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Analysis and definition of a ZEB building at optimum level of efficiency and costs

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ABSTRACT

The urban regeneration actions arise by the growing importance of information and communication technologies, moving to sustainable solutions, energy saving and security. New energy planning tools are adopted suggesting the legislator towards large-scale energy policies, by setting up all the information related to the building fabric whose representativeness can be defined through Reference Buildings.
The aim of this study is the definition of a suitable methodology based on an energetic and economic approach able to detect refurbishment scenarios of existing buildings, in compliance with the ZEB requirements. For this purpose two residential reference buildings, located in Milan and Reggio Calabria representative of different climatic conditions, are defined aimed at analyzing the energy saving and the CO_2 reduction of a series of refurbishment scenarios. Ten energy improvement packages, related both to the envelope and to the technical systems, are considered for the achievement of NZEB and ZEB target. Among these technologies, the best solutions are selected from an energy and economic point of view. Finally, the results are applied to the Italian buildings stock with the same characteristics of the reference building, through a simplified bottom-up approach.

1. INTRODUCTION

The increase of the anthropic activities and the needs of population have caused a growth in energy demand and related pollutant emissions. Building construction is one of the most energy-consuming sectors. Residential and commercial buildings account for more than 40% of the primary energy in European Countries with a rate of about 30% of CO_2 emissions; the residential sector accounts alone for about 27% [1]. To escape this path, many governments and international institutions, primarily US and EU, have defined different set of specific rules thought to prevent the energy consumption for buildings and their environmental impact in terms of greenhouse polluting gasses. This approach directly supports the improvement of energy performance of buildings and the diffusion of solutions involving renewable energies [2]. In this context, the role of Zero Energy Buildings (ZEB) has been consolidated as the standard reference for the target achievements in terms of balance between needs and self-sufficiency for a building in its operating conditions [3]. Data on building stock, referred to international and local levels, suggest the primary role played by existing buildings in achieving the target of an overall energy needs reduction for society, mainly due to their high number if compared to the new ones, but also related to their poor performance level [4]. Several political actions sustain the refurbishment of buildings promoting the diffusion of modern technologies for the improvement of energy performance, reducing their environmental, economic and social impacts [5].

The European Directive 2002/91/EU established specific criteria to improve the energy performance of buildings. On the pathway defined by the European Directive 2010/31/EU (the so called EPBD recast) these criteria have been strongly reaffirmed and the concept of near-ZEB was identified as the target for public buildings, starting from 2019, for all new buildings, from 2021. The application of the nZEB standard to the existing buildings is yet a challenge for the research and for the professional world [6].

Looking at the Italian situation, the ISTAT (the Italian National Institute of Statistics), observes that about 65% of the buildings were built more than 40 years ago, when there was no laws limiting building consumption and emissions. Thus, the role of existing buildings in the improvement of the energy efficiency and in the reduction of CO_2 emissions is of primary importance.

The aim of the study is the definition of a suitable methodology based on an energetic and economic approach able to detect refurbishment scenarios of existing buildings, in compliance with ZEB requirements. The methodology is based on the identification of a residential Reference Building (RB) representative of a specific class of the Italian building stock, in terms of location, period of construction, geometrical, morphological and thermo-physical characteristics. The RB is simulated in two reference climates, Milan and Reggio Calabria, located respectively in the Northern part of Italy and in the Southern one, in order to identity the most suitable refurbishment interventions in different climatic condition. Finally, the potential of the refurbishment scenario on the building stock is analyzed extending the results to the whole national residential building stock.

2. METHODOLOGY

The methodology developed in the present study follows four main steps, as described in Figure 1:

(1) Definition of the RB through the analysis of the characteristics of the residential building stock;

(2) Definition of the refurbishment scenarios for the ZEB target achievement;

(3) Detection of the best technical solutions from an energy and economic point of view;

(4) Energy saving and emission reduction potential at urban level through a diffuse application of the chosen refurbishment scenario to the selected building stock.

