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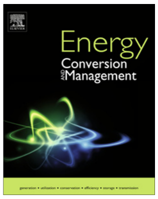

Heading towards the nZEB through CHP+HP systems. A comparison between retrofit solutions able to increase the energy performance for the heating and domestic hot water production in residential buildings

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ABSTRACT

Optimizing consumptions in the field of civil construction led to define energy labels for residential buildings. To calculate the building energy demand the EPgl was determined, i.e. the annual consumption per m^2 of primary energy. This paper examines the technical solutions useful to optimize the energy demands for heating during space-heating season and domestic hot water production (thanks to energy analysis softwares as MC11300 and TRNSYS) and, at the same time, to take into account the financial issues those interventions implied. The total inside heated surface of the building case study is 1204.00 m^2, hence the inside heated volume is about 3250.80 m^3. Besides the more traditional interventions concerning the building envelope and its systems, the paper examined the performance of a system obtained through the combination of a cogenerator (CHP) and a heat pump (HP), thus, substituting the conventional boilers of the buildings. CHP+HP solution increases the most the energy label of the building (from a D class with EPgl = 59.62 kW h m^{-2} $year^{-1}$, to an A class, with EPgl = 25.64 kW h m^{-2} $year^{-1}$), determining an annual energy cost saving of 3,114 € $year^{-1}$, allowing to amortize installation costs (54,560 €) in a reasonable payback period, i.e. 15.4 years. This innovative solution in the residential sector can be realized through retrofit interventions on existing buildings, hence it leads the current dwelling towards nZEB with a remarkable benefits for the environment.

1. Introduction

Recent outlooks revealed a constant increase in the global energy consumption until 2040, whatever the economic and political scenarios might be [1]. Right now the residential sector reports an influence of 18% on the entire global energy demand. The new overspreading demand of the emerging economies in the non-OECD Countries is leading to new residential conditions with higher living standards. Hence some other factors will increase in the residential sector as well: heating consumptions, the production of domestic hot water, air-conditioning and lighting. The estimation is that until 2040 the demands of this sector will increase with an average annual rate of 0.4% in developed Countries and 2.5% in the developing Countries, until reaching a 31% of total world residential delivered energy consumption.

To be more specific, in Europe the 2010 residential sector reported a 26.65% of total final energy consumption [2]. According to the geographical location in EU, the energy mix that wants to fulfill the demand is formed by the combustion of fuel and gas derivatives (55% of the total) in the South of Europe, whereas a certain quantity of energy derived from the coal must be added in the Centre and East of Europe (51% of the total) and in the North and West of Europe as well (60%) [3]. Nowadays these energy choices cannot be environmentally sustainable anymore. The solution is to regulate the demand of the residential sector by reducing the exertion of traditional energy sources and at the same time using renewable sources [4]. This is why the EU issued a legislation [5–8] that wanted to promote the energy efficiency in buildings by making homogenous regulations in all those Countries part of the community seeking for new technical solutions that might

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Nomenclature

C	internal heat capacity of the building [J K^{-1}]
CHP	combined heat and power [–]
CO_2	carbon dioxide [–]
COP	coefficient of performance [–]
CTI	Italian Technical Committee [–]
EP_{acs}	energy performance for the production of domestic hot water [kW h m^{-2} $anno^{-1}$]
EPBD	Directive on the Energy Performance of Buildings [–]
EP_e	performances for the air-conditioning in the summer [kW h m^{-2} $anno^{-1}$]
EP_{gl}	global energy index [kW h m^{-2} $anno^{-1}$]
EP_i	energy performance for the heating during cold season [kW h m^{-2} $anno^{-1}$]
EP_{ill}	energy used for the lighting [kW h m^{-2} $anno^{-1}$]
EP_v	energy used for the ventilation [kW h m^{-2} $anno^{-1}$]
HIPs	Home Information Packs [–]
HP	heat pump [–]
I_{el}	power to heat ratio [–]
I_t	global radiation [W m^{-2}]
k_e	coefficient of external adduction [W m^{-2} K^{-1}]
k_i	coefficient of internal adduction [W m^{-2} K^{-1}]
nZEB	nearly Zero Energy Building [–]
PCI	Lower Heating Value [kW h/S m^3]
$P_{el,CHP}$	CHP electrical power [kW]
$P_{el,HP}$	HP electrical power [kW]
P_{fuel}	CHP fuel consumption [kW_t]
$P_{heat,b}$	thermal power necessary to the building for the heating [kW]
$P_{heat,CHP}$	CHP thermal power [kW_t]
$P_{heat,HP}$	HP thermal power [kW_t]
PVC	polyvinyl chloride [–]
Q_{gn}	total heat gains [J]
$Q_{H,ht}$	total heat exchange between confined environment and the outside [J]
$Q_{H,nd}$	heat provided by the system to the confined environment [J]
$Q_{H,tr}$	transmission heat exchange for heating season [J]
$Q_{H,ve}$	ventilation heat exchange for heating season [J]
Q_{int}	internal gains [J]
Q_{sol}	solar gains [J]
Rh	relative humidity [%]
RT	Thermal Regulation [–]
t_a	room temperature [°C]
t_m	average temperature [°C]
U	thermal transmittance [W m^{-2} K^{-1}]
$\eta_{exchanger}$	efficiency of the heat exchanger [–]
$\eta_{h,gn}$	heating utilization factor [–]
$\eta_{heat,CHP}$	CHP heat recovery efficiency [–]

increase the energy performances in new and existing buildings while taking into consideration costs and benefits [9].

1.1. Energy certification of European buildings

The emission of the Directive on the Energy Performance of Buildings (EPBD) [5] was performed after the Kyoto protocol [10], and it was a legislative instrument used by the EU to reduce CO_2 emissions with respect to 1990. Each country, according to both its climatic and constructive features of the existing buildings and its own national regulations, was asked to set the rules to perform the energy analysis of the buildings (both existing and new) with respect to common principles dictated on a supranational level through the European regulations. The goal is to have a decrease in the energy consumptions on a communitarian level in the residential sector, with the objective that in 2020 it will be possible to build only nZEB (nearly Zero Energy Building) [11,12].

According to the national regulation, the amount of specific energy (kW h/m^2) indicates the energy performances and the energy class of the building examined. The resulting value will be in a certain range set by the regulations: with the decrease in the energy demand the building will have a higher energy class (identified by a letter, from A to G, if the class is high it will correspond to one of the first letters of the alphabet). The certificate must present the recommendations for the improvement of the energy performances of the building, that is technical interventions on the building envelope and/or on the energy system used.

In the United Kingdom the energy performance certificates were introduced in 2007 in the documentation Home Information Packs (HIPs). Meant for the owners of domestic apartments, they are the result of the exertion of the [5] in the English legislation through the Housing Act 2004 [13] and The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007 (S.I. 2007/991) [14]. Denmark made obligatory the energy certificate of the buildings in 1997, before the European Directive, which joined in 2006 [15]. France adopted the European Directive through the 2005-781 regulation [16] which was then updated at the end of 2015 and it is based on the Thermal Regulation TR [17] updated in 2012. Portugal, through the regulation no. 78/2004 [18] realized the Directive, as Italy with the no. 192 in 2005 [19].

1.2. The energy requalification of the Italian house block

In this context the issue that wants to be stressed is the Italian building scenario. Italy is a country whose boundaries extend from the North to the South between the 47° and 35° parallel respectively [20,21]. It is characterized by a variety of different climates which makes harder to have constructive standards both for the optimization of buildings' envelope and planning of the systems meant for the building. For new buildings, planned to decrease energy consumptions, it is possible to have great results in terms of energy performances; on the other hand for existing buildings (which usually were realized through old planning criteria with economic necessities that were different with respect to nowadays demands) is more complicated to improve their efficiency. Statistically speaking, Italy is characterized by a building scenario with old structures. According to the latest Italian census [22], carried out in 2011, the total of the residential buildings presents 12.2 millions structures; 56.7% of them were built before 1970 (that is before 1976 which is when the first law [23] for the restraint of the energy consumption in the buildings was issued), 29.4% of them were built between 1970 and 1990 and only 13.9% was built between 1990 and 2011. This is why most of the structures report a low efficiency with high primary energy supplying costs [24,25].

Then it should be also said that the Italian real estate sector is mainly formed by small owners [22] who often, due to initial investment costs, do not want to perform interventions on their properties to improve their energy efficiency. This is one of the main barriers to the technological refurbishment necessary for a wider optimization on a national level [26]. The financial incentives of the government can be a benefit, though the most important thing is to understand what type of energy interventions must be performed on the building envelope/technological systems together with their realization and installation on existing buildings and which are economically advantageous [27,28].

These evaluations are performed through the energy class analysis. It is affected by the global energy index EP_{gl} (expressed in $kW\,h\,m^{-2}\,year^{-1}$) which is the sum of the partial indexes EP_i (energy performance for the heating during cold season), EP_e (performances for the air-conditioning in the summer), EP_{acs} (energy performance for the production of domestic hot water), EP_{ill} (energy used for the lighting), EP_v (energy used for the ventilation) and EP_t (energy performance for the transportation of people).

However this paper will focus on the thermal demands for the heating of the building and the production of domestic hot water.

1.3. nZEBs in Italy

Nearly Zero Energy Building must respect the regulations [29,30]. According to the Directive 2010/31/UE [6], L.D. no. 63 [26] states that new buildings realized from 2021 on (if public from 2019) must respect the regulations presenting characteristics which make it more highly energy efficient than the building taken into consideration (virtual building, presenting the same geometry of the one of the plan with low thermal features – Appendix A of the L.D. [31]). One of the next regulations will define, in Europe, the performances limits of the building but the numbers have not been set yet [32–34]. Realizing buildings with technologies able to guarantee a certain energy performance implies an ad hoc planning and high investment costs for the construction. However it is already possible to have these results. The main problems do not concern the realization of a building, but rather those buildings already constructed. In Italy there is not a tendency to demolish old buildings to construct new buildings thus occupying new soil and overspreading urban centers to suburban areas which are cheaper (sale per m^2) and this represents an obstacle to the investments for the construction of high energy class buildings with higher realization costs [35].

