit state the minimum seismic excitation level is the one corresponding to the probability of exceedance of 5% in 50 years. Here, a PGA of 0.35 g is assumed for the seismic excitation level corresponding to the probability of exceedance of 10% in 50 years. Based on this assumption, the PGA corresponding to the probability of exceedance of 5% in 50 years is equal to 0.45 g according to the provisions of EC8-Part 1 [55].

4.4.1 A case study RC frame

The analysed frame belongs to a typical apartment building with RC framed structure designed before the enforcement of seismic regulations and is representative of the buildings belonging to this structural type constructed in Italy in the seventies. It is six-story high and its plan layout (Figure 18) is symmetric with respect to the *y*-axis. The inter-story height is equal to 3.2 m at all stories, while the span lengths of the beams are shown in Figure 18. The structure consists of four frames arranged along the x-direction and four frames arranged along the y-direction. Out of these latter frames, two are located at the two sides of the building and two are close to the staircase. The regulations in force during the seventies in Italy [106][107] are applied for design of beams and columns.



Storey	Columns		Beams
	1 and 4	2 and 3	
6th	30x30	30x30	30x60
5th	30x30	30x30	30x60
4th	30x30	30x30	30x60
3rd	35x30	30x40	30x60
2nd	40x30	30x50	30x60
1st	50x30	30x60	30x60

Figure 18. Features of the analysed RC frame: (a) Plan layout of the building, (b) geometrical scheme of the frame, (c) cross-sections of the frame members

The design internal forces of structural members are evaluated considering gravity loads only. Dead and live gravity loads are determined considering the nominal values given in [108]. The size of the cross-sections and the area of steel reinforcements of beams and columns are determined by the allowable stress method [107]. The minimum reinforcement ratio prescribed in [107] for the tension zone of beams is equal to 0.0015. Columns are designed to resist axial force only. Indeed, the design practice of the seventies neglected the bending moment. The design axial force of the column N is evaluated according to the tributary area concept.

Furthermore, the minimum requirements stipulated by the aforementioned regulations for the cross-section area and the steel reinforcement of columns are taken into account. In particular, the minimum required cross-section area of the column $A_{c,req}$ is calculated by the following relation:

$$A_{c,req} = \frac{N}{0.7 \cdot \bar{\sigma}_c \cdot (1 + n \rho_l)} \quad (20)$$

where $\bar{\sigma}_c$ is the allowable stress of concrete, n is the homogenization coefficient for steel rebars assumed equal to 10, and ρ_l is the ratio of the longitudinal rebar area A_s to $A_{c,req}$ assumed equal to the minimum value required by the code (0.006). The characteristic compressive cubic strength R_{ck} of concrete is assumed equal to 25 MPa (corresponding to cylinder strength f_{ck} equal to 20 MPa), while steel grade Feb38K with a characteristic yield stress f_{yk} = 375 MPa is used for reinforcement. The values of the allowable stresses are 8.5 MPa and 215 MPa for concrete and steel reinforcement, respectively. Furthermore, the area A_s of the longitudinal rebars of columns is not smaller than the minimum value

$$A_{s,min} = \max \begin{cases} 0.003\, A_c \\ 0.006\, A_{c,nec} \end{cases} \quad (21)$$

where A_c is the actual cross-section area of concrete of the column. Rebars with diameter of 8 mm are used for stirrups. Spacing of stirrups is 150 mm for columns and 200 mm for beams.
The building opposes to the earthquake lower lateral stiffness and strength in y-direction. Hence, the seismic response to earthquakes acting in this direction is analysed.

4.4.2 Seismic excitation

A suite of ten artificial ground motions, compatible with the EC8 elastic spectrum for soil type C and characterized by 5% damping ratio and reference peak ground acceleration for soil type A equal to 0.35 g, is adopted as reference seismic input. Each ground motion is characterized by a total duration of 30.5 s and is enveloped by a three branch compound function: the first branch is an exponential increasing function, the second one is a constant function (strong motion phase), and the third one is a function with exponential decay. The duration of the strong motion phase of the accelerogram is equal to 7.0 s. Details about the envelope intensity function and the procedure for the determination of the lengths of the parts of the compound function may be found in [109]. The SIMQKE computer program [110] is used to generate these ground motions. For each step of the IDA, this reference suite of ground motions is scaled by the ratio of the relevant PGA to the value 0.35 g. Totally, nine seismic excitation levels are considered to perform the IDA and the values of PGA range from 0.05 g to 0.45 g in step of 0.05 g.

