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Energy-Efficient Solutions: A Multi-Criteria Decision Aid Tool to Achieve the Targets of the European EPDB Directive

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Abstract: The building and construction sector has a significant impact on the CO_2 emissions and pollutants released into the atmosphere, which contribute to climate change. The EPDB Directive mandates the achievement of minimum energy class E for all residential buildings by 2030 and energy class D by 2033. Particularly, in Italy, about 86% of the existing building stock predates the enactment of any energy laws or regulations, making it imperative to apply the energy efficiency interventions. This paper provides a support decision tool for the identification of the standardized interventions in the building envelope, the air conditioning system, and domestic hot water production. This study is focused on a specific construction period class (1976–1990) in six different climatic zones. The methodological approach is based on a cataloguing phase and the definition of ante operam energy classes as well as on case study identification, energy requalification intervention identification, solution simulations, and cost estimation. By simulating the standardized interventions for each climatic zone, a range of possible combinations is identified. The most advantageous ones are determined based on a cost–benefit analysis considering the potential class jump achieved. The research result is a matrix of energy efficiency interventions that is applicable to each climatic zone and can be extended to the existing housing stock.

Keywords: energy requalification; standardized efficiency solutions; cost–benefit analysis; existing building stock; building energy performance

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1. Introduction

In recent decades, there has been an increasing focus on the environment and global warming due to the substantial greenhouse gas emissions (GHG) released into the atmosphere because of anthropogenic activities. These activities include the ongoing urbanization processes in developing countries and the global expansion of the building construction sector [1], which disrupt natural balances.

The environmental issue is closely intertwined with energy, encompassing the way energy is produced, distributed, and consumed [2]. According to the Intergovernmental Panel on Climate Change (IPCC), the energy supply sector represents the primary contributor to GHG [3], making it one of the critical challenges that must be addressed and resolved in the near term to mitigate the damages inflicted upon ecosystems and human health.

Furthermore, the IPCC's findings indicate that the building sector is accountable for 40% of global total energy consumption and 25% of the total CO_2 emissions [4].

According to the Global Status Report for Buildings and Construction 2022 [5], the operational energy demand of buildings for space heating and cooling, water heating, lighting, and cooking has increased to approximately 135 EJ, showing an increase of about 4% from 2020 and surpassing the previous peak in 2019 by over 3% [6]. As for the energy demand, there has been a 5% rise in the global building sector's CO_2 operational emissions compared to 2020, reaching a level of approximately 10 $GtCO_2$; this increase in emissions exceeds the pre-pandemic all-time high in 2019 by 2% [6].

The Tracking Report on Buildings published by the International Energy Agency—the IEA—in September 2022 indeed indicates that the building sector is "not on the right track".

European Building Scenario

The European Union is a member of the United Nations Framework Convention on Climate Change (UNFCCC), which was adopted at the Rio Earth Summit in 1992 and serves as the principal international agreement on climate policy action. The international community recognizes the need to collectively protect people and the environment and to contain greenhouse gas emissions.

In 1997, the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Kyoto Protocol, which implemented the initial legally binding emission reduction targets for developed countries.

Climate change is a global issue that necessitates collaborative efforts from countries worldwide to limit global warming. The Paris Agreement, adopted during the meeting of the parties in the UNFCCC in 2015, saw that governments agree to keep the increase in the global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit it to 1.5 °C [7]. In line with these goals, the European Union Green Deal aims to cut emissions by at least 55% by 2030 compared to the 1990 levels and to achieve climate neutrality by 2050 [8].

In December 2021, the European Commission proposed a revision of the "Energy Performance of Buildings Directive—EPDB" as part of the "fit for 55" package.

The objective is to achieve a minimum 55-percent reduction in the EU's greenhouse gas emissions by 2030 as stipulated by the 2021 European Climate Act [9]. The revised EPBD outlines a roadmap for the EU to achieve a zero-emission and fully decarbonized building stock by 2050, emphasizing the acceleration of renovation efforts for the poorest-performing buildings in each EU member state. The European Commission's proposal mandates that all the new buildings in the EU should be at zero emissions by 2030 (by 2027 for all the new public buildings). To foster greater standardization across its member states, EU-wide minimum energy performance requirements will be implemented. Residential buildings are expected to attain Class E by 2030 and Class D by 2033.

According to a technical report by the Joint Research Centre, 90% of the building stock in the EU was constructed before 1990, with approximately 50% built before 1970 [10]. This indicates that the majority of the EU building stock was constructed prior to any energy efficiency regulations and, therefore, has inefficient performance [11].

Approximately 97% of EU buildings require refurbishment to achieve the 2050 decarbonization target, yet only 0.4–1.2% undergo updates each year [12].

Therefore, in the European Union, buildings still account for 40% of total energy consumption and 36% of greenhouse gas emissions, primarily stemming from construction, usage, renovation, and demolition [13]. In particular, the main energy consumption source in EU households is related to the 77.9% of consumption used for home space and water heating, the other 14.5% used for lighting and appliances, and the 0.4% used for space cooling [14].

It is evident that the European construction sector must undergo decarbonization, necessitating the development of new sustainable strategies. An effective approach to implement such policies and to achieve the climate neutrality goals while reducing dependence on energy imports is through energy efficiency and the renovation of the building stock. This includes rational energy use during all construction phases and the incorporation of systems powered by renewable energy sources (RES) [15]. In order to reduce the impacts produced by the construction sector, it is therefore crucial to improve energy efficiency, which is considered by the European Commission (EC) to be a key element in the community energy policy [13].

Energy efficiency is defined as the proportion between performance and energy input; in other words, it represents the ratio of what is produced and the energy used for its purpose. Greater energy efficiency and energy saving can be achieved both through the application of simple and complex technologies, components, and systems and through a more conscious and responsible end-user behavior: energy efficiency has the objective of primary energy saving, CO_2 emission reduction, and a consequent reduction in energy costs. It appears necessary to encourage the transformation of existing buildings into high-performance energy constructions through implementations of various kinds of interventions, such as interventions in the building envelope of roofs, walls, and transparent closures; in lighting system upgrading; in thermal energy production and distribution systems; or in the installation of energy production systems based on renewables [16].