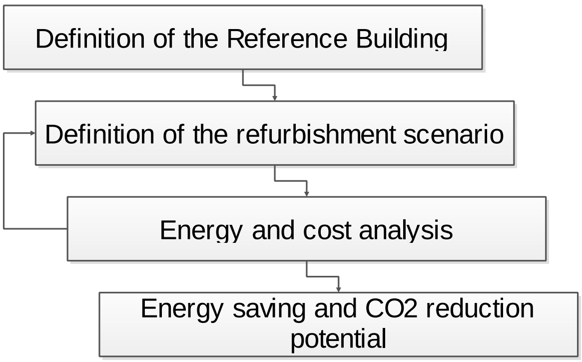

Figure 1. Methodological approach

2.1 Definition of the reference building

The use of RBs is a consolidated methodology to analyze the performance of the building sector and to detect the effect of refurbishment scenarios in improving the efficiency and reducing the consumption and the related emissions. This technique has been applied with good results both in residential [7], [8], [9], [10] and non-residential sectors [11], also considering all the buildings of the urban fabric [12]. In the present study the attention is paid on the residential sector.

The pathway for defining RB is well established in the current scientific literature [13]. Several research projects where developed for this aim (TABULA [14], INSPIRE [15], RepublicZEB [16], etc.). Based on these considerations, a RB has been defined analyzing the national residential building stock using the data provided by several sources: census ISTAT 2011, statistical data from national researches, technical standards, etc. For the purpose of the study, the data are aggregated in three regional macro-areas, representative of the national climatic conditions:

(1) Northern Italy (Lombardy, Piedmont, Valle d'Aosta, Trentino Alto Adige, Friuli Venezia Giulia, Emilia Romagna);

(2) Central Italy (Tuscany, Marche, Lazio, Umbria, Abruzzo, Molise);

(3) Southern Italy (Puglia, Campagna, Calabria, Basilicata, Sicily, Sardinia).

2.1.1 Construction typology

Figure 2 shows the residential buildings by period of construction and construction typology. About 60% of the buildings were built between 1961 and 1980 with a predominance of masonry constructions in the period 1961-1970 and a much more diffusion of reinforced concrete in 1971-1980. The masonry buildings are overall outnumber in the two decades (Figure 3). Masonry has been chosen as the reference construction typology of the RB.

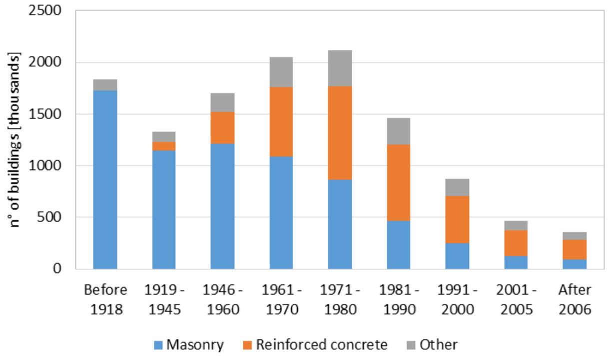

Figure 2. Residential building by period of construction and construction typology (elaboration of ISTAT data)

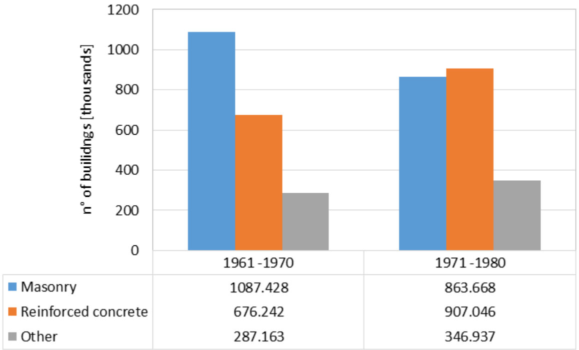

Figure 3. Number of buildings by type of materials, between 1961 and 1980 (elaboration of ISTAT data)

2.1.2 Building dimensions

The definition of the RB dimensions has been deducted by analyzing the number of dwellings for each building and the area of each unit. The average area of the apartments is between 80 and 99 m^2 (Figure 4). In the reference period the census data show a significant number of buildings consisting of 16 and more dwellings distributed on 4 or more floors (Figure 5).