For what concerns the energy retrofit interventions [36–38] for the existing heritage where the energy demand depends on the heating during cold season and the production of domestic hot water, the solution might be the exertion of micro generation system (CHP) dimensioned for the production of electrical energy required by the heat pump (HP). The combination of the CHP and HP generates the necessary amount of thermal energy to fulfill the demand of the building, replacing the heat generators previously present. The goal of this paper is to understand the contribution of such retrofit solution to the objective of having nZEB standards for the consumptions in existing buildings.

1.4. Combination of CHP and HP for the heating and the production of domestic hot water

The combination of the cogeneration system and heat pumps can be advantageous for the energy optimization in buildings in terms of heating and production of domestic hot water (both for new and existing buildings) [39–46].

The scientific world has been exploring the possibility of combining old technologies as the CHP with HP [47], to satisfy the same demand of thermal energy (for the heating in wintertime and the production of domestic hot water) which in the buildings is currently provided by systems whose heat generator is mainly formed by boilers (in the best situations by condensation systems). As boilers, CHP+HP systems convert the chemical energy of the fuels into heat [48–50].

An example can be found [25,35,51,52] in the combination of micro and mini cogeneration systems (with devices ranging from ten to hundreds kW), based on old technologies (as otto cycle engines that can be gas methane supplied as the boilers that they should substitute) and hydronic heat pumps. The purpose is to provide the final user (e.g. the owner of the property [53]) whose demand is based on: (i) a system that can decrease deeply the cost of the heating during cold season and the production of the ACS, (ii) the substitution of the old heat generator without an installation process that might be too complicated with a system which is similar to the one that will substitute it (a device which presents in just one body machine everything that it needs to operate), gas supplied (already present) and necessitates the existing pipes for the connection to the heat distribution system (the delivery of hot water to the heating system and its return).

The system is formed by a heat pump and one cogenerator that will be adjusted for the electrical load that the user requires (the HP) [54,55]. The combination of the heat generated by the heat pump (degrading the electrical energy provided because of the work of the compressor with a multiplicative coefficient which is equal to the COP – a value that usually, thanks to modern technologies, is higher than 3) and the one recovered from the cogenerator that supplies it, leads to a global output of the system of 160%. In other words, the combustion of the methane generates the work that will be degraded into thermal energy with a multiplicative coefficient which is equal to the COP of the heat pump, plus the heat produced and recovered from the cogenerator that supplied the heat pump with electrical energy. Hence thermal demand being the same, the result is that a minor amount of primary energy (methane) was consumed with respect to other commonly used traditional technologies [56].

If the heat production and distribution systems already present in the properties were slightly modified, it would be perfect for retrofit interventions in the existing house block. The efficiency, in new buildings, can be even higher thanks to ad hoc systems. These values of global output of the system allow to increase the index of the energy performance of a building (EP_i) [57,58] hence its energy class (in particular if the benefits of this solution will be added to other technologies generating heat through the solar source).

This paper, through a sample building, wants to quantify the energy optimization that can be obtained with this technology and compare the improvement in the energy class with that deriving by other traditional solutions.

This financial benefit can be added to positive consequences in terms of a lower gas emission level, hence a better respect for the environment with a less dependence from traditional energy sources [59] and a lower energy demands of the country from those Nations exporting hydrocarbon.

2. Purpose of the work

This paper examines how some interventions meant for the energy improvement might affect a building (in particular for those operating on the thermal demand for the heating during cold season and the production of domestic hot water). The regulation about energy retrofit, which can be defined as traditional, concerns the building envelope (1, 2) and the systems for the heat production and their proper functioning (3, 4, 5, 6, 7):

- improvement of the insulation of the boundary surfaces of the building (thermal coat);
- improvement of the thermal insulation properties of glass surfaces and frames;
- substitution of the control system with smart control units, more efficient sensors and installation of thermostatic valves;

- substitution of the 3-stars-methane boiler with a condensing boiler;
- substitution of the 3-stars-methane boiler with heat pump systems;
- installation of solar panels for the production of domestic hot water;
- installation of photovoltaics panels for the production of electrical energy for private consumption and net metering.

The goodness of fit of those measures was examined for both each intervention and their combination with the others (1 + 2; 4 + 6; 5 + 7; 3 + 4 + 6; 1 + 2 + 3 + 4 + 6).

Moreover, the substitution (more innovative) of the heat generator with a CHP+HP system (8) was also analyzed. The interventions were evaluated with respect to the improvement of the energy class of the building and a cost-benefit analysis. This is why the improvements were studied according to the installation cost in the existing building and the payback period of the investment depending on the savings of the annual energy costs. This matter can help all those engineers that, once asked to write certificates for the energy performance of a building (or part of it), in the final part must write the type of interventions suggested to increase the energy class [19].

This paper does not examine the ordinary and extraordinary maintenance costs of the interventions here suggested.

3. Material and methods

For what concerns the evaluation of the thermal comfort of the building and its energy demand (heating during cold season and production of domestic hot water), it complied with the current Italian regulation about the energy class. This is why engineers must respect the technical regulation UNI EN 11300 - Part 1,2,4 [60–62] for the assessment of these demands (which in Italy corresponds to the UNI EN ISO 13790 [63]). These regulations decide how the primary energy exerted for the standard use in a building should be estimated. These assessments can be performed through software that study the dynamic behavior of the building examined (e.g. TRNSYS [64] analyzes its behavior during the transitional arrangements), or through simplified procedures (semi-stationary approach) that estimate the demand through a simple software (e.g. MasterClima MC11300 [65]). Simplified software, in order to be appropriate for the certification of the energy class, must be able to estimate the demand of a sample building (considered as a benchmark) with a maximum approximation of 5% with respect to the calculations carried out through simulations during the transitional arrangements. The promotion of these software (and their exertion from technical users for the energy certification of buildings) depends on the examination of these requisites from the CTI (Italian Technical Committee, whose authority has been recognized from the current regulation) that gives a certificate if it complies with the standards [19].

TRNSYS is an extensible simulation environment for the transient simulation of buildings and their systems.

It is a software able to solve algebraic and differential equations through a modular approach. It is also able to solve complex problems (concerning the energy issues of the building envelope and its systems) as all the easy problems summed together through the Types (components characterizing its library or that can be programmed by the user) implemented inside it. Each Type receives an input and provides output to other Types implemented in the calculation sequence (iterative) set by the user to simulate the problem. To insert the data of the building model into TRNSYS (geometrical characteristics and thermophysical properties of the materials characterizing the building's envelope), the Type56 is implemented into the tool TRNBuild, which is provided with the software [64].

MC11300 is a semi-stationary software assessing the energy demand of the building according to the UNI/TS 11300 [60,65,66] and the calculation models were defined in regulations as the ISO 13790 [63] (that gives calculation methods for assessment of the annual energy use for space heating and cooling of a residential or a non-residential building).

TRNSYS examines the behavior of the building while taking into consideration the hour variation of the outside temperature, based on files (that can be provided from the outside to the program) with meteorological data available online [67]. MC11300 will implement average climatic data in accordance with the regulation UNI 10349 [68].

Inside these two software the case study was implemented (hereafter described) and the results obtained were compared for a mutual validation. Then MC11300 was used to examine the interventions identified from number (1) to number (8) in the list that can be found in Paragraph 2 (and their combination) since the regulations take into account these interventions [60–62] and they are implemented into the software. On the other hand through TRNSYS the behavior of the building was simulated thanks to dynamic simulations [69], taking into account a CHP+HP system for the heat generation.

Once the study, in terms of energy, was performed for each intervention the realization cost was determined through, when possible, an official regional price list [70] for the purchase and installation of building materials and alike. For those things that were not present in the price list, the choice was to use the commercial price list currently available on the Italian market. This allowed to carry out a financial analysis and estimate, through the payback period, the benefits determined by the energy saving for every technological solution suggested. For what concerns the energy cost, the data provided by the authorities in charge were taken into consideration [71].

4. The case study

4.1. The building ante operam

To evaluate the afore mentioned interventions, a typical residential building realized according to the standards set at the beginning of 2000 in Italy was taken into consideration. The building is formed by 5 storeys with 3 apartments on each floor. The planimetry is the same for every floor and the orientation of the structure is reported in Fig. 1. The inside surface of each floor is of 339.75 m^2 (240.80 m^2 are heated) and apartments A and C (Fig. 1) present a surface of 87.3 m^2 each, whereas apartment B 66.2 m^2. The total inside surface of the building is 1698.75 m^2 (1204.00 m^2 heated). The height of each floor (from the floor to the ceiling) is of 2.7 m, hence the inside volume is about 45,867 m^3 (3250.80 m^3 are heated). The ratio (dispersant surface/volume) of the building is of 0.38 m^{-1}. The building is isolated from the ground through a pilotis floor and the last floor confines upward with the outside through a covering terrace.

This paper focuses on the energy demand of the building related to the production of the required annual amount of domestic hot water and to the heat flux exchanged through the boundary surfaces of the building in the space-heating season. This is why an inside temperature of the heated areas in the building to 20 °C was set (as the regulations expect [57]). The outside climatic conditions used for the simulations are the typical conditions characterizing Rome (Italy). The city is characterized by a typical Mediterranean climate and it presents mild and warm temperatures during spring and fall. Summer season is usually hot, humid,

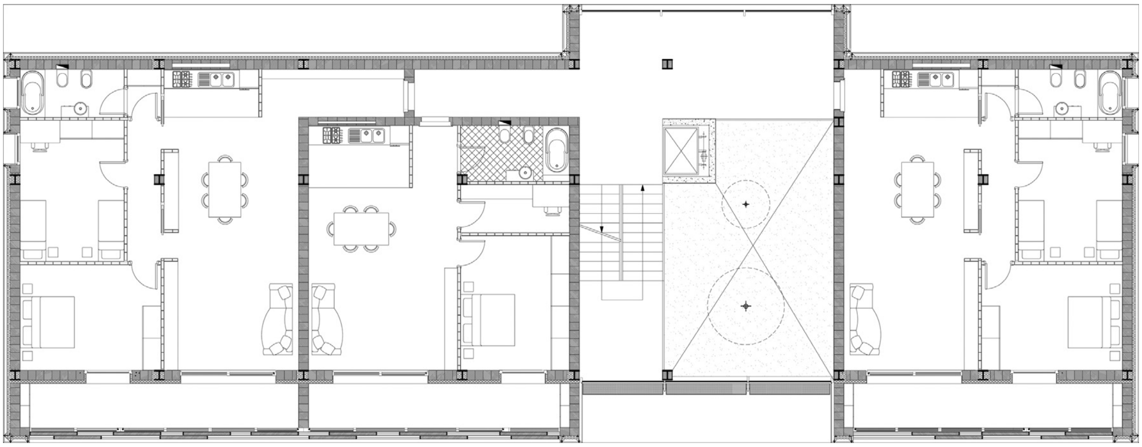

Fig. 1. Planimetry of the apartments characterizing every floor of the building.

and characterized by low precipitation, whereas space-heating season tends to be mild and wet with isolated phenomena of low temperatures and snowfall. According to Köppen's classification, such weather belongs to the Csa category [21]. While taking into consideration the S/V ratio of the building and the climatic data of the city, it can be noticed how the regulations set some limits to the annual energy demand for what concerns the unitary walkable surfaces. These limits are reported briefly in Fig. 2.