A study by Jafari et al. [17] states that building renovation interventions can reduce energy consumption by 30–40%. According to an estimate of the energy-saving potential developed by Tuominen et al., in the majority of European Union countries, cost-effective energy savings of approximately 10% can be attained by 2020, and those of 20% can be attained by 2030 [18].

Numerous research activities have been dedicated to defining interventions aimed at improving the energy efficiency of building stocks both at the national and international levels. These studies are based on the analysis of the typological, morphological, and geographical characteristics of buildings. They examine various aspects, including the thermal transmittance of transparent and opaque surfaces, the location within specific climatic zones, the construction period, orientation, and the type of building elements.

Among the various research projects aimed at defining methodologies and evaluation tools for energy retrofit interventions, notable examples are TABULA [19], EPIQR [20], IFORE [21], SUSREF [22], and MultiOpt [23]. These tools outline potential measures for energy savings and CO_2 emission reduction in buildings. However, in some cases, these tools do not delve into the analysis of the costs associated with the proposed interventions or the aspect related to energy class improvement.

Diverse decision-making methods have been formulated to choose the most appropriate insulation material or building façade solution for the energy retrofitting of buildings [24,25].

Papapostolou et al. [26] developed the tool that exploits the multi-criteria decision analysis method ELECTRE Tri, incorporating the prominent key performance indicators commonly employed by investors and financing institutions to discern bankable energy efficiency investments and to facilitate the transition towards green initiatives. This tool does not assess the energy class improvement that is achievable through energy efficiency interventions, but it proves valuable for those seeking sustainable investments in this sector.

In conclusion, the literature review revealed that the majority of methodologies and tools related to building energy efficiency do not incorporate the verification of the energy class upgrades mandated by the new European regulations.

In this study, the authors present a decision support tool aimed at promptly identifying the optimal combination of energy efficiency solutions tailored to the prevailing building typology and construction period: multi-apartment residential buildings constructed between 1976 and 1990. The standardized energy efficiency interventions proposed focus on the building envelope, the air conditioning system, and domestic hot water production.

The pre-calculated solutions provided by the tool ensure the achievement of the objectives set by the new European EPBD directive.

The tool also conducts an analysis of the incurred costs and benefits obtained from the proposed interventions in terms of improving the energy class of each Italian climatic zone.

The authors consider their contribution to the knowledge on this topic to be as follows: the study of the state-of-the-art national residential building stock, the characterization and cataloging of existing buildings pertaining to the construction era class of 1976–1990, simulations of energy efficiency interventions to verify the improvement of the energy class, the economic estimation of energy efficiency interventions, and the creation of a matrix for the automatic recognition of the most effective and economically advantageous solutions according to the climatic zone.

2. Materials and Methods

With the view of formulating technological solutions aimed at promoting deep renovation interventions in the housing sector of Italian building heritage as well as internationally, the imperative to achieve the class advancement goals by 2030 and 2033 paves the way for the rehabilitation of the existing built environment based on sustainability principles and the utilization of renewable energy solutions. It appears highly practical to conceptualize an integrated decision support tool, rooted in a methodological procedure, that defines standardized interventions to be applied in the context of a specific existing building structure within the building heritage considering its current state.

The methodology devised to create the tool for pre-calculated identification of energy efficiency solutions for existing buildings was grounded on 5 key steps:

1st step: Italian residential building stock state-of-the-art study.
2nd step: Characterization and cataloging of existing buildings pertaining to the construction era class of 1976–1990.
3rd step: Definition of simulations of energy efficiency interventions.
4th step: Economic estimation of energy efficiency interventions.
5th step: Dynamic matrix elaboration.

An outline of the methodology developed to obtain a tool for the identification of the energy optimization strategies for the existing multi-apartment residential buildings is shown in Figure 1.

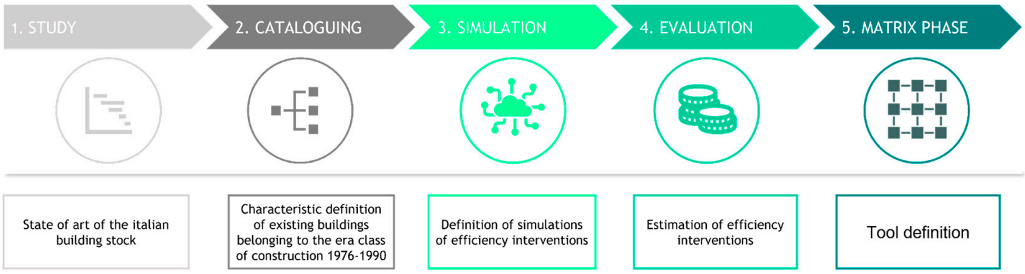


Figure 1. Methodology flow chart of the development of the guiding support tool.

The first step provided the necessary data for the selection of a specific construction era class and building typology on which to apply the proposed tool.

The second step involved the study and definition of the technological aspects of the selected building typology, which is widely spread across the national territory and exhibits poor energy performance. This step allowed for obtaining the current state of the buildings in six different Italian climatic zones and highlighted the main deficiencies in the building envelope and air conditioning system.

The third step, "Simulation", allowed for the definition of intervention solutions that would achieve the minimum energy class improvement required to reach Class E by 2030. Additionally, it also illustrated interventions that would lead to a higher energy class improvement (e.g., reaching Class D by 2030). Various types of interventions were described for a selected multi-apartment residential building in a representative case study, starting from those related to the opaque and transparent envelope and extending to interventions applicable to the conditioning system.

The fourth step involved estimating the costs per square meter of all intervention combinations, referencing the National "DEI 2023 Price List". For each energy efficiency intervention, it was quantified, and a price range was defined to assess the cost effectiveness of the specific combination.

The final step entailed creating a matrix summarizing all proposed energy efficiency intervention combinations, the achieved energy class improvement, and the cost-effectiveness ratio. An analysis of incurred costs and obtained benefits was also provided. This way, the user could identify the combination of interventions to adopt in order to achieve a specific post-intervention energy class and the associated expenses that they would incur.