Table 47. Characterization of materials for the dynamic analysis of the frames

Concrete	
Cylinder Compressive strength	29 MPa
Young's modulus	30279 MPa
Strain at maximum strength	2.0×10^{-3}
Ultimate strain	3.5×10^{-3}
Tensile strength in tension	Null
Rebars	
Yielding strength	375 MPa
Young's modulus	210000 MPa
Strain-hardening ratio	0.0049

4.4.3 Numerical model of the case study building

A two-dimensional numerical model with masses concentrated at the floor levels is used to evaluate the nonlinear response of the analysed structures. The floor mass is determined as a percentage of the total mass of the deck. It is assumed that the seismic force acting along y-direction is resisted by four frames (Figure 18) which are not identical. The outermost frames are stiffer than those close to the staircase and provide a larger contribution to sustain seismic force. Hence, the floor mass assigned to these frames is equal to 30% of the total one (103 t). In order to account for the P-Δ effects, a leaning column is included in the numerical model. The nominal dead loads plus quasi-permanent live loads are assigned as initial gravity loads in the analysis. The gravity load applied to the leaning column is equal to the weight of the numerical model minus that applied directly to the RC frame. A Rayleigh viscous damping is used and set at 5% for the first and the third mode of vibration. All the nodes of the same floor are constrained to have the same horizontal displacement, in order to simulate the rigid diaphragm effect due to the concrete deck.

A member-by-member modelling with beam with hinges elements is adopted for beams and columns. In particular, the "Beam With Hinges Element" implemented in OpenSees is used, and beams and columns of the RC frame are modelled as members constituted by an elastic element with plastic hinges at their ends. The length of the plastic hinge is equal to the depth of the cross-section. A fibre cross-section is assigned to each plastic hinge, where both concrete and steel components are considered. The concrete part of the cross-section is subdivided into fibres having 5 mm depth and width equal to the width of the cross-section. Single fibres enclosed in the cross-section are used to model rebars. The Mander constitutive law ("Concrete04" uniaxial material) is assigned to concrete fibres. An elasto-plastic with strain kinematic hardening constitutive law ("Steel01" uniaxial material) is assigned to steel fibres. The parameters used for materials are summarized in Table 47. These values are representative of the mean value properties of the existing materials that could be obtained from in-situ tests and are derived from the assumed characteristic values. The area, the moment of inertia of concrete cross-section and the Young's modulus of concrete are assigned to the elastic element. However, the Young's modulus is reduced by 0.5 and 0.8 with respect to the nominal value to account for the effect of cracking in concrete.

A "ZeroLength Element" is added at one end of each beam. This element connects the end of the beam to the corresponding node restrained by the rigid deck and is characterized by a large axial deformability. This expedient allows the beams to deform axially and avoids arising of axial force, which typically leads RC beams modelled by fibre elements to an artificial stiffening and strengthening [111]. Furthermore, large shear and flexural stiffnesses are assigned to the ZeroLength Element to transfer shear force and bending moment from the beam to the frame node.

4.4.4 Results of the numerical analyses

Since columns are generally the most vulnerable members of framed structures designed without considering seismic provisions, the seismic performance of the analysed frame is evaluated in terms of maximum chord rotation demand to capacity ratio θ/θ_u of columns. However, it is monitored also the maximum drift, which is a very effective Engineering Demand Parameter (EDP) for illustrating if the demand is widespread in the structure as desirable or not. The results are shown in Figure 19 for PGAs from 0.05 g to 0.25 g. Results for PGA larger than 0.25 g are not reported because the frame exceeds the NC limit state for PGA = 0.25 g.

For each of the nine considered seismic excitation levels, the storey drift angle (Δ/H, H being the inter-story height) of each story is determined for the 10 ground motions. Then, the average over the values of the 10 ground motions is calculated and the heightwise distribution of Δ/H is shown in Figure 19. The building suffers from drift concentration at the fourth story, which becomes more significant for increasing PGA. Furthermore, for large PGAs, some dynamic analyses terminated prematurely due to numerical instabilities, which can be identified with collapse in occurrence of the related accelerograms.

The chord rotation demand and capacity ratio θ/θ_u is determined at each time step of nonlinear dynamic analysis and their maximum ratio over the duration of the ground motion is evaluated. The average value of θ/θ_u over the ten accelerograms is determined for the two end cross-sections of all the columns of each story. Hence, the maximum ratio θ/θ_u is assumed as representative of the story and its heightwise distributions is shown in Figure 19. The frame attains the NC limit state (θ/θ_u equal to one) for a PGA larger than 0.15 g and smaller than 0.25 g. This PGA represents the capacity of the analysed frames, and is smaller than the minimum values stipulated in EC8 equal to 0.45 g for NC limit state. In conclusion, the analysed RC frame does not meet the minimum requirement of EC8 for NC limit state and needs to be upgraded.

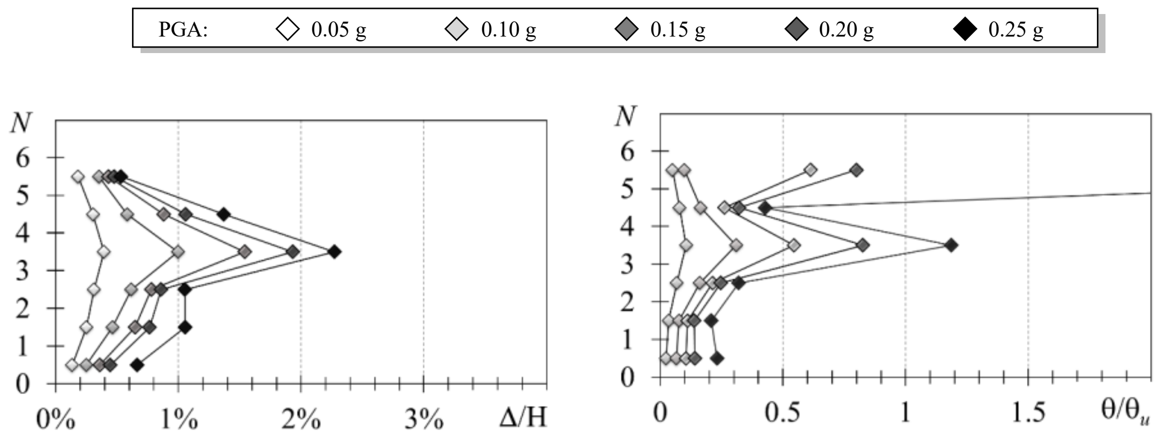


Figure 19. Height wise distribution of story drift angle of the frame (on the left) and chord rotation demand to capacity ratio of columns for NC limit state (on the right)

4.4.5 Expected seismic performance improvements

The deficiencies of the analysed RC frame are common to many existing buildings with RC framed structure. Stiffness and lateral strength are in most cases clearly smaller than those of buildings designed to resist seismic actions. Important aspects pointed out by precedent studies are:

- the main structural elements, columns and beams, necessary to sustain only vertical loads are usually disposed along a single direction, making the global structure particularly flexible and weak under horizontal actions acting along the orthogonal direction;
- the lack of correlation of the distribution of stiffness and strength along the height of the building, given by vertical loads design, to the one required for seismic actions makes really probable the development of a single-storey collapse mechanism, which reduces the capability of dissipating the input-energy of the seismic event, strongly penalising the non-linear response of the structure;
- the inelastic behaviour is worsened by the irregular distribution of plastic-rotation capacity along the height, which at the lower storeys is often smaller than at the upper storeys because of the larger mean stress due to vertical loads.

The application of CLT panels with friction dampers to the RC frames appears to be a promising technique for providing seismic resistance to existing buildings. The insertion of such elements provides an existing RC structure with both lateral stiffness, which reduces the damage in reinforced concrete members during medium intensity seismic events, and dissipating capability, thus preventing collapse during strong seismic events. Furthermore, stiffness and strength of the e-CLT may be defined, practically independently the one to the other, by choosing appropriate cross-section of CLT panels and size of the friction damper, which makes the design very flexible. The application of the e-EXOS to the building is also a suitable intervention to improve its seismic performance. Indeed, the exoskeleton increases lateral stiffness and strength of the building structure. In addition, the exoskeleton acts like a continuous beam pinned to the bottom and to the top of the building, thus avoiding the formation of the single-storey collapse mechanism, which is the main reason of the poor behaviour of existing buildings. Finally, also the exoskeleton can be equipped with dampers that further reduce the seismic response by dissipating part of the seismic input energy.

4.5 Safety performance

4.5.1 Fire reaction and fire resistance

As explained in Section 3.5.1, currently each EU member Country adopts regulations or guidance at national level to ensure specific fire performance of façades elements, and a European harmonised approach to the fire performance assessment and classification for façade systems is still missing. Therefore, the performance of the **e**-SAFE prefabricated components (e-PANEL and e-CLT) in terms of fire reaction and fire resistance should differ according to prescriptions adopted in each EU countries. For the real pilot building, the normative reference to design the e-CLT and e-PANEL components will be the Italian Technical Guidance on

"Fire safety requirements for facades (facings) on civil buildings", currently under update and transposition into Vertical Technical Rule (VTR) concerning "Civil buildings closures". Accordingly, the insulation and cladding materials of both e-SAFE prefabricated components will be properly selected to ensure high fire reaction performance in their final operating conditions. If required, special façade components acting as compartmentation elements and having high fire resistance and fire reaction performance will be also designed in order to prevent or delay the spread of fire along the building façade.

4.5.2 Impact resistance

As explained in Section 3.5.2, both the e-SAFE prefabricated components (e-PANEL and e-CLT) will be properly designed to ensure impact resistance requirement in order to accommodate different load conditions during their lifetime, without any risk of damage and ensuring high safety conditions for the occupants or those around the building. To this end, according to ETAG 007 [76] concerning timber building kits, satisfactory impact resistance performance for wall-functioning timber building kit can be achieved using well-known internal lining materials such as wood-based panel products and solid timber boards with suitable thickness and stud spacing. Specific impact resistance performance of these components will be defined in the design stage of the same.

4.5.3 Wind load resistance

As explained in Section 3.5.3, both the e-SAFE prefabricated components (e-PANEL and e-CLT) will be properly designed to resist to specific design wind pressure, which is generally calculated according to EN 1991-2-4 [77] or national regulations and is based on the building's exposure classification as well as the building's height, type and configuration. According to the European standard EN 14351-1 [78], also the windows integrated into the e-PANEL will have proper wind load resistance performance in order to resist to design wind pressure without any damages and functional impairment. Specifically, the minimum wind load resistance class of windows will depend on the design wind pressure. In Italy, where the real pilot building is located, the choice of the minimum windows performance characteristics based on design wind pressure is chosen according to the Italian Technical Standard UNI 11173 [112] (Table 48).

Table 48. Choice of the wind load resistance class for external double-glazed windows according to UNI 11173 [112]

Design wind pressure [Pa]	**Wind load class** **(According to EN 12210)**	**Wind load class of double-glazed windows combined with maximum deflection class C (According to EN 12210)**	**Wind load class of double-glazed windows combined with maximum deflection class B (According to EN 12210)**
		L* ≤ 1500mm	L* > 1500mm
p ≤ 400	1	1C	1B
400 < p ≤ 800	2	2C	2B
800 < p ≤ 1200	3	3C	3B
1200 < p ≤ 1600	4	4C	4B
1600 < p ≤ 2000	5	5C	5B

* Length of the most stresses windows element

4.6 Construction products quality performance

In general terms, quality is the compliance to requirements of the totality of characteristics of the building products and processes that bears on their ability to satisfy stated and implied needs. Stated needs are available in the form of specifications, conditions or bill of quantities; implied needs are not defined and sometimes not even expressed. The dimensions of products quality are performance, reliability, conformity to specifications/standards, durability, serviceability, aesthetics and perceived quality. All the dimensions will be addressed in a holistic approach to design.