The internal distribution provides four rooms, with the same percentage in the three macro-areas.

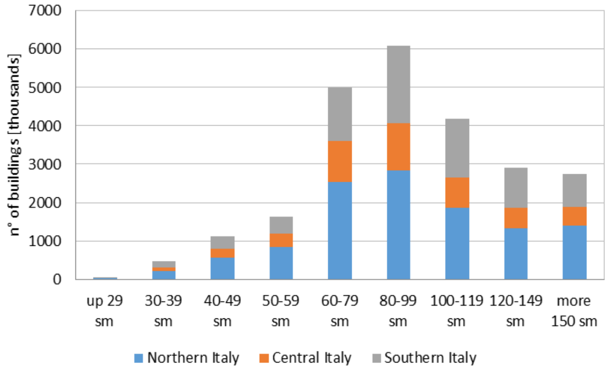

Figure 4. Number of buildings by dwelling dimensions (elaboration of ISTAT data)

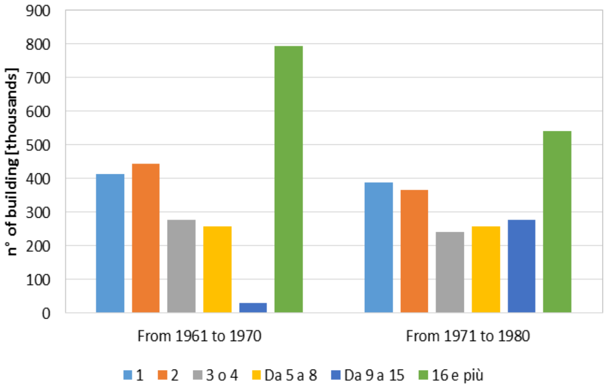

Figure 5. Number of dwellings for buildings (elaboration of ISTAT data)

2.1.3 Thermo-physical properties and plant characteristics

The thermo-physical properties of the envelope are deducted by the data provided by the Italian technical standard UNI TS 11552:2014 [17].

Accordingly to ISTAT data, on the basis of the highest diffusion of typical heating systems, the reference building located in Milan, belonging to the macro-region of Northern Italy, is considered as characterized by a centralized plant system for heating and DHW, while the building located in Reggio Calabria, belonging to the macro-region of Southern Italy, is provided with an autonomous conditioning plant system for heating and DHW for all 16 apartments.

2.1.4 Design of the reference building

The RBs consist of 16 apartments arranged on four heated floors. The buildings have some difference due to the different construction typologies in the two areas.

In particular, the RB located in Milan consists of an unheated basement (the cellar), an unheated attic and four heated floors. The RB located in Reggio Calabria is characterized by an unheated floor (the cellar) and four heated floors with a flat roof, being the most adopted solution in Southern Italy. The floors are connected through two unheated stairwells, equipped with a lift and with an unheated entrance placed on the ground floor. The structural elements are thermally uninsulated. The overall characteristics of the RBs are shown in Table 1, for each location.

The geometrical and thermo-physical characteristics of the building envelope are reported in Table 2.

The energy performance of the RBs is calculated by using a steady-state calculation procedure. The resulting indicators expressed in terms of primary energy are: $EP_{gl,tot}$ = 201,49 kWh/m^{2}y (Milan) and $EP_{gl,tot}$ = 108,18 kWh/m^{2}y (Reggio Calabria).

Figure 6 and Figure 7 show 3D views of the RB located in Milan and Reggio Calabria, respectively.

Table 1. Characteristics of the RB

	Milan	Reggio Calabria
Gross volume	5981.19 m^3	6008.30 m^3
Net volume	4073.64 m^3	4073.64 m^3
Gross area	1778.15 m^2	1778.15 m^2
Net area	1357.88 m^2	1357.88 m$_2$
S/V	0.4745	0.4738
Average area of apartment	84 m^2	84 m^2

Table 2. Geometrical and thermo-physical characteristics of the building envelope

Technical element	Milan		Reggio Calabria	
	A [m^2]	U [W/m^2 K]	A [m^2]	U [W/m^2 K]
Wall	1484.30	1.14	1484.30	1.14
Ceiling (for Milan)	434.00	1.62	-	-
Roof (for Reggio Calabria)	-	-	434.00	1.45
Floor	492.00	1.71	492.00	1.71
Windows	182.30	5.02	182.30	5.02

Figure 6. 3D view of the RB located in Milan

Figure 7. 3D view of the RB located in reggio calabria

2.2 Refurbishment scenarios

A series of refurbishment scenarios were hypothesized, which concern the insulation of the envelope and the replacement of the plant, to achieve the ZEB and nZEB requirements.

The minimum requirements of the intervention packages have been defined according to the current Italian laws referring to the energy performance of buildings.

In particular, the main national references are the Inter-ministerial Decree of 26th June 2015 [18] and the Legislative Decree n. 28 of 3rd March 2011 [19]. The former defines the minimum thermo-physical requirements of the envelope and plant to achieve the nZEB standard. The latter promotes the use of renewable energy sources, prescribing the minimum amount of energy produced by these kind of systems. Furthermore, the definition of ZEB has been considered to define the refurbishment scenarios in order to detect the technical solution able to guarantee the balance of the non-renewable primary energy ($EP_{gl,nren}$=0).

Starting from these references, several technologies are hypothesized according to different possible combinations.

The materials used for the thermal insulation of the envelope are: expanded polystyrene (EPS), wood fibers and fiberglass. In Table 3 the values of thermal conductivity (λ), density (ρ) and dynamic viscosity (δ) of the materials are reported [20].

Table 3. Characteristics of the insulating material

Materials	λ[W/mK]	ρ [kg/m^3]	δ [kg/ms]
EPS	0.033	35	1.3x10^{-12}
Fiberglass	0.036	40	193x10^{-12}
Wood fibers	0.040	110	97x10^{-12}

The replacement of the window frames and the entrance doors has been considered, in order to reduce the heat losses through the light elements. Existing frames have been replaced with aluminum ones with thermal break or PVC frames combined with the installation of low-emissivity glass, with argon gas filled cavity.

The interventions for the energy efficiency improvement of the HVAC include: substitution of the current generator system with geothermal heat pump, condensing boiler and district heating; insulation of the distribution pipes and installation of a more efficient emission system; use of advanced control systems such as PID control; mechanical ventilation with recovery units and free-cooling. The installation of solar thermal (ST) and photovoltaic (PV) panels is considered.

The combination of the previous solutions has generated 10 refurbishment scenarios for both the RBs, as summarized in Table 4.

Table 4. Refurbishment scenarios

Scenarios	Description
Case 1	External insulation with EPS; windows with thermal break aluminium frame and low-emissivity glass with cavity filled with argon gas; electrically-driven geothermal reversible heat pump; thermally decoupled radiant panels; PID control; PV.
Case 2	Case 1 with: PV according to ZEB requirements.
Case 3	Case 2 with ST panels.
Case 4	Case 1 with: condensing boiler (RB of Milan) - heat pump (RB of Reggio Calabria); AHU with heat recovery; ST panels.
Case 5	Case 1 with: existing radiators (for heating mode) and fan coils (for cooling mode); chiller; ST panels.
Case 6	Case 1 with: external insulation with wood fiber.
Case 7	Case 1 with: windows with PVC frame.
Case 8	Case 1 with: external insulation with fiberglass.
Case 9	Case 5 with: PV according to ZEB requirements.
Case 10	Case 5 with: district heating (RB of Milan) - biomass boiler (Reggio Calabria).

2.3 Energy and cost analysis

The primary energy related to each refurbishment scenario is calculated in order to detect the energy saving potentials. The energy performance indicators can be determined by applying simplified thermal models [21], hourly calculation methods [22] or steady-state approaches [23], [24]. The general equations of steady-state method are used and reported above:

Net energy

$$Q_{H,nd} = (Q_{tr} + Q_{ve}) - \eta_H (Q_{sol} + Q_{int}) \quad (1)$$

$$Q_{C,nd} = (Q_{sol} + Q_{int}) - \eta_C (Q_{tr} + Q_{ve}) \quad (2)$$

where: $Q_{H,nd}$ and $Q_{C,nd}$ are the thermal need for heating and cooling; Q_{tr} and Q_{ve} are the thermal losses for transmission and ventilation; Q_{sol} and Q_{int} are the solar and internal gains; $_H$ and $_C$ are the gain and loss utilization factors.

Primary energy

$$Q_p = \sum(Q_{del,i} \times f_{p,del,i}) - \sum(Q_{exp,i} \times f_{p,exp,i}) \quad (3)$$

where: Q_{del} is the delivered energy for the i-th service (heating, cooling, domestic hot water), Q_{exp} is the exported energy for the i-th service; $f_{p,del}$ and $f_{p,exp}$, are the primary energy factors.

According to the national standard and the Italian laws, the nZEB balance between the primary energy exported (E) to the energy grid and the delivered one (D) is given by $E - D > 0$ for each energy carrier, expressed in kWh, where the very low or almost zero energy needs is significantly covered by renewable energy sources [25].

When the balance is equal to zero, $E - D = 0$, the building is a Zero Energy Building (ZEB).

The evaluation of the investments is a fundamental operation to verify the economic impact of an intervention. One of the most diffused methods is the simple payback time (SPBT). It represents the number of years necessary to offset the initial investment. Equation 4 shows the formula for calculating the index:

$$SPBT = \frac{I_0}{R} \quad (4)$$

where, I_0 is the initial investment and R is the annual economic savings, calculated as the difference between energy consumption before and after the intervention.

The analysis allows to identify the most suitable solution for achieving the required energy saving and CO_2 reduction in compliance with an economic sustainability.

2.4 Energy saving and CO_2 reduction potential of the building stock

The study is carried out analyzing the refurbishment scenarios in order to reach nZEB and ZEB requirements.

A simplified bottom up approach was adopted to evaluate the energy saving and CO_2 reduction potential of the residential building stock.

Starting from ISTAT data and knowing the consumption before and after the intervention, the estimation of the energy saving in kWh/m^{2}y has been calculated. Through ENEA data, the kilograms of CO_2 equivalent for each kilowatt-hour delivered were used: 0.3524 kg$_{CO2eq}$/kWh. Multiplying this value for the energy saving, the kilograms of CO_2 saved in a year were obtained.

3. RESULTS

The refurbishment scenarios are investigated and compared in terms of primary energy, both from renewable ($Q_{p,ren}$) and non-renewable ($Q_{p,nren}$) sources and for each energy service: heating, cooling and domestic hot water.

In Figure 8 and Figure 9, the partial results of non-renewable (blue bar) and renewable (orange bar) primary energy for each refurbishment scenario of the RB located in Milan and Reggio Calabria are presented.

Case 4 and Case 10 show the higher amount of non-renewable energy: in the former a condensing boiler is supposed in both the location; in the latter a district heating and a centralized biomass boiler are installed in the RB located in Milan and in Reggio Calabria, respectively.

Case 2, 3 and 9 comply with the ZEB requirements, through the increase of the areas of both solar systems, ST and PV. More specifically, Case 2 has undergone an increase in the area of PV, obtaining a renewable energy performance index, $EP_{gl,ren}$, of 50.78 kWh/m^{2}y, in Milan, and 35.17 kWh/m^{2}y in Reggio Calabria. In Case 3, the installation of ST panels is considered with a reduction of the PV system. In this case, the $EP_{gl,ren}$ obtained are equal to 51.46 kWh/m^{2}y and 35.04 kWh/m^{2}y for Milano and Reggio Calabria, respectively. Finally, for Case 9, a geothermal heat pump with fan coils is considered. The $EP_{gl,ren}$ values are equal to 52.4 kWh/m^{2}y in Milan and 40.01 kWh/m^{2}y in Reggio Calabria.

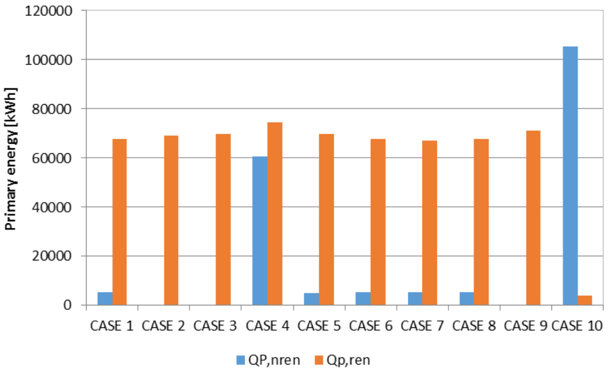

Figure 8. Total primary energy need, renewable and non-renewable (RB of Milan)

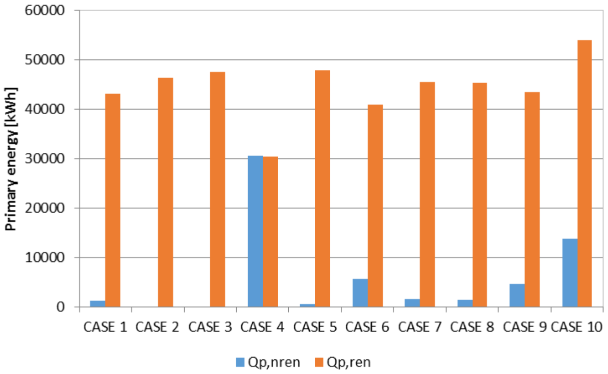

Figure 9. Total primary energy need, renewable and non-renewable for different services (reggio calabria)

The economic assessment of the case studies is carried out considering the price lists for the execution of public works and maintenance (2017-2018) of Milan and Calabria Region [26] and [27]. In the identification of individual price items, the relative percentage of materials used and the manpower are assessed. Each cost is increased by VAT. Public incentives are also considered for energy efficiency measures (65% of detractions) and on-site exchange for photovoltaic electricity. The global costs for purchase and installation are shown in Figure 10.

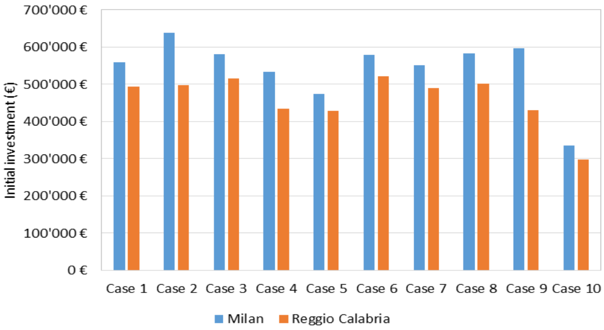

Figure 10. Initial investment

The installation of the external insulation system includes the cost of: material, manpower and the finishing. Among the analyzed insulating materials, EPS is the cheapest and the most performing, with a cost of about 50 €/m^2, compared with 60 €/m^2 of wood fiber and 52 €/m^2 of fiberglass.

The costs of windows and doors include material, manpower and assembly of frame and glasses. Aluminum frames with thermal break are more expensive than PVC ones, with total cost of about 400 €/m^2 against 300 €/m^2 of the latter.

The cost of geothermal heat pump includes: drilling, vertical probes, horizontal connections, geothermal collector, heat pump, assembly, connection materials, testing and insulation of the technical room and hydraulic supply. The installation of radiant panels radically increases the cost. In addition to materials and installation, the demolition and the reconstruction of the floor and the waste disposal must be considered. The condensing boiler and the district heating are the cheapest plant systems, but they are associated with the lowest building performance. The cost of the condensing boiler is about 80.000 € (including boiler, installation and initial fire tests). For district heating, the costs related to the connection to the external network, those of the heat exchanger and its installation are considered.

Solar systems are generally very expensive, indeed for the Case 2, 3 and 9 the total cost increases due to increment of the systems areas. This is the compromise that must be undergone for the construction of a ZEB. The costs of PV technology fall around 2000-3000 €/kWp and those of solar thermal collectors are around 400 €/m^2.

Finally, the procedure considers the cost related to the construction site, included the costs due to the rental of scaffolding, worktops, demolition and disposal.

Figure 11 highlights that the most suitable refurbishment scenarios in energy and economic perspective are Case 5 for Milan and Case 10 for Reggio Calabria.

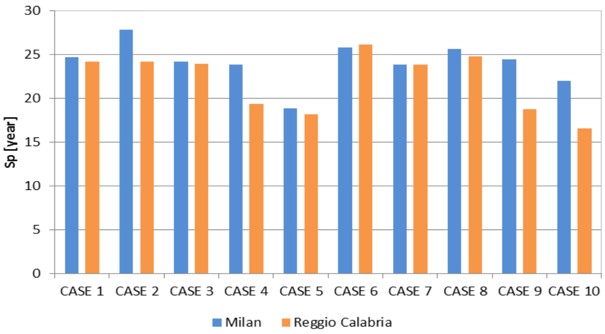

Figure 11. Simple payback time

3.1 Best cases

The case studies are aggregated in four macro-areas: insulation (cases 1, 6 and 8), windows frame (cases 1 and 7), emission system (cases 1 and 5) and plant system (cases 1, 3, 4, 5 and 10), keeping the same other characteristics and analyzing their differences.

On the basis of these considerations, chosen according to Figure 11 and Table 4, the solutions of each macro-area in terms of the best SPBT are compared.

In this way the best cases can be highlighted. The comparison among different insulations showed that the most convenient insulation is the EPS (case 1) because it is cheaper and has better performance.

For the identification of the best windows, the buildings located in Milan and Reggio Calabria require high performance on the thermal insulation and reduction of solar gains, respectively. The PVC (case 7) frame with 6 hollow chambers provides lower costs and higher performances than the aluminum one (e.g. for Milan: $U_w = 1.22$ W/m^{2}K for PVC against $U_w = 1.32$ W/m^{2}K for aluminum).

The best solution among the emission systems is chosen by comparing case 1 and case 5. Both cases have the same type of plant system, a centralized geothermal heat pump. The case 1 presents the radiant panels, while the case 5 fan coils and radiators. The latter system is chosen because the total cost for their installation is lower than the interventions required for the radiant panels.

The choice of the best plant system for the building located in Milan fell on the case 5, where the best solution of the emitters (radiators and fancoils) is coupled with a geothermal heat pump.

For the building located in Reggio Calabria, the pellet boiler plant is chosen due to its energy efficiency and low costs (case 10).

The combination among the best solutions generated a best case for each location (Table 5).

Table 5. Best case

Location	Solution	Case
Milan	Insulation EPS	1
	Window frame PVC	7
	Emission system: radiator and fancoil	5
	Plant system: geothermal heat pump	5
Reggio Calabria	Insulation EPS	1
	Window frame PVC	7
	Emission system: radiator and fancoil	5
	Plant system: biomass	10

The best case fell on nZEB building, both Milan and Reggio Calabria because considering ZEB requirements means to increase costs and surface of PV panels. According to the previous analysis, the SBPT of ideal case in Milan decreases to 18 years and the ideal case of Reggio Calabria to 16 years.

3.2 Extension of results to the class of buildings

It is possible to estimate the avoided kilograms of CO_2, through the ideal improvement interventions and to extend these results to the residential stock of Italian buildings, to which the original case study belongs.

In Northern Italy the number of residential buildings is about 300.000, in Southern Italy about 350.000.

For the Milan building, a 73 % of saving was assessed, for the Reggio Calabria building a 54 % of saving.

Appling this improvements in the building located in Milan a value of 70327.2 kg$_{CO2eq}$/year saved has been calculated, instead, through the intervention on the building located in Reggio Calabria 27925.9 kg$_{CO2eq}$/year saved.

By extending the Milan's best refurbishment project to the buildings of the same class, in Northern Italy, a saving of around 52 kg$_{CO2eq}$/m^{2}year could be obtained. Considering the best refurbishment of Reggio Calabria and extending it to the buildings of the same class, located in Southern Italy, about 21 kg$_{CO2eq}$/m^{2}year saved could be obtained.

4. CONCLUSIONS

The definition of the reference building, located in Milan and Reggio Calabria, and the choice of 10 intervention packages, can obtain useful results.

With the comparison among different case studies, an analysis of the payback period of investments was carried out.

The payback period calculated for each case assumes, for the nZEB buildings, an average value of 20 years, for ZEB buildings a value increased on average by 24 years.

The choice of the best cases for the two reference cities took place, in fact, through a combination of different case studies, considering both the economic convenience and the improvement of the building performance.

The best case chosen for Milan consisting of insulation with EPS, centralized geothermal heat pump, fancoils for the summer cycle and radiators for the winter one, PVC windows and photovoltaic of 12.3 kWp, has a payback period of 18 years with an investment cost of about 370 €/m^2 and an energy saving of the 73%. The best case chosen for Reggio Calabria, consisting of insulation with EPS, pellet boiler, fancoils, radiators, PVC windows and photovoltaic of 12.3 kWp, has a payback period of 16 years, an investment cost of approximately 220 €/m^2 and an energy saving of 54%.

If it were possible to extend the best cases to all building with the same characteristics, located in the North and South of Italy, an average saving of about 63% of total consumption would be obtained. Specifically, the best cases chosen are both nZEB, which, according to the economic analysis, are more economically feasible. The construction of a nZEB building entails a huge amount of money; pushing towards the ZEB an increase of 150 €/m^2 has been estimated, compared to the cost calculated for the nZEB.

The result is that today, on a large scale, a nZEB refurbishment target is cheaper than a ZEB target.

The importance of the reference building lies, precisely, in the identification of a possible solution, to extend the topic of energy efficiency to the urban scale.

The definition of the reference building aims to support the legislator in designing energy policies, on a large scale, through new and increasingly developed, energy planning tools, pushing everyone to awareness and to the importance of creating smart cities.

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NOMENCLATURE

D	Delivered primary energy, kW.h

E	Exported primary energy, kW.h
EP	Energy Performance index, kW.h.m^{-2}
Q	Energy, kW.h
f	Primary energy factor
ZEB	Zero Energy Building
nZEB	Near Zero Energy Building
SPBT	Simple payback time, y
I	Investment, €
R	Annual economic saving, kW.h
CO_2	Carbone dioxide
U	Thermal transmittance, W.m^{-2}.K^{-1}

Greek symbols

	thermal conductivity, W.m^{-1}.K^{-1}
	density, kg.m^{-3}
	Dynamic viscosity, kg.m^{-1}.s^{-1}

Subscripts

gl	global
tot	total (renewable + non-renewable)
tr	thermal transmission
ve	thermal ventilation
sol	solar gains
int	internal gains
H	heating
C	cooling
nd	energy need
p	primary