Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings

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http://dx.doi.org/10.1016/j.enbuild.2016.07.044

Keywords:
Retrofit actions
Energy performance
Economic analysis
Historical building

abstract

The application of retrofit actions to existing building stocks can improve the energy performance of the residential sector. In this context, particular attention should be given to historical buildings, which represent a large part of the Italian building stock. To improve the energy performance of them, adequate retrofit actions must be applied. Many studies and regulations have focused on identifying the best refurbishment measures. However, the selection of these measures is difficult due to restrictive regulations, which are dictated by the Ministry of Cultural Heritage and Activities, high retrofit costs, and variable climate zones. Thus, energy renovations in Italian buildings are not simple, and it is very difficult to find generic solutions that can be applied to buildings across the entire territory.

In this paper, the authors investigated the most common retrofit solutions used in Italy, focusing in particular on the energy performance of historical building envelopes. First, energy performance analyses were conducted for two typical base cases in four different Italian cities using TRNSYS software, and some common retrofit measures were analysed. In some cases, the results showed Primary Energy saving of 44.6% (sample A) and 56.7% (sample B). Furthermore, these were used to identify different energy and economic impacts associated with the same refurbishment measures in different climatic contexts, highlighting the non-existence of a generic solution suitable for all regions or countries.

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1. Introduction

The primary energy demand has been continuously rising, and this trend is likely to continue in the future as affirmed by British Petroleum [1]. However, thanks to EU energy policies restricting primary energy consumption, several goals have been achieved, including an approximately 20% decrease in greenhouse gas emissions, a 20% increase in renewable energy installations, a 20% increase in overall energy efficiency, and other goals [2–4]. In this regard, many energy measures have been developed and applied in various sectors, paying particular attention to existing buildings, which account for approximately 40% of the primary energy demand in Europe [5]. There is currently a focus in Italy on improving the energy performance of historical buildings [6].

In the framework of conservation, integrated refurbishment and retrofit actions, many aspects of energy performance must be considered and resolved.

Over 4,000,000 of the 5,367,000 monuments worldwide are located in Italy. These monuments often involve compromise between architectural heritage, public administrations, offices and housing units [7,8], which have the common characteristics of poor energy performance and high primary energy demand.

Moreover, energy retrofit actions have often focused on modern buildings, generally built before the Second World War. However, the national building stock includes many buildings built before 1919 intended for public or residential use. According to Italian regulations, these buildings are excluded from minimum energy requirements after the energy retrofit actions, if such retrofits are even feasible. Particularly, it is difficult to reduce primary energy consumption in residential buildings because these actions are often expensive, voluntary and linked to irregular decisions. Furthermore, refurbishment is often based on generic indications of retrofit actions without considering the economic feasibility and energy feasibility, which are dependent on the climate context and the shape factor of the building.

This paper aims to recognize, analyse and dynamically simulate several energy retrofit solutions applicable to historic residential buildings in Italy. In particular, the authors analysed the major

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Nomenclature

C_{Cool}	Cost of consumed kWh for cooling [D/year]
CF	Cash flows [D]
C_{Heat}	Economic cost of consumed kWh for heating [D/year]
C_{kWht}	Specific kWh economic cost [D]
DCF	Discounted cash flow [D]
Fc	Fuel cost [D]
LHV	Lower heating value [kWh]
PE	Primary energy [kWh]
PV	Present value [D]
RES	Renewable energy sources [–]
S_{Cool}	Economic energy saving (cooling) [D/year]
S_{Heat}	Economic energy saving (heating) [D/year]
$S_{PE,h}$	Primary energy savings (heating) [kWh]
$TC_{Heat,x}$	Generic thermal consumption based on heated floor area and kWh cost [D/year]

retrofit actions that affect the building envelope, because in the historic building context is often difficult to integrate the installation of a heating/cooling system. In fact, in order to reduce the primary energy demand of a building it is necessary to investigate the relationship between the envelope and climate, and to evaluate internal loads.

A good performance of the building envelope permits to minimize the power of a heating/cooling system and so to reduce the consumption. By this way, two representative case studies with two different shape factors (Base case A and Base case B) were hypothesized; and for each case, eight different retrofit actions were proposed. The energy performances of these cases were simulated by using TRNSYS software [9] in four Italian cities (Palermo, Cagliari, Roma and Milano) representative of four different climate zones (B, C, D and E). Simultaneously, energy and economic evaluations were conducted to determine the feasibility of and prioritize the best retrofit actions; this analysis permits to underline, as the choice of the most important retrofit action is not immediate.

2. Italian historical building stock

Since 1991, Italian standards and regulations have focused on the energy refurbishment of existing buildings. However, according to the Legislative Decree 192/2005 [10] and the subsequent modifications [11,12], no energy retrofits were mandated for historical buildings due to their "historical protected status" [13].

The entire Italian residential building stock amounts to 11,226,595, with an average area of approximately 96m^2. Of these residential buildings, 1,200,000 are considered "historical".

Key goals were established by EPBD regulations in European countries; however, the degrees of adoption and implementation of these measures vary by country and are based on building stocks [2–4,14].

In Italy, focusing on the ages of buildings, the results showed that just 6.0% of buildings built before 1950 have energy certificates [15]. Although the regulations have been upgraded by the Italian government, the issue of historical building refurbishment has not been solved [16,17], while other countries have already proposed solutions [18–21]. In this context, many international projects [22,23], guidelines and approaches have been developed and suggested based on nZEB requirements for existing buildings [24–26]. In all of the previously assessed cases, inadequate energy performance, non-feasible RES installation and high costs were the most significant issues for buildings built before 1919 [27–29].

Italy has a "unicum" overview of architectural heritage, which spans from the X to the XXI century. The TABULA project is classifying residential buildings [30,31]. By conducting a data analysis, eight "building age classes" can be identified, each representing a construction period, reflecting changes in the morphological, constructive and technical system characteristics of the Italian building stock. The building age classes are as follows: Class I (up to 1900), Class II (from 1901 to 1920), Class III (from 1921 to 1945), Class IV (from 1946 to 1960), Class V from (1961–1975), Class VI (from 1976 to 1990), Class VII (from 1991 to 2005) and Class VIII (after 2005).

To conduct an energy analysis of this building stock, TABULA, Italian climate zones and ISTAT data were combined. The result shows that over 2,147,400 residential buildings were built before 1919 [32–34]. In Fig. 1, the distribution of these buildings, for different climate zones, is reported.