2.1. Italian Residential Building Stock State-of-the-Art Study

The exploration of the current state-of-the-art building stock enabled us to identify the prevailing construction types and to discern those that required upgrading in terms of energy efficiency. The Italian territory is classified into six climatic zones ranging from A to F as per D.P.R. no. 412/1993, which is based on the number of heating degree days (HDD—EN ISO 15927-6:2007).

In Italy, the building stock is heterogeneous and quite dated. According to the data from the 15th general population and housing census conducted by ISTAT (National Institute of Statistics) until 9 October 2011, out of the 14,515,795 units of the Italian residential building stock, more than half, approximately 60 percent, were built in the post-World War II period to the 1990s [27]. Out of the 2,740,018 residential buildings, only 14% were constructed after 1990 (379,190 buildings), 53% were constructed between 1946 and 1990 (1,444,160), 12% were constructed between 1919 and 1945 (328,988), and 21% were constructed before 1919 (587,680) [28]. This indicated that the implementation of legislation that requires increasing attention to the rational use of energy and thermal insulation of buildings began with the enactment of Law No. 10 of 1991, titled “Regulations for the implementation of the National Energy Plan for the rational energy use, energy saving, and development of renewable energy sources”. However, this legislation only covers 14% of the Italian building stock, leaving the remaining 86% unaffected. Indeed, over 25% of the buildings constructed before this law exhibit annual energy consumption ranging from a minimum of 160 kWh/m^2 per year to more than 220 kWh/m^2 per year [29]. The matter of energy efficiency in the national building stock is of significant importance since 86% of existing buildings were constructed before any energy laws or regulations were enacted, necessitating the implementation of energy efficiency interventions. When analyzing the diagram of residences classified by energy rating in different countries, Italy ranked third, with more than 70% of buildings exhibiting low energy performance and having an energy class higher than D, indicating one of the poorest energy efficiency ratings. (Figure 2) [30].

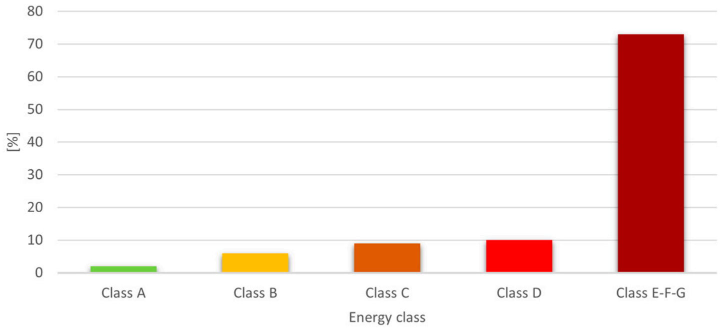


Figure 2. Categorization of the Italian building stock based on energy efficiency on a class rating scale from A (the most performant) to > D (the less performant).

The national real estate stock is predominantly composed of buildings falling into energy classes F and G, accounting for 25% and 37.3%, respectively, according to the Energy Performance Certificates Information System—SIAPE—during the period of 2016–2019 based on ENEA’s calculations [31].

Fortunately, there is a growing trend of nearly zero-energy buildings (nZEBs) in all regions of Italy. The number of nZEBs reached approximately 1400 in 2018, with the majority being new constructions (90%) and being used for residential purposes (85%), as reported by the nZEB Observatory. The non-residential nZEBs also showed a positive upward trend, partly due to the implementation of incentive policies for public buildings [27]. As previously described, out of the 2,740,018 residential buildings in Italy, 53% were constructed between 1946 and 1990 (1,444,160). The construction era class from 1976 to 1990 was found to be the most prevalent in Italy, so the research focused on this specific reporting period.

2.2. Characterization and Cataloging of Existing Buildings Pertaining to the Construction Era Class of 1976–1990

The second step of the methodological procedure involved the determination of parameters aimed at classifying the national residential building stock, developed as part of the research conducted by the research center of Sapienza University of Rome—CITERA—in collaboration with the "Research of the Electricity System" program with ENEA and the Ministry of Economic Development on "Improving the energy efficiency of production processes and management of the built environment" [32]. An elaborate preliminary classification of the building based on reference parameters—climatic zone, era of construction class, building type ("Abacus of building envelope types: stratigraphy and characteristics"), characteristics of the building envelope—represents the first step towards a further accurate formulation of the minimum interventions to be applied to building structures belonging to a specific era of construction and with certain defined typological, constructive, and energy features in order to ensure a minimum double energy class jump in their sustainable renovation of the building envelope and systems.

This study and the subsequent simulations were conducted on a multi-apartment residential building comprising 60 residential units. The building consisted of eight aboveground floors, a basement level, and an accessible flat roof. The construction era of the building fell between 1976 and 1990 (specifically 1982). The choice to consider a case study from this period was motivated by the fact that, according to ISTAT data, more than half of the Italian residential buildings, approximately 60%, were constructed in the post-war period to the 1990s. In order to formulate a decision support tool for selecting the energy efficiency of the building, the characteristics of the building envelope were standardized, and, for this reason, they were inferred from the "Abacus of Building Envelope Types" [32]: for the following sample, four different combinations were identified, derived from the characteristics of the building envelope encountered in the era of construction that was analyzed, and, for each of which, the energy class of the state-of-the-art building stock (ante operam) was extrapolated. The ante operam combinations focused on the characteristics of the dispersing surfaces—bordering the exterior—and were the following: roof, external wall, and floor. Table 1 shows the U-values of the most common types of building envelope closures in the analyzed construction era class in this study.

Regarding the window typology during the period between 1976 and 2005, they were mainly double-glazed windows with an air gap, generally with a wooden frame, with a solar heat gain coefficient (ggl) of 0.75, and with a thermal transmittance (U) of 2.80 W/m^{2}K. These specifications were used in the energy simulation of the ante operam condition. Similarly to what was done for the envelope types, the most commonly used conditioning system typology during the construction period was considered. Specifically, a standard boiler for a centralized system with an atmospheric burner and a chimney over 10 m high with an efficiency (n) of 0.73 was used as the heating generator, and radiators, whose specifications are given in the UNI/TS 11300-2 standard, were used as emission terminals. The chosen building type for the simulations was associated with the most common different envelope typologies encountered in the construction era class under study. The building was placed in six different climatic zones (Table 2) to determine the ante operam energy class (Table 3). This phase of investigation was conducted with the support of certified energy modeling software, which was used to determine the energy models of the actual state of the sample typologies.

