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Towards High-Efficiency Buildings for Sustainable Energy Transition: Standardized Prefabricated Solutions for Roof Retrofitting

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Abstract: Enhancing energy efficiency in buildings plays a pivotal role in realizing the ambitious objective of achieving carbon neutrality by 2050, as outlined in the European Green Deal. Roofs represent the technical element most affected by energy phenomena related to heat transfer: in winter, roofing can lose up to 35% of heat, and the summer heat flux can even be higher. This paper provides a catalogue of optimized and sustainable solutions, with a specific focus on standardization and prefabrication principles, for enhancing the energy efficiency of the most prevalent types of roofs that characterize the national residential building heritage. The methodological approach that guided the research presented in this article was based on the identification and study of the most common roofings in the diverse national residential building heritage, followed by their classification according to their construction era. In the context of essential energy retrofitting of deteriorated residential building stock, 21 optimized standardized solutions have been identified. The outcome of performance evaluations of the proposed solutions allowed the implementation of a matrix that can be a valuable support for designers in selecting the most efficient precalculated and prefabricated solutions for the national residential building heritage based on energy performance and sustainability criteria.

Keywords: energy requalification; standardized sustainable efficiency solutions; existing building stock; building energy performance; cost analysis; multi-criteria analysis; sustainable building

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1. Introduction

In recent years, a growing interest has emerged in addressing energy efficiency as a pathway for carbon mitigation, constraining energy usage, and enhancing building energy performance to achieve sustainable buildings [1]. This focus has become a pivotal concern for both developing and developed countries in the twenty-first century, with energy efficiency standing as an integral, if not paramount, component of green and sustainable buildings [2]. Notably, the building sector ranks among the highest in energy consumption [3]. As such, increasing awareness of environmental constraints and available resources necessitates a renewed perspective on sustainable development [4]. Within this evolving paradigm, principles of energy efficiency and sustainability should guide all sectoral policies [5]. Given the close relationship between environmental issues and resource consumption, it is evident that the construction sector significantly impacts the utilization of non-renewable raw materials, land occupation, and energy consumption across the entire lifecycle of buildings—from material production to management and eventual decommissioning.

According to the European Commission, most of the European and national real estate stock is still outdated and inefficient, accounting for approximately 40% of the total energy consumption and 36% of energy-related greenhouse gas emissions [6,7]. Buildings are places where a significant amount of time is spent, and therefore, a renovated and more energy-efficient building stock could significantly contribute to combating climate change and minimizing its effects. In Europe, households consume 80% of the energy for heating, cooling, and domestic hot water. Thirty-five percent of the EU building stock is over 50 years old, and nearly 75% of buildings are considered energy inefficient. Moreover, merely 1% of buildings undergo renovation annually [8]. The need for decarbonization in the European construction sector is evident, requiring the development of innovative sustainable strategies, with the importance of interventions for the renovation of both public and private buildings underscored by data and confirmed by the European Green Deal [9]. This deal is an integral part of the European Commission's strategy for implementing the United Nations' Agenda 2030 and sustainable development goals, which is poised to become one of the primary key actions to pursue. The pivotal initiative for promoting energy efficiency identified in the European Green Deal is the Renovation Wave [10,11]. It is at the core of national programs for economic recovery, aiming to double the rate of building renovations by 2030. The Renovation Wave has identified three areas of interest: tackling energy poverty and buildings with the worst performance, improving public buildings and social infrastructure, and decarbonizing heating and cooling [12]. Such an initiative will not only achieve results in terms of environmental sustainability but also provide a substantial boost to the renovation sector. This sector is characterized by a significant number of local businesses, making it a crucial driver for the economic and employment revival of the entire construction industry.

In December 2021, the European Commission introduced a proposed amendment to the Energy Performance of Buildings Directive (EPBD) within the framework of the "fit for 55" legislative package. This proposed revision seeks to realize a minimum reduction of 55% in European Union greenhouse gas (GHG) emissions by 2030, consistent with the stipulations of the 2021 European Climate Law [13,14]. This revision of the EPBD establishes how the EU can achieve a zero-emission and fully decarbonized building stock by 2050. Specifically, it involves increasing the renovation rate for the least performing buildings in each EU member state. The European Commission's proposal includes a requirement, starting from 2030, for all new buildings in the EU to be zero-emission (by 2027 for all new public buildings). To ensure more harmonized standards among member states, minimum energy performance requirements will be set at the EU level. Residential buildings are expected to achieve Class E by 2030 and Class D by 2033.

At the national level, according to data provided by the 15th census of population and housing in 2011 by ISTAT, the overall national residential building stock amounts to 14,515,795 units, among which 12,187,698 are residential buildings or complexes (approximately 84%). As can be seen from the graph shown in Figure 1, over 70% of Italian buildings are over 45 years old, meaning that they predate the first national energy-saving regulation No. 373 of 1976 [15]. Over 25% of buildings constructed before this regulation exhibit annual consumption ranging from a minimum of 160 kWh/m^2 per year to over 220 kWh/m^2 per year [16]. The national real estate stock predominantly comprises buildings falling within energy classes F and G, accounting for 25% and 37.3%, respectively. These statistics are derived from the Energy Performance Certificate Information System (SIAPE) during the period 2016–2019, based on analyses conducted by the National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) [16].

It seems imperative to promote the conversion of existing buildings into high-performance energy structures through the implementation of diverse interventions. These interventions may include enhancements to the building envelope, such as roofs, walls, and transparent closures, as well as upgrades to lighting systems, thermal energy production and distribution systems, and the installation of renewable energy-based production systems [17]. It is known that the overall energy efficiency of a building is predominantly influenced by the effectiveness of its envelope, which serves as the delineation between the indoor and outdoor environments [18]. Specifically, half of a building's total energy consumption for general purposes is expended through its envelope [19]. Roofs represent the technical element most affected by energy phenomena related to heat transfer: in winter, a roof can lose up to 35% of heat, and the summer heat flux can even be higher [20] (these data are indicative as they are strongly influenced by geometric parameters, building stratifications and volumes, as well as climatic conditions).

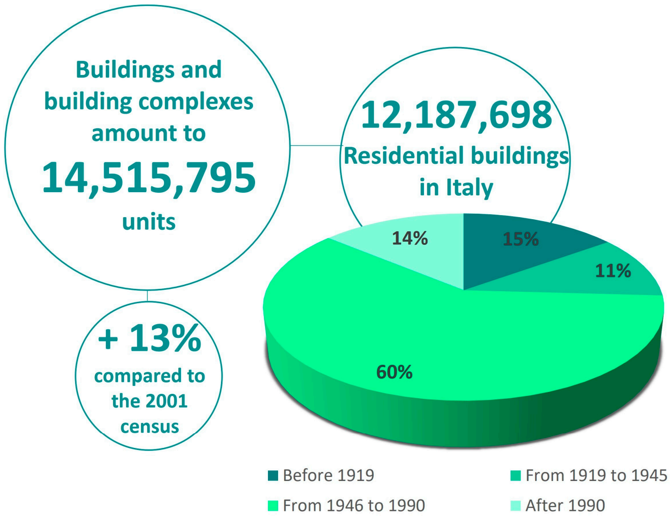


Figure 1. State of the art of the national residential building stock divided by construction era.

Numerous research efforts have focused on evaluating the energy consumption of the existing building stock, and on some factors that can contribute to its reduction, such as the thermal transmittance of both transparent and opaque surfaces, geographical location within specific climatic zones, construction period, orientation, and the characteristics of building elements. Zhenjun Ma et al. [21] asserted that "building retrofit with comprehensive energy simulation and economic analysis is an effective approach to identify the best retrofit solutions, but further research and investigation in this field are required to facilitate economically viable building retrofits." Lizana et al. [22] have stated that selecting the correct method and variables to identify the most effective retrofit solutions still represents a technical challenge. Paraschiv et al. [23] emphasized that a significant portion of the potential for energy savings and, consequently, a plausible reduction in greenhouse gas emissions, resides in the thermal renovation of existing buildings. This requires improvements in thermal efficiency to building energy consumptions. Other investigations typically solely focus on assessing the winter heating demand, concentrating on optimizing the steady-state thermal transmittance of building envelope components [24].

Numerous methodologies and tools have been developed to support the decision-making process towards a conscious and effective promotion of energy efficiency through the renovation of the building envelope such as "façade refurbishment toolbox (FRT) approach" [25], a bottom–up model for analyzing the Italian residential sector [26], IEE-TABULA Project (Typology Approach for Building Stock Energy Assessment) [27], and others [28–31]. Even the most recent Building Information Modeling (BIM) methodology supports energy efficiency enhancement processes. Alhammad et al. [32] asserted that "the integration of Building Information Modeling (BIM) with Building Energy Modeling (BEM) provides an innovative opportunity to leverage the full potential of BIM for optimizing the energy consumption of existing high-energy-efficient Building Automation Systems". However, there are still significant limitations and challenges associated with this method, despite the promised advantages. For instance, transitioning from BIM to BEM through the IFC data model results in the loss of numerous details, such as building envelope stratifications [33–35]. Additionally, there are methods and approaches based on digital-twin technology aimed at developing an intelligent optimization and automation system for energy management, ranging from building scale to neighborhood scale. This is achieved through the use of a three-dimensional data model integrated with Internet of Things (IoT), artificial intelligence (AI), and machine learning [36]. This methodology requires advanced computer skills and significant financial investment for the purchase and installation of sensors. Therefore, various innovative simulation tools are accessible for the energy modeling of new constructions and can also be applied to simulate existing buildings. However, many of them require the user to possess a profound technical understanding of the construction system, the thermal properties of materials, and retrofitting options available on the market, along with their associated costs [37].

These tools do not incorporate standardized insulation solutions, primarily prefabricated, and furthermore, they do not provide an estimate of the costs associated with energy efficiency interventions. It is crucial to also note that these renovation research projects do not encompass an assessment of the environmental sustainability associated with the proposed energy efficiency interventions. In summary, the literature review uncovered that most methodologies and tools associated with building energy efficiency lack the incorporation of verification processes for the mandated energy class upgrades under the new European regulations [38]. It is therefore evidently important that new studies and tools are aimed at promoting and supporting energy efficiency interventions in the building stock to achieve ambitious regulatory goals.

Hence, the final aim of this paper is to improve the energy efficiency of the nation's residential building inventory, emphasizing the construction or the renovation of high-efficiency buildings in accordance with upcoming energy transition regulations. This objective is pursued through the development of a standardized catalogue of optimized building and the implementation of retrofit systems applicable to building roofs. The authors of this research are driven by the aim of developing a methodology and a tool that allow for the identification and promotion of sustainable solutions guiding designers in implementing tailor-made energy renovation interventions, capable of adapting to the different scenarios within the national residential building landscape. The energy efficiency solutions are characterized by significant prefabrication and recycled content, aligning with the prevailing minimum environmental criteria (CAM) [39,40].

The proposed methodology was developed by CITERA, the research center of Sapienza University of Rome, as part of the "Research of the Electricity System" program with ENEA and the Ministry of Economic Development concerning "Solutions and tools for the energy efficiency improvement of buildings on a territorial scale".