Climate zones are areas in the Italian territory that (theoretically) have the same climate and identical or similar climatic conditions. Indeed, Italian Standards are based on ideal heating energy demands (considering 24 h operation) and heating systems turning on or off based on the interactions of building plant systems in the six climate zones from A (the hottest zone) to F (the coldest zone) and on heating degree days (HDD) classifications. For each zone, the daily use turn-on heating systems and their periods vary from six to "unlimited" operating hours [35,36]. By matching data between the ISTAT and ENEA databases [37], the municipal distribution per climate zone and the distribution of historic residential buildings have been determined. As shown in Fig. 1, most historical buildings (~70%) are within zones D and E, while just 0.011% are located in zone A.

2.1. Feasibility of energy retrofit actions in historical buildings

Typical residential Italian buildings built before 1919 have large thermal envelopes and were generally constructed using local stones or brick and mortar, with important thickness characteristics. Originally, horizontal structures were often composed of wooden double walls with canes vaults supported by stone and mortar. Often, these buildings had underground spaces and ground floors for gigs or carriages. The first floor was typically composed of sequential rooms. The windows had wood frames and were often different sizes depending on the building value. The heating system, when present, was a heater or fireplace, while modern heating/cooling and domestic hot water production systems have been progressively introduced [38,39].

The increasing interest in the energy knowledge of the Italian residential building stock has prompted many researchers to develop and propose retrofit energy actions by developing urban energy maps and characterizing actual energy conditions associated with architectural heritage, seasonal heating and cooling, and electrical energy demand of buildings [40–44]. The major questions are as follows: what retrofit action is most applicable to historical Italian buildings and how much does each action decrease the primary energy consumption?

In this context, each energy retrofit must be weighted. First, detailed knowledge of the thermo-physical parameters of the entire thermal envelope of a building, including thermal heat flow, thermal inertia, insulation level, etc., must be obtained to identify the proper actions [45]. In historical buildings, refurbishment materials must meet requirements associated with hydrophobic properties, fire safety, aesthetic quality, cultural heritage impacts, maintenance, etc. [46–48].

A focused literature review shows that the preferred best practices take into account the insulation proprieties of several plasters available for external and internal applications [49,50], while few studies have focused on interior wall insulation via application of an internal coat or specific insulation panels [51,52].

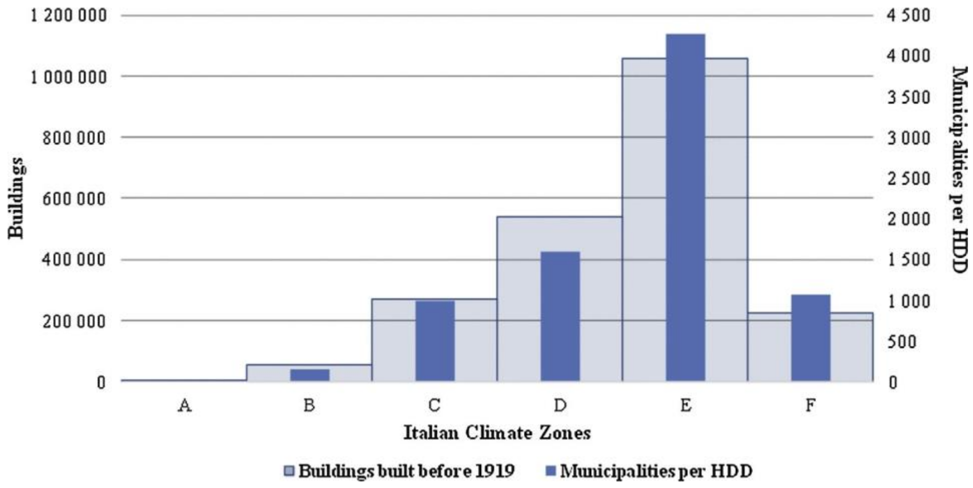


Fig. 1. Matching data between historical residential building per Climate zone.

In the first case, the action applicability is very easy and material quality is often implemented by using natural vegetal aggregate deriving from the corn production waste. While, in the latter case, despite considerably improving the energy envelope performance, the application must account for the wall orientation and climate zone to avoid condensation phenomena. However, this type of solution can be feasible if proper application techniques are used.

Large primary energy demands are due to heating, ventilation and air conditioning systems [53], especially in historical buildings due to several architectural characteristics and legal exemptions. However, some smart solutions can be adopted by taking into account a building's historical value. The solutions include modifying seasonal, indoor temperature set points; installing thermostatic valves and zone thermostats; and introducing heat accounting [54], BACS [55] and lighting control mechanisms [56]. Note that in the Italian historical centre, it is difficult to install renewable energy sources due to strict regulatory constraints [57–60]. It must be highlighted that some energy retrofit actions are easier to apply than other ones i.e. window replacement. Therefore, in terms of operational and energy advantages, the implementation of these actions is not always easy or feasible and in any case an unique way. At this purpose, several authors have been analysed some methods able to identify retrofit scenario optimization by using: a) multi-criteria optimization through uncertainties in Life Cycle Assessment and Life Cycle Costs [61]; b) multi-objective analysis (maximum economic performance, energy consumption minimization and lowest achievable indoor thermal discomfort) [62]; c) climate change prediction [63]; d) stakeholder involvement [64]. However, in all analysed studies, concerning the retrofit measures optimization old buildings are not taken into account. As discussed below, this work could help to fill this gap by focusing on Italian old building retrofit. So, in the following sections, two representative case studies are described and analysed.

3. Case studies: a typical residential old building

To improve the energy efficiencies of buildings, it is necessary to evaluate each retrofit action's feasibility. Indeed, not all retrofit actions are necessary and they may not improve the energy performances of buildings based on the boundary conditions, building geometry and building orientation, particularly in a historical context.

In this paper, the authors analysed the energy performances of typical, residential, historical buildings (base cases) in the four climate zones of the Italian peninsula (from B to E) and calculated generalized results for two different base cases considering different shape factors, losses and surface/heated gross volumes (S/V) (Fig. 2). In each case, several retrofit actions improved the energy performance, and the results of these actions were analysed.

Table 1
Thermal transmittance of the case study building.

Envelope opaque Element	Thickness [m]	Transmittance U_{pre} [W/m2K]	
external wall	0.55	1.04	U_{ew}
roof	0.08	1.89	U_r
ground floor	0.45	0.65	U_g
internal wall	0.10	1.78	U_{iw}
ceiling	0.32	1.96	U_c

A single-family house, representing a typical dwelling, located in the historical centre of an Italian town and constructed before 1919 was chosen for analysis. This typology is characterized by a multifunctional volume from ground to roof, two or three floors, limited floor space and the presence of other adjoining dwellings.