Table 1. Combinations of the opaque envelope types in the ante operam sample referred to the construction era class of 1976–1990.

ANTE OPERAM SAMPLE ENVELOPE TYPE COMBINATIONS					
	Building type Construction type Costruction era class	Multi-family multy-story block building Reinforced concrete framed structure 1976 to 1990			
COMBINATION N°:		1	2	3	4
BUILDING ENVELOPE FEATURES *	UHC	Flat roof made of late concrete, low level of insulation (1976 to 1990) U = 1.01 W/m^{2}K	Flat roof made of late concrete, low level of insulation (1976 to 1990) U = 1.01 W/m^{2}k	Flat roof made of late concrete, low level of insulation (1976 to 1990) U = 1.01 W/m^{2}k	Flat roof made of late concrete, low level of insulation (1976 to 1990) U = 1.01 W/m^{2}K
	LHC	Concrete basement on ground, low level of insulation (1976 to 1990) U = 1.24 W/m^{2}k	Concrete basement on ground, low level of insulation (1976 to 1990) U = 1.24 W/m^{2}k	Concrete basement on ground, low level of insulation (1976 to 1990) U = 1.24 W/m^{2}k	Concrete basement on ground, low level of insulation (1976 to 1990) U = 1.24 W/m^{2}k
	VC	Hollow-case masonry with hollow bricks, low level of insulation (1976 to 1990) 30 cm thick U = 0.76 W/m^{2}K	Hollow-case masonry with hollow bricks, low level of insulation (from 1976 to 1990) sp. 40 cm U = 0.78 W/m^{2}K	Hollow brick masonry, low level of insulation (1976 to 1990) 25 cm thick U = 0.80 W/m^{2}K	Hollow brick masonry, low level of insulation (1976 to 1990) sp. 40 cm U = 0.76 W/m^{2}K

* Defined according to the "Abacus of Envelope Types"; UHC—Upper horizontal closure; LHC—Lower horizontal closure; VC—Vertical closure.

Table 2. Climate zones chosen for simulations and energy class legend.

CLIMATE ZONE		
A	Porto Empedocle	(AG)
B	Crotone	(KR)
C	Capistrano	(VV)
D	Castiglion Fibocchi	(AR)
E	San Didero	(TO)
F	Setriere	(TO)

ENERGY RATING	
	A4
	A3
	A2
	A1
	B
	C
	D
	E
	F
	G

Table 3. Simulations' ante operam energy class rating for each typology identified as function of climate zone.

ANTE OPERAM ENERGY CLASS BY CLIMATE ZONE																								
Sample Building with Reinforced Concrete Frame Structure																								
N° ANTE OPERAM TYPE	**1**						**2**						**3**						**4**					
CLIMATE ZONE	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
ENERGY RATING	F	F	F	G	G	G	F	F	F	G	G	G	F	F	F	G	G	G	F	F	F	G	G	G
EPgl,nren (kWh/m^2 year)	80.00	91.73	114.77	182.78	223.43	371.68	80.70	92.58	115.85	184.51	225.62	375.18	81.82	93.94	117.75	187.49	229.38	381.37	81.09	93.06	116.65	185.66	227.10	377.52
CO_2 emissions (kg/m^2 year)	1036.14	1188.10	1485.63	2368.11	2894.84	4816.07	1046.57	1200.69	1501.72	2392.91	2927.20	4867.76	1060.39	1217.50	1525.30	2431.06	2975.24	4945.52	1051.70	1207.13	1512.19	2408.94	2946.71	4898.79

2.3. Definition of Simulations of Efficiency Interventions

In the following phase, all potential combinations of energy efficiency improvement interventions were formulated, varying in their impact on the building and in the potential inconveniences they may cause to the residents. These interventions aimed to achieve the targets set by the new regulations, a transition to energy class E by 2030 and energy class D by 2033, compared to the existing state-of-the-art building stock for each identified ante operam typology. All post operam simulations of the sample were conducted, once again using an energy performance certificate software.

The methodological process for conducting all case simulations was specifically focused on a single typological combination. This combination was precisely determined by the fact that, for all four building types, there exists a similar building structure in which, as demonstrated, the same energy class was achieved in the ante operam phase.

Firstly, interventions that could be replicated uniformly across each multi-apartment residential building were identified. The simulated interventions fell into three types:

- Interventions on the external walls and roof, including windows;
- Interventions for the replacement of the conditioning system;
- Combined interventions for the building envelope and the system.

Each type of intervention was associated with specific nomenclature (Table 4).

To achieve the energy class jump to E by 2030 and the energy class jump to D by 2033, possible combinations of primary and secondary interventions were defined. All combinations of simulated interventions were generated while adhering to the minimum U-values of the architectural components, including horizontal opaque structures (roofs and floors), vertical opaque structures (perimeter walls), and vertical transparent structures (windows and doors). The minimum U-values of the building envelope elements were defined based on the climatic zone in which the building was located as stipulated in "Annex E—Requirements for thermal insulation measures" (5/10/2020, *Official Gazette of the Italian Republic* [33]) and were calculated according to UNI EN ISO 6946:2007 standards.

For the replacement of the winter air conditioning system, two options were considered: the installation of a condensing boiler (S_IMP_CO-CON) or the implementation of a hybrid system that combined a heat pump with a condensing boiler (S_IMP_SI). The primary intervention, which involved replacing the standard boiler with a condensing boiler, had to meet the requirement of a minimum useful thermal efficiency at full load equal to 100% as mandated by regulations, where $\eta s \geq 93 + 2\log Pn$. Additionally, the system itself had to belong to product class A.