Surfaces characterizing the building envelope are in part opaque and in part made of glass. Boundary horizontal surfaces concern the first floor only (whose floor confines with the outside standing on a pilotis surface; this architectural solution allows to have a thermal insulation from the ground) and the last floor (confining with the outside through a covering terrace). The dimensions of these surfaces for the entire building envelope are reported in Table 1 together with their exposure with respect to the cardinal points.

Vertical opaque surfaces are realized through a different stratigraphy according to their exposure towards the outside (Vertical 1) or unheated inside sections (Vertical 2). Even the horizontal boundary surfaces are different. The horizontal partitions in the middle were not taken into consideration because they divide spaces which are thermally neutral hence they are not a contribution both to the thermal exchanges with the outside (assuming a stationary regime) and the energy demand of the building. Table 2 reports briefly the stratigraphies of the opaque surfaces and the thermophysical properties of the materials used.

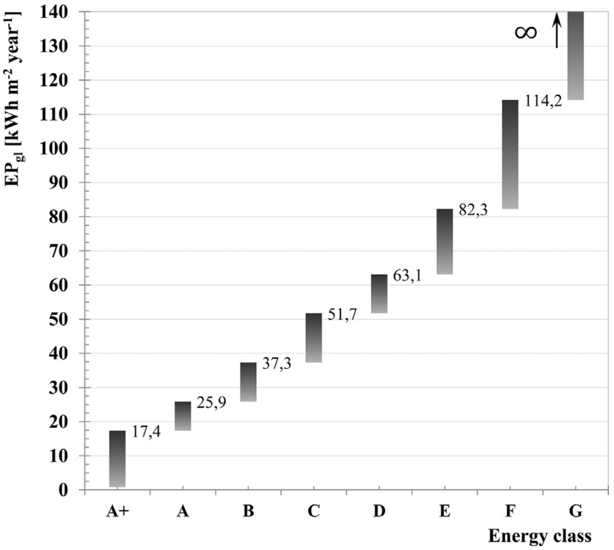

Fig. 2. Limit values of the energy class in the case study.

Table 1
Boundary surfaces of the entire building and their orientation.

Exposure	Typology	Surface [m^2]
N	Vertical 1	276.75
	Window	0.00
E	Vertical 1	124.35
	Window	12.00
S	Vertical 1	351.50
	Window	121.50
W	Vertical 1	124.35
	Window	12.00
Unheated	Vertical 2	301.70
Horizontal	Ground and last floor	454.90

Transparent surfaces are windows or door windows (overlooking the terraces outside the apartments) whose dimensions are reported briefly in Table 3. All windows present the same structure formed by a PVC frame with a double glass whose stratigraphy presents an inside glass of 12 mm, an air space of 8 mm and an outside glass of 6 mm. Their cost is of 407.00 €/m^2 and leads to a total cost of 59,020.00 € [70].

The ventilation of residential spaces is natural (air exchanges assumed to be 0.5 volumes per hour [60]). The heat gain inside the building, in accordance with the current regulations [60], is assumed to be of 4.07 W m^{-2}. The demand of domestic hot water, in accordance with [61], for the occupants of a residential building of this size is of 3750 L per day for the entire building, which is characterized by domestic hot water storage systems.

Besides the building envelope with its own features there is a heat generation system for the heating in the cold season and the production of domestic hot water. For what concerns the boiler, supplied by natural gas (with a Heating Value of 9.54 kW h/Nm^3), a modulating blast air standard generator with a furnace power of 74.9 kW was assumed, an efficiency at 100% of the nominal power of 91.1% and an efficiency at 30% of 91.8%. The boiler is characterized by a climatic probe placed on the shaded North-oriented outside wall. The emission system of the heat inside the heated spaces is centralized with a horizontal distribution formed by radiators placed on the outside wall. The cost of the boiler is of 14,420.00 € [70].

Table 2
Stratigraphy and features of the materials forming the opaque surfaces of the building.

Typology	Stratigraphy[a]					Transmittance[b]
	Material	Thickness [m]	Thermal conductivity [W m^{-1} K^{-1}]	Volumic mass [kg m^{-3}]	Thermal capacity [J kg^{-1} K^{-1}]	U [W m^{-2} K^{-1}]
Vertical 1	Plaster	0.01	0.800	1600.00	1000.00	0.273
	Air brick	0.15	0.159	693.30	840.00	
	Polyurethane	0.08	0.032	32.00	1400.00	
	Air brick	0.15	0.159	693.30	840.00	
	Gypsum mortar	0.01	0.290	600.00	1000.00	
Vertical 2	Plaster	0.01	0.400	1000.00	1000.00	0.656
	Air brick	0.15	0.247	600.00	840.00	
	Plaster	0.01	0.400	1000.00	1000.00	
Roof	Tiles	0.015	1.300	2300.00	840.00	0.263
	Tar paper	0.002	0.230	1100.00	1000.00	
	Concrete	0.05	0.300	1000.00	1000.00	
	Polyurethane	0.08	0.034	25.00	1400.00	
	Concrete	0.33	0.300	1000.00	1000.00	
	Plaster	0.01	0.400	1000.00	1000.00	
Floor	Tiles	0.015	1.300	2300.00	840.00	0.343
	Concrete	0.33	0.186	400.00	1000.00	
	Polyurethane	0.08	0.034	25.00	1400.00	
	Concrete	0.05	0.300	1000.00	1000.00	
	Alluminium	0.002	160.00	2800.00	880.00	

[a] Materials are listed from the inside to the outside

[b] Adduction coefficients: $k_i = 10$ W m^{-2} K^{-1}; $k_e = 25$ W m^{-2} K^{-1}.

Table 3
Dimensions and features of windows.

Typology	Glass surface [m^2]	Surface of the frame [m^2]	Total surface [m^2]	U[a] [W m^{-2} K^{-1}]
Window 1	0.94	0.26	1.20	3.064
Window 2	1.50	0.30	1.80	3.048
Window 3	5.88	0.42	6.30	3.049

[a] Adduction coefficients: $k_i = 10$ W m^{-2} K^{-1}; $k_e = 25$ W m^{-2} K^{-1}.

4.2. Interventions for the improvement

As previously said, the interventions performed to improve the energy performance of the building are:

– Applying an insulating coating on the vertical opaque outside surfaces: in order to have a wall (Vertical 1b) characterized by a lower transmittance, the interventions concerned the stratigraphy, by applying to the existing wall (Vertical 1) a further insulating material and, due to structural issues, air bricks. Table 4 reports the characteristics of the wall. The cost for the equipments and installation for each m^2 of insulating coating (superficial finishing materials included) is of 49.40 € and the intervention on the entire building is of 53,970.00 € [70].

– Substitution of the glass surface with double chamber triple glass: to better insulate the spaces and minimize the thermal exchanges through transparent surfaces, which are the weak point of the building envelope, the improvement in the realization of a transparent surface formed by a metal frame with thermal break covered with hardwood characterized by a triple glass was examined. Its stratigraphy is formed by an internal glass of 4 mm, a first cavity made of argon of 12 mm, an intermediate pane of glass of 4 mm and a second cavity made of argon of 12 mm and an external glass of 4 mm. The characteristics are reported in Table 5. The cost of the equipment and installation is of 356.00 €/m^2. The cost of all doors and windows forming the building is of 55,190.00 € [70].

Table 4
Stratigraphy and features of the materials forming the opaque surface “Vertical 1b” of the building.

Typology	Stratigraphy[a]					Transmittance
	Material	Thickness [m]	Thermal conductivity [W m^{-1} K^{-1}]	Volumic mass [kg m^{-31}]	Thermal capacity [J kg^{-1} K^{-1}]	U [W m^{-2} K^{-1}]
Vertical 1b	Plaster	0.01	0.800	1600.00	1000.00	0.187
	Air brick	0.15	0.159	693.30	840.00	
	Polyurethane	0.08	0.032	32.00	1400.00	
	Air brick	0.15	0.159	693.30	840.00	
	Polyurethane	0.06	0.032	32.00	1400.00	
	Air brick	0.04	0.159	693.30	840.00	
	Gypsum mortar	0.01	0.290	600.00	1000.00	

[a] Materials are listed from the inside to the outside.

Table 5
Dimensions and characteristics of windows after the improvements.