This type of building belongs to the terraced houses type. It is characterized by a combination of more housing units, side-by-side. The single housing unit has a narrow front developing in depth and height of several floors. Generally, it is a family housing, characteristic of the urban centre of the Italian cities. In order to evaluate the different heat losses conditions, two typical positions were chosen, a middle building and an end/beginning building of row.

The building is characterized by a bearing wall made of local stone with internal and external plaster, internal walls made of hollow brick and a sloping tile roof. In this case, a dwelling with three floors constructed before 1919 was chosen. The dwelling floor space is 6.40×9.50m^2 and the average height of each floor is approximately 3.2 m. To analyse a possible configuration, two typical boundary conditions are studied. Sample A represents a dwelling with two bordering dwellings (S/V = 0.43), while Sample B has one bordering dwelling, as shown in Fig. 2. (S/V = 0.85). So, thermo-physical characteristics are shown in Table 1.

To evaluate the energy requirements, a dynamic model has been implemented by using TRNSYS 17.

In detail, two different models with different shape factors were built. The transparent envelope of each model was characterized as in the following: wooden frame windows with single glazing and wooden shutters are installed in this building. The average U-value of a standard window (1.24m×1.48m) is approximately 5.68W/m^{2}K. As mentioned above, historical buildings are characterized by small window areas, and in both analysed cases, the

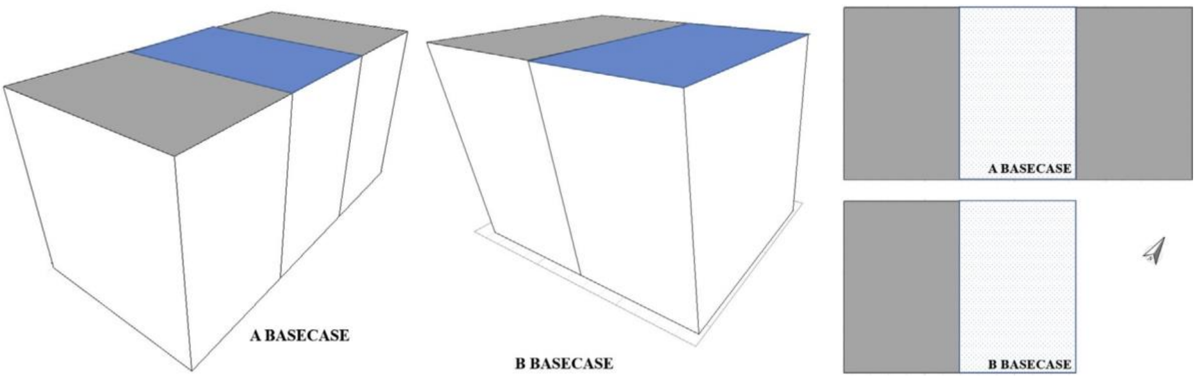


Fig. 2. Schema of Base Cases: Sample A and Sample B.

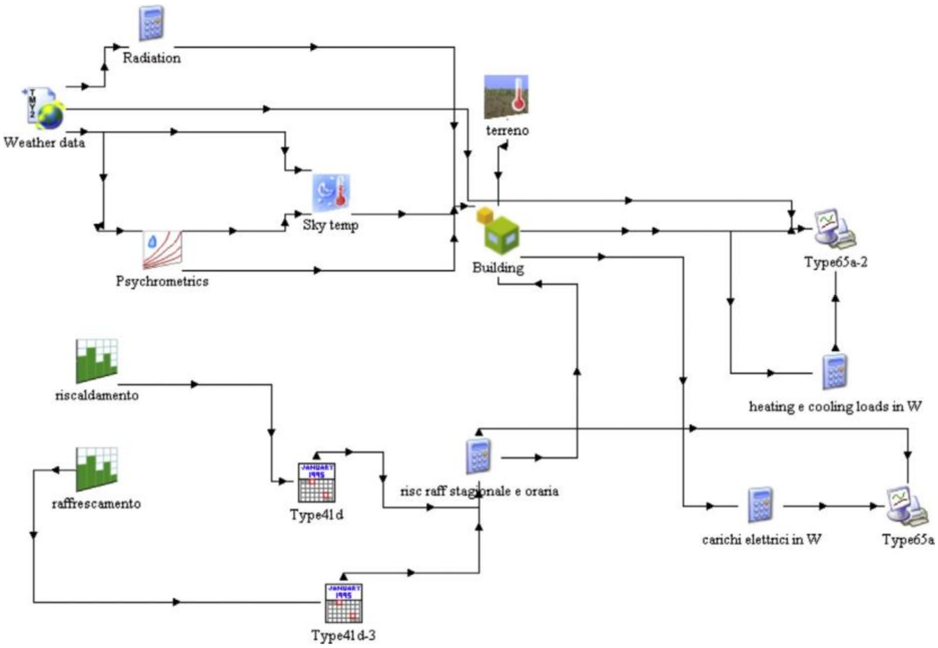


Fig. 3. TRNSYS model description.

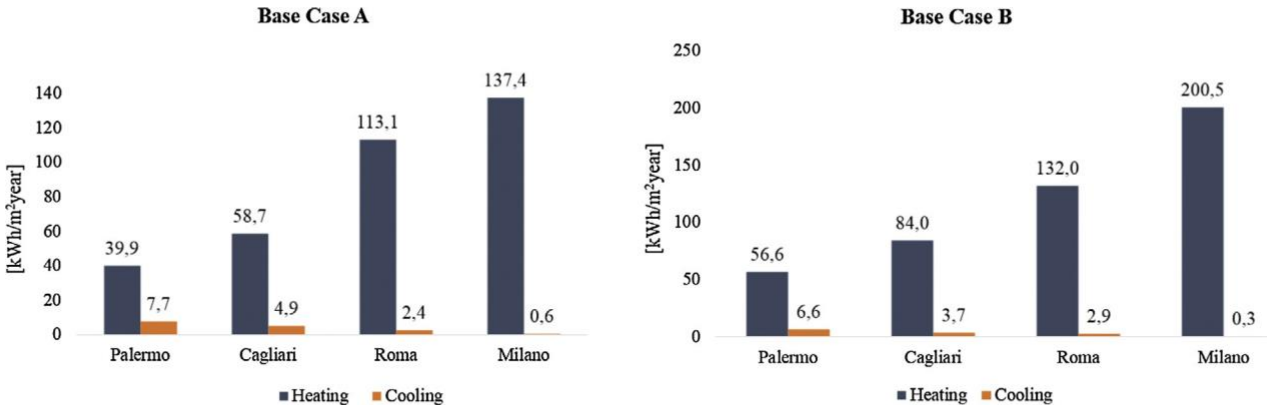


Fig. 4. Primary Energy demand of Base Case A and Base Case B for each Climate zone.

considered window surface/opaque envelope ratios are approximately 0.04.