2. Materials and Methods

This research aims to empower architects, engineers, and planners in optimizing energy efficiency interventions within residential buildings. The professionals will be equipped with a methodology to calculate insulation scenarios and determine optimal thicknesses for different technological solutions, further promoting energy efficiency. This guidance will steer them towards more efficient, prefabricated, and sustainable standardized solutions, contributing to overall energy efficiency improvements. Economic assessments will enable these professionals to evaluate the feasibility of implementing these solutions in the context of energy efficiency. Moreover, architects, engineers, and planners will benefit from an optimized technological solutions diagram, tailored to climatic, geometric, and technical parameters, aiding in informed decision-making and supporting energy efficiency initiatives. With a focus on prefabrication criteria, they will have clear guidance in selecting suitable solutions for energy efficiency interventions. Performance data compiled into accessible sheets will facilitate them in identifying the most suitable options based on climatic zones, ultimately contributing to enhanced energy efficiency outcomes. This comprehensive approach will empower designers to select effective technological solutions tailored to construction era, building type, and climatic zone, thereby promoting energy efficiency across residential buildings in both winter and summer seasons. This is achieved through the development of a catalogue of standard construction configurations to define sustainable retrofit systems applicable to upper closures.

A schematic of the methodology devised to derive optimized standardized solutions for existing building roofs is depicted in Figure 2.

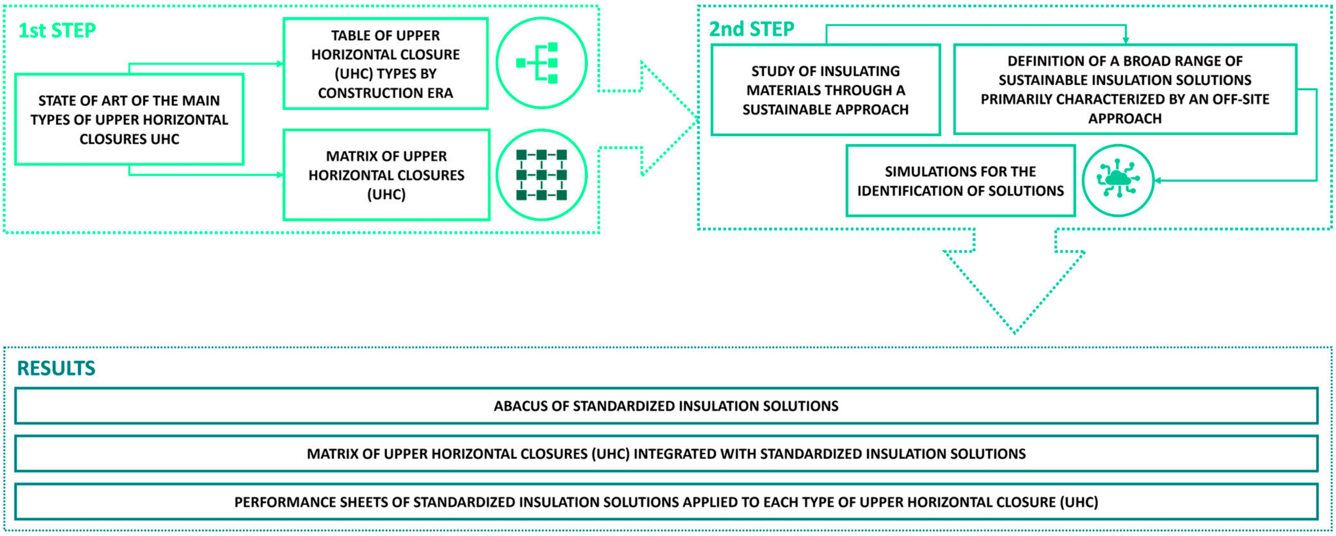


Figure 2. Schematic of the research methodology.

2.1. State of the Art of the Main Types of Upper Horizontal Closures

The subject of this paper is roofing, namely the classes of technical elements that horizontally separate the interior of the building from the exterior. They bear natural loads related to atmospheric agents (such as wind, snow, hail, rain) and those due to the passage of people, animals, and objects. The methodological approach guiding this research involved identifying and studying the most common upper horizontal closures (UHC) in the diverse national residential building stock, classifying them by construction era. The evolution of building envelope typologies in different construction era classes has depended on changes in construction techniques, the materials used, the coupling of building components, and the insulation level. These changes primarily affect the selected insulating materials, the thicknesses and the thermal transmittance values, which constitute essential parameters for selecting the most representative building envelope typologies.

This study identified prevalent construction types and those likely to undergo energy retrofit interventions, predating energy efficiency regulations. The selection of the most representative stratifications and construction era classes for the development of the following abacus was based on the Technical Report elaborated by CTI UNI/TR 11552:2014, which lists all the elements of the building envelope closures, including flat and sloped roofs.

The various types of roof coverings that characterize the national residential building heritage have been classified based on slope, type of resistant layer, accessibility, and construction era. Based on the slope, the following were identified:

- 14 sloped roofs;
- 16 flat roofs.

According to the type of resistant layer, the following were identified:

- 6 roofs with a wooden structure;
- 24 roofs made of reinforced concrete.

Based on the level of accessibility, the following were identified:

- 8 accessible roofs;
- 22 inaccessible roofs.

The construction era classes were identified in relation to specific historical events and the enactment of energy-related regulations that influenced building types and construction techniques, as follows:

- Up to 1950;
- From 1930 to 1975;
- From 1976 to 1990;
- From 1991 to 2005;
- Since 2006.

Figure 3 shows the number of roofs identified and presented in the matrix based on the construction era class.

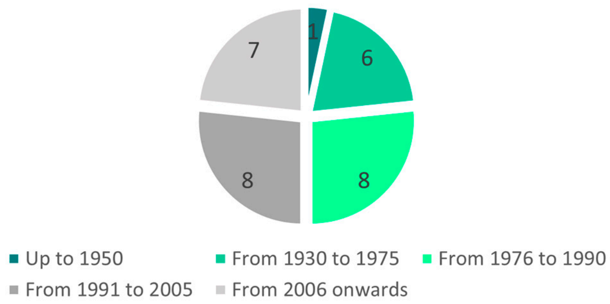


Figure 3. Number of roof types by construction era classes.

Table 1 provides a summary overview of upper horizontal closures (brief description and nomenclature) categorized by construction era class, further explored in detail within Supplement S1, crucial for understanding the evolution of construction systems that characterize the national residential building heritage.

Table 1. Classification of upper horizontal closures by construction era class.

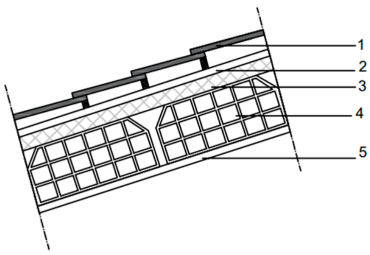
Construction Era Class	Roof Typology
Up to 1950	A pitched roof with a wooden structure and decking (UHC.01)
From 1930 to 1975	Latero-cement pitch roof (UHC.05–UHC.05.1) A non-walkable flat latero-cement roof (UHC.09–UHC.09.1–UHC.09.2–UHC.09.3)
From 1976 to 1990	A pitched roof with a wooden structure and decking, low level of insulation (UHC.02–UHC.02.1) A pitched roof with brick tiles, low level of insulation (UHC.06–UHC.06.1) A non-walkable latero-cement flat roof, low level of insulation (UHC.10–UHC.10.1–UHC.10.2–UHC.10.3)
From 1991 to 2005	A pitched roof with a wooden structure and decking, medium level of insulation (UHC.03–UHC.03.1) A pitched roof with brick tiles, medium level of insulation (UHC.07–UHC.07.1) Non-walkable latero-cement flat roof—medium level of insulation (UHC.11–UHC.11.1–UHC.11.2–UHC.11.3)
Since 2006	A pitched roof with a wooden structure and decking, high level of insulation (UHC.04) A pitched roof with brick tiles, high level of insulation (UHC.08–UHC.08.1) Non-walkable latero-cement flat roof—high level of insulation (UHC.12–UHC.12.1–UHC.12.2–UHC.12.3)

The table below (Table 2) provides an extract from the abacus of various types of upper horizontal closures, including the following information:

- Roof coding;
- Designation;
- An image with highlighted and numbered components;
- The period during which it was most prevalent;
- Description of each numbered component;

- Thickness of each numbered component;
- Energetic performance parameter—steady-state and periodic thermal transmittance.

Table 2. Extract from the abacus of existing upper horizontal closures.

UHC.05	Latero-Cement Pitch Roof
	Used from 1930 to 1975 Stratigraphy: 1. Roof tiles/waterproofing element: 1.5 cm 2. Cement mortar: 2 cm 3. Reinforced concrete: 4 cm 4. Latero—cement floor/supporting element: 16 cm 5. Internal plaster: 2 cm U = 1.82 W/m^{2}K YIE = 1.03 W/m^{2}K

As mentioned above, the entire abacus of existing upper horizontal closures has been documented in Supplement S1 through summary tables for each closure.

2.2. Study of Insulating Materials for the Redevelopment of Existing Upper Closure Types

The incorporation of an insulating layer is essential to achieve the thermal transmittance values required by current regulations, ensuring a reduction in heat losses and, consequently, energy consumption. A properly insulated roof allows for the elimination of surface condensation phenomena on the intrados of the technical element, the containment of thermal losses, and the maintenance of comfortable conditions in spaces beneath the upper closure in both summer and winter. Building energy efficiency regulations emphasize the performance attributes of thermal insulation materials, aligning with principles of the circular economy [41]. This has led to the introduction of various high-performance materials to the market. To make an informed and critical choice from the extensive range of insulation materials on the market, which vary in performance, type, and origin, as well as in application and production methods, it is necessary to conduct a comparison of the characteristics of each material [42]. The comparison of insulation materials was carried out to identify the most effective types, particularly from an energy and environmental perspective. To facilitate this comparison, several parameters were selected, not only related to winter and summer insulation capabilities but also considering the environmental impact, usage type, and cost [25]. In particular, in relation to performance indicators, the following parameters were chosen: thermal conductivity (λ), density (ρ), specific heat (c), thermal diffusivity (α), and water vapor diffusion resistance factor (μ) (Figure 4). To estimate the environmental impact, the following aspects have been analyzed: the origin of the raw material (natural organic insulators, synthetic organics, synthetic inorganics), the amount of energy required in the insulation's production phase, linked to the Potential Environmental Impact (PEI) value, expressed in MJ/kg and the possibility of recycling the material at the end of its life. Aspects related to usage have been further investigated since insulators present heterogeneous characteristics regarding both potential use and the format in which they are produced. These indications have been developed based on specific insulator characteristics, such as impact resistance, compactness, or weight. It was deemed important to conduct an economic assessment of insulating materials based on the DEI 2023 price list, as the cost per square meter is considered a significant selection parameter.