The intervention involving the installation of a hybrid system had to include a condensing boiler belonging to product class A. The hybrid system should have a useful thermal efficiency at 100% load equal to $\eta s \geq 93 + 2\log Pn$, and the heat pump component should have a minimum coefficient of performance (COP) of 3.8 for air–water heat pumps with a useful heating thermal output less than 35 kW. These requirements applied to interventions with a work start date after October 6, 2020, which included the simulation case. Furthermore, the ratio of the rated useful heating output of the heat pump to the rated useful heating output of the boiler had to be ≤ 0.5 [34]. Moreover, in conjunction with such interventions, where technically feasible, there was an obligation to install low-thermal-inertia thermostatic valves (or another modulating-type thermoregulation system) to control the flow rate in the existing heating bodies (I_VLV-TER_SAM-CLIM).

Table 4. Possible energy efficiency interventions' definitions with their own nomenclature.

ENERGY EFFICIENCY INTERVENTIONS								
DESCRIPTION	**CODING 1**	**INTERVENTION SPECIFICATIONS**	**CODING 2**	**OTHER SPECIFICATIONS**				**NOMENCLATURE**
Winter air conditioning system replacement in the common parts	S_IMP_	Condensing boiler * Hybrid system **	CA-CON SI					**S_IMP_CA-CON** **S_IMP_SI**
Thermostatic valves installation	I_VLV-TER_	Single room plus climatic	SA-CLIM					**I_VLV-TER_SA-CLIM**
Existing windows replacement	S-INF_	Double low-e double glazing air gap, metal frame with thermal break	DV-BE-A	TRANSMITTANCE U	2.50 W/m^{2}K	ggl,n	0.50	**S-INF_DV-BE-A**
		Double glazing low-e double glazing Argon cavity, metal frame with thermal cut	DV-BE-ARG		1.50 W/m^{2}K		0.50	**S-INF_DV-BE-ARG**
		Triple glazing low-e double glazing Argon cavity, metal frame with thermal cut	TV-BE-ARG		1.00 W/m^{2}K		0.50	**S-INF_TV-BE-ARG**
Opaque envelope thermal insulation	IS-TERM_	Roofing insulation in XPS panels - extruded polystyrene foam	CO-XPS	**THICKNESS**				**IS-TERM_CO-XPS_10 cm**
				_10 cm	_12 cm	_14 cm	16 cm	
				THERMAL CONDUCTIVITY (λ) λ = 0.031 W/mK				**IS-TERM_CO-XPS_12 cm**
				c = 1450 J/kgK ρ = 35 kg/m^3				**IS-TERM_CO-XPS_14 cm**
								IS-TERM_CO-XPS_16 cm
		Rock wool panel coating system ***	SC-LR	**THICKNESS**				**IS-TERM_SC-LR_6 cm**
				_6 cm	_8 cm	_10 cm	_12 cm	
				THERMAL CONDUCTIVITY (λ) λ = 0.032 W/mK				**IS-TERM_SC-LR_8 cm**
				c = 1030 J/kgK ρ = 30 kg/m^3				**IS-TERM_SC-LR_10 cm**
								IS-TERM_SC-LR_12 cm
		Phenolic foam board coating system ***	SC-SF	THICKNESS				**IS-TERM_SC-SF_4 cm**
				_4 cm	_6 cm	_8 cm	-	
				THERMAL CONDUCTIVITY (λ) λ = 0.021 W/Mk				**IS-TERM_SC-SF_6 cm**
				c = 1750 J/kgK ρ = 35 kg/m^3				**IS-TERM_SC-SF_8 cm**

* Class A condensing boiler ($\eta s \geq 93 + 2$ logPn); ** Hybrid system: Class A condensing boiler ($\eta s \geq 93 + 2$ logPn) and air-water heat pump COP = 3.8; *** In accordance with the transmittance limits provided for the considered climatic zone for transparent and opaque surfaces based on "Annex E - Requirements for thermal insulation interventions" - 5/10/2020, Gazzetta ufficiale della Repubblica italiana.

Regarding the efficiency of the vertical opaque envelope, simulations were conducted using two different types of thermal insulation with distinct technical specifications and costs per square meter: rock wool and phenolic foam. The first type of insulation (IS-TERM_SC-LR_sp) is commonly utilized for external cladding due to its water-repellent and fire-retardant properties; recyclability; excellent sound absorption; and resistance to mold, fungi, and bacteria formation. It falls within the low price range (<EUR 30/m^2) and has a good thermal conductivity value (λ = 0.032 W/mK). The second type of insulation (IS-TERM_SC-SF_sp) belongs to the medium–high price range (>70 and <EUR 100/m^2), but it boasts an excellent thermal conductivity value (λ = 0.021 W/mK), allowing for thinner panels to be applied on the facade compared to the first option of rock wool insulation. The selection of these two different insulation solutions was motivated by the desire to subsequently compare the simulations based on the cost effectiveness of the class jump ratio and the final price.

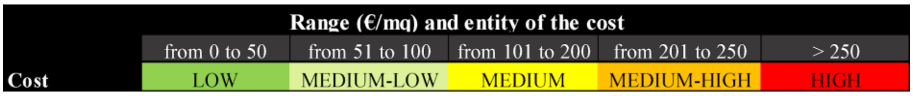
For opaque horizontal surfaces, such as roofs, the preferred insulation material used was XPS (extruded expanded polystyrene). XPS offers excellent impact resistance and has a good thermal conductivity value (λ = 0.031 W/mK). Additionally, it falls within the low price range (<EUR 30/m^2). The thickness of the insulation panels was determined based on the requirement to comply with the maximum values of thermal transmittance for the specific climate zone. Consequently, the insulation thickness increased when transitioning from climate zone A to climate zone F. Concerning the efficiency of the transparent envelope, the simulations incorporated three distinct types of window frames with varying transmittance and specifications depending on the climate zone in which they were installed as replacements for existing ones. The most commonly employed window frame types were as follows:

- Low-emissivity double-glazed window frames with air gap and metal frame with thermal break from the manufacturer transmittance (Uf = 2.5 W/m^{2}K) and solar factor (gg,l = 0.50) (S-INF_DV-BE-A);
- Low-emissivity double-glazed window frames with argon cavity and metal frame with thermal break from manufacturer transmittance (Uf = 1.50 W/m^{2}K) and solar factor (gg,l = 0.50) (S-INF_DV-BE-ARG);
- Low-emissivity triple-glazed window frames with argon cavity and metal frame with thermal break from manufacturer transmittance (Uf = 1.00 Q/m^{2}K) and solar factor (gg,l = 0.50) (S-INF_TV-BE-ARG).