All U-values are calculated according to the UNI EN ISO 6946:2008 standard [65] for the opaque envelope and the EC 22012 UNI EN ISO 10077-1:2012 standard [66] for glass enclosures.

Furthermore, the ground floor U-value (U_{pre} = 0.65 W/m^{2}K) was evaluated considering the ground heat exchange using the Type 77 “Simple Ground Temperature Profile” in TRNSYS software 17.

Then, to analyse the energy performances of the buildings in all climate zones [67], four different Italian cities were chosen. Table 2 provides information for the chosen Italian cities used as case stud-

Table 2
Climate zones, HDD, Heating season and operating hours of four Italian cities.

Italian Cities	HDD	Climate Zones	Heating season	Operating hours
Palermo	751	B	from 1st dec to 31th mar	8
Cagliari	990	C	from 15th nov to 31th mar	10
Roma	1415	D	from 1st nov to 15th apr	12
Milano	2404	E	from 15th oct to 15th apr	14

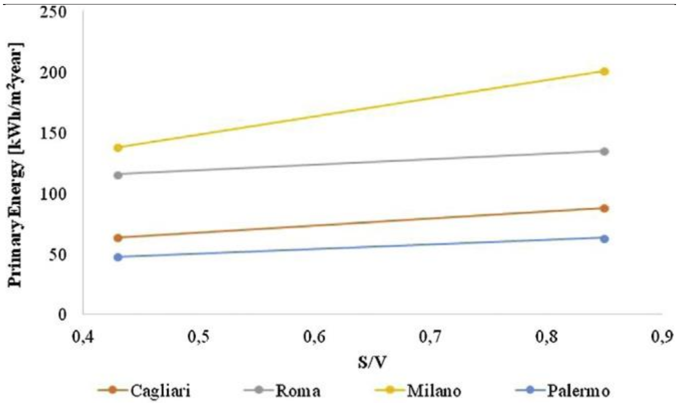


Fig. 5. Primary Energy demand and S/V variation in the base cases.

Table 3 list of the proposed retrofit actions.

Scenario		Description
1	IC	Internal Coat system
2	TP	internal/external Thermal Plaster application
3	RI	Roof Insulation
4	IC+RI:	Internal Coat system + Roof Insulation
5	TP+RI	internal/external Thermal plaster application + Roof Insulation
6	W	Window substitution
7	IC+RI+W	Internal Coat system + Roof Insulation + Window substitution
8	TP+RI+W	Thermal Plaster + Roof Insulation + Window substitution

Table 4
Thermo-physical properties of the scenarios.

Scenario		Upost [W/m^{2}K]		- U=(Upre-Upost) [W/m^{2}K]
IC		0.47		0.57
TP	0.68	0.36 R	0.38	1.51
W		1.40		4.28

ies. The authors considered the cities of Palermo, Cagliari, Roma and Milano to represent the climate zones from B to E.

Furthermore, Table 2 reports the heating season and the operational hours, respectively, based on DPR 412/93.

By this way for each city, weather conditions and the respectively specific operation hours of the systems were implemented. In total were implemented two base cases (A and B cases) for each city, a total of eight simulation base cases.

The A and B cases concern a standard cooling/heating systems of 10 kW with different heating seasons and operational hours according to standards and local regulations.

As mentioned above, contributions from renewable energy sources (RES) have not been considered because restrictions enacted by specific Italian authorities called "Soprintendenza dei beni culturali e archeologici" do not permit roof-based installations of thermal or PV systems. Furthermore, because geothermal energy use is difficult in historical centres and heating/cooling districts are uncommon, only energy retrofit strategies have been considered.

Fig. 3 shows the base case energy demands during the heating and cooling seasons in each climate zone for the case of S/V = 0.43 (Sample A) and the case of S/V = 0.85 (Sample B). In general, for the same boundary conditions, higher shape factors increased the primary energy (PE) requirement.

In Fig. 4, by plotting the results of the two base cases, it is possible to note how the primary energy demand changing simultaneously with the HDD and S/V values, also it increases according to the high HDD and S/V values.

The trend of the total primary energy demand for different climate zones and different S/V values are showed in Fig. 5. In the following, the authors will investigate the correlation between the primary energy demand and the simultaneously changing of S/V and HDD values.

4. Methodology

As mentioned above, several retrofit actions can be applied to historical buildings. In this framework, the installation feasibility and energy improvement of the building have been analysed in each climate zone. The applied retrofit actions are described in Table 3; in detail eight scenarios were considered.

Note that the applied methodology analyses the effects of each energy retrofit action and the combinations of various actions on the building energy demand in each climate zone.

The energy performance of the wall insulation was evaluated using two energy strategies: an internal coat system (IC) and an internal/external thermal plaster application system (TP). These strategies address difficult applications because the morphological peculiarities (generally) cannot be changed. Therefore, the discussed energy strategies have been chosen.

According to Johansson et al. [51,52], an IC scenario has been developed that uses a 0.06 m polystyrene panel on the internal wall. Furthermore, an air gap of 0.05 m is included between the stone and the panel. This type of solution generally involves condensation issues inside the wall, but it can be effectively used if installed properly.

The TP scenario involves the use of a commercial plaster with specific hydrophobic, fire safety, aesthetic, cultural heritage (low impact) and maintenance (minimal) properties. A 0.04 m thermal plaster layer was applied to both internal and external walls.

The RI scenario includes wooden roof insulation using the previously described thermal plaster on the internal side, while scenario W replaces single pane wooden windows with double pane windows with argon air-gaps (U_w = 1.40 W/m^{2}K).

Ground floor insulation was not considered because it is an extremely challenging retrofit action in historical buildings due to the often maintained, aged floor.

Table 4 reports the U-values of the new wall, ceiling and window configurations. Furthermore, the U-value reduction in comparison to base case configurations is shown (U). Note that the new U-values are not regulated because the building is a historical building.

Based on the scenarios presented in Table 4, several actions were combined to compare energy performance results.