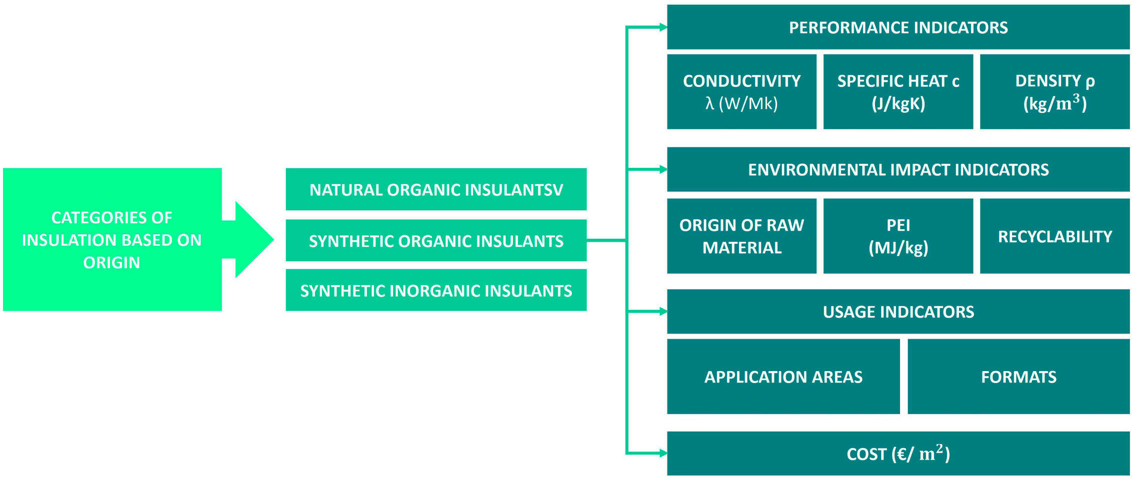


Figure 4. Comparison parameters for insulation materials.

Based on the prices identified in the DEI 2023 price list and through market research, four cost categories were determined:

- Low < 30 EUR/m^2;
- Medium > 30 and ≤70 EUR/m^2;
- Medium-high > 70 and ≤100 EUR/m^2;
- High > 100 EUR /m^2.

To express a comparative evaluation to some characteristic parameters (thermal conductivity, density, specific heat, PEI) of the main selected insulating materials (natural organic, synthetic organic, synthetic inorganic materials), radial diagrams were used. To facilitate the comparison among insulation materials, ranges have been defined for each indicator based on the performance values representative of all insulating materials (Table 3).

Table 3. Range of indicators for insulation materials comparison.

	Insulation Material Indicators			
	Conductivity W/m²K	**Density Kg/m³**	**Specific Heat J/kgK**	**PEI MJ/kg**
1	$\lambda \leq 0.015$	$\rho > 200$	$c \geq 2000$	$PEI \leq 10$
2	$0.015 < \lambda \leq 0.030$	$150 < \rho \leq 200$	$1700 \leq c < 2000$	$10 < PEI \leq 30$
3	$0.030 < \lambda \leq 0.040$	$50 < \rho \leq 150$	$1300 \leq c < 1700$	$30 < PEI \leq 60$
4	$0.040 < \lambda \leq 0.050$	$20 < \rho \leq 50$	$1000 \leq c < 1300$	$60 < PEI \leq 100$
5	$\lambda > 0.050$	$\rho \leq 20$	$c < 1000$	$PEI > 100$

At the center of the radar, the highest value is assigned, and the values decrease towards the periphery on a scale from 5 to 1, where 1 corresponds to the best performance: the further away from the center, the more relevant the performance is, positively speaking. Each insulation material is represented by a colored trace that allows for the evaluation of similarities and differences in performance; the larger the area delimited by the trace, the better the performance of the insulating material. The comparison graphs clearly show the following:

- Among natural organic insulators, wood fiber insulation performs better across most indicators, particularly in terms of thermal conductivity (Figure 5);
- Among synthetic organic insulators, rigid expanded polyurethane exhibits better performance, especially in terms of thermal conductivity (Figure 6);
- Among synthetic inorganic insulators, aerogel and rock wool demonstrate superior performance, especially in terms of thermal conductivity and density (Figure 7).

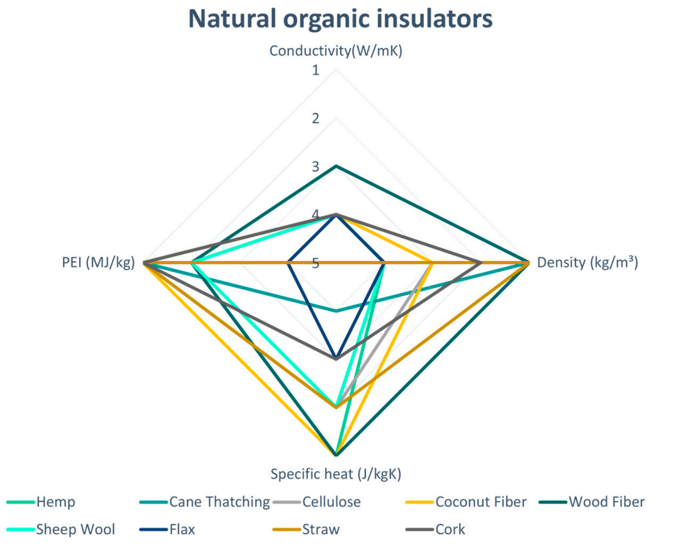


Figure 5. Comparison of natural organic insulation materials.

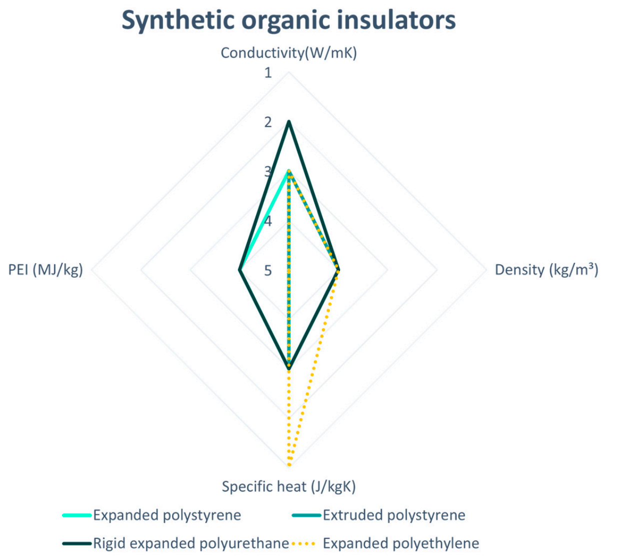


Figure 6. Comparison of synthetic organic insulation materials.

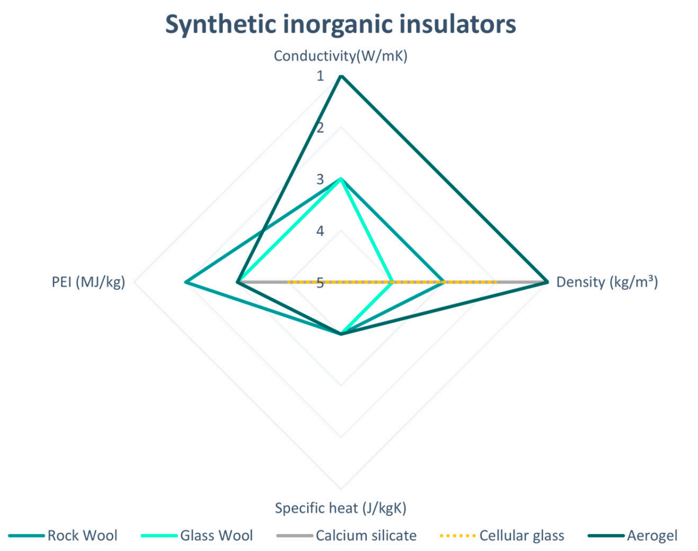


Figure 7. Comparison of synthetic inorganic insulation materials.

The Supplement S2 illustrates the entire process of selecting insulating materials for use in opaque horizontal closure solutions for energy efficiency.

2.3. Definition of a Broad Range of Sustainable Insulation Solutions Primarily Characterized by an Off-Site Approach

The insulation of the roof is a crucial aspect in the energy efficiency enhancement of existing building stock [43]. Insulation solutions for the roofs of existing residential buildings can be applied either on the external side (extrados) or on the internal side (intrados), or on the top floor just beneath the roof. The latter solution was not investigated in the present study. The solutions vary based on the slope of the roof and, consequently, the level of accessibility. In general, three main functional models are distinguished based on the placement of the insulation in relation to the waterproofing layer:

- Warm roof insulation, where the insulation material is positioned below the waterproofing layer;
- Cold (or inverted) roof insulation, where the insulation material is positioned above the waterproofing layer;
- Insulated and ventilated roof, a type of building covering that incorporates an air space between the roof surface and the underlying insulation layer.

To identify insulation solutions for the most common national upper closures, a study of products available on the market was carried out based on the previously described comparison parameters. With the aim of promoting environmental sustainability in the construction sector and minimizing impacts during construction, reducing the time for the implementation of redevelopment interventions was considered. The installation methods of each solution were evaluated, favoring mostly pre-assembled construction systems that significantly reduce execution times and related environmental impacts. By selecting mostly prefabricated technological solutions, the following were identified:

- 7 solutions applicable to non-ventilated or micro-ventilated roofs;
- 8 solutions for insulated and ventilated roofs;
- 4 solutions applicable to the intrados.

The most commonly used insulating materials for thermal insulation of horizontal closures are as follows: expanded polyisocyanurate foam, expanded polystyrene (EPS) with graphite (Neopor), wood fiber, blonde cork, closed-cell polyurethane foam, rock wool, aerogel, and rigid closed-cell polyisocyanurate foam (Figure 8). The identified solutions were studied and compared with a performance, environmental sustainability and economic perspective. Each identified solution has been associated with an acronym accompanied by a progressive number:

- IE—insulation on the extrados;
- VEI—ventilated external insulation;
- II—insulation on the intrados.

To compare the various identified solutions and identify the most efficient ones, the following parameters were taken into consideration:

- From an energy performance perspective, thermal conductivity was primarily assessed;
- From an environmental standpoint, PEI and the percentage of prefabrication were considered;
- From an economic perspective, the cost range and applicability to the main types of roofing existing nationally were evaluated.

Table 4 presents the legend of the comparison parameters used to select the most efficient insulation solutions in various aspects. The colors indicate the ranges identified for each parameter: green represents the best values, ochre-yellow represents average values, and red indicates the least performing values.

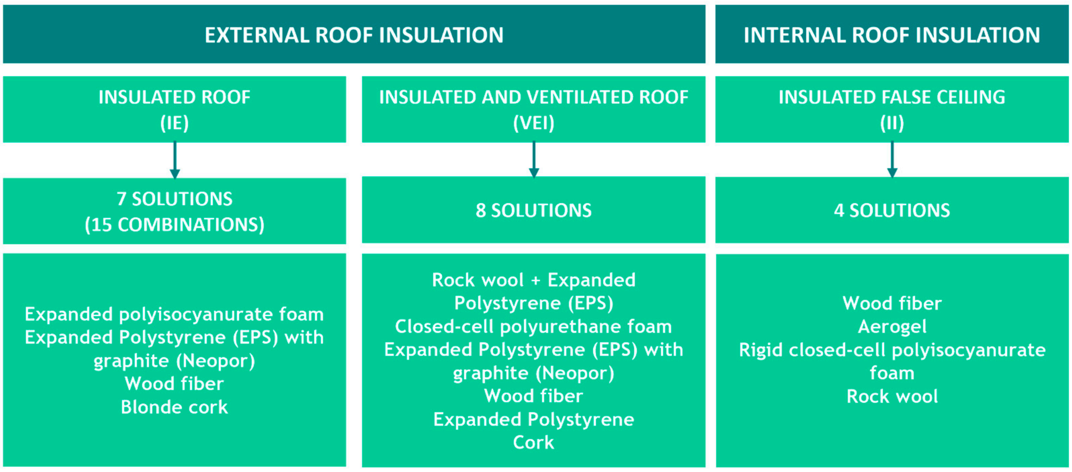


Figure 8. Prefabricated insulation solutions available on the market.

Table 4. Comparison parameters for insulation solutions.

Cost range (EUR $/m^2$)	≤100.00	>100.00 and ≤200.00	>200.00
Conductivity (W/m^2K)	≤0.025	>0.025 and ≤0.040	>0.040
PEI (MJ/kg)	≤30	>30 and ≤60	>60
Prefabrication (%)	>70	>30 and ≤70	≤30
Applicability (n. of roofs)	>20	>10 and ≤20	≤10

Note: The colors indicate the ranges identified for each parameter: green represents the best values, ochre-yellow represents average values, and red indicates the least performing values.

The following images (Figures 9–11) depict the comparisons made among the various insulation solutions identified in the market. The selected solutions are highlighted in green.

SOLUTIONS		IE01	IE01.a	IE01.b	IE01.PAV	IE02	IE02.a	IE02.b	IE02.bPAV	IE03	IE04
INSULATION thickness		Polyisocyanurate foam				Polyisocyanurate foam				Rigid expanded polyurethane	Neopor
6 mm	m²										
10 mm	m²										
20 mm	m²										
30 mm	m²									98.15 €	
40 mm	m²					139.16 €	71.59 €		241.27 €		
50 mm	m²									103.09 €	
60 mm	m²					145.63 €	78.06 €	115.10 €	247.74 €	105.57 €	
80 mm	m²	155.45 €	87.88 €	124.92 €	257.56 €	155.00 €	87.43 €	124.47 €	257.11 €	110.51 €	83.88 €
100 mm	m²	**163.52 €**	**95.95 €**	**132.99 €**	**265.63 €**	163.52 €	95.95 €	132.99 €	265.63 €	115.45 €	92.69 €
120 mm	m²	172.74 €	105.17 €	142.21 €	274.85 €	168.27 €	100.70 €	137.74 €	270.38 €		101.08 €
140 mm	m²										105.85 €
160 mm	m²										
PEI	MJ/kg	101				101				90	98.5
Thermal conductivity	W/mK	0.026				0.023				0.026	0.03
Prefabrication	%	75%				75%				100%	100%
Applicable to roofs	n.	30				30				14	14

SOLUTIONS		IE05	IE05.a	IE05.b	IE05.PAV	IE06	IE06.a	IE06.b	IE06.PAV	IE07
INSULATION thickness		Wood fiber				Cork				Extruded Polystyrene
6 mm	m²									
10 mm	m²									
20 mm	m²									
30 mm	m²									
40 mm	m²					161.48 €	123.14 €	119.57 €	292.83 €	
50 mm	m²									
60 mm	m²	144.52 €	107.32 €	103.74 €	277.00 €	182.62 €	142.88 €	139.30 €	312.56 €	
80 mm	m²	152.71 €	114.96 €	111.39 €	284.65 €	204.23 €	163.05 €	159.48 €	332.74 €	180.33 €
100 mm	m²	161.35 €	123.02 €	119.45 €	292.71 €	225.85 €	183.22 €	179.65 €	352.91 €	198.82 €
120 mm	m²	169.93 €	131.03 €	127.46 €	300.72 €	247.46 €	203.39 €	199.82 €	373.08 €	217.31 €
140 mm	m²	178.60 €	139.13 €	135.56 €	308.82 €					235.79 €
160 mm	m²	187.28 €	147.23 €	143.65 €	316.91 €					254.28 €
PEI	MJ/kg	12.7				6.4				94
Thermal conductivity	W/mK	0.038				0.041				0.035-0.037
Prefabrication	%	40%				40%				50%
Applicable to roofs	n.	30				30				6

Figure 9. Comparison of selection parameters for unventilated or micro-ventilated roof insulation solutions. (The colors indicate the ranges identified for each parameter: green represents the best values, ochre-yellow represents average values, and red indicates the least performing values).

SOLUTIONS		VEI01	VEI02	VEI03	VEI04	VEI05	VEI06	VEI07	VEI08
INSULATION thickness		Rock wool + Expanded extruded polystyrene foam	Rigid closed-cell polyurethane foam	Neopor	Wood fiber	Neopor	Expanded extruded polystyrene foam	Expanded extruded polystyrene foam with graphite	Cork
60 mm	m²	178.55 €	134.14 €	155.41 €	145.19 €		122.64 €		182.46 €
80 mm	m²	192.68 €	143.90 €	160.44 €	159.05 €	148.29 €	130.24 €	105.88 €	205.72 €
100 mm	m²	204.88 €	153.15 €	165.47 €	173.29 €	156.15 €	139.04 €	114.69 €	228.85 €
120 mm	m²		161.68 €	170.50 €	178.08 €	164.01 €	146.54 €	123.08 €	252.10 €
140 mm	m²			175.53 €	190.87 €	171.87 €	154.04 €	127.85 €	
160 mm	m²				203.60 €	179.73 €		136.67 €	
180 mm	m²				216.32 €				
PEI	MJ/kg	22.12 / 93.6	92	98.5	12.7	98.5	93.6	98.5	6.4
Thermal conductivity	W/mK	0.038 / 0.034	0.022	0.03	0.042	0.03	0.033	0.031	0.0375
Prefabrication	%	50%	75%	75%	40%	40%	40%	75%	40%
Applicable to roofs	n.	14	14	14	14	14	14	14	14

Figure 10. Comparison of selection parameters for ventilated roof insulation solutions. (The colors indicate the ranges identified for each parameter: green represents the best values, ochre-yellow represents average values, and red indicates the least performing values).

SOLUTIONS		II01	II02	II03	II04
INSULATION thickness		Wood fiber	Aerogel	Polyiso foam	Rock wool
6 mm	m²		144.34 €		
10 mm	m²		176.58 €		
20 mm	m²		301.06 €		
30 mm	m²		424.96 €	60.02 €	
40 mm	m²	58.66 €	549.29 €	63.68 €	
50 mm	m²		673.91 €	67.34 €	61.40 €
60 mm	m²	65.08 €	797.66 €	71.00 €	65.45 €
80 mm	m²	71.50 €		78.32 €	73.55 €
100 mm	m²			85.64 €	81.65 €
120 mm	m²			92.96 €	89.75 €
140 mm	m²			100.28 €	
160 mm	m²				
PEI	MJ/kg	12.7	35.5	101	22.12
Thermal conductivity	W/mK	0.037	0.015	0.022	0.035
Prefabrication	%	70%	70%	70%	70%
Applicable to roofs	n.	30	30	30	30

Figure 11. Comparison of selection parameters for internal roof insulation solutions. (The colors indicate the ranges identified for each parameter: green represents the best values, ochre-yellow represents average values, and red indicates the least performing values).

Verification of Sustainability through Minimum Environmental Criteria: Disassembly and Recovered or Recycled Material

The prevailing national legislation, encompassing the 'Decreto Rilancio' (Relaunch Decree), offers valuable guidance for securing tax deductions associated with specific energy requalification interventions. It stipulates that the insulating materials employed must adhere to minimum environmental criteria, aimed at identifying the optimal solution from an environmental standpoint across the life cycle, considering market availability. To meet the minimum environmental criteria (CAM), with the perspective of promoting "environmentally preferable" technologies and products, common criteria applicable to all building components were assessed. These include the percentage of disassembly

(Criterion 2.4.14 Disassembly and end-of-life) and the percentage of recovered or recycled material (2.5_Technical specifications for construction products).

Each material may contribute with varying impacts within the framework of current regulations, respecting the specified percentages. At these percentages, each material may contribute with varying impacts in accordance with current regulations. Both in the minimum environmental criteria (CAM) and in the economic assessment, for pitched roofs with a brick sealing layer, a minimum recovery of 70% of existing tiles was considered. In the case of flat roofs with a gravel protective layer for the waterproofing membrane, a minimum recovery of 80% of existing pebbles was considered.

Data regarding the remaining materials were derived from product environmental declarations and literature. Below, there is an extract from the calculations performed to determine the quantity of disassembled material and recycled/recovered material for each proposed insulation solution, aiming to assist designers in preparing the CAM report (Figure 12).

2.4.14_End-of-life disassembly
At least 70% by weight of the building components and prefabricated elements used in the project, excluding the systems, should be capable of end-of-life disassembly or selective demolition (deconstruction) for subsequent preparation for reuse, recycling, or other recovery operations

2.5_Technical specifications for construction products
Percentage value of recycled material or recovered material or by-products content

						Criterio 2.4.14		**Criterio 2.5**	
Material	**Surface (m²)**	**Thickness (m)**	**Volume (m³)**	**Density (kg/m³)**	**Weight (kg)**	**Disassemblyability (%)**	**Disassemblyability (kg)**	**Minimum value of recycled material or recovered material or by-products (%)**	**Minimum value of recycled material or recovered material or by-products (kg)**
IE.01.a									
Vapor barrier	1	0.0005	0.0005	289	0.1445	100.00%	0.1445	20.00%	0.0289
Rigid expanded Polyurethane insulation PIR.GI.	1	0.04	0.04	34	1.36	100.00%	1.36	5.00%	0.068
Bituminous felt cardboard	1	0.001	0.001	1100	1.1	100.00%	1.1	5.00%	0.055
Polymer-modified bitumen membrane	1	0.003	0.003	1200	3.6	0.00%	0	5.00%	0.18
Elevated point supports for canal tiles, using spacer feet made of UV-stabilized copolymer polypropylene	1	0.05			0.88	100.00%	0.88	20.00%	0.176
Clay roof tiles	1	0.015	0.015	1800	27	100.00%	27	70.00%	18.9
						% Disassemblyability assessed on the total of the insulation solution elements	**Total weight of disassemblable materials (kg)**	**Minimum percentage of recovered or recycled material assessed on the total of all materials used (%)**	**Total weight of recovered or recycled material assessed on the total of all materials used (kg)**
				Total weight per m²	**34.0845**	**89.44**	**30.48**	**56.94**	**19.41**

Figure 12. Verification of CAM for unventilated or micro-ventilated extrados insulation solutions—IE.

2.4. Simulation for the Identification of Solutions

The selected insulation solutions have been applied to the types of roofing found in the Abacus of existing upper horizontal closures, which characterize the residential building heritage.

To identify the thickness of the insulation material for each proposed technological solution, simulations were performed using certified BIM energy software (TerMus-BIM v.52.00h (x64). An excerpt of the energy simulations conducted using this software is provided in Figure 13.

This allowed the verification of periodic and steady-state thermal transmittance values to identify applicable solutions for each roofing type and climatic zone.

The limit values for steady-state thermal transmittance (Table 5) were derived from the 6 August 2020 decree, "Technical Requirements for Accessing Tax Deductions for the Energy Requalification of Buildings—so-called Ecobonus" (Official Gazette General Series no. 246 of 5 October 2020) Attachment E—Requirements for Thermal Insulation Interventions [44] Table 1—Maximum Allowed Thermal Transmittance Values for Accessing Deductions.

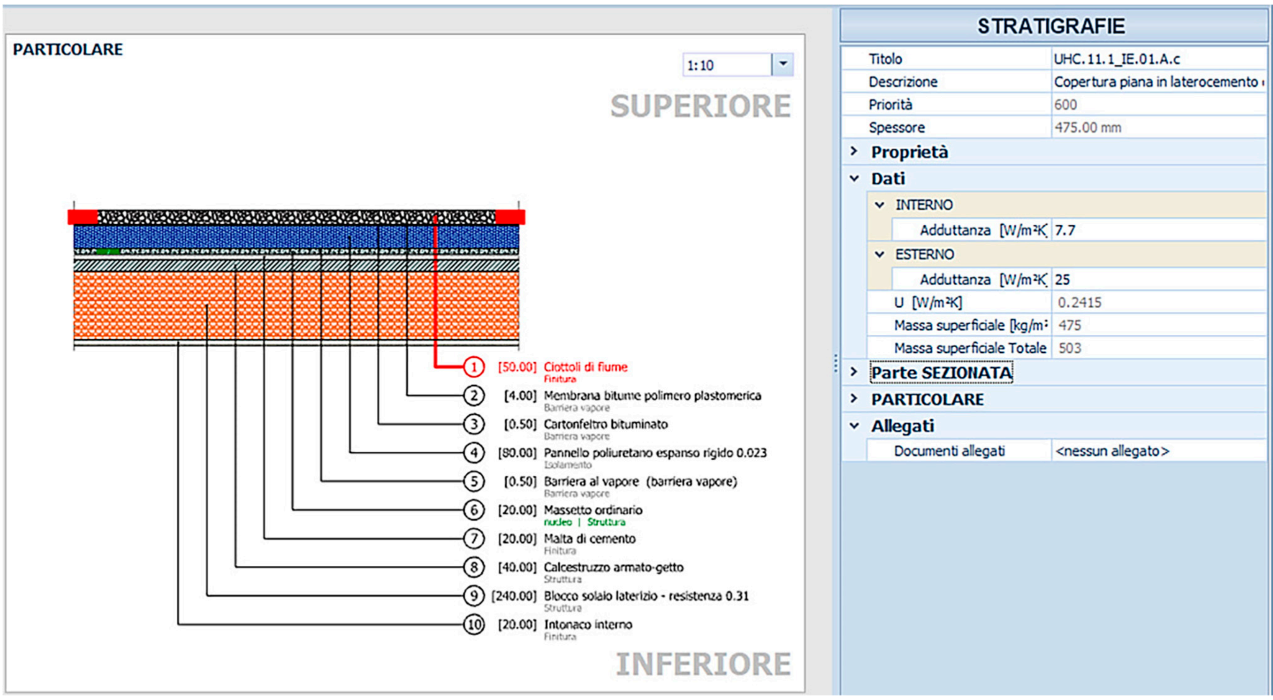


Figure 13. Excerpt of the energy simulations conducted using certified BIM energy software.

Table 5. Steady-state thermal transmittance limit values specified by the Ecobonus Requirements Decree of 05/10/2020 (calculated according to UNI EN ISO 6946) for horizontal opaque structures.

UNI EN ISO 6946	
Climate Zone	**W/m^{2}K**
A	≤0.27
B	≤0.27
C	≤0.27
D	≤0.22
E	≤0.20
F	≤0.19

The periodic thermal transmittance values, attenuation factor, thermal lag, and obtained through the application of various thermal insulation solutions have been compared with the limit values specified by the Minimum Requirements Decree of 26 June 2015 and the UNI EN ISO 13786:2008 standard [45] (Tables 6 and 7).

Table 6. The limit values for periodic thermal transmittance as stipulated by the Minimum Requirements Decree of 26 June 2015.

Periodic thermal transmittance (calculated according to UNI EN ISO 13786:2008 and subsequent updates)	<0.18 W/m^{2}K

To verify the thermal transmittance values of ventilated roofs, the reference standard considered for calculating the thermal resistance of air gaps is UNI EN ISO 6946:2018—Building components and structures—Thermal resistance and thermal transmittance—Calculation methods. This standard identifies three types of air gaps: non-ventilated, weakly ventilated, and strongly ventilated. The following Table 8 outlines the method for determining the thermal resistance of the air gap for each of the three cases.

Table 7. Qualitative parameters—UNI EN ISO 13786:2008.

Lag Time (Hours)	Attenuation	Performance	Performance Quality
S > 12	fa < 0.15	Excellent	I
12 ≥ S > 10	0.15 ≤ fa < 0.30	Good	II
10 ≥ S > 8	0.30 ≤ fa < 0.40	Average	III
8 ≥ S > 6	0.40 ≤ fa < 0.60	Sufficient	IV
6 ≥ S	0.6 0 ≤ fa	Mediocre	V

Table 8. Non-ventilated air gaps thermal resistance values (m^2K/W).

Type of Air Gap	Thickness of the Air Gap (mm)								
	0	5	7	10	15	25	50	100	300
	Thermal Resistance (m^2K/W)								
Horizontal air layer (upward heat flow)	0	0.11	0.13	0.15	0.16	0.16	0.16	0.16	0.16
Vertical air layer (horizontal heat flow)	0	0.11	0.13	0.15	0.17	0.19	0.18	0.18	0.18
Horizontal air layer (downward heat flow)	0	0.11	0.13	0.15	0.17	0.19	0.21	0.22	0.23

To assess the outcomes of the conducted simulations and identify the solutions and corresponding applicable thicknesses for each roof to be included in the matrix, a spreadsheet was created for each horizontal closure. The spreadsheet includes the following columns:

- Indication of the roof type with its corresponding code (UHC and progressive number found in the chart of upper horizontal closures);
- Indication of the solution type with its corresponding code (IE–VEI–II and progressive number);
- Thickness of the simulated solution expressed in millimeters;
- Steady-state thermal transmittance value achieved with the application of the solution, highlighted in light blue to indicate compliance with the limits set by current regulations; in yellow otherwise, and in white when the values specified for the colder climatic zones have already been satisfied by previous thicknesses and, therefore, were not considered in the preparation phase of the performance data sheets;
- Periodic thermal transmittance value achieved with the application of the solution, highlighted in green to indicate compliance with the limits set by current regulations, and in red otherwise.
- Indication of the climatic zones in which solutions are applicable based on the achieved thermal transmittance values;
- The code of the performance sheet given by the combination of the code of the existing roof and the applied and simulated solution, followed by a letter distinguishing them by the thickness of the insulating material;
- Cost of the solution per square meter (the color of the cell indicates the cost range to which it belongs—green if ≤EUR 100; ochre if >EUR 100.00 and ≤EUR 200.00; red > EUR 200.00).

An extract of the spreadsheets for the verification of the analyzed solutions is presented below (Figure 14).

UHC	Solution Encoding	Insulation Thickness [mm]	Steady-state Thermal Transmittance U = W/m2K	Periodic Transmittance YIE < 0.18	CLIMATIC ZONE A-B-C	CLIMATIC ZONE D	CLIMATIC ZONE E	CLIMATIC ZONE F	PERFORMANCE EVALUATING CODING (click and open)	COSTS
UHC.05	IE.01.c	80	0.2432	0.04	A-B-C				UHC.05_IE.01.c	145.63 €
UHC.05	IE.01.d	100	0.2007	0.03	A-B-C	D			UHC.05_IE.01.d	155.00 €
UHC.05	IE.01.e	120	0.1709	0.02	A-B-C	D	E	F	UHC.05_IE.01.e	163.52 €
UHC.05	IE.02.d	80	0.2494	0.04	A-B-C				UHC.05_IE.02.d	110.51 €
UHC.05	IE.02.e	100	0.2049	0.03	A-B-C	D			UHC.05_IE.02.e	115.45 €
UHC.05	IE.03.d	120	0.2596	0.02	A-B-C				UHC.05_IE.03.d	169.93 €
UHC.05	IE.03.f	160	0.2039	0.01	A-B-C	D			UHC.05_IE.03.f	187.28 €
UHC.05	VEI.01.a	60	0.2374	0.03	A-B-C				UHC.05_VEI.01.a	178.55 €
UHC.05	VEI.01.b	80	0.2111	0.03	A-B-C	D			UHC.05_VEI.01.b	200.29 €
UHC.05	VEI.01.c	100	0.1900	0.02	A-B-C	D	E	F	UHC.05_VEI.01.c	221.29 €
UHC.05	VEI.02.a	80	0.2356	0.04	A-B-C				UHC.05_VEI.02.a	143.90 €
UHC.05	VEI.02.b	100	0.1940	0.03	A-B-C	D			UHC.05_VEI.02.b	153.15 €
UHC.05	VEI.02.c	120	0.1649	0.02	A-B-C	D	E	F	UHC.05_VEI.02.c	161.68 €

Figure 14. Extract of the spreadsheets for the verification of the analyzed solutions.

3. Results

Based on simulations carried out to identify standardized energy efficiency solutions applicable to the upper closures that characterize the national residential building stock, an abacus of the most efficient standardized retrofit solutions has been developed. This abacus facilitated the formulation and definition of performance sheets aimed at providing a broad range of solutions for the renovation of existing roof structures, including parametric construction costs. The simulation results for standardized solutions, as detailed in the performance sheets, allowed the creation of a matrix serving as a valuable tool for identifying the most suitable retrofit solutions for a specific type of upper closure characterizing the building subject to energy retrofit interventions.

3.1. Abacus of Standardized Sustainable Insulation Solutions

The simulations conducted on the most common upper horizontal closures in the national residential building stock, along with assessments related to the sustainability and costs of the solutions, have led to the identification of 13 non-ventilated solutions at the extrados, 4 ventilated solutions, and 4 solutions applicable to the intrados, mostly prefabricated. An abacus has been developed for the 21 proposed insulation solutions, as detailed below:

- Performance indicators related to the materials constituting the stratigraphy (thickness, conductivity, specific heat, and density);
- PEI as an environmental impact indicator for the insulation material;
- Percentage of disassembly of the insulation system;
- Minimum total percentage of recycled or recovered content of the insulation system;
- Most EUR/m^2 resulting from the price analysis for each simulated thickness.
- Installation methods.

The abacus of the identified solutions is presented as an example (Figure 15).

The comprehensive abacus is presented in Supplement S3.

3.2. Performance Sheets of the Identified Solutions

Once the insulation solutions described in the chart were identified through simulations conducted on the most prevalent upper horizontal closures in the national residential building stock, which are the most distinctive, performance data sheets were developed. These sheets allow for a comparison of the performance parameters achievable with the application of the identified solutions on the same type of upper horizontal closure they are applicable to. The proposed solutions contribute to reducing the energy consumption of existing buildings, with reference to both winter and summer air conditioning. Each performance data sheet includes the following information:

IE.01

Synthetic organic insulation

Rigid Expanded Polyurethane PIR.GI

Performance indicators

Vapor Barrier			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[W/mK]	[J/kgK]	[kg/m³]
0.00045	0.22	1700	289

PIR.GI Insulation			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[W/mK]	[J/kgK]	[kg/m³]
0.04-0.06-0.08-0.10-0.12	0.023	1442	34

Bituminous Felted Cardboard			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[W/mK]	[J/kgK]	[kg/m³]
0.0005	0.23	1000	1100

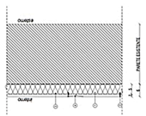
Polymer-Modified Plastomeric Bitumen Membrane			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[W/mK]	[J/kgK]	[kg/m³]
0.003	0.17	1470	1200

Ventilated subroof space			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[m²K/W]	[J/kgK]	[kg/m³]
0.03	0.055	1000	1.3

Sealing Layer (Roof Tiles)			
Thickness (s)	Conductivity (λ)	Specific heat (c)	Density (ρ)
[m]	[W/mK]	[J/kgK]	[kg/m³]
0.015	0.72	840	1800

Synthetic inorganic insulation

Expanded polyisocyanurate foam



Insulation Solution Stratigraphy

1 SEALING LAYER
2 SUBROOF AIR GAP
3 POLYMER-MODIFIED PLASTOMERIC BITUMEI
4 BITUMINOUS FELTED CARDBOARD
5 PIR INSULATION
6 VAPOR BARRIER

Environmental impact indicators

PEI INSULATION [MJ/kg]		80
DISASSEMBLABILITY OF THE COMPONENT [%]	0.04 m	89.43%
	0.06 m	89.64%
	0.08 m	89.84%
	0.10 m	90.03%
	0.12 m	90.41%
RECYCLABILITY OF THE COMPONENT [%]	0.04 m	56.94%
	0.06 m	55.92%
	0.08 m	54.95%
	0.10 m	54.01%
	0.12 m	52.17%

Cost €/m²

0.04 m	139.16 €
0.06 m	145.63 €
0.08 m	155.00 €
0.10 m	163.52 €
0.12 m	167.27 €

Installation method

1.Surface Preparation: Ensure that the surface is clean, free of debris, and smooth. Additionally, verify that it is dry before starting the installation
2. Vapor Barrier Installation
3.PIR Insulation: Application of a thermal insulation system with expanded polyisocyanurate foam, finished with bituminous cardboard felt, available in roll format (composed of slats) or sheet, coupled with a polymer-modified bitumen membrane (APP).
4.Microventilation Layer: Placement of raised elements for channel tiles.
5. Installation of the brick tile sealing layer.

Figure 15. Abacus of the most performing solutions—IE01.

- UHC code of the existing upper horizontal closure, the time during which it was most widely used, and the stratigraphy to which the proposed solution is applicable;
- Code of the insulation solution (IE = insulation at the non-ventilated or micro-ventilated extrados, VEI = ventilated external insulation, II = intrados insulation);
- Type, thickness, and conductivity of the insulation material of the proposed solution, PEI value, percentage of disassembly, and percentage of prefabrication;
- Drawing of the roof stratigraphy and the applied insulation solution with a description of its components;
- Thermophysical properties of the building components of UHC and the proposed insulation solution;
- Results of the performance values achievable in winter and summer by applying the insulation solutions;
- Verification of the absence of surface condensation (isotherms);
- Verification of the absence of interstitial condensation (Glaser diagram—critical month);
- Radial chart to compare values related to steady-state U-value, periodic Y-value, PEI, percentage of disassembly, and prefabrication percentage of the proposed solution;
- Verification of compliance with the limit values specified by current regulations in winter and summer conditions.

The thermophysical properties of the building components of the upper horizontal closures and the proposed insulation solutions were studied to assess their ability to reduce the transmission of thermal energy, preventing its dissipation to the external environment in winter and its entry into the conditioned environment in summer. The studied parameters reported in each performance data sheet include the following: the thickness (s) of each material, thermal conductivity (λ), thermal resistance (R), specific heat (c), density (ρ), and surface mass (Ms).

The thermal transmission parameters of the studied opaque envelope components, which define their ability to control the flow of heat due to a temperature difference between the internal and external environment, are as follows: steady-state thermal transmittance (U) to verify performance in winter conditions according to the limit values specified by Annex E of the Eco-bonus Requirements Decree GU 5 October 2020 (calculated according to UNI EN ISO 6946); periodic thermal transmittance (Yie) to verify performance in summer conditions according to the limit values specified by the Minimum Requirements Decree 26 June 2015 (calculated according to UNI EN ISO 13786:2008 Thermal performance of building components—Dynamic thermal characteristics—Calculation methods and subsequent updates); phase shift (Φ) of the thermal wave verified according to qualitative parameters specified by UNI EN ISO 13786:2008; coefficient of attenuation (f_a) of the thermal wave verified according to qualitative parameters specified by UNI EN ISO 13786:2008; areic thermal capacity calculated according to UNI EN ISO 13786:2008, represents the ability of a building component to accumulate heat from the internal side of the closure.

An opaque envelope characterized by high heat accumulation capacity allows for the reduction in unwanted temperature fluctuations in both summer and winter periods, contributing to reducing energy consumption for air conditioning. Low values of the attenuation factor f_a, together with high values of periodic thermal transmittance, areic thermal capacity, and the phase shift Φ of the thermal wave, denote the good behavior of opaque closures in attenuating the effects of external summer thermal stresses. The analysis and performance verification of existing and optimized structures were conducted using energy performance certificate software. Simulations with different insulation thicknesses were performed on each type of roof from the matrix to define sustainable standardized insulation solutions. The matrix and performance data sheets contain the results of the simulations conducted in climate zone E, in the municipality of San Didero (Province of Turin), because this climatic zone hosts the most significant national residential building stock, as shown in Table 9 [16].

Table 9. Number of residential buildings in 2018 by climate zone.

Climate Zone	Number of Buildings	m^2
A	5217	170,118,357
B	710,079	
C	2,737,222	615,486,151
D	2,896,204	734,707,925
E	5,340,672	1,383,758,265
F	731,009	145,735,486

The thermo-hygrometric verification aims to ensure that the following phenomena do not occur:

- Interstitial condensation between the layers that make up the upper horizontal closure, as the occurrence of such a condition causes material degradation, especially of the insulating material, compromising the thermal performance of the roof;
- Surface condensation can lead to a conducive environment for mold and fungal growth.
- The calculation for verifying interstitial condensation is defined by the European Standard EN 13788 (Glaser diagram). The profiles of temperatures and water vapor pressures (saturated and actual) within the roof have been calculated: if the actual vapor pressure (Pe) reaches or exceeds that of the saturated vapor pressure (Ps), condensation will occur in the wall. Each data sheet includes the Glaser verification for the most critical month. To facilitate the comparison between the proposed insulation systems, ranges have been defined for each indicator based on the limit values specified by current regulations. A score from 1 to 5 has been assigned to each range, where 1 corresponds to the best performance.
- The data identified for the ranges of each indicator are reported in Table 10.

Table 10. Range of indicators for insulation solutions comparison.

Classification	Steady-State Thermal Transmittance (U) (W/m^2K)	Periodic Thermal Transmittance (Yie) (W/m^2K)	PEI (MJ/kg)	Disassembly (%)
1	$U \leq 0.19$	$Yie \leq 0.04$	$PEI \leq 10$	Disa. = 100
2	$0.19 < U \leq 0.20$	$0.04 < Yie \leq 0.06$	$10 < PEI \leq 30$	$50 <$ disa. ≤ 75
3	$0.20 < U \leq 0.22$	$0.6 < Yie \leq 0.10$	$30 < PEI \leq 40$	$25 <$ disa. ≤ 50
4	$0.22 < U < 0.27$	$0.10 < Yie \leq 0.17$	$40 < PEI \leq 100$	$0 <$ disa. ≤ 25
5	$U = 0.27$	$Yie > 0.18$	$PEI > 100$	Disa. = 0

An example of the performance sheets is provided in Figure 16.

UHC.11_IE.01.A.c

UPPER HORIZONTAL CLOSURE UHC.11

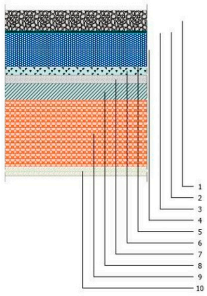
Used from 1991 to 2005

Total thickness: 370mm

1 : River pebbles
2 : Waterproofing membrane
3 : Insulation panel
4 : Concrete screed
5 : Cement mortar
6 : Reinforced concrete
7 : Lateral-cementitious floor
8 : Internal plaster

U 0.57 W/mqk
YIE 0.08 W/mqk

Insulating material
Expanded polyurethane
λ : 0.023
Thickness 80 mm
PEI : 80
DISA 94
PREF 70



Description of the stratigraphic solution	Thickness (mm)
EXTERNAL	
1 River pebbles	**50**
2 Polymer-modified bitumen plastomeric m	**4**
3 Bituminous cardboard felt	**1**
4 Rigid expanded polyurethane panel	**80**
5 Vapor barrier	**1**
6 Ordinary screed	**20**
7 Cement mortar	**20**
8 Reinforced concrete casting	**40**
9 Lattice concrete block slab	**160**
INTERNAL	(mm)
Spessore tot:	**396**

THERMOPHYSICAL PROPERTIES OF BUILDING COMPONENTS

LAYER	DESCRIPTION	s [mm]	λ [W/mK]	C [W/m²K]	M [kg/m²]	c [J/kgK]	R [m²K/W]
EXT	**Adduttanza**	0		25.00			0.0400
1	River pebbles	50	0.70	14.00	75.00	1,000	0.0714
2	Polymer-modified bitumen plastomeric r	4	0.17	42.50	4.80	1,470	0.0235
3	Bituminous cardboard felt	1	0.23	460.00	0.55	1,000	0.0022
4	Rigid expanded polyurethane panel	80	0.023	0.29	2.72	1,442	3.478
5	Vapor barrier	1	0.22	440.00	0.14	1,700	0.0023
6	Ordinary screed	20	1.06	53.00	40.00	1,000	0.0189
7	Cement mortar	20	1.4	70.00	40.00	1,000	0.0143
8	Reinforced concrete casting	40	1.91	47.75	96.00	1,000	0.0209
9	Lattice concrete block slab	160		3.70	144.00	1,000	0.2700
10	Internal plaster	20	0.7	35.00	28.00	1,000	0.0286
INT	**Adduttanza**	0		10.00			0.1000

RESULTS

TOTAL TRANSMITTANCE	W/m²K	0.2439
SURFACE MASS	kg/m²	403.21
PHASE SHIFT	ore	11.42
ATTENUATION FACTOR		0.12
AREAL HEAT CAPACITY	kJ/m²K	60.11
PERIODIC TRANSMITTANCE	W/m²K	0.03

THERMOHYGROMETRIC VERIFICATIONS

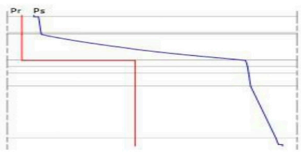
SURFACE CONDENSATION

Minimum temperature factor fRsi = 0.9386,
Maximum critical month temperature factor, fRsi,max = 0.7242,
Critical month = December,
Vapor concentration class = Medium,
Maximum allowable U value = 1.1032 W/m²K.

fRsi ≤ fRsi,max ✓

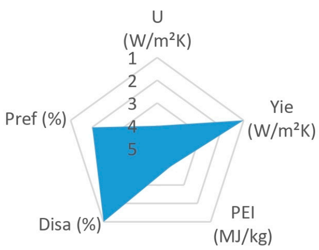
INTERSTITIAL CONDENSATION

Critical Month **December**



Pv ≤ Ps ✓

COMPARATIVE RADAR



LIMIT VALUES VERIFICATION

Winter Mode

Allegato E (UNI EN ISO 6946)

A-B-C	≤	0.27 W/m2*K	☑
D	≤	0.22 W/m2*K	☐
E	≤	0.20 W/m2*K	☐
F	≤	0.19 W/m2*K	☐

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Figure 16. Example of a performance sheet.

3.3. Matrix of Upper Closures and Their Corresponding Most Efficient Solutions

Following the development of the abacus for existing upper horizontal closures, the abacus for the most efficient solutions, and the performance sheets of the identified solutions for each roof, it was deemed appropriate to compile a matrix summarizing the results obtained from the simulations and already reported in the aforementioned sheets.

The building matrix is a scheme that represents possible configurations of building envelope types found within the national residential building stock. The matrix serves as a useful tool for identifying the most suitable retrofit solution for a specific roof type characterizing a building undergoing energy retrofit interventions. This tool is valuable for designers, guiding them towards the selection of the most suitable sustainable solution based on the characteristics of the building to be improved and the intervention location. The rows composing the matrix represent possible roof types, organized based on the construction era class, building typology, and the most prevalent construction type.

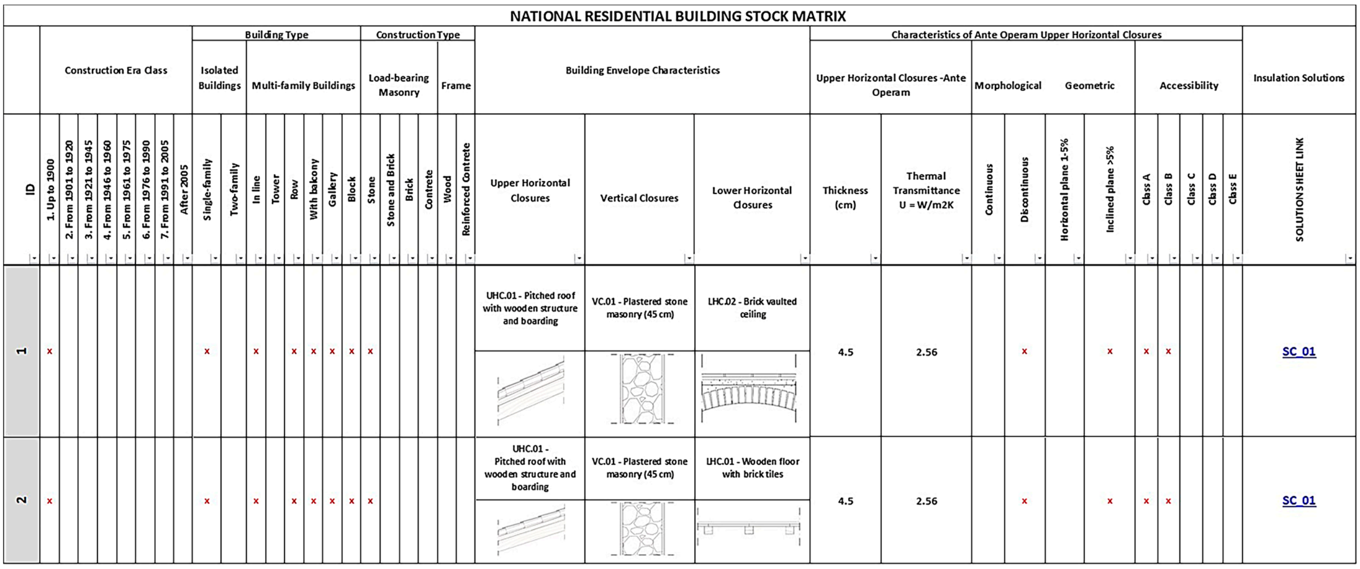
The sequence of different closure types follows the chronological evolution of construction techniques. The matrix is based on a system of sequential filters. Once the construction period of the building undergoing an insulation intervention is identified and cross-referenced with the building typology and construction type, the existing closure types of the opaque building envelope can be selected. At this juncture, transitioning to the delineation of geometric, performance, and morphological attributes, the categories of extant horizontal upper enclosures are recognized.

Each row of the matrix includes the following:

- Configuration number (ID);
- Construction era class (Class 1: up to 1900; Class 2: 1901–1920; Class 3: 1921–1945; Class 4: 1946–1960; Class 5: 1961–1975; Class 6: 1976–1990; Class 7: 1991–2005; Class 8: after 2005);
- Main building typologies, subdivided into isolated buildings (single-family and multi-family) and aggregated buildings (detached, tower, row, balcony, small building, and block);
- Construction types, subdivided into load-bearing masonry (stone, stone, and brick, brick and reinforced concrete) and framed (wood, reinforced concrete, and steel);
- Characteristics of the existing building envelope;
- Characteristics of the pre-existing upper horizontal closures, including the following:
- Thickness of the opaque building envelope;
- Steady-state thermal transmittance (W/m^{2}K);
- Morphological and geometrical characteristics;
- Accessibility level.
- Link to the sheet containing simulation outcomes with an indication of the performance sheets of solutions applicable to the specific opaque building envelope.

It is then possible to proceed by coupling the identified renovation solutions with different thicknesses of insulating material to the existing enclosure, determining the thermal transmittance (steady-state and periodic) of the entire stratigraphy. This tool is able to provide the climatic zones in which individual solutions can be adopted to meet the minimum requirements specified by current regulations, and a link is provided that allows viewing the descriptive and performance sheet resulting from the coupling of the insulation solution to the existing structure. The technical sheets are identified by combining the code of the upper horizontal closure UHC and the code of the retrofit solution IE, VEI, II, followed by a lowercase letter indicating the type of thickness of the solution.

An excerpt of the matrix is presented in Figure 17.



NATIONAL RESIDENTIAL BUILDING STOCK MATRIX																																					
	Construction Era Class								Building Type								Construction Type						Building Envelope Characteristics			Characteristics of Ante Operam Upper Horizontal Closures											Insulation Solutions
									Isolated Buildings		Multi-family Buildings						Load-bearing Masonry				Frame					Upper Horizontal Closures -Ante Operam		Morphological		Geometric		Accessibility					
ID	1. Up to 1900	2. From 1901 to 1920	3. From 1921 to 1945	4. From 1946 to 1960	5. From 1961 to 1975	6. From 1976 to 1990	7. From 1991 to 2005	After 2005	Single-family	Two-family	In line	Tower	Row	With balcony	Gallery	Block	Stone	Stone and Brick	Brick	Contrete	Wood	Reinforced Contrete	Upper Horizontal Closures	Vertical Closures	Lower Horizontal Closures	Thickness (cm)	Thermal Transmittance U = W/m2K	Continuous	Discontinuous	Horizontal plane 1-5%	Inclined plane >5%	Class A	Class B	Class C	Class D	Class E	SOLUTIONS SHEET LINK
1	x								x		x		x	x	x	x	x						UHC.01 - Pitched roof with wooden structure and boarding	VC.01 - Plastered stone masonry (45 cm)	LHC.02 - Brick vaulted ceiling	4.5	2.56		x		x	x	x				SC_01
2	x								x		x		x	x	x	x	x						UHC.01 - Pitched roof with wooden structure and boarding	VC.01 - Plastered stone masonry (45 cm)	LHC.01 - Wooden floor with brick tiles	4.5	2.56		x		x	x	x				SC_01

Figure 17. Excerpt of the national residential building stock matrix.

4. Discussion

The age of the existing national residential building stock highlights the need to intervene in the building stock with energy efficiency measures, including thermally insulating the building envelope [46]. This measure reduces heat loss in winter and heat gain in summer, enhancing climate control efficiency. Energy retrofit interventions aim to decrease energy consumption for heating and cooling while reducing greenhouse gas emissions and improving comfort. The promotion of sustainable construction goes beyond the efficiency of existing assets. This also means rethinking materials, components, and building systems more efficiently in terms of resource consumption. This involves the use of recycled and recyclable materials, streamlining installation methods, as well as designing prefabricated and dry-assemblable systems to maximize recycling or reuse of components at the time of decommissioning. This must be performed in compliance with the technical specifications provided by the minimum environmental criteria (C.A.M.) applicable to building components.

During this research, a wide range of insulation materials available on the market was examined, comparing them based on specific energy performance indicators, environmental impact, cost, and usage indications. This analysis allowed for the selection of twenty-one insulation solutions characterized by the best performance and limited environmental impact. To determine the thickness of the insulation material for each proposed technological solution, a methodology was developed in which the performance of insulation scenarios was precalculated. This guides the designer towards more efficient, prefabricated, and sustainable standardized solutions for the national residential building stock. Simulations were carried out for each solution with different thicknesses of insulating material on each type of upper horizontal closure present in the diagram. To ensure the applicability of the proposed insulation solutions, compliance with common criteria for all building components, such as the percentage of disassembly and the percentage of recovered or recycled material content, was verified. These criteria both reduce the need for raw materials and stimulate the waste valorization chain from construction and demolition.

An examination of insulation intervention costs facilitated an economic assessment of the viability of implementing the identified solutions, offering the designer an additional selection criterion. This process culminated in the creation of an optimized technological solutions diagram based on climatic, geometric/dimensional, and technical/performance parameters. The solutions were primarily chosen based on prefabrication criteria, providing guidance for designers involved in energy efficiency interventions within the residential real estate sector. Following the identification of the most efficient standardized insulation solutions, performance data for each solution pertaining to every type of upper horizontal closure in the national residential building stock were compiled through simulations. Subsequently, these performance data were consolidated into performance sheets for each solution and for every roof, facilitating the immediate identification of the most performance-oriented system based on climatic zones. These elaborations have given rise to the development of a matrix populated by the configurations of the most common opaque closures in the national residential building stock, with a description of existing roofs and a link that allows access to a summary of the simulation results subsequently detailed in the relevant performance sheet. Through the matrix and performance sheets, the designer can easily identify the case that best corresponds to the specific energy efficiency intervention based on the construction era, building type, construction type, climatic zone, and the most effective technological solutions according to the performance requirements to be met in both winter and summer. The matrix produced is an open system that can be implemented following the evolution of new components and systems. Dashboards have also been developed that provide a summary for each UHC:

- Description of the upper horizontal closure before work;
- The number and type of applicable solutions;
- The minimum number of applicable solutions in different climatic zones based on the results of energy simulations;
- The number of solutions by type of insulation (IE = non-ventilated or micro-ventilated insulation solutions, VEI= ventilated external insulation; II = underside insulation solutions);
- The minimum number of solutions by type of insulation applicable for each climatic zone;
- Classification of solutions by type of insulation based on cost per m^2.

The following is an example of a dashboard (Figure 18).

