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Feasibility analysis of retrofit strategies for the achievement of NZEB target on a historic building for tertiary use

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Abstract

According to directive 2010/31/EU, a NZEB (nearly zero energy building) is defined as a high performance building whose very low or almost zero energy needs should be mostly provided by renewable sources. The study reported in this work has the objective to establish criteria and design solutions to improve buildings energy performances in order to reach NZEB targets for those buildings characterized by historical constraints. For this purpose, a comparative numerical analysis on the space cooling and heating of a historical building sited in Agrigento (Sicily, Italy) was performed by means of two energy tools: Termo and Trnsys. The first one is a stationary energy certification software based on the algorithms and mathematical methods listed in the UNI TS 11300 standard reference. The second one is a well calibrated dynamic tool based on hourly climate data and able to take into account the thermal inertia phenomena of structures. In order to obtain reliable results, measured climate data extracted from a weather station located near the reference building were used as input for the simulations. Starting from the simulation results, several retrofit scenarios were hypothesized, in order to achieve NZEB target, and then followed by a cost analysis carried out to reach optimal economic solutions and energy savings. The study can constitute a contribution to policy formulation and adoption of measures to facilitate design choices for the energy improving of historical buildings.

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Keywords: NZEB; Trnsys; Retrofit strategies; Historic building; Feasibility analysis.

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1. Introduction

For some years by now the issues of efficiency and energy saving arouse growing interest between the insiders. The importance assumed by these topics is justified by the need to reduce the use of fossil fuels and by the will of governments and institutions to reduce CO_2 emissions and other pollutants. In this context, a smart planning and an efficient management of urban transports [1], buildings and plants can be an important lever on which to act since in Italy the energy demand of the civil building stock covers a share of about 40% of energy consumption. In effect most of the civil buildings are predating the first legislation on energy efficiency (1976) and this fact constitutes the reason why all the projects did nott pay any attention to the minimization of energy losses. Furthermore, it must be highlighted that about half of current civil building stock has never been retrofitted. It is clear that the range of the achievable interventions in this field may guarantee sensible results as required by the objectives set by the Kyoto Protocol and by the European Directives on energy saving in buildings. For this reasons, worldwide researchers, in accordance with the governments, are developing useful criteria to identify the most efficient building design solutions [2-4] and the most suitable building integration of energy-saving and renewable energy technologies [5-7], considering as final goal the achieving of NZEBs. The optimization of the mix of passive [8-10] and active solutions can be investigated exploiting dynamic energy simulation software (BES). Most of the studies cperformed about this topic are oriented on residential buildings, mainly located in heating dominated climate zones, while very few research works concern non-residential NZEBs [11-12]. In this paper, the energy performances of a tertiary use building, sited in a hot climate (Sicily), have been analyzed. The specificity is due to two facts: (i) the case study building is located in a cooling dominated climate zone as Agrigento; (ii) it presents building constraints since it is a historical structure. The energy consumptions of all the plants deputed to each service have been determined. It is important to notice that in the building there are only electrical loads since it presents air-to-water heat pumps for space heating and cooling, in addiction to other typical electrical services of tertiary use building. The work is divided into two parts: (i) a comparison between the results of energy simulations obtained by means of Trnsys (a transient system program) and Termo (a stationary program used for energy certification based on the algorithms of the UNI/TS 11300 standards); (ii) an economical feasibility analysis of various scenarios of retrofit interventions, aimed at the NZEB pursuit, in order to find the matching between the achievement of the energy saving target and minimization of costs. Although the obtained data are referred to a single case study, they can be compared with the results of all other cases of non-residential NZEBs analysis located in temperate climates. Moreover, they can be also taken as reference for: (i) the NZEB target implementation in case of a historical building, (ii) the comparison with other future NZEBs in similar operating conditions.

2. Case study

The case study building is the headquarter of the Province of Agrigento, situated in Piazzale Aldo Moro 1, in the city center of Agrigento. The orientation of the building is such that its four façades can be considered oriented according to the four cardinal points as you can see in Fig. 1.