Table S1 presents the complete set of combinations derived from the simulation conducted on the selected sample, serving as a guide for improving the energy efficiency of the Italian residential building stock constructed during the 1970s and 1980s. The table below provides the specifications for each combination, with their nomenclature derived from the climate zone in which the multi-apartment residential building was situated. The combinations were categorized based on the specific technical element on which the interventions were focused: envelope only, air conditioning system only, or a combination of interventions targeting both the envelope and system.

2.4. Economic Estimation of Energy Efficiency Interventions

In this phase, the costs per square meter for each combination of interventions were determined to classify them into specific price ranges: low, medium–low, medium, medium–high, or high. This would allows beneficiaries of this tool to align their chosen intervention typology with their budgetary constraints. Following the identification of the potential intervention combinations, the energy performance certificates (A.P.E.) for the various post operam scenarios were systematically processed considering the new energy class ranking. The ranking began with minimal class jumps and progressed towards more comprehensive interventions that yielded higher energy performance, particularly in cases of mixed interventions targeting both the building envelope and system. Furthermore, for each combination, the parametric cost per square meter was estimated and depicted in a graph, reflecting the magnitude of the cost within the low, medium, or high range (Figure 3).



	Range (€/mq) and entity of the cost				
	from 0 to 50	from 51 to 100	from 101 to 200	from 201 to 250	> 250
Cost	LOW	MEDIUM-LOW	MEDIUM	MEDIUM-HIGH	HIGH

Figure 3. Cost range per square meter defined for every intervention.

3. Results

The study of the national building heritage clearly indicates that the existing buildings constitute a crucial sector for reducing greenhouse gas emissions in the coming years. In this context, the proposed research aims to develop a decision support tool for improving the energy efficiency of the existing buildings through an analysis of the building stock and through a systematic approach to retrofitting.

The study described so far has allowed for the identification of all the intervention combinations that enable the improvement of the energy class as required by the new regulations and assesses their economic feasibility based on the climatic zone.

The graphs in Figure 4, categorized by climate zone, display all the intervention combinations (COMBO_Climatic Zone—N°). The green areas represent the most cost-effective interventions in terms of the quality–price ratio, while the yellow areas indicate moderately convenient interventions. The red areas represent interventions that are less economically viable considering the combination of high costs and a minimal energy class improvement. These cost estimates were derived from the example building, using the DEI 2023 Price List ("Prezzario DEI 2023") as a reference.

The cost–benefit analysis tables containing each combination provide a clear and concise overview of the most and least advantageous interventions to implement and the achievable energy class improvements. Each graph shows on the x-axis the energy class improvement achievable through a specific combination of interventions, while the y-axis represents the cost per square meter. Additionally, the graphs are divided into four different cost-effectiveness areas: in the red area, the combinations offer a low energy class improvement and are expensive; the two yellow areas represent combinations that have either a low energy class improvement but are cost effective or that have a high energy class improvement but are not cost effective; and, finally, in the green areas, the best combinations in terms of the quality–price ratio (energy class improvement vs. price) are found. Each combination is classified into one of the four aforementioned zones based on the achieved energy class improvement and the cost per square meter. In other words, from the cost–benefit analysis (Figure 4), it is evident that the most advantageous interventions, considering the amount spent and the achieved energy class jump, in all six climatic zones involve replacing the existing conditioning system with a hybrid system and installing thermostatic valves. Similarly, interventions that include rock wool insulation for opaque surfaces show a favorable cost-effectiveness ratio. On the other hand, interventions focused solely on the opaque and transparent envelope appear to be less advantageous. In particular, to achieve an increase of at least one energy class and to move to class E, as required by 2030 for zones A, B, and C, a thermal insulation intervention in the horizontal and vertical opaque surfaces is sufficient. However, for zones D, E, and F, it is also necessary to replace the existing windows with more efficient ones to achieve the same result. If the aim is to reach energy class D, as required by the directive by 2033, for climatic zones A, B, and C, a combined intervention involving the thermal insulation of the building envelope and the replacement of the existing windows with more efficient fixtures is necessary. Alternatively, it is possible to replace the existing air conditioning system with a high-performance condensing boiler and to install thermostatic valves. For zones D and E, it is necessary to replace the existing air conditioning system with a condensing boiler system and to install thermostatic valves. As for zone F, a combined intervention involving the thermal insulation of both the opaque and transparent surfaces and the replacement of the air conditioning system is required. The various combinations of interventions in the building envelope and system will subsequently ensure the achievement of higher energy classes. Therefore, this tool will also be useful for future directives with stricter energy efficiency requirements.

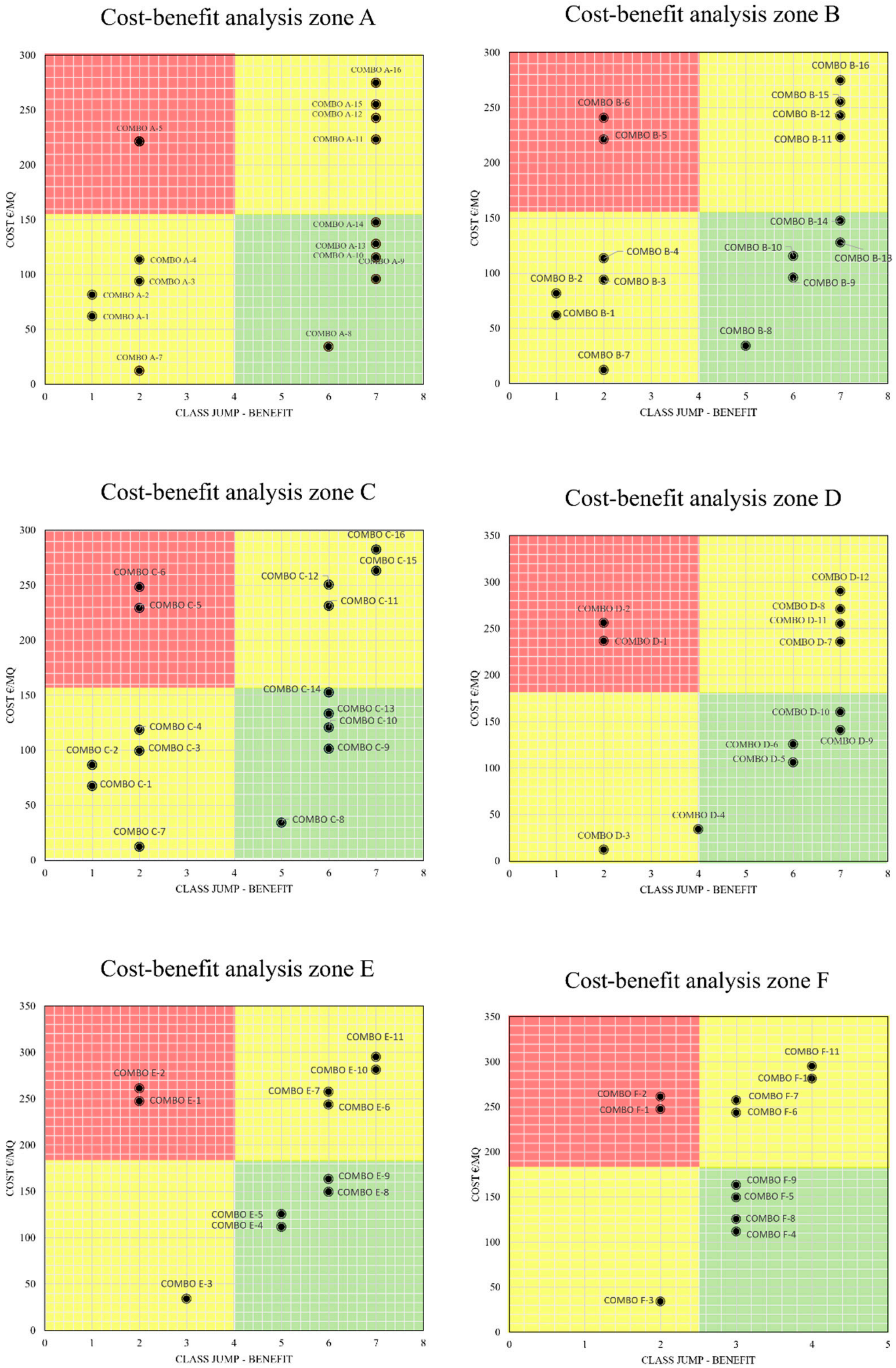
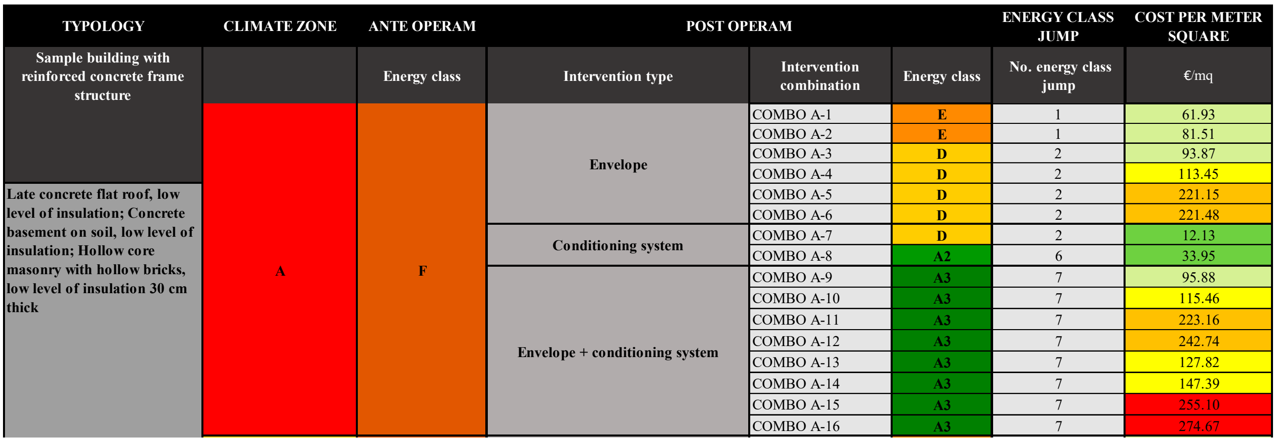


Figure 4. Cost–benefit graphs according to the climatic zone.

The research outcome is an Energy Efficiency Improvement Matrix that allows the user to identify a comprehensive set of combinations to employ based on their specific needs in terms of the desired quality, the materials to be used, and budget considerations. In fact, this tool illustrates, for each Italian climatic zone, the types and quantities of interventions required to achieve a certain energy class improvement. The user will directly observe, starting from the pre-intervention energy class, what the final post-intervention energy class will be, which interventions need to be implemented to achieve this improvement, the technical specifications of these interventions, and the total cost per square meter. This means that this study involves data processing and identifying all the intervention combinations associated with a specific energy class jump. Therefore, the proposed tool for improving the energy efficiency of buildings constructed in the 1970s and 1980s provides standardized and applicable intervention solutions to achieve the desired class jump, aiming for a minimum of class E by 2030 and class D by 2033, up to higher energy class jumps while considering the cost–benefit ratio.

Table S2 provides a dynamic summary matrix of all the intervention combinations categorized by climate zone, ante operam energy class, intervention type, post operam energy class, the number of energy class jumps, and cost per square meter.

In Figure 5, an excerpt from the matrix of energy efficiency interventions is presented, containing the following information: the description of the building envelope, the climatic zone, the pre-intervention energy class, the applicable intervention types and their combinations, the achievable energy class, the energy class improvement achievable with the proposed interventions, and the cost per square meter of the intervention.