Typology	U [W m^{-2} K^{-1}]
Window 1b	2.09
Window 2b	2.01
Window 3b	1.88

- Changes performed on the control system: a simple intervention performed to optimize the functioning of the control system for the production and distribution of thermal energy into the building is possible by substituting the present system (with just the external climatic probe) with a finer control system as an automatically controlled compensation unit with proportional regulation and a distribution system able to provide the necessary heat according to the temperature of every environment. Therefore this intervention sees probes for the compensation of the pressure and rate and thermostated probes regulating the rate of the thermovector fluid circulating in every radiator. The cost of the equipment and installation of the system here described is of 13,870.00 € [70].
- Substitution of the condensing boiler: the boiler of the building ante operam to function needs only a part of the heat generated by the combustion because traditional boilers should avoid condensation phenomena of the smoke in the chimneys due to corrosion problems. The substitution of a traditional boiler with a condensing one must be performed with the realization in a technical environment of a condensate drain piping (and the devices useful to the neutralization of the acid condensation) together with the substitution of the flue pipe with a stainless steel pipe. The cost for the materials and installation of this solution is of 32,560.00 € [70].
- Substitution of the heat generator with a heat pump of the air-water type: providing the work through a mechanical compressor supplied by electrical energy while exploiting the technology of the inverse Carnot-cycle heat pumps. This system can substitute the role of a boiler in a building, which is thus freed from the consumption of combustible fuel because the heat pump is supplied by electrical energy. The financial benefit of this technology is affected by the cost of the electrical energy in the country where the building is placed, whereas for what concerns the environment the goodness of fit of such solution depends on the amount of carbon dioxide generated for every unit of electrical energy produced according to the National energy mix for the electricity production. Therefore the substitution of the boiler with an air-water type heat pump with a nominal thermal power of 90 kW, able to heat the thermovector fluid (water) delivered to the heat distribution system at a temperature of 60 °C and with a return from the users of 50 °C, was assumed. The COP of the machine chose can change and is affected by the outside temperature. The trends of the COP are reported in Fig. 3. The cost for the materials and installation of the system described is of 29,960.00 € [70].
- Realization of a solar heating system for the production of domestic hot water: the space which is available on the outside of the building is appropriate for the installation of solar panels for the production of 50% of the annual demand of domestic hot water in the building (in accordance with [19]). Flat solar panels made of glass present a variable efficiency to converse the solar energy into thermal energy according to the outside temperature conditions. Trends are reported in Fig. 4 [72]. Panels have a total reception surface of 75 m^2 and they produce hot water which will be collected in the existing storage tanks. On the terrace outside of the building it is possible to install these panels with an azimuth angle (with respect to the South) of 0° and a tilt angle (with respect to the horizontal surface) of 60°. The cost for the materials and installation of the system is of 37,180.00 € [70].
- Realization of a PV system: a system for the production of electrical energy from a solar source allows to fulfill the electrical demand of the systems present in the building without using the electrical energy from the network (in presence of solar radiation). Thanks to the net metering of the electrical energy produced, it is possible to sell the extra energy and buy it again when the PV system is not able to produce electricity. The PV system here examined presents a total area of the panels (used for the reception of solar energy) of 112 m^2 (in accordance with [19] it must be provided with 1 kW$_p$ to each flat, besides 1 kW$_p$ for every 100 m^2 of common spaces) and it is formed by unventilated modules of 0.3 kW$_p$ each in monocrystalline silicon. They are characterized by a conversion efficiency of 16.7% and placed with an azimuth angle of 0° and a tilt angle of 60°. This study assumed that the electrical energy produced was not used for the lighting demand of the building, for the electrical appliances or similar, but rather for the extra electric consumptions determined by other systems used for the heating during cold season and to produce domestic hot water. The cost for the materials and installation and the equipment necessary for their right functioning is of 85,690.00 € [70].

Traditional interventions here listed were also combined. In particular, the following solutions were analyzed: (1 + 2); (4 + 6); (5 + 7); (3 + 4 + 6); (1 + 2 + 3 + 4 + 6).

- (8) Substitution of the heat generator with a CHP+HP system: while taking into consideration the residential building examined, the technological solution used for the cogeneration is based on an Otto cycle alternative internal combustion engine. This engine is supplied with methane provided by the city network to which the building was already connected to supply the combustion boiler substituted by the CHP [73]. A cogenerator able to express to the alternator a power of 15 kW$_{el}$ and a thermal power of 31 kW$_t$ was chosen, characterized by a condensation heat recovery to make the system as much efficient as possible. The efficiency of the CHP in accordance with the expressed load percentage is reported in Fig. 5.

The CHP produces electrical energy which is useful to the air-water heat pump combined with it. The heat pump chose is a single stage with an absorbed nominal electrical power of 15.4 kW able to provide a nominal thermal power, while heating, of 42.5 kW and a maximum one of 50.5 kW. Since it is placed in a residential environment, it uses the R-410 refrigerant gas. The COP of the heat pump can vary according to outside conditions (Fig. 3). Thermally speaking, the combination of the CHP and HP for retrofit solutions in heating systems is possible with different system layouts which are reported in the bibliography [46]. The efficiency of the heat exchangers necessary between the CHP+HP system and the heat distribution system is of $\eta_{exchanger} = 0.9$.

Domestic hot water, produced by the CHP+HP system, is stored in tanks. The following schedule for the system to start was assumed: (i) when the heating is turned on (from the second half of October to mid-April), from 8.00 a.m. to 10.00 a.m. it will supply the heat system, from 10.00 a.m. to 3.00 p.m. it must generate and store domestic hot water and from 3.00 p.m. to 10.00 p.m. it must supply the heat system again; (ii) when it is off, during the hottest hours of the day (to support the functioning of the system during the highest conditions of efficiency of the heat pump) it must generate domestic hot water.

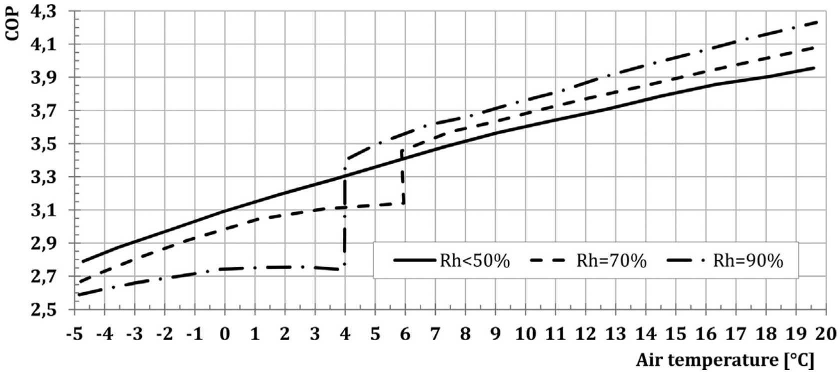

Fig. 3. Trend of the COP of the heat pump according to the outside air temperature.

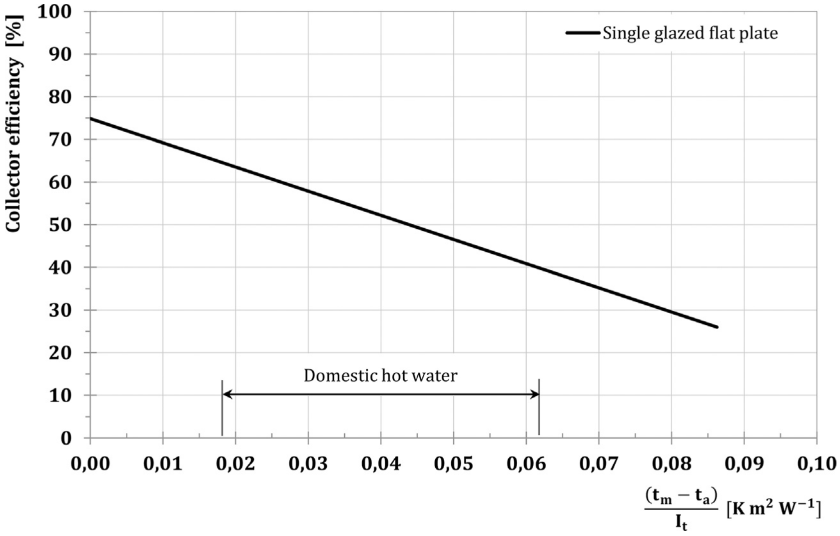

Fig. 4. Trend of the efficiency of the solar heat collectors.

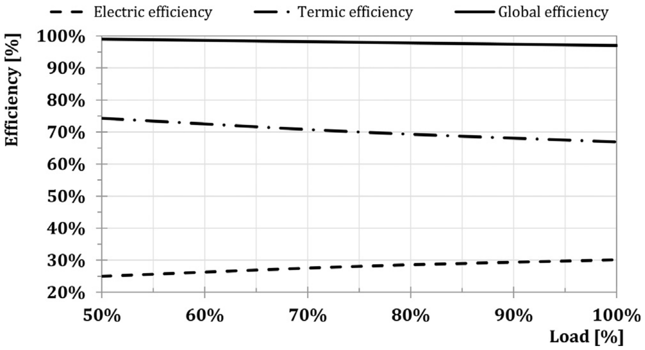

Fig. 5. Trend of the efficiency of the CHP.

Thanks to the dynamic simulations performed through the software TRNSYS, it was possible to determine the hourly thermal demand for the heating in the building and these data will give the energy provided by the CHP+HP system to the building, hence the consumptions of primary energy provided to the system through the methane combustion. Since the thermal power necessary to the building for the heating $P_{heat,b}$ was defined, it is possible to determine the thermal power provided by the combustible to fulfill this demand. Since the heat recovery efficiency of the cogenerator, the power to heat ratio of the cogenerator and the COP of the heat pump are defined in this way respectively:

$$\eta_{heat,CHP} = \frac{P_{heat,CHP}}{P_{fuel}} \tag{1}$$

$$I_{el} = \frac{P_{el,CHP}}{P_{heat,CHP}} \tag{2}$$

$$COP = \frac{P_{heat,HP}}{P_{el,HP}} \tag{3}$$

given that:

$$P_{el,CHP} = P_{heat,HP} \tag{4}$$

the thermal power provided by the combustible is:

$$P_{fuel} = \frac{1}{\eta_{heat,CHP} \cdot (1 + COP \cdot I_{el})} \cdot \frac{P_{heat,b}}{\eta_{\text{exchanger}}} \tag{5}$$

Hence it is possible to determine the annual primary energy necessary for the assessment of the energy performance of the building supplied by this system.

The installation costs of this type of solution (non-commercial) were estimated through a price analysis in terms of industrial production (able to exploit the effect of the economies of scale) of the single components and their assembly. The estimated costs allow to have a payback for what concerns the production costs, but at the same time have an income for the producers. After such estimation, the costs of the system here suggested range between a minimum of 1670.00 €/kW$_t$ of the CHP and a maximum of 1790.00 €/kW$_t$ of the CHP. The average cost of this range is 1730.00 €/kW$_t$ of the CHP. In particular a precautionary value which is about 75% of this range will be taken into consideration. Therefore the cost of the equipment and installation of the CHP +HP system (given its size) and all the necessary for its right functioning is of 1760.00 €/kW$_t$ of the CHP [74] with a total cost of 54,560.00 €.