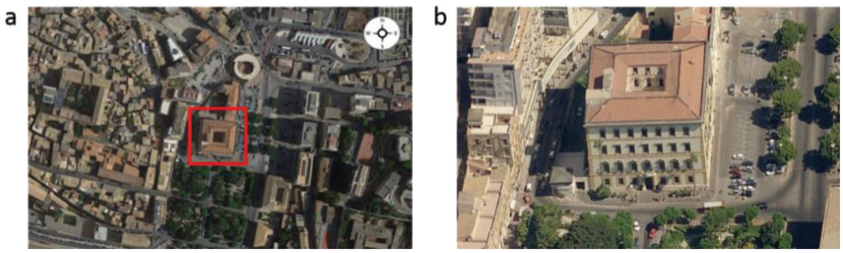

Fig. 1. (a) satellite view; (b) south face perspective view.

Constructed in 1860, the building type is a palace of pre-unitary era with internal courtyard. It presents five floors above ground with different use destinations as is shown in Table 1, below. It is also possible to see the features of the different thermal zones in the building. In Fig. 2 is shown a 3D view with the different thermal zones.

Table 1. Building features overview.

Floor (thermal zone name)	Use destination	Net floor area *(m²)*	Average rooms height h_m *(m)*	Air-conditioned net floor area *(m²)*	Air-conditioned volume *(m³)*
G (ZT1)	Offices, apartments, services	768.1	5.3	524.9	2759.5
1° (ZT2)	Apartments	1008.7	5.3	925.9	4921.3
2° (ZT3)	Offices, services	1008.7	5.3	910.4	4825.1
3° (ZT4&ZT5)	Offices, services	1776.4	4.9	996.7	4883.8
4° (ZT6)	Offices, services	522.3	3.5	164.7	568.3

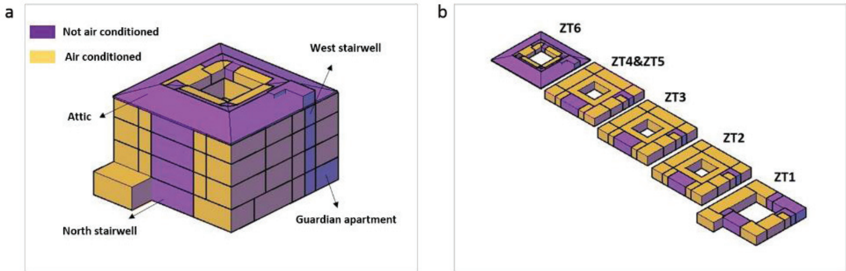

Fig. 2. (a) zones view of whole building; (b) zones view of single floors.

Regarding the usage profile, the building has been considered 100% occupied from January to December, from Monday to Friday, between 8.00 and 16.00. The density of occupation was defined in accordance with the prospectus 8 of UNI 10339 standard. Since the building has both individual offices and open space offices, an average value of 0.09 persons/m² per floors has been adopted. For the first floor, an apartment, it was considered an occupancy density value of 0.04 persons/m². Global average inner gains have been defined equal to 6 W/m² according to the prospectus E.3 of UNI 11300. The air flows set in the heat balance of the building, with natural ventilation, have been defined equal to 11 m³/s per person, according to the specifications of air quality of the UNI 10339. The corresponding value, for office use environments, is equal to 0.48 vol/h with an addition of air infiltration rate of 0.20 vol/h. For the apartment the values 0.5 vol/h for ventilation and 0.20 vol/h for infiltration have been adopted. The building envelope presents various opaque and glazed elements with different geometric and thermos-physical features. In Table 2 and Table 3 are listed the features of opaque and glazed elements.

Table 2. Features of vertical (PPx code) and horizontal (SCx code) opaque elements.

Code	A *(m²)*	S *(cm)*	U *(W/m² K)*	Ms *(kg/m²)*	C (kJ/m² K)	Yie *(W/m² K)*	f_a	Φ *(h)*
PP1	863.0	120	0.78	2088	63.3	0.001	0.001	11.15
PP2	2706.3	100	0.91	1728	63.3	0.003	0.003	5.26
PP3	836.1	85	1.04	1458	63.2	0.010	0.009	0.84
PP4	231.1	56	1.36	1008	63.2	0.067	0.050	17.47
SCT	750	48	1.72	119.9	61.4	0.57	0.333	6.90
SCO1	934	9	1.77	99	53.3	1.551	0.877	2.87
SCO2	340	40	0.99	100	60.7	0.757	0.761	3.94

Table 3. Features of glazed elements.