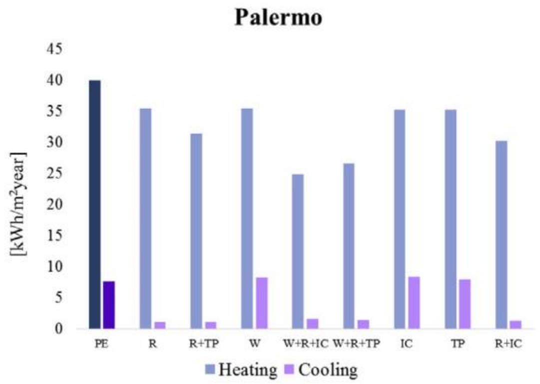
5. Results

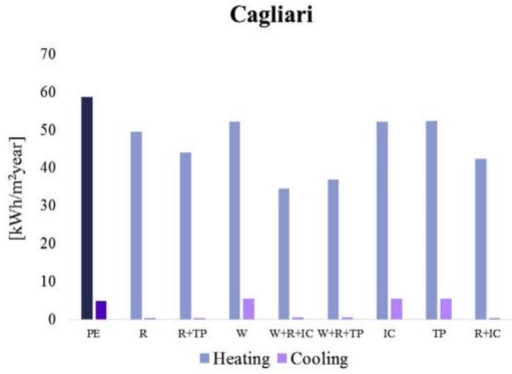
To evaluate the feasibility of a retrofit action, the energy performance of the building in the new configuration must be known.

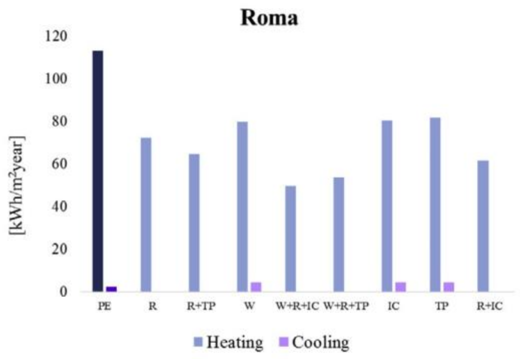
For this reason, the two base cases were simulated considering eight different retrofit actions. Fig. 6 shows comparisons between the primary energy demands related to the base cases with respect

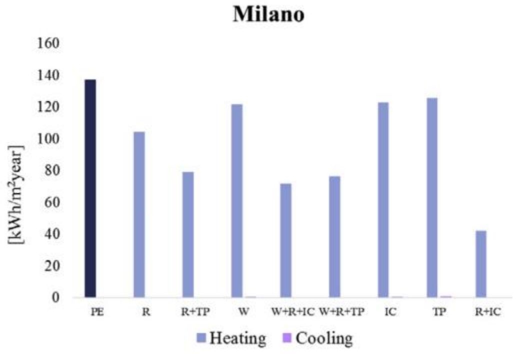
Building heating/cooling PE requirements

Sample A: S/V=0.43

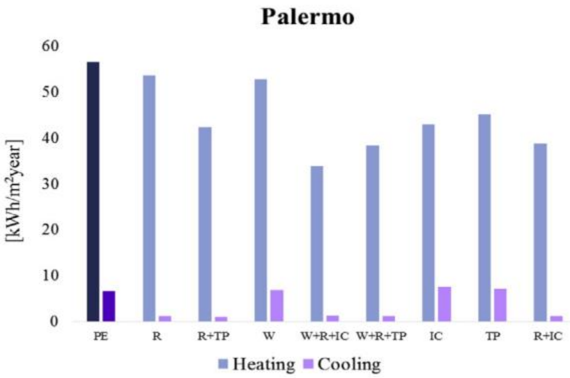


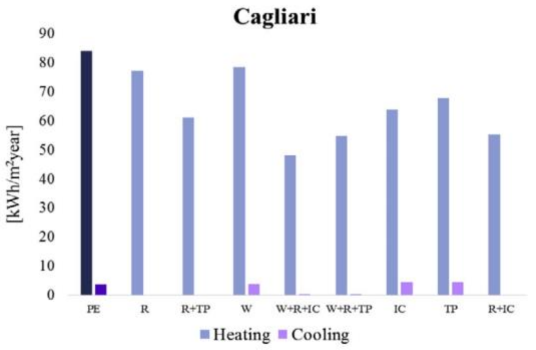


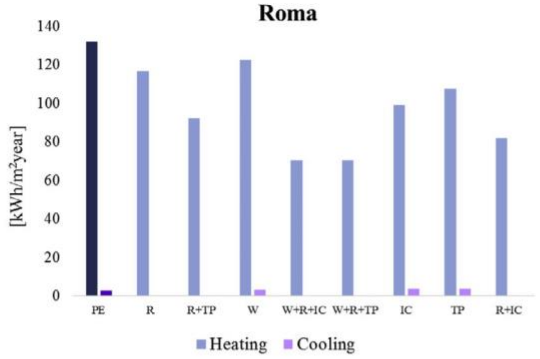




Sample B: S/V=0.85







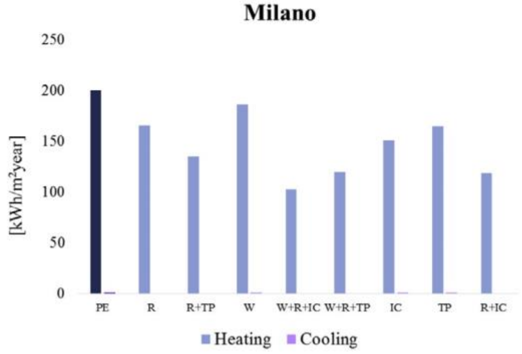


Fig. 6. Primary Energy Demand for heating and cooling season.

Table 5
Primary energy demand and energy saving of Sample A.

Sample A	Palermo		Cagliari		Roma		Milano	
	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving[%]
Base Case	47.67	--	63.7	--	115.51	--	137.91	--
R	36.59	23.2	49.88	21.5	72.59	37.2	104.37	24.3
R+TP	32.54	31.7	44.42	30.1	64.98	43.8	79.08	42.7
W	43.81	8.1	57.65	9.3	84.47	26.9	122.53	11.2
W+R+IC	26.40	44.6	35.16	44.7	49.96	56.7	72.00	47.8
W+R+TP	27.98	41.3	37.53	41.0	54.02	53.2	76.47	44.6
IC	43.59	8.5	57.72	9.2	84.94	26.5	123.80	10.2
TP	43.32	9.1	57.82	9.0	86.57	25.1	126.75	8.1
R+IC	31.50	33.9	42.74	32.8	61.68	46.6	42.74	69.0

Table 6
Primary energy mand and energy saving of Sample B.

Sample B	Palermo		Cagliari		Roma		Milano	
	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving [%]	PE[kWh/m^{2}year]	Saving[%]
Base Case	63.19	--	87.75	--	134.89	--	200.79	--
R	54.85	13.2	77.34	11.9	116.73	13.5	165.88	17.4
R+TP	43.56	31.1	61.25	30.2	92.35	31.5	135.11	32.7
W	59.83	5.3	82.49	6.0	125.77	6.8	186.62	7.1
W+R+IC	35.32	44.1	48.41	44.8	70.61	47.7	102.53	48.9
W+R+TP	39.56	37.4	55.17	37.1	70.61	47.7	120.09	40.2
IC	50.60	19.9	68.43	22.0	102.81	23.8	151.45	24.6
TP	52.42	17.0	72.21	17.7	111.20	17.6	165.48	17.6
R+IC	40.00	36.7	55.42	36.8	81.73	39.4	118.76	40.9

Table 7
Analysis of Priority action of Sample A.

R	5	5	5	5
R+TP	4	4	4	4
W	7	6	6	6
W+R+IC	1	1	1	2
W+R+TP	2	2	2	3
IC	6	6	7	7
TP	6	6	8	8
R+IC	3	3	3	1

to the efficiency scenarios. The first and second columns present data from Sample A and Sample B, respectively.

The interventions can be prioritized based on the energy performance evaluation. As shown, the simultaneous application of several retrofit actions results is a greater reduction of the energy requirements of both cases (Samples A and B) and in all climate zones.

The evaluation of the percentage reduction of the primary energy demand after each single retrofit action is shown in the following tables. The first is related to Sample A (Table 5), while the second shows Sample B (Table 6).

In this way, it is possible to identify, for each Climate Zone, a ranking from 1 (more efficient action) to 8 (least efficient action) of the priorities of intervention.

For Samples A and B, and in all the climate zones, the first three retrofit actions simultaneously combine several actions, namely, W+R+IC, W+R+TP and R+IC. The order of the three actions is only different for the Milano case study (Tables 7 and 8).

5.1. Economic analysis

To properly assess the priorities of actions based on improving energy efficiency, the economic feasibility and the pay-back time (PBT) must also be evaluated.

Table 8

Analysis of Priority action of Sample B.

Sample A	Priority Action			
	Palermo	Cagliari	Roma	Milano
R	7	7	6	7
R+TP	4	4	3	4
W	8	8	7	8
W+R+IC	1	1	1	1
W+R+TP	2	2	1	3
IC	5	5	4	5
TP	6	6	5	6
R+IC	3	3	2	2

Table 9
Specific costs for each retrofit action.

	Retrofit Action	Specific cost [D/m^2]
IC	Internal Coat system	40
TP	internal/external Thermal Plaster application	25
RI	Roof Insulation	80
W	Window substitution	250

After a careful economic investigation across the Italian peninsula, were evaluated the following specific costs per single action (Table 9).

Based on the two different cases (Sample A and Sample B), it was possible to evaluate the costs, as reported in Table 10.

To calculate the PBTs of investments related to the proposed improvement measures, an initial economic analysis was conducted based on the assessments. The economic analysis is based on the evaluation of the Net Present Value (NPV_n), which is defined as the sum of the present incoming and outgoing Cash Flows (CFs) and the Present Value (PV) over a period, as reported in Eq. (1). Incoming and outgoing CFs can also be described as benefit and cost cash flows, respectively.

$$NPV_n = (CF_{inf+int} + PV) \tag{1}$$

Table 10
Total costs for each retrofit action in Sample A and Sample B.

Retrofit Action	Sample A		Sample B	
	m^2	Cost [D]	m^2	Cost [D]
IC	84.9	3396	238.0	9522
TP	84.9	2123	238.0	5951
RI	65.0	5200	65.0	5200
W	10.0	2510	10.0	2510
IC+RI		8593		14,722
TP+RI		7323		11,151
IC+RI+W		11106		17,232
TP+RI+W		9833		13,661

Table 11
Total costs for each retrofit action and BT for Sample A.

Retrofit Action	Total Cost	PBT-Sample A			
	[D]	Palermo	Cagliari	Roma	Milano
W	2510	17	14	4	8
IC	3,396.4	20	17	6	10
W+R+TP	9,832.75	20	15	8	8
W+R+IC	11,106.4	20	15	8	8
R+TP	7,322.75	22	16	7	7
R+IC	8,596.4	22	17	8	5
TP	2,122.75	17	13	4	9
R	5200	25	17	7	8

Sample B	Priority Action			
	Palermo	Cagliari	Roma	Milano

Table 12
Total costs for each retrofit action and PBT for Sample B.

Retrofit Action	Total Cost	PBT-Sample B			
		Palermo	Cagliari	Roma	Milano
W	2510	19	15	11	8
IC	9522	19	16	12	9
W+R+TP	13,661.25	20	16	10	8
W+R+IC	17,232	20	16	11	8
R+TP	11,151.25	21	16	11	8
R+IC	14,722	21	16	12	8
TP	5,951.25	17	13	10	8
R	5200	>25	20	13	7

$CF_{inf+int}$ considers the inflation (Inf) and interest (Int) rates and is defined in Eq. (2).

$$CF_{(inf+int)_n} = DFC_n \frac{(1+I_{inf_n})}{(1+I_{int_n})} \tag{2}$$

DCF is the discounted cash flow and is a function of the fuel cost (Fc). It can be calculated according to Eq. (3).

$S_{PE,h}$ is the primary energy savings and LHV is the lower heating value. $S_{PE.h}$ considers the difference between energy consumption before and after the retrofit action according to Eqs. (4)–(6).

$$S_{PE,h,n} = Q_{PE,before} - Q_{PE,after} \tag{4}$$

$$Q_{PE,before} = PE_{before} \times A \tag{5}$$

$$Q_{PE,after} = PE_{after} \times A \tag{6}$$

In these equations, A is the heated floor area.

By applying an iterative procedure for each retrofit action, the pay-back time can be evaluated, as reported in Tables 11 and 12.

Furthermore, to evaluate the economic savings, the thermal and electric kWh savings were calculated. The yearly economic savings (S_{Heat}) was determined as the difference between the yearly cost of consumed kWh pre-retrofit actions ($C_{Heat,pre}$) and the yearly cost of

Table 13
Yearly economic saving for each retrofit action for Sample A.

Retrofit Action	Annual economic saving [D/year] Sample A			
	Palermo	Cagliari	Roma	Milano
	Palermo	Cagliari	Roma	Milano
W	54.90	82.66	426.52	445.04
IC	57.98	81.63	419.92	189.43
W+R+TP	228.30	324.18	810.21	817.82
W+R+IC	250.64	356.24	864.54	877.55
R+TP	166.24	231.29	663.07	782.91
R+IC	180.74	253.77	706.92	1270.54
TP	59.74	80.12	398.62	151.60
R	111.97	157.95	560.95	445.04

Table 14
Yearly economic saving for each retrofit action for Sample B.

Retrofit Action	Annual economic saving [D/year] Sample B			
W	46.68	74.24	123.35	189.78
IC	173.81	263.08	432.93	660.37
W+R+TP	285.76	263.08	843.38	1076.51
W+R+IC	343.48	507.05	843.38	1311.01
R+TP	232.01	335.09	552.97	875.75
R+IC	279.91	412.80	694.46	1094.17
TP	147.00	212.13	321.00	474.15
R	81.63	119.84	227.22	464.75

consumed kWh post-retrofit actions ($C_{Heat.post}$), as reported in Eq. (7).

$$S_{Heat} = (C_{Heat,pre} - C_{Heat,post}) \frac{D}{year} \tag{7}$$

The generic thermal consumption ($TC_{Heat,x}$) is a function of the Primary Energy (PE), the heated floor area (A) and the kWht cost (C_{kWht}) based on Eq. (8) for a generic gas cost of 0.08 D/kWht.

$$TC_{Heat,x} = PE_x \times A \times C_{kWht} \frac{D}{year} \tag{8}$$

Similarly, the electric kWhe cost savings based on the nonconsumed kWhe after a retrofit application were determined during the cooling period.

$$S_{Cool} = (C_{Cool,pre} - C_{Cool,post}) \frac{D}{year} \tag{9}$$

$C_{Cool,xx}$ is defined by Eq. (10), and COP is equal to 3.5. Additionally, the kWhe cost is equal to 0.165 D/kWhe in this study.

$$C_{Cool,x} = \frac{PE \times A}{COP} \times C_{kWhe} \frac{D}{year} \tag{10}$$

The sum of S_{Heat} and S_{Cool} represents the yearly economic savings for each retrofit action in the four cities and for the two samples (Tables 13 and 14).

To better understand these results, all data were plotted in the following graphs. Figs. 7 and 8 illustrate the PBT and economic savings for each city related to Sample A and Sample B.

The above results were compared to establish a feasibility priority for the different analysed retrofit actions. Based on the PBT values and annual cash flows, this ranking is shown in Table 15.

In Table 15, the lower the number, the higher the feasibility priority. In each climate zone and for each sample, the best three options are highlighted. Generally, these results presented in this table suggest that, at the national level, the least efficient retrofit action is R, while the most effective is TP.

Therefore, taking into account the Mediterranean climate zones, the best possible action is TP, while the worst is R. R+IC actions are recommended in colder climates.

Table 15
Retrofit Action Ranking.

Retrofit Action Ranking	Sample A				Sample B			
	Climate Zone							
	B	C	D	E	B	C	D	E
W	2	2	1	5	3	2	5	8
IC	5	8	3	8	2	7	7	6
W+R+TP	4	4	7	4	5	6	1	4
W+R+IC	3	3	6	3	4	3	3	2
R+TP	7	5	4	2	7	5	4	5
R+IC	6	6	8	1	6	4	6	3
TP	1	1	2	7	1	1	2	7
R	8	7	5	6	8	8	8	1

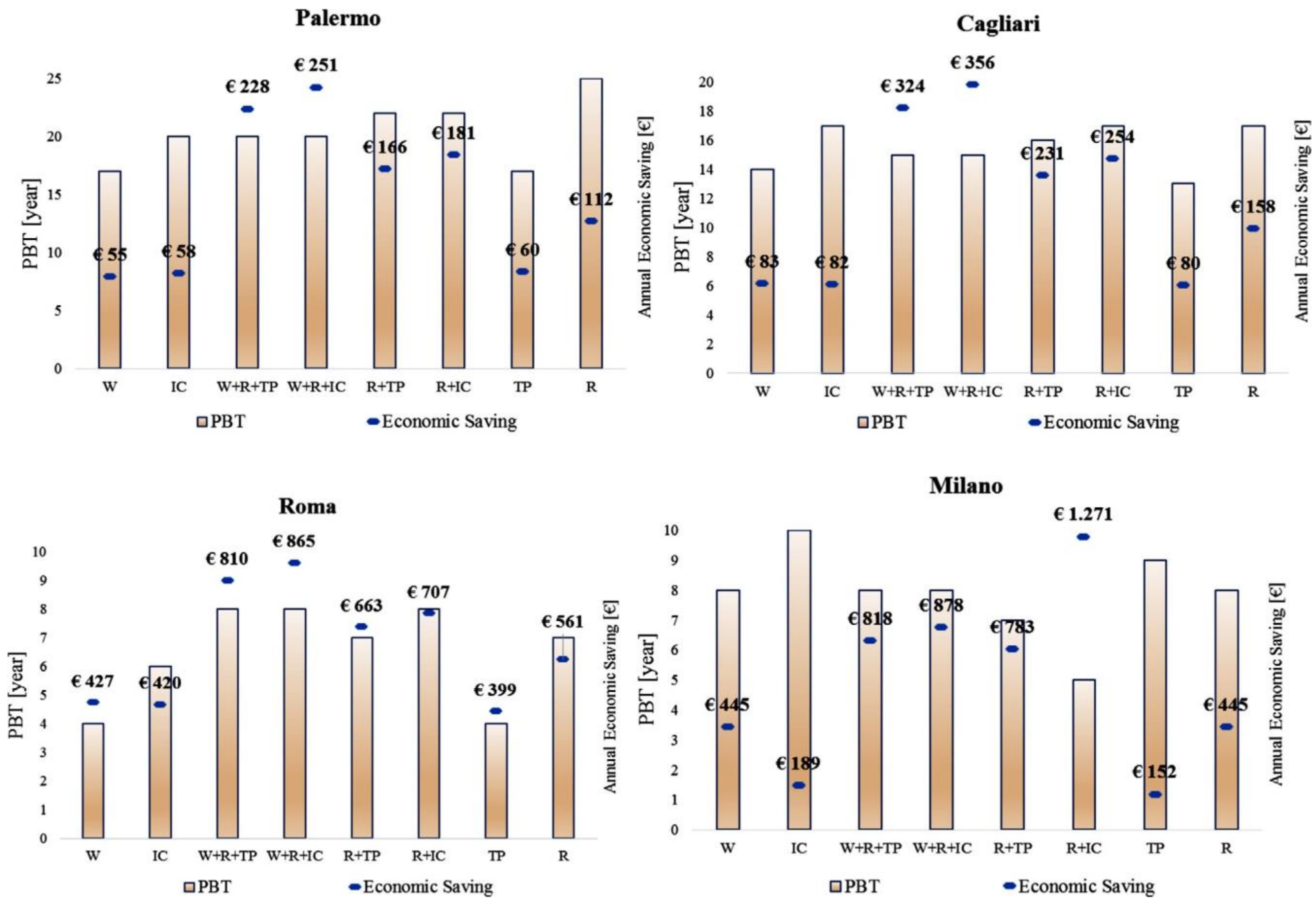


Fig. 7. PBT and Annual economic saving for each retrofit action related to Sample A.