5. Results

Before carrying out the energy analysis of the results, the data about the thermal behavior of the building obtained through MC11300 (a certified software used for the assessment of the energy performance of buildings) were compared to the demand determined through a dynamic simulation performed with TRNSYS. The goal of this comparison is to verify if both simulations led the examined building to have comparable thermal demands, in this way the demand of primary energy might be validated (influenced by the systems performances as well), hence calculate the energy class. Table 6 reports the energy demand of the heating related to the energy performances of the building's envelope assessed through the simulations performed with both software plus the variance in their results. It must be kept in mind that the CTI (Italian Technical Committee) gives the certification to the commercial software to be used for the drafting of the energy performance and allows a maximum values variance of 5% with respect to a building considered as a benchmark.

Since the variance in the values of the simulations is lower than the value that the CTI considers proper to certify the goodness of fit of the assessments, it can be stated that the software provide results that can be mutually compared and might simulate with validity the performances of the examined building.

5.1. Improvements in the energy performance

The simulations of the improvements suggested allowed to assess the index EP$_{gl}$ with reference to the sum of the indexes EP$_i$ and EP$_{acs}$. Results are showed in Table 7 and the energy class of the building, with respect to what was previously defined in Fig. 2, is reported briefly in Fig. 6.

5.2. Costs of the interventions and financial saving

For a proper financial evaluation of each improvement suggested, besides installation costs, the energy saving obtained each year must be examined. For the assessment of the annual saving the Lower Heating Value of the natural gas of 9.39 kW h/Sm^3 with a cost of 0.698 €/Sm^3 was taken into consideration. Moreover, in relation to the discount rate, an annual inflation (whose average was assessed according to the Italian values of the past 20 years) of 2.23% was considered. Then the annual increase in the energy price was assumed to be 0.58% [75]. All prices are reported in euros (€), with an exchange rate euro/US dollar of 1.122.

Table 6
Validation of the energy demand related to the building envelope in the simulations performed through MC11300 and TRNSYS.

	Software		Variance [%]
	MC11300	TRNSYS	
Annual energy demand related to the building envelope in space-heating season [kW h/year]	14,487	13,944	3.9%

Financial evaluations are based on the comparison between the solution analyzed and the Base Case. If there is an extraordinary maintenance intervention performed on the system used for the production of the heat necessary to fulfill the demand of the building, the substitution with another technology implies the amortization of the extra cost due to a technological improvement. If an intervention for the improvement of the building's envelope or sections which are not part of the system is performed, the cost must be amortized in its totality. As simplifying assumption, this analysis does not take into consideration maintenance costs which are affected by the reliability of the systems here suggested [76,77] for what concerns their installation and proper functioning.

Just for the intervention (5) it must be specified that on one hand the fossil fuel is saved because the boiler is not used as a heat generator, on the other hand an electric consumption occurs. Even if energetically speaking the consumptions of the primary energy decrease, the energy source is more expensive (the price of the current domestic power in Italy is of 0.157 €/kW h [71]). Given the cost of the electricity which must be assessed without taking into consideration the cost of the gas that is not used, the result is that the saving obtained every year is not enough. Hence the solution is not financially advantageous.

Before comparing the solutions examined, it is important to stress that the uncertainty caused by the costs (described in Section 4.2) of a non-commercial system as the solution (8), formed by CHP+HP, determines payback periods whose range is reported in Table 8.

To make things simple from now on this study will refer to just one estimated cost of the CHP+HP system of 1760.00 €/kW$_t$ of the CHP with a total cost of 54,560.00 € for this solution.

Table 9 reports the results obtained. It is possible to notice how solutions (1), (2), (5), (7), (1 + 2), (1 + 2 + 3 + 4 + 6) present payback periods which are higher than 30 years. Such solutions are considered to be technically feasible, but not sustainable from a financial point of view.

Fig. 7 reports the investment costs of the suggested solutions.

Then Fig. 8 reports the payback periods for the amortized solutions between 20 and 30 years since the installation was performed.

Fig. 9 reports the payback period just for those solutions that might be amortized within 20 years since the installation was performed. These solutions are the most advantageous financially speaking.

5.3. Multivariate analysis: Determining the Pareto solutions

As determined through the energy and financial analysis, the choice of a technician who wants to optimize an existing building with one of the interventions actually considered feasible must take into considerations different factors.

It is not possible to limit a study to energy aspects only, but rather make a wider analysis on more variables and understand (while keeping in mind financial factors as well) what is the best choice. The annual energy saving is not affected by the realization cost of the intervention. Especially in the residential sector this is one of the factors that private owners tend to take into consideration while carrying out the intervention for the energy optimization. A solution that can consider all these aspects together must be found.

This analysis wants to focus on three different set of technical solutions:

Table 7
Energy performances of the building once the improvements were performed.

ID	EP_i [kW h m^{-2} year^{-1}]	EP_{acs} [kW h m^{-2} year^{-1}]	EP_{gl} [kW h m^{-2} year^{-1}]
Ante operam:			
Base Case	23.07	36.55	59.62
Passive interventions:			
(1)	20.39	36.55	56.94
(2)	17.23	36.55	53.78
Interventions on the systems:			
(3)	11.89	36.55	48.44
(4)	18.25	31.83	50.07
(5)	8.16	20.65	28.81
(6)	23.07	5.40	28.47
(7)	22.89	36.27	59.16
Mixed interventions:			
(1 + 2)	14.69	35.55	51.24
(4 + 6)	20.09	4.70	24.79
(5 + 7)	0.16	0.17	0.33
(3 + 4 + 6)	11.14	4.70	15.84
(1 + 2 + 3 + 4 + 6)	6.12	4.70	10.82
New interventions:			
(8)	9.09	16.54	25.64

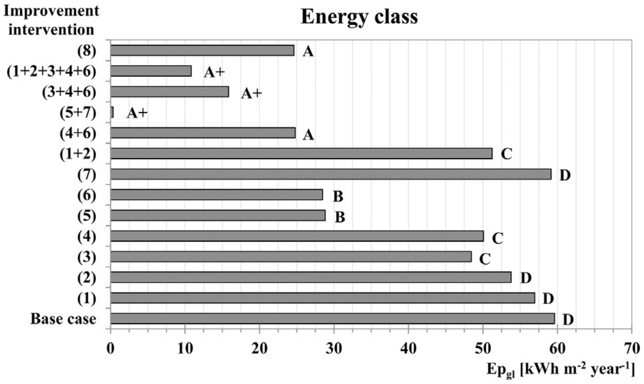

Fig. 6. Improvements suggested and energy classes that can be reached.

Table 8
Payback period of solution (8) with respect to installation costs.

Value	Specific costs [€/kW$_t$]	Total costs [€]	Amortization [years]
Minimum	1640.00	51,770.00	14.3
Average	1730.00	53,630.00	14.9
Chose	1760.00	54,560.00	15.4
Maximum	1790.00	55,490.00	15.8

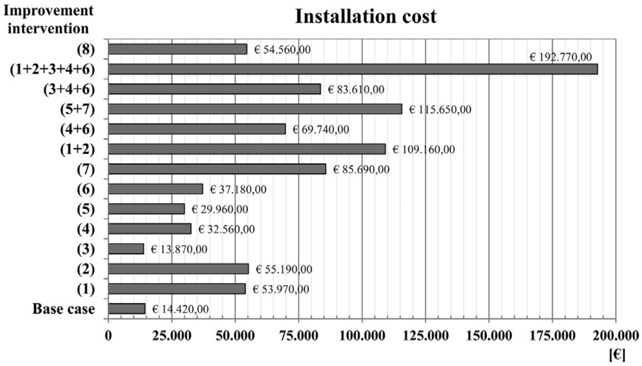

Fig. 7. Installation costs of the interventions for the energy improvement suggested.

(i) Set "Annual Economic Return": energy optimization of buildings (in a way it is possible to reduce the total energy demand with reference to fossil fuels), thanks to a higher energy class, implies a proper reduction of primary energy demanded which determines an annual economic return that justifies the financial effort performed to carry out the refurbishment of the building and the system;

Table 9
Installation and amortization costs, annual energy and financial savings and payback periods of every solution with respect to the Base Case.

ID	Installation costs [€]	Amortization costs [€]	Annual energy saving kW h/year	Financial saving [€/year]	Amortization [years]	
					<20 years	<30 years
Base Case	14,420.00	0.00	–	–	–	–
(1)	53,970.00	53,970.00	3227.00	239.00	x	x
(2)	55,190.00	55,190.00	7031.00	520.00	x	x
(3)	13,870.00	13,870.00	13,461.00	995.00	16.9	–
(4)	32,560.00	18,140.00	11,498.00	850.00	–	29.3
(5)	29,960.00	15,540.00	37,095.00	−37.00	x	x
(6)	37,180.00	37,180.00	37,505.00	2772.00	16.1	–
(7)	85,690.00	85,690.00	554.00	41.00	x	x
(1 + 2)	109,160.00	109,160.00	10,090.00	746.00	x	x
(4 + 6)	69,740.00	55,320.00	41,935.00	3100.00	–	27.6
(5 + 7)	115,650.00	101,230.00	71,385.00	5276.00	–	25.3
(3 + 4 + 6)	83,610.00	69,190.00	52711.00	3896.00	–	26.8
(1 + 2 + 3 + 4 + 6)	192,770.00	178,350.00	58,755.00	4343.00	x	x
(8)	54,560.00	40,140.00	42,128.00	3114.00	15.4	–

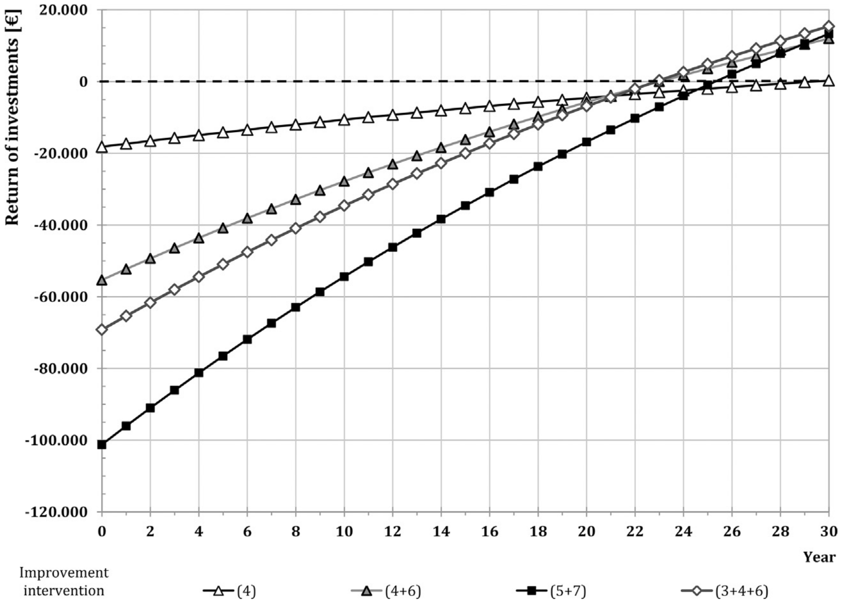

Fig. 8. Investments with a payback period within 30 years.