The **e**-SAFE project aims at achieving high quality targets within the EU building sector context: in the project, it is important to make a distinction between single construction products and construction intended as the entire building after refurbishment. Single products and components will follow the rules of quality, but the final building as a whole entity will be able to meet the quality requirements.
There is a difference between quality assurance and quality control of a building product. The former is referred to all the actions taken to design and manufacture a safe and effective product by building quality controls into the product life cycle. Quality controls are test procedures used to verify that a product is safe and effective after manufacturing is done. Both of them are pursued in the **e**-SAFE project according to EU standards.
The quality of materials and components will be then evaluated in relation to the principles of circular economy and, specifically, according to three main aspects: products durability, adaptability and waste reduction.
Durability of products can be achieved encouraging a medium to long term focus on the design life of major building elements, as well as their associated maintenance and replacement cycles. Adaptability can be addressed extending the service life of the building as a whole, either by facilitating the continuation of the intended use or through possible future changes in use, with a focus on replacement and refurbishment. Finally, the goal of reducing waste and facilitating high-quality waste management of building elements, components and parts is obtained focusing on the potential for the reuse, following deconstruction. This includes efforts along the value chain to promote:

- the reuse or recycling of resources, (i.e. materials) in a way that most of the material's value is retained and recovered at the end of the building's life span;
- the component design and the use of different construction methods to influence the recovery for reuse or recycling to avoid down-cycling.

In terms of ecological impact, an LCA analysis, according to international standards, will be carried out in Task 3.3 to calculate the ecological impact of products. The following tools will be used for the analysis: Carbon Calculated Construction Calculator, Environment Agency Carbon Calculator for Construction, Footprinter, LCA in Sustainable Architecture (LISA), SimaPro, open LCA.
Not only Global Warming Potential (GWP), but other impacts might be included in the impact assessment of products, such as Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP) and Primary Energy Use.
Environmental Product Declarations (EPDs) are becoming a valuable source of information. However, with so many different products, it is important to understand the methodology behind an EPD, before starting any direct comparison. The use of EPDs in LCA analysis will be strongly considered in the future steps of the research project. Regarding the impact of CLT panels, which are a key factor in the **e**-SAFE project, there is much debate surrounding the carbon storage benefits of timber products: studies on carbon cycle and carbon storage are still developing; the inclusion of carbon storage benefits could result in negative or positive embodied carbon factors depending on the boundaries. Moreover, arguments are different for sustainably sourced timber and non-sustainably sourced timber. There is a risk of the embodied carbon coefficients being applied inappropriately: a superficial and inaccurate understanding would suggest that increasing the amount of timber will give a lower carbon footprint of the product, leading to inappropriate use of the material. On the other hand, the absence of carbon storage does not penalise timber products. Therefore, this issue will be analysed carefully in the ongoing research.
According to ICE methodology, the values of Embodied Energy for some timber products are reported in Table 49

Table 49. More and detailed data will be added in the following steps of the research.

Table 49. Embodied energy and carbon figures for various timber materials

Timber material	Embodied Energy ($MJ \cdot kg^{-1}$)	Embodied Carbon ($kgCO_2 \cdot kg^{-1}$)	Embodied Carbon (GHG) ($kgCO_{2e} \cdot kg^{-1}$)
General (high range for all timber products)	10	0.31 fos + 0.41 bio	
Glue laminated timber (including 4.9 $MJ \cdot kg^{-1}$ of bio energy)	12	0.42 fos + 0.45 bio	
Medium density fibreboard (MDF, not very accurate data including 3.8 $MJ \cdot kg^{-1}$ of bio energy)	11	0.39 fos + 0.35 bio	

Another important factor in embodied carbon and LCA studies for **e**-SAFE components is recycling of metallic components. When analysing a metallic product, there is a range of options to account for the benefit of recycling. Three fundamental methods are: recycled content approach, substitution method and 50:50 methods. The first method considers the benefit from using recycled material in full, but this leaves no room in the analysis for recyclability benefits. The second method is the opposite to the recycled metallic content approach, giving a full benefit to recyclability and leaving no room for consideration of the benefit of using recycled material. The third method falls in between the first two methods. Which option to use will be addressed further on in upcoming tasks.