6. Conclusions

In Italy, a large portion of energy consumption is attributed to the residential sector, particularly in historical centres. Indeed, applying energy improvement measures in historical buildings is challenging for architects, engineers and owners due to several restrictions and indifference towards energy refurbishment.

In this paper, an analysis of the most common energy retrofit techniques applicable to residential historical buildings in Italy is presented, paying particular attention to strategies for improving energy envelope performance. In addition, the energy and economic feasibilities of each action have been evaluated. Using two residential housing scenarios representative of a typical historical building in Italy, an energy framework is provided for the energy statement of a typical residential building in four Italian cities (Palermo, Cagliari, Rome and Milan). The analysis highlights the lack of Italian regulation and the difficulty of enhancing energy performance with retrofits by applying eight different retrofit actions focused on the building envelope. Furthermore, for each action or combination of actions, economic feasibility analyses were performed. These analyses highlight the issues associated with various retrofit actions. These issues often include high costs for owners, poor energy benefits and high PBTs. Furthermore, the investment PBTs and the yearly economic savings were calculated.

As showed by energy and economic analysis, old building refurbishment must be evaluated case-by-case considering climate zone, S/V ratio, PBT and so on. Indeed, the same energy action can result more advantageous in some Climate Zone that the other one by having the same cost. However, the results of these calculations suggest the following conclusions:

- In different climate zones, PBTs vary for the same action, increasing from colder to warmer zones;
- The analysed retrofit actions are more convenient if the PBT<15 years. This relationship is generally valid in climate zones D and E and less or not convenient in B and C; – More modern retrofit actions are not suitable; – The PBT of sample B is higher than that of Sample A.

In Sample B, the most unsuitable retrofit action with the highest PBT is R in 3 zones. In climate zone E, the highest PBT is related to the IC retrofit action.

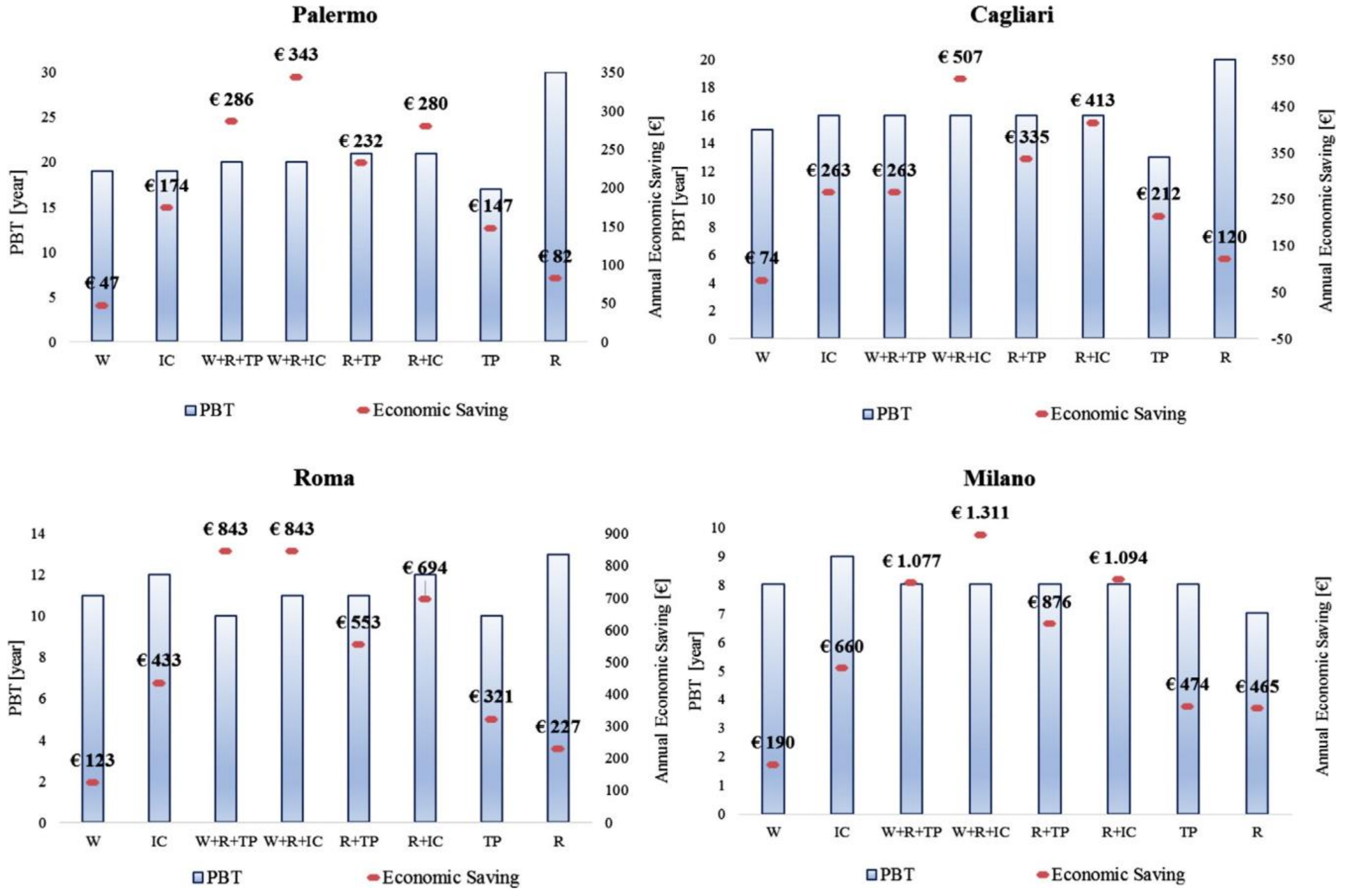


Fig. 8. PBT and yearly economic saving for each retrofit action related to Sample B.

The authors believe providing an useful tool through comparison among representative scenarios and feasibility actions also by giving a priority ranking of them that can be approached, by involved people, in a first building refurbishment step.

Finally, these results confirm that the general directions, which are dictated by the redevelopment the historical buildings, should be critically reviewed according to a careful assessment of the system-building balance that properly takes into account the thermal inertia of the historical building and the climate context. This work provides a starting point for future studies in this sector. However, the first stage of this process should be performed by the Italian Government through energy rehabilitation in Italian historical centres, improving regulation and encouraging owner investments using financial incentives to move towards energy independence.

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