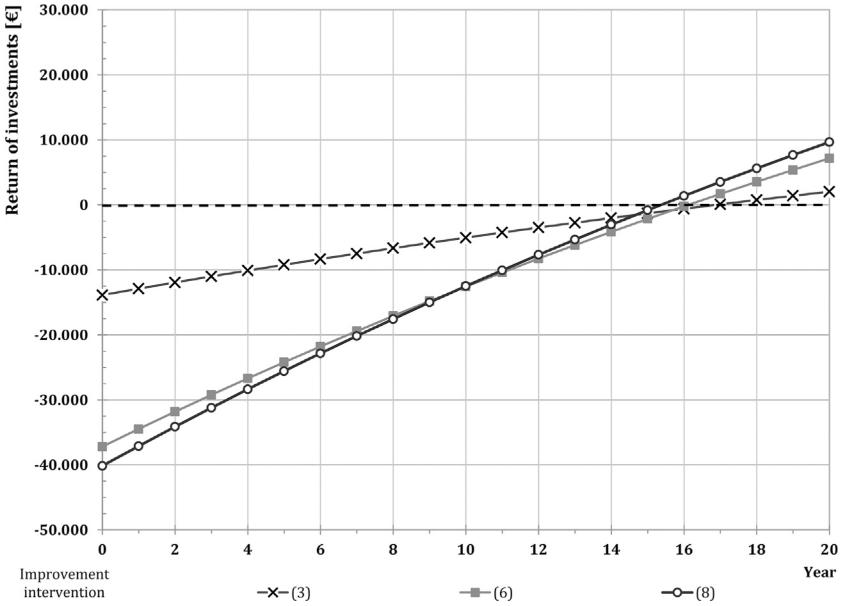

Fig. 9. Investments with a payback period within 20 years.

(ii) Set "Installation Costs": perform interventions meant to increase the efficiency with installation costs as low as possible;

(iii) Set "Return of Investments": have a return in a time interval which is considered reasonable.

These necessities are reported briefly in Fig. 10.

If there is not a solution that might fulfill at the same time all demands of the sub-set "Installation Costs" ∩ "Annual Economic Return" ∩ "Energy Saving", a technician can choose to realize solutions that represent at least 2 intersection sub-sets taking into consideration two different necessities. From this point of view in this part of the study those solutions that optimize two different necessities ("Installation Costs" ∩ "Annual Economic Return"; "Installation Costs" ∩ "Energy Saving"; "Annual Economic Return" ∩ "Energy Saving") are analyzed (Fig. 11) while trying to find the best solution or Pareto solutions [78]. Pareto solutions are those solutions representing the Pareto efficiency since the problem here examined might not guarantee the improvement of a variable without worsening the condition of the other [79].

Fig. 11 compares the interventions suggested. Solutions that can be amortized within 30 years are characterized by a filled symbol, whereas those solutions that cannot be amortized within this deadline present an index which is unfilled.

Fig. 11a shows that there is not just one solution that might be considered the one that optimizes the two variables taken into consideration: based on the factor considered (minimize installation costs or obtain the maximum annual economic return) it is possible to make different choices with respect to the intervention examined. If the goal is to have lower installation costs, the solution meant for the improvement of the control system (3) is more interesting, though the consequence is a minimum level of the

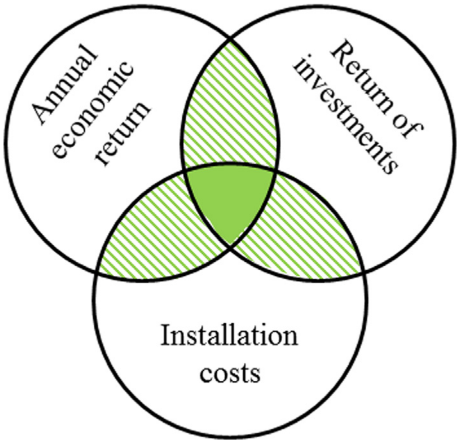

Fig. 10. Representation of the set of goals during an intervention of energy optimization.

annual return; if it is possible to afford high installation costs to have an annual return as high as possible, the solution with the installation of a heat pump combined with a PV system becomes the most attractive. The graph reports the Pareto frontier where the solution expects the installation of the CHP+HP (8) system can be also found. This solution is a mix of both necessities.

Fig. 11b presents solution (3) with the minimum investments and the lowest return period.

In Fig. 11c it is possible to notice how solution (5 + 7) generate the highest annual economic return, with a low payback period.

6. Discussion

It is clear that the starting energy class (hence the annual energy consumptions) of the building examined affects the type of technological interventions that must be performed, and in turn the energy class is affected by the ratio surface/volume of the building and the climate of the site where the building is placed.

In this study, starting with a D class building (just one step before the class entry level for buildings that must be guaranteed in order to have the authorization to build), taking into consideration Figs. 6–9 and 11, and limiting the choice to just one improvement among those listed (meant both for the building envelope and the systems) it was possible to notice (in the order of increasement in the energy class of the building):

- Carrying out interventions on a building characterized by a good building envelope to make it more performing does not mean lower consumptions that might justify the high installation cost of these interventions. The realization of an exterior insulation finishing system (1) or the substitution with highly performing window fixtures (2), even if they imply a higher energy performance with respect to the base case (from 59.62 kW h m^{-2} $year^{-1}$ to 56.94 kW h m^{-2} $year^{-1}$ and 53.78 kW h m^{-2} $year^{-1}$ respectively), do not determine the same increase in the energy class (which remains the D class), hence even annual savings (expressed in money are 239.00 €/year and 520.00 €/year respectively) do not determine reasonable payback periods (both more than 30 years).
- The realization of a PV system (7) does not affect deeply the primary energy consumed by the building if the thermal demand during space-heating season and for the production of domestic hot water are based on the exertion of systems supplied by combustible fuels. The PV panel does not determine an increase in the energy class, but through the production of power that can be net metered can provoke a financial income for the property (but this study will not focus on this aspect). The energy class remains the D class (EP_{gl} = 59.16 kW h m^{-2} $year^{-1}$), even though this is an intervention whose energy costs are high (85,690.00 €). In order to have an influence on the energy of the building and the system the solution is to combine the PV panel with a thermal system able to exploit the electrical energy as a primary source.
- Modernizing the regulation system (3) of the existing heating system determines an annual energy saving (995.00 €/year) which generates an increase in the energy class leading to a C class (EP_{gl} = 48.44 kW h m^{-2} $year^{-1}$). This intervention is the cheapest and its amortization period is really interesting (16.9 years).
- The substitution of the boiler, once the service life is over, with a more efficient one characterized by a condensation technology (4), leads the building examined to a C energy class (EP_{gl} = 50.07 kW h m^{-2} $year^{-1}$). The installation of the boiler is not very expensive, but if the building does not have a proper flue and a condensation removal system, realization costs will be higher (32,560.00 € with an overcharge due to the substitution long service life of the existing boiler of 18,140.00 €). This intervention, on a low energy class building, can determine satisfying results, but in this case the amortization period (29.3 years) can represent an obstacle.
- Substitute the boiler, once the service life is over, with a heat pump (5), allows in terms of energy to reach a B class (EP_{gl} = 28.81 kW h m^{-2} $year^{-1}$). Installation costs are average (29,960.00 € with an overcharge with respect to the substitution for long service life of the existing boiler of 15,540.00 €), though it must be kept under control the cost of the electrical energy supplying it. This solution is financially sustainable only in those Countries where the kW h presents an extremely advantageous price.
- The realization of a solar heating system meant for the production of domestic hot water (6) allows to reach a B energy class (EP_{gl} = 28.47 kW h m^{-2} $year^{-1}$). It presents an average installation cost (37,180.00 €, without substituting the heat generator for the heating during cold season) and it presents a proper annual economic return (2,772.00 €/year) allowing an amortization (16.1 years) period which corresponds to what expected.
- Substitution of a traditional boiler with a CHP+HP (8) system to fulfill the thermal demand of the building during space-heating season and the production of domestic hot water gives the possibility to pass from a D class to an A class (EP_{gl} = 24.63 kW h m^{-2} $year^{-1}$). Even if installation costs are still high (54,560.00 € with an overcharge with respect to the substitution due to long service life of the boiler of 40,140.00 €), economies of scale could lead to lower cost and make this solution very interesting. As a matter of fact it determines a good annual energy saving (3114.00 €/year) hence the most advantageous amortization period (15.4 years) between the different solutions when considered individually.