TYPOLOGY	CLIMATE ZONE	ANTE OPERAM	POST OPERAM			ENERGY CLASS JUMP	COST PER METER SQUARE
Sample building with reinforced concrete frame structure		Energy class	Intervention type	Intervention combination	Energy class	No. energy class jump	€/mq
Late concrete flat roof, low level of insulation; Concrete basement on soil, low level of insulation; Hollow core masonry with hollow bricks, low level of insulation 30 cm thick	A	F	Envelope	COMBO A-1	E	1	61.93
				COMBO A-2	E	1	81.51
				COMBO A-3	D	2	93.87
				COMBO A-4	D	2	113.45
				COMBO A-5	D	2	221.15
				COMBO A-6	D	2	221.48
			Conditioning system	COMBO A-7	D	2	12.13
				COMBO A-8	A2	6	33.95
			Envelope + conditioning system	COMBO A-9	A3	7	95.88
				COMBO A-10	A3	7	115.46
				COMBO A-11	A3	7	223.16
				COMBO A-12	A3	7	242.74
				COMBO A-13	A3	7	127.82
				COMBO A-14	A3	7	147.39
				COMBO A-15	A3	7	255.10
				COMBO A-16	A3	7	274.67

Figure 5. Extract from Table S2 which presents the research results for climatic zone A.

The tool allows users to determine the climatic zone in which the building that is subject to future energy efficiency interventions is located. Subsequently, the characteristics of the opaque and transparent building envelope before the intervention as well as the type of installed system are identified. The tool automatically presents the user with the most suitable combinations of solutions for the specific case study. Additionally, it further allows for the selection of combinations based on their cost within a specified price range.

4. Discussion

In recent years, the threats of global warming have become increasingly apparent, leading to a heightened focus on energy and environmental issues [35,36].

It is evident that the building and construction sector exerts a significant impact on the phenomenon of climate change. It stands as one of the primary contributors to pollution, attributable to the excessive emissions released into the environment as a result of the heating and cooling processes in buildings [37]. At the same time, the building sector has evolved into a strategic domain, given its potential to implement energy-saving measures more effectively compared to other sectors, such as transportation and industry [38].

In the EU, for example, residential buildings hold the most substantial potential for energy savings [39], with household energy savings comprising the highest proportion (44%) compared to other sectors [40].

The poor thermal performance of residential buildings and the consequent increasing energy demand can also lead to energy poverty, which refers to the inability of households to meet their energy needs [41]. In EU countries, many people struggle to heat or cool their homes or pay energy bills, resulting in a prevalence of energy poverty [42].

Reducing greenhouse gas (GHG) emissions requires a simultaneous improvement in energy efficiency and the increased implementation of renewable energy sources (RESs).

Such actions will not only enable a reduction in greenhouse gas emissions but will also promote energy savings to address energy poverty, improve health and well-being, and create new growth and employment opportunities [43–45]. Most EU countries, including Italy, experience low levels of energy efficiency in the residential sector, primarily due to aging buildings and a lack of renovation strategies in recent years. Therefore, tools and measures that promote energy efficiency in residential housing are crucial.

As in similar studies [46–49], the results of this work aim to promote energy efficiency interventions considering the high percentage of buildings with an outdated energy performance and the urgent need to upgrade the entire building stock. Unlike other studies that focus solely on defining energy efficiency interventions, this research has proposed a valuable tool to identify effective solutions both from an energy and economic perspective, ensuring compliance with the increasingly stringent energy class requirements imposed by new regulations. These findings represent an excellent starting point for proposing and promoting the retrofitting measures that are essential to reducing CO_2 emissions.

However, the conducted research provides a decision support tool to promote the application of energy efficiency solutions currently focused on a specific building typology and a specific construction period. Therefore, this study can be expanded to other building typologies (such as isolated buildings, single-family buildings, or duplexes; towers; buildings with balcony access; palazzine; or block buildings) and other construction era classes (until 1900, from 1901 to 1920, from 1921 to 1945, from 1946 to 1960, from 1961 to 1975, from 1991 to 2005, or after 2005). To improve the energy performance of buildings, combinations of solutions that also include the installation of photovoltaic systems will be integrated into the tool. These systems are essential for achieving the objectives set by the REPowerEU plan, which aims to increase energy savings, diversify the energy supply, and promote the rapid dissemination of renewable energies [50]. The promotion of photovoltaic system installations will enable the creation of new renewable energy communities together with the development of more decentralized energy resources [51]. Energy communities represent an innovative strategy to respond to the growing need to combat energy poverty and to encourage citizens' participation in the energy transition, focusing on self-consumption and collaboration [52].

For future research, the selection of solutions currently based on energy and economic performance parameters may be complemented with environmental parameters. Indeed, although such measures result in a reduced operational energy demand, they increase material usage and, consequently, the production energy demand. Therefore, the role of the embodied and operational life cycle energy performances should be considered together before proposing retrofit actions for buildings [53].

Minimum environmental criteria and a Life Cycle Assessment (LCA) approach will be fundamental in the choice of energy efficiency solutions for buildings [54]. The Life Cycle Assessment (LCA) is an analytical tool that enables a holistic view of the potential environmental impacts associated with a product or service throughout its entire life cycle from raw material extraction to end-of-life management (from cradle to grave). The LCA can be utilized in decision-making processes that inherently consider the global, national, regional, and local impacts on social and environmental issues, such as human health, resource depletion, and ecosystem quality [55]. The retrofitting measures to be simulated to verify the energy class balance will, therefore, be subsequently based on the results of the

LCA, allowing for a comparison between the different materials and technologies available on the market for a more informed choice.

Furthermore, future developments of the proposed energy efficiency tool will focus on creating an advanced BIM-based tool that can automatically identify the recommended interventions for users based on factors such as climatic zone, building typology, construction type, and cost considerations [56].

The selection of the most sustainable options in each situation therefore requires a decision-making methodology that can be used to prioritize the available retrofit solutions based on economic, functional, environmental, and social criteria. These aspects will be studied by the authors to provide a new tool aimed at supporting the ongoing ecological and digital transition.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en16176245/s1, Table S1: Summary of all the hypothesized intervention combinations in the simulations; Table S2: Summary of dynamic matrix of all combinations of interventions.

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