5. Conclusions

The first part of this report presented the technological solutions implemented by **e-**SAFE for the energy refurbishment of existing buildings, making a distinction between the envelope solutions, such as e-PANEL and e-CLT, and the technical systems including reversible air-to-water heat pumps, heat storage tanks and renewable energy production from photovoltaic panels.
Then, the report introduced different options for structural reinforcement, ranging from CLT panels to metal exoskeletons connected to existing RC frames.
The following sections, instead, detailed the main thermal, energy, IEQ, acoustic, seismic, technological and safety requirements that must be satisfied, and the relevant EU regulation framework that **e-**SAFE must comply with. Finally, a preliminary analysis of the **e-**SAFE response to such requirements and regulations is given.
The main outcomes of this research activity are intended to inform the detailed design stage that will be carried out within Task 3.3 activities, and can be summarised as follows:

- The achievement of the main technological and safety requirements analysed in this Report have to guide the design stage of e-SAFE prefabricated components (e-CLT and e-PANEL), from the selection of suitable materials to the definition of the final configuration of these construction products. Specifically, e-SAFE prefabricated components must be designed and produced to ensure high safety performance in use, without risk of damage when subjected to different load conditions, as well as in case of fire, preventing or delaying its spread along the building envelope. The fire safety requirements have a key role, also taking into account the considerable number of wooden materials envisaged for those elements. Further details on this topic can be addressed in next reports, in view of the ongoing EU regulatory developments. The e-CLTs and e-PANELs must ensure also high durability and environmental quality performance. To this end, their tightness to rainwater and melting snow under normal climatic conditions is required. Furthermore, the quality of materials and components must be evaluated according to the principles of circular economy, i.e. products durability, adaptability and waste reduction.
- The technological and safety requirements reported are related to the single e-SAFE prefabricated components. Further technological measures and solutions will be investigated at building level after the design stage of these components to ensure the e-SAFE system high quality and safety performance during use.
- From the thermal point of view, both e-PANEL and e-CLT easily adapt to the U-value requirements set by EU countries by simply varying the insulating layer thickness. However, from the hygrometric point of view, the performance of e-PANEL is slightly worse than e-CLT because of the lower water vapour resistance that facilitates the water vapour motion towards the coldest points of the walls, thus eventually condensing. In cold climates, this may lead to an excessive amount of condensate that can eventually deteriorate the insulating material, especially if this is of organic nature. For these reasons, the use of a vapour screen/barrier on the internal/external face of the insulation might be necessary, along with the use of a waterproof breathable membrane to shelter the insulation material from wind driven. These aspects will be addressed in detail during the activities of Task 3.3.
- Both e-PANEL and e-CLT ensure high sound insulation level for the facades. However, the compliance with national regulations is strongly influenced by the properties of the glazed components: the choice of the window is then a key element in the acoustic design of e-PANEL and e-CLT, and must be attentively verified case-by-case in relation to the outdoor noise level and the local regulations.
- Experimental tests have to be conducted on the friction damper used in e-CLT. The tests will be devoted to define the shape of the damper that optimises its performance and to characterise its cyclic response. Experimental tests have also to be conducted on single-storey RC frames representative of old seismic deficient RC framed structure. These tests will be conducted on two specimens with and without e-CLT to characterise the seismic response of the structural systems and the interaction between RC frame and e-CLT. Proper numerical models will be developed based on the results of the tests.

- Effective design procedures to size the seismic retrofit interventions by e-CLT and e-EXOS have to be formulated. These design procedures will be different for the two structural systems to exploit their potentialities and features, which are different. The parameters ruling the design procedures will be calibrated based on the condition that a seismic deficient building upgraded by e-CLT or e-EXOS has to fulfil the target performance objectives related to the structural safety. The calibration of the design procedures will be done by a parametrical investigation performed by the numerical models developed in the previous point. The fulfilment of the target performance objectives will be checked according to the criteria resumed in Section 3.4.

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