Then, for what concerns the combined solutions:

- Those formed by passive interventions, that is (1 + 2) and (1 + 2 + 3 + 4 + 6), present installation costs of 109,160.00 € and 192,770.00 € respectively. They will change to 178,350.00 € due to the substitution of the traditional boiler because of a long service life with an amortization period which is not advantageous (higher than 30 years). In terms of energy, solution (1 + 2) allows the building to have a C class (EP_{gl} = 51.24 kW h m^{-2} $year^{-1}$), whereas the most complete solution (1 + 2 + 3 + 4 + 6) is the one which expects the strongest optimization determining an A+ class (EP_{gl} = 10.82 kW h m^{-2} $year^{-1}$). It

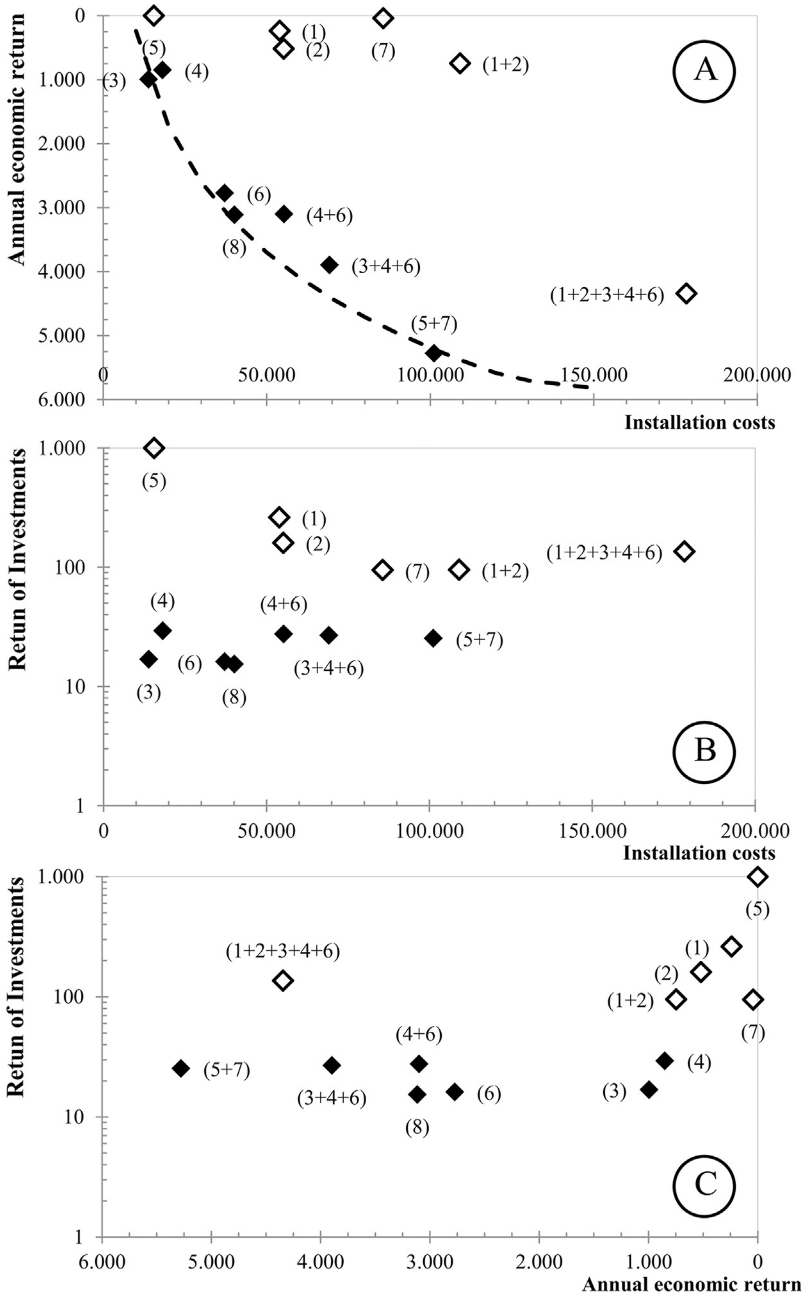

Fig. 11. Pareto solutions: (A) "Installation Costs" ∩ "Annual Economic Return", (B) "Installation Costs" ∩ "Energy Saving", (C) "Annual Economic Return" ∩ "Energy Saving".

determines a high annual energy saving (4343.00 €/year), though it is not high enough to guarantee an advantageous payback period.

- The solution combining a new condensing boiler and a solar heating system (4 + 6) determines an A class ($EP_{gl} = 24.79$ kW h m^{-2} $year^{-1}$), though it presents high installation costs (69,740.00 € with an overcharge with respect to the long service life of the boiler of 55,320.00 € hence higher than solution (8)). The amortization period is of 27.6 years (higher than 20 years, which is the limit considered preferable) and this solution determines an annual saving (3100.00 €/year) which is slightly lower than the one of solution (8).
- Combining the previous solution with an improved regulation system (3 + 4 + 6) allows to reach an A+ energy class ($E_{Pgl} = 15.84$ kW h m^{-2} $year^{-1}$), though installation costs are even higher (83,610.00 € with an overcharge with respect to the substitution due to long service life of the existing boiler of 69,190.00 €); this determines a longer payback period (26.8 years) of the initial investment, though it generates a remarkable annual saving (38,960.00 €/year).
- The solution (5 + 7) with the combination of PV panels (generating electrical energy that must be consumed in situ) to supply the heat pump, generates an independence from the combustible fuel for the fulfillment of the thermal demand of the building. This leads to a higher energy class (A+), with low EP_{gl} values (0.33 kW h m^{-2} $year^{-1}$). The actual obstacle to their exertion is determined by the high installation cost (115,650.00 € with an overcharge with respect to the substitution due to a long service life of the existing boiler of 101,230.00 €), which leads to (even in presence of an energy saving of 5,276.00 €/year) longer payback periods (25.3 years) when the service life of the system is almost over.

7. Conclusion

The necessity to keep under control the energy demand of the residential sector, due to both environmental and geopolitical reasons determined by the supplying of fossil fuels, led legislators of different industrialized Countries to regulate the sector providing a system that might be easily understood even by the non-experts to quantify the level of goodness of fit of a building and the energy systems forming it. Therefore the classification of the buildings based on the combination of the efficiency of the building and the system with the corresponding letter of the alphabet was realized. The goal is to persuade owners to perform technical interventions to have an energy optimization to reduce consumptions and the purpose was to create a phenomenon that might involve both financial and environmental aspects (for the single user and the community).

Society understood the benefits which the energy saving implies, the highest obstacle to the realization of these interventions is the financial issue. Technically it is possible to take different patterns to increase the energy class of a building, thus obtaining the same results for what concerns the final consumptions of primary energy. It must not be forgotten that the legislators set the goal to decrease as much as possible the thermal demand of a really wide sector which is characterized by a variety of different residential realities with high percentages of old buildings (hence they are not fit to save energy). However the idea of increasing the energy class of just the new buildings does not lead to substantial reductions of the energy consumptions supplied by fossil fuels. The thermal demand must be kept under control, in particular among the existing house block.

This study, starting with a D class building (below the minimum class currently required for the construction) examined different type of interventions (performing changes on the building envelope and/or on its systems) with the goal to evaluate what kind of intervention might fulfill the heating demand during cold season and the production of domestic hot water required by its inhabitants.

Among the interventions for the optimization here examined, the solution that can combine a higher energy class with sustainable installation costs and payback periods, thanks to a consistent annual energy saving, is a new solution which has not been diffused yet. It is characterized by the combination of a small cogenerator that, while electrically supplying a compression heat pump, also uses the heat generated by the pump (exploiting the multiplicative effect of the electrical energy provided to the machine to generate a higher amount of energy in the form of heat thanks to its COP) with the one it recovered. Managing in the right way this system to fulfill the heat demand, the primary energy demand will decrease and there is the passage from a D class to an A class (differently from what was showed in other interventions which were less incisive in terms of primary energy consumption). Even financially speaking, this solution determines some benefits and it can be considered feasible since it presents an amortization period of the installation costs of about 15.4 years. In order to obtain energy results which are similar to those or even better, more than just one traditional intervention (as the exertion of a condensing boiler characterized by a thermostatic radiator valves control system with solar heat panels) must be combined, though this implies higher installation costs, hence too long payback periods.

Over the next years, industrialized Countries will face a transition period that will be characterized by the passage from fossil fuels (that will be used even less) to the exploitation of renewable energy sources and in the future, this transition might occur in the residential sector thanks to CHP+HP systems. These systems can lead the house block to have the performances of a nZEB, thanks to aimed energy retrofit interventions. The technology is ready and economies of scale might allow to have a cost reduction, thus removing the existing financial obstacles with respect to more traditional technologies which have been used until now.

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References

[1] International Energy Outlook 2013 with Projections to 2040. U.S. Energy Information Administration Office of Energy Analysis. U.S. Department of Energy. Washington, DC 20585; 2013. <www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf> [last access on 10 January 2016].

[2] Bertoldi P, Hirl B, Labanca N. Energy efficiency status report 2012. electricity consumption and efficiency trends in the EU-27. European Commission, Joint Research Centre, Institute for Energy and Transport. Luxembourg: Publications Office of the European Union; 2012. http://dx.doi.org/10.2788/37564.

[3] Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings. Buildings Performance Institute Europe (BPIE) ISBN: 9789491143014; 2011.

[4] Dresselhaus MS, Thomas IL. Alternative energy technologies. Nature 2001;414:332–7. http://dx.doi.org/10.1038/35104599. 15 November 2001.

[5] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities. L 1/65. <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0091&from=EN> [last access on 10 January 2016].

[6] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Communities. L 153/13. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF> [last access on 10 January 2016].

[7] Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of the European Communities. L 114/64. <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0032&from=EN> [last access on 10 January 2016].

[8] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Official Journal of the European Communities. L 315/1. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:en:PDF> [last access on 10 January 2016].

[9] Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. Official Journal of the European Union 21.3.2012, L 81/18. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:EN:PD> (last access January 2016).

[10] Kyoto Protocol to the united nations framework convention on climate change. United Nations; 1998. <http://unfccc.int/kyoto_protocol/items/2830.php> [last access January 2016].

[11] Tereshchenko T, Nord N. Implementation of CCPP for energy supply of future building stock. Appl Energy 2015;155:753–65.

[12] K. Darcovich, E. Entchev, P. Tzscheutschler, Current Updates on the Development and Implementation of Micro-Cogeneration System Models for Building Simulation Programs. A Report of Annex 54 "Integration of Micro-Generation and Related Energy Technologies in Buildings". Energy in Buildings and Communities Programme (2014) Technische Universität - München, Germany; 2014.

[13] Housing Act 2004, CHAPTER 34, The Stationery Office Limited (UK), Crown copyright 2004. <http://www.legislation.gov.uk/ukpga/2004/34/contents> [last access on 10 January 2016].

[14] The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007 (S.I. 2007/991). Department for Communities and Local Government; 2007. <https://www.gov.uk/government/publications/the-energy-performance-of-buildings-certificates-and-inspections-england-and-wales-regulations-2007-si-2007991> [last access on 10 January 2016].

[15] Building Regulations. Danish ministry of economic and business Affairs, Danish enterprise and construction authority, Copenhagen 12 of December 2010. ISBN: 978-87-92518-60-6, Electronic ISBN: 978-87-92518-61-3. <http://bygningsreglementet.dk/file/155699/BR10_ENGLISH.pdf> [last access on 10 January 2016].