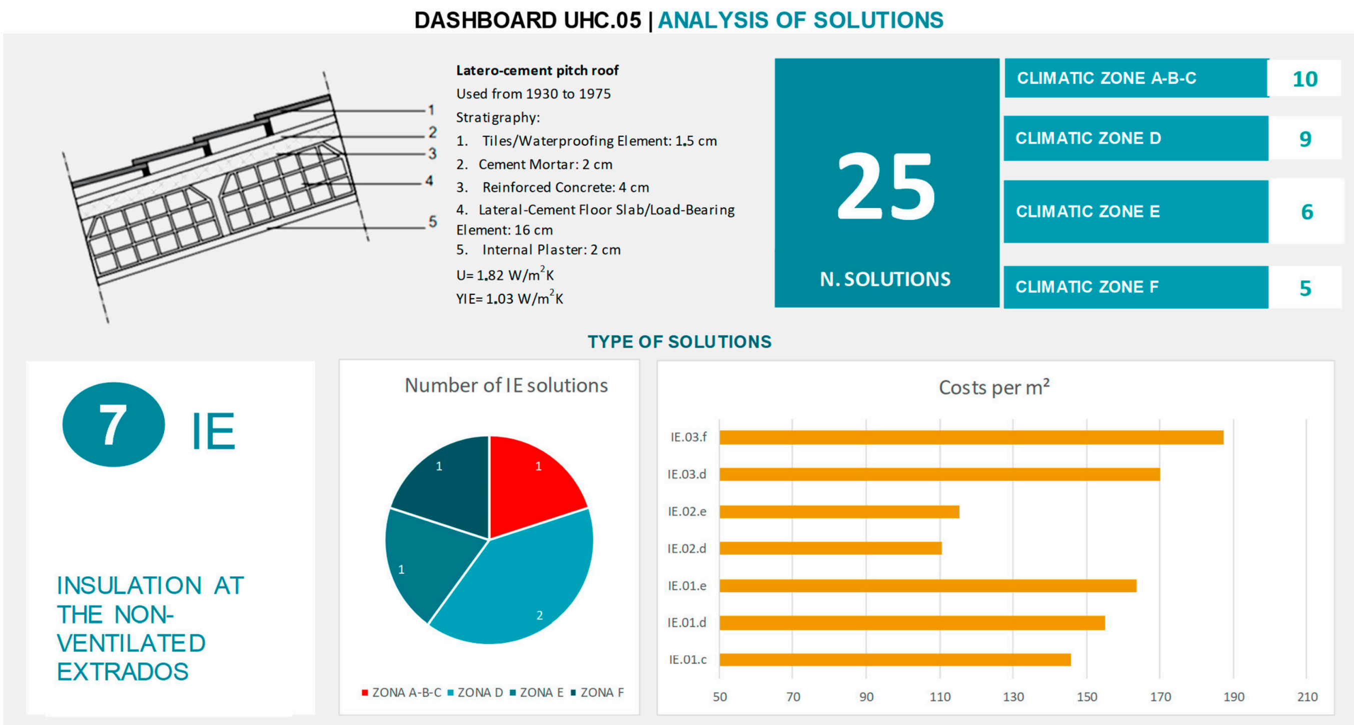


Figure 18. *Cont.*

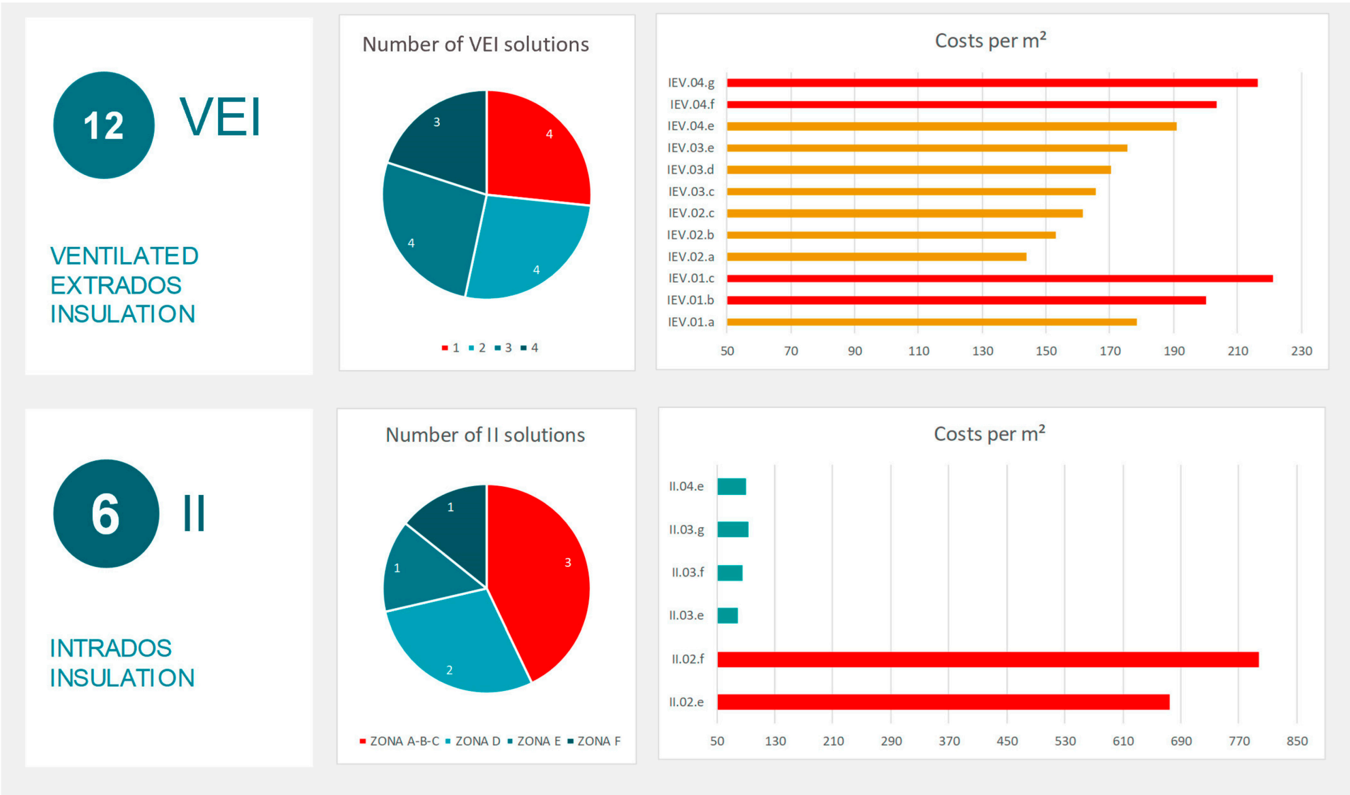


Figure 18. Example of a dashboard.

5. Conclusions and Future Developments

Defining eco-sustainable solutions is one of the most crucial challenges for the future, particularly in the context of energy retrofitting.

It is an innovation process that is affecting the entire construction supply chain and the renewal of existing building stock, as increasingly, plans are being implemented to align buildings with new criteria for energy efficiency and eco-sustainability.

The objective guiding the research presented here consists of attempting to identify and promote sustainable solutions capable of directing designers towards energy retrofit interventions for the upper closures of national residential buildings, primarily characterized by high levels of prefabrication and recycled content, in accordance with current minimum environmental criteria (CAM). The main limitations of this research are related to the absence of an evaluation of maintenance costs for the standardized thermal insulation solutions proposed. Furthermore, the roofing considered for defining the pre-calculated solutions are those most commonly found within the national residential building stock and may not include some types. Lastly, for a comprehensive energy analysis, it is necessary to consider all building envelope closures. Indeed, this study will be integrated in the second year of ENEA research with a prior focus on identifying standardized thermal insulation solutions for vertical closures—vertical perimeter walls [23].

The research outcomes will constitute the core for the development of a tool supporting energy efficiency interventions in residential buildings during renovation. The development in the second year of research will indeed focus on creating a tool to guide the designer in identifying scenarios that best correspond to the real situation of the property to be redeveloped, based on the construction era class, building type, construction type, and climatic zone. Utilizing the database of identified optimized proposals, the tool will enable the selection of the most effective technological solutions (standardized, energy-efficient, and sustainable) that ensure compliance with performance requirements set by current regulations in winter conditions, following Off-Site construction indications.

The tool will provide the opportunity to conduct a preliminary energy analysis capable of outlining the potentialities offered by a range of proposed retrofit interventions concerning the opaque building envelope. It will be a valuable instrument for the professional technician, who, during the selection of redevelopment options for a building, can efficiently assess, through preliminary energy performance simulations, the outcome of applying the different optimized solutions of the opaque building envelope previously selected through the dynamic matrix in terms of energy savings and economic feasibility. The calculation of energy demand will encompass both heating and cooling requirements. The tool's calculations will cover both the building envelope and the most common plant types.

The research findings underscore the effectiveness of adopting the described methodology in enhancing the percentage improvement of steady-state thermal transmittance (W/m^{2}K). Notably, a substantial average improvement of over 66% is observed in upper horizontal closures, ranging from a minimum of 34% to a maximum of 92%. This indicates a substantial enhancement in energy efficiency achievable through targeted interventions. The graph visually represents the distribution of improvement percentages in steady-state thermal transmittance across the existing roofs of the national building stock utilizing optimized, standardized, and sustainable solutions. It is evident that the percentage improvement in transmittance is particularly higher in cases where the existing roof system belongs to an older construction era class, characterized by significantly higher pre-renovation transmittance values. These values necessitate post-renovation adjustments to comply with prevailing regulatory standards. This observation underscores the need for tailored interventions to address specific building characteristics and regulatory requirements, ensuring optimal energy efficiency outcomes (Figure 19).

Figure 19. Steady-state thermal transmittance improvement (%).

The tool will allow for the identification of the economic savings achievable with the application of the proposed insulation solutions and the net present value (NPV). It will inform the user about any incentives available for the implementation of the simulated intervention.

The user can download performance sheets containing the stratifications of applicable solutions on vertical closures (perimeter walls) and upper horizontal closures (roofs), thermophysical properties, simulation results, thermo-hygrometric verifications, and sustainability indicators. When there is a need to intervene in a property, the tool will enable following:

- Creating an energy model of the building subject to redevelopment interventions in the pre-intervention situation using the matrix of existing vertical and horizontal closures that characterize the national residential building stock.
- Evaluating the energy performance of the real building in its current state through synthetic indicators.
- Guiding the choice using databases of identified optimized solutions for both perimeter walls and roofs.
- Constructing a post-intervention building model.
- Evaluating the outcome of adopting the identified solutions in terms of technical/economic feasibility downstream of the simulated scenarios.

Using the tool, it will also be possible to create a "ranking" of priority for energy redevelopment actions by comparing different solutions.

In conclusion, the new European directives represent a significant step towards a more sustainable and energy-efficient Europe, laying the groundwork for a comprehensive transformation of the construction sector towards climate neutrality. By adopting ambitious measures and innovative tools, such as the one proposed in this article, it will be possible to enhance the durability and overall performance of existing buildings and drastically reduce greenhouse gas emissions and energy consumption in the construction sector by 2030.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16093850/s1, Supplement S1: Abacus of existing upper horizontal closures; Supplement S2: Study of insulating materials for the redevelopment of existing upper closure types; Supplement S3: Abacus of insulation solutions for upper horizontal closures (UHCs).

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