Code	n°	A *(m²)*	P *(m)*	L *(m)*	U *(W/m² K)*	g
FLS3	86	4.2	8.6	1.5	3.23	0.85
FAS1	24	3.6	7.8	1.5	3.27	0.85
PFAD1	12	3.6	7.8	1.5	2.59	0.75
PFLD1	12	4.1	8.4	1.4	2.76	0.75

Regarding plants, the building is served by the following systems: electrical, heating, cooling, DHW, lift and special (telephone, data transmission, etc.). Table 4 provides some details of all the air conditioning plants.

Table 4. Heating and cooling plants.

Type and model	n°	Heating/Cooling rate (kW_{th})	COP/EER	Thermal zones
Heat pump, Airwell AQH 30 HP B COIL STD PUMP	3	53.3/48.6	3.29/3.00	ZT2, ZT3, ZT4
Heat pump, Airwell AQH 20 HP B COIL STD PUMP	1	32.1/30.7	3.21/3.07	ZT5
Refrigeration unit, Airwell AQH 30 HP B COIL STD PUMP	6	- /48.6	- /3.00	ZT2, ZT3, ZT4
Refrigeration unit, Airwell AQH 20 HP B COIL STD PUMP	1	- /30.7	- /3.07	ZT5
Various dual-split units	6	7.95/7.5	3.53/3.33	ZT1, ZT6
Various monosplit units	23	2.61/2.5	2.9/2.78	ZT1, ZT6

The emission terminals installed in the thermal zones are fan coils. DHW is produced by 10 electric boilers each of 1.2 kW rated power. The lighting system consists of overhead lights in neon tubes, halogen and incandescent lamps. Outside there are LED lights and metal halide lamps for a total of 27.5 kW of rated power. In the building there are two elevators driven by electric motors respectively of 4 kW and 6 kW rated power, three hydraulic pumps of 1.5 kW, 1.4 kW and 0.7 kW. The number of PCs (each 500 W power) is equal to 108, printers and faxes (300/10 W each) are 62, photocopiers (1200/30 W each) are 19, while plotters (300 W each) are 4 in total. There are also 5 data processing cabinets (500 W each). Moreover, the apartments have typical domestic loads, such as refrigerators, washing machines, dishwashers, therefore it has been taken into account only the rated power, equal to 7 kW.

3. Results

The results of simulations performed with the above mentioned programs are presented matched for what concerns the energy demands for space heating and cooling. Firstly, the ante-operam simulations are proposed while in a second section, after a description of the pursued retrofit strategy, the results of the different retrofit scenarios, up to the design solution that has allowed the achievement of NZEB, are presented. For what concerns the weather data, three kinds of simulations have been carried out: (i) the one named Termo presents the software database weather data (established by UNI 10349 standard), (ii) the one named Trnsys presents a user defined typical hourly weather file, built with a five years (2010-2014) measured data, obtained by SIAS (Sicilian agro-meteorological information service), (iii) the one named Termo_Averaged, presents a monthly averaged weather file, obtained by SIAS data, in order to compare properly the results of Trnsys and Termo. In that way, it has been possible to evaluate properly the effects due to different weather data [13] and those due to thermal inertia phenomena [14].

3.1 Ante operam

It is important to specify that the energy demands for air-conditioning reported in Fig. 3 have been obtained with a "standard" usage profile, as reported in the UNI TS 11300, that represents a conventional usage where the air-conditioning plants are powered on twenty-four hours a day during the corresponding season.

a b

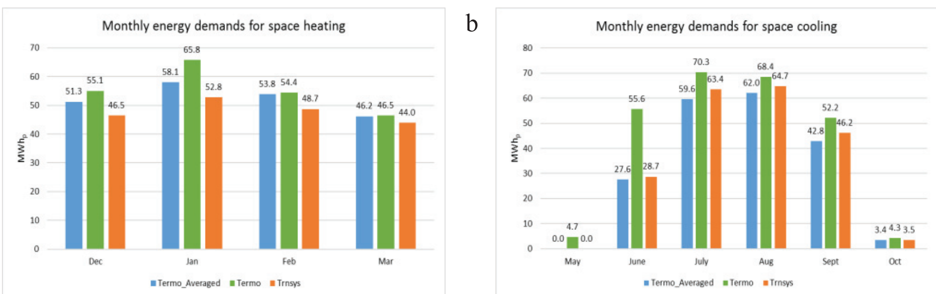

Fig. 3. (a) Primary energy demands for space heating; (b) primary energy demands for space cooling;

Analyzing the Table 5, it is clear that Termo overestimates the energy needs, compared to the other two cases. It means that an updating of UNI10349 weather data is necessary. It is also possible to notice that the results obtained with Termo_Averaged and with Trnsys are close. In this case, the differences are strictly due to thermal inertia phenomena.

Table 5. Overview of yearly energy demands for air-conditioning.

Software	Yearly space heating demands *(MWh_p)*	Yearly space cooling demands *(MWh_p)*
Termo_Averaged	209.3	195.3
Termo	221.7	254.3
Trnsys	192.4	206.5

Downstream of the simulations carried out on energy requirements related to space cooling and heating, the trend of electricity consumption, based on the building usage profile, has been estimated. The obtained results, presented in the graphs in Fig. 5, are only conventional consumptions but they provided support for the determination of adopted retrofit strategies.

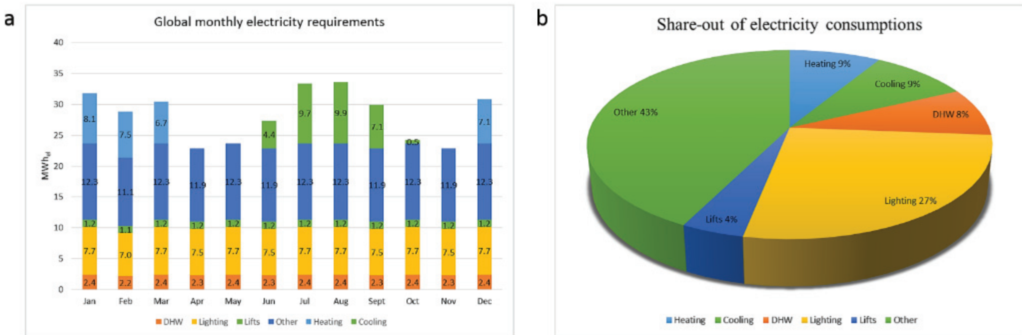

Fig. 4. (a) Estimated monthly electricity consumptions; (b) share-out of electricity demands

3.2 Post operam

Starting from the results obtained through the building energy simulations and according to the consumptions related to different services, I have chosen the following typologies of intervention: 1) improvement of building envelope performance by increasing the thermal insulation; 2) replacing the air-to-water heat pumps with geothermal heat pumps; 3) replacing fluorescent, halogen and incandescent lamps with LED and building automation controls; 4) installation, on the roof, of a traditional photovoltaic plant, with monocrystalline panels; 5) installation of a photovoltaic skylight over the internal courtyard with thin film transparent panels. In Table 6 it is possible to see a detailed overview of retrofit solutions for the envelope.

For opaque elements a rockwool internal panel with thermal conductivity λ=0.019 W/m K has been adopted. For glazed elements I decided to replace existing windows with new ones with better thermal insulation value and lower solar factor.

Table 6. An overview of the new thermophysical features of building envelope elements.

Opaque Code	New U *($W/m^2 K$)*	Glazed Code	New U *($W/m^2 K$)*	New g
PP1	0.256	FLS3	0.87	42.5
PP2	0.268	FAS1	0.85	42.5
PP3	0.393	PFAD1	0.90	42.5
PP4	0.297	PFLD1	0.85	42.5
PP5	0.304	-	-	-
SCO	0.320	-	-	-

The existing heat pumps have been replaced by geothermal heat pumps (GHP). For what concerns the performance indexes, Trnsys provided values of COP and EER respectively of 3.31 and 4.24 with an undisturbed soil temperature, at 22 m depth, considered equal to 17.9 °C. The replacement required the implementation of supply and return pipelines of the heat transfer fluid to the first and fourth floor and the installation of geothermal probes in the square inside of the building. The total installed capacity was 167.2 kWh_{th} for heating and 194.1 kW_{th} for cooling. Regarding the artificial lighting system, neon fluorescent lamps, incandescent and halogen lamps have been replaced with LED lamps and a presence detection system and a crepuscular sensor have been installed in the offices for a total installed power of 11.3 kW_{el}, thus decreasing the installed power that was previously about 28 kW_{el} [15-16]. Since the initial goal of this paper was to pursue a policy that lead to NZEB, it's been necessary covering the remaining energy requirements by installing photovoltaic panels and a photovoltaic skylight over the courtyard, although not allowed by the building regulation. In the following Table 7 are reported the features of the PV plants. Fig. 5 shows the ideal productivity of the plants in the traditional (a) and with skylight configuration (b).

Table 7. Features of the PV plants adopted.

PV plant typology (CODE NAME)	K_{pv}	f_{pv}	South surf. *(m^2)*	East surf. *(m^2)*	Skylight surf. *(m^2)*	kW_p
Monocrystalline silicon panels (PV1)	0.15	0.75	300	300	-	90
PV1 + thin film CIGS skylight (PV2)	0.105	0.75	220	220	570	126

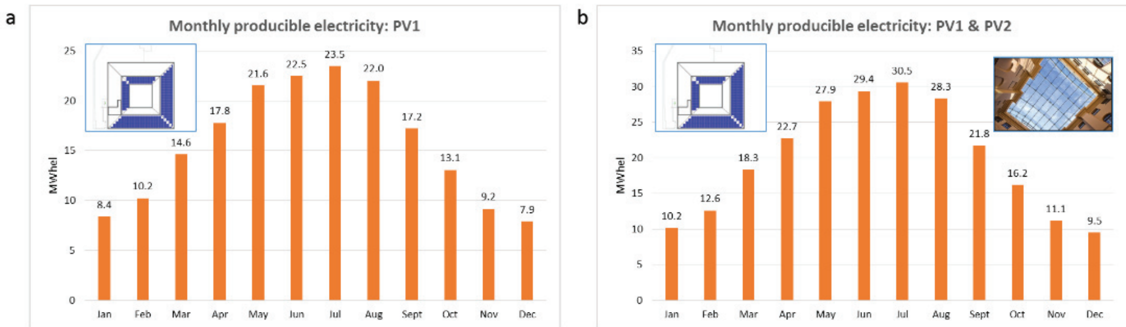

Fig. 5. (a) Producible electricity with traditional PV; (b) Producible electricity with traditional and skylight PV

The matching of the solutions adopted generates several combinations of retrofit strategies. The NZEB target is approached only with the overlapping of all the considered solutions as it is evident in the following Table 8.

Table 8. Overview of considered scenarios for retrofit strategies.

Retrofit Scenarios	Specific energy consumption *(kWh/m^3)*	Specific CO_2 emission *($kgCO_2/m^3$)*
Pre.ENV + Pre.PLA	23.6	4.68
New.ENV + Pre.PLA	22.4	4.63
Pre.ENV + GHP	21.4	4.53
New.ENV + GHP	21.1	4.47
Pre.ENV + LED	19.7	4.10
New.ENV + GHP + LED	16.2	3.80
New.ENV + LED + PV1	14.5	3.42
New.ENV + LED + PV1 + PV2	13.0	3.18
Pre.ENV + LED + PV1	11.0	2.06
Pre.ENV + LED + PV1 + PV2	7.8	1.76
New.ENV + GHP + LED + PV1	7.5	1.30
New.ENV + GHP + LED + PV1 + PV2	4.3	1.00

4. Costs analysis

The cost analysis has been conducted referring to annual total cost, defined as the sum of annual cost of operation and maintenance (O&M) and actualized annual installment of investment costs. The investment cost (IC) is constituted by the capital connected to the implementation of intervention, in terms of installation of materials and plants. The annual discount factor, also called present value (PV), allocates the initial capital investment in equal annual installments, taking into account the interest rate, over a number of years equal to the life of the system.

Table 9. Costs and % annual energy savings for each retrofit intervention.

Retrofit Intervention Code	IC (k€)	O&M (k€/y)	AES
New.ENV	393.2	-	2 %
GHP	130.7	5.3	3 %
LED	41.3	1.8	13 %
PV1	418.3	3.5	35 %
PV2	274.5	3.2	20 %

It must be underlined that in this study has been considered a calculation period of 30 years as provided for by the EU Chief Regulation No. 244/2012, since the object of analysis is a public building. In addition, in order to contemplate a scenario of rising energy costs, the net present values (NPV) of the interventions and the return on investments have been calculated. The following economical parameters have been adopted: a) discount rate equal to 3%, b) rate of increase in energy cost equal to 5%, c) rate of increase of O&M cost equal 2%, d) electric energy cost equal to 0.19 €/kWh. In Fig. 6 are shown the NPV trend of some significant retrofit scenarios.

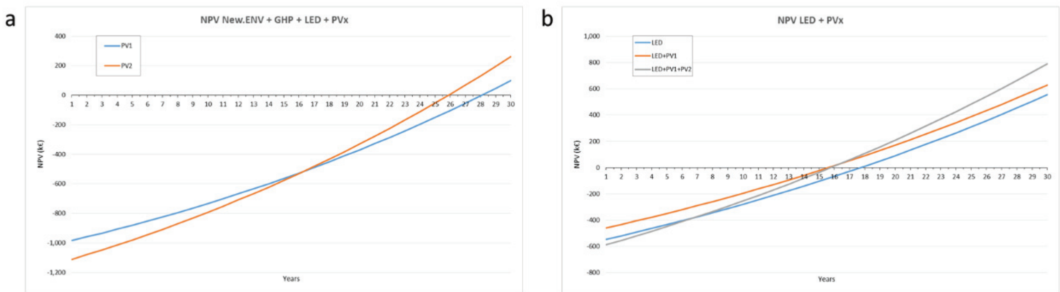

Fig. 6. (a) The NPV of scenarios that would ensure NZEB target; (b) the most economical feasible-NZEB target oriented scenarios;

Fig. 7 represents a map of economical feasibility of each retrofit scenario. To properly read the map, each scenario, more is higher and to the left in the graph, more is economically feasible.

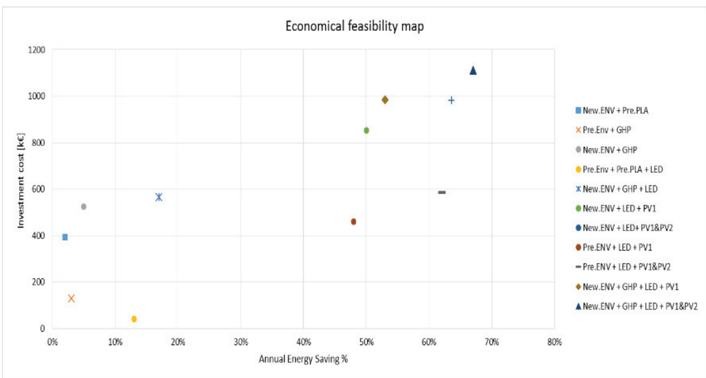

Fig. 7. Economical feasibility map of each scenario

5. Conclusions

The comparison of the energy needs results of the building has highlighted some differences between softwares. The energy demands for space heating and cooling obtained with Termo were higher than those provided by TRNSYS. The reason lies in two factors: (i) the different weather data, and (ii) the fact that one software is static while the other dynamic. Therefore, in addition to the different climatic boundary conditions imposed, the inertial phenomena have contributed to generate differences. Then, starting from the results of the simulations performed with TRNSYS, a mix of retrofits has been suggested. The results of this study show that by retrofitting the existing with common technological solutions it is possible to reduce energy needs and greenhouse gases emissions, of about 30%. It is however clear that only using energy produced on-site from renewable sources, the budget can ensure the achievement of the NZEB target. In our case, only those scenarios that involve the use of PV technology made possible to cut down the threshold of specific primary energy needs under 10 kWh/m³. Only by adopting skylight PV is possible to reach values lower than 5 kWh/m³, thus approaching the NZEB target. Unfortunately, this last scenario is not feasible if we consider the restrictions imposed by the building regulation of Agrigento with regard to historical buildings. The criteria for defining the retrofit strategies to reach the NZEB target cannot ignore the economical aspects. In this regard, these study has highlighted the criticity in adopting some solutions: for example, increasing levels of building envelope thermal insulation and replacement of existing heat pumps with geothermal ones are not cost-effective if not combined with other design choices, despite the same solutions, by themselves, contribute to approach the desired target. Conversely, even combining with them usually profitable technological solutions, such as photovoltaic and LED, the NZEB target involves a significant delay in return on investment which, if associated with the variability of market interest rates, makes the results uncertain in such scenarios.

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