[16] LOI n° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique. JORF n°163 du 14 juillet 2005 page 11570 texte n° 2. Republique Francaise; 2005. <http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000813253&categorieLien=id> [last access on 10 January 2016].

[17] La régulation thermique RT 2005. Th-CE 2005 Version 7.3 15/03/2006. <http://www.rt-batiment.fr/fileadmin/documents/RT2005/pdf/Methode_Th_CE.pdf> [last access on 10 January 2016].

[18] Decreto-Lei n.o 78/2004 de 3 de Abril. Ministério Das Cidades, Ordenamento Do Território E Ambiente. Diário Da República - I Série-A N.O 80 - 3 de Abril de; 2004. <https://dre.pt/application/dir/pdf1sdip/2004/04/080A00/21362149.pdf> [last access on 10 January 2016].

[19] Decreto Legislativo 19 agosto 2005, n. 192, Gazzetta Ufficiale n. 222 del 23 settembre 2005 - Supplemento Ordinario n. 158. <http://www.camera.it/parlam/leggi/deleghe/05192dl.htm> [last access on 10 January 2016].

[20] Petrarca S, Spinelli F, Cogliani E, Mancini M. Climatic profile of Italy (in Italian). Edizioni ENEA; 1999 [ISBN 88-8286-075/082].

[21] Köppen W. Das geographische system der climate. In: Köppen W, Geiger R, editors. Handbuch der Klimatologie. Berlin: Gebrüder Borntraeger; 1936. p. 44.

[22] Census of population and housing – 2011 (in Italian). ISTAT; 2011. <http://dati-censimentopopolazione.istat.it/> [last access on 10 January 2016].

[23] Law n. 373. Standards for the containment of energy consumption for thermal use in buildings (in Italian). 30 March 1976, Official Gazette 148 of 06.07.1976.

[24] Salata F, De Lieto Vollaro A, De Lieto Vollaro R. A case study of technical and economic comparison among energy production systems in a complex of historic buildings in Rome. Energy Proc 2014;45:482–91.

[25] Energy strategy for the redevelopment of the national real estate (in Italian). Minister of Economic Development and ENEA; November 2015. <http://www.sviluppoeconomico.gov.it/images/stories/documenti/STREPIN_13_11_2015.pdf> [last access on 10 January 2016].

[26] Verbeeck G, Hens H. Energy savings in retrofitted dwellings: economically viable? Energy Build 2005;37:747–54.

[27] DeBoeck L, Verbeke S, Audenaert A, DeMesmaeker L. Improving the energy performance of residential buildings: a literature review. Renew Sustain Energy Rev 2015;52:960–75.

[28] Tan Barış, Yavuz Yahya, Otay Emre N, Çamlıbel Emre. Optimal selection of energy efficiency measures for energy sustainability of existing buildings. Comput Oper Res 2016;66:258–71.

[29] Kylili A, Fokaides PA. European smart cities: the role of zero energy buildings. Sustain Cities Soc 2015;15:86–95.

[30] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build 2013;56:189–203.

[31] Decree-Law of the June 4, 2013, n. 63, Urgent measures for transposition of Directive 2010/31 / EU of the European Parliament and of the Council of 19 May 2010 on the Energy performance of buildings. Official Gazette 03/08/2013, n. 181.

[32] Cao S, Sirén K. Matching indices taking the dynamic hybrid electrical and thermal grids information into account for the decision-making of nZEB on-site renewable energy systems. Energy Convers Manage 2015;101:423–417219.

[33] Mohamed A, Cao S, Hasan A, Sirén K. Selection of micro-cogeneration for net zero energy buildings (NZEB) using weighted energy matching index. Energy Build 2014;80:490–503.

[34] A. Hermelink, S. Schimschar, T. Boermans, L. Pagliano, P. Paolo Zangheri, R. Roberto Armani, K. Voss, E. Musall, Towards nearly zero-energy buildings. Definition of common principles under the EPBD. Final report, European Commission. Ecofys, Köln – Germany; 2013.

[35] National action plan to increase to nearly zero energy buildings (in Italian). Minister of Economic Development and ENEA; November 2015. <http://www.sviluppoeconomico.gov.it/images/stories/documenti/PANZEB_13_11_2015.pdf> [last access on 10 January 2016].

[36] Franco A, Fantozzi F. Experimental analysis of a self-consumption strategy for residential building: the integration of PV system and geothermal heat pump. Renewable Energy 2016;86:1075–85.

[37] Good C, Andresen I, Hestnes AG. Solar energy for net zero energy buildings – a comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems. Sol Energy 2015;122:986–96.

[38] Lamnatou C, Mondol JD, Chemisana D, Maurer C. Modelling and simulation of Building-Integrated solar thermal systems: behaviour of the coupled building/system configuration. Renew Sustain Energy Rev 2015;48:178–91.

[39] Smith MA, Few PC. Domestic-scale combined heat-and-power system incorporating a heat pump: analysis of a prototype plant. Appl Energy 2001;70(3):215–32.

[40] Zeghici RM, Damian A, Frunzulicə R, Iordache F. Energy performance assessment of a complex district heating system which uses gas-driven combined heat and power, heat pumps and high temperature aquifer thermal energy storage. Energy Build 2014;84:142–51.

[41] Cho H, Sarwar R, Mago PJ, Luck R. Design and feasibility study of combined heat and power systems integrated with heat pump. Appl Therm Eng 2016;93:155–65.

[42] Cao S, Mohamed A, Hasan A, Sirén K. Energy matching analysis of on-site micro-cogeneration for a single-family house with thermal and electrical tracking strategies. Energy Build 2014;68(Part A):351–63.

[43] Kayo G, Hasan A, Siren K. Energy sharing and matching in different combinations of buildings, CHP capacities and operation strategy. Energy Build 2014;82:685–95.

[44] Alahäivälä A, Heß T, Cao S, Lehtonen M. Analyzing the optimal coordination of a residential micro-CHP system with a power sink. Appl Energy 2015;149:326–37.

[45] Mohamed A, Hamdy M, Hasan A, Sirén K. The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions. Appl Energy 2015;152:94–108.

[46] Smith MA, Few PC. Domestic-scale combined heat-and-power system incorporating a heat pump: analysis of a prototype plant. Appl Energy 2001;70:215–32.

[47] Lucas K. Efficient energy systems on the basis of cogeneration and heat pump technology. Int J Therm Sci 2001;40:338–43.

[48] Pineau D, Rivière P, Stabat P, Hoang P, Archambault V. Performance analysis of heating systems for low energy houses. Energy Build 2013;65:45–54.

[49] Mıguez JL, Murillo S, Porteiro J, Lopez LM. Feasibility of a new domestic CHP trigeneration with heat pump: I. Design and development. Appl Therm Eng 2004;24:1409–19.

[50] Murillo S, Mıguez JL, Porteiro J, Lopez LM. Feasibility of a new domestic CHP trigeneration with heat pump: II. Availability analysis. Appl Therm Eng 2004;24:1421–9.

[51] Mohamed A, Hasan A, Sirén K. Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. Appl Energy 2014;114:385–99.

[52] Mancarella Pierluigi. Cogeneration systems with electric heat pumps: energy-shifting properties and equivalent plant modelling. Energy Convers Manage 2009;50:1991–9.

[53] Lo Basso G, de Santoli L, Albo A, Nastasi B. H2NG (hydrogen-natural gas mixtures) effects on energy performances of a condensing micro-CHP (combined heat and power) for residential applications: an expeditious assessment of water condensation and experimental analysis. Energy 2015;84:397–418.

[54] Few PC, Smith MA, Twidell JW. Modelling of a combined heat and power (CHP) plant incorporating a heat pump for domestic use. Energy 1997;22(7):651–9.

[55] Smith MA, Few PC. Second law analysis of an experimental domestic scale co-generation plant incorporating a heat pump. Appl Therm Eng 2001;21:93–110.

[56] Cao S, Hasan A, Sirén K. Analysis and solution for renewable energy load matching for a single-family house. Energy Build 2013;65:398–411.

[57] Cardona Ennio, Piacentino Antonio, Cardona Fabio. Matching economical, energetic and environmental benefits: an analysis for hybrid CHCP-heat pump systems. Energy Convers Manage 2006;47:3530–42.

[58] Mohamed A, Hasan A. Energy matching analysis for net-zero energy buildings. Sci Technol Built Environ 2016;22(7):885–901.

[59] Cao S, Hasan A, Sirén K. On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections. Energy Build 2013;64:423–38.

[60] UNI/TS 11300-1: 2014. Energy performance of buildings - Part 1: Determination of the thermal energy demand of the building for summer and winter air conditioning (in Italian). UNI - Ente Nazionale Italiano di Unificazione. Milano – Italy; 2014.

[61] UNI/TS 11300-2:2014. Energy performance of buildings - Part 2: Determination of primary energy demand and efficiency for space heating, to produce domestic hot water, ventilation and lighting in non-residential buildings (in Italian). UNI - Ente Nazionale Italiano di Unificazione. Milano – Italy; 2014.

[62] UNI/TS 11300-4:2012. Energy performance of buildings - Part 4: Use of renewable energy and other methods of generation for space heating and to produce hot water (in Italian). UNI - Ente Nazionale Italiano di Unificazione; Milano – Italy; 2012.

[63] ISO 13790:2008. Energy performance of buildings - Calculation of energy use for space heating and cooling. International Organization for Standardization. Geneva – Switzerland; 2008.

[64] TRNSYS - TRaNsient SYstems Simulation. Thermal Energy System Specialists. Madison, WI - USA. <http://sel.me.wisc.edu/trnsys/index.html> [last access on 10 January 2016].

[65] MasterClima MC11300 v2.22. Multimedia Technology Department - Aermec. Verona, Italy. <http://www.masterclima.info/> [last access on 10 January 2016].

[66] de Lieto Vollaro R, Guattari C, Evangelisti L, Battista G, Carnielo E, Gori P. Building energy performance analysis: a case study. Energy Build 2015;87:87–94.

[67] Weather Data. University of Wisconsin. <http://sel.me.wisc.edu/trnsys/weather/weather.htm> [last access on 10 January 2016].

[68] UNI 10349:1994. Heating and cooling of buildings. Climatic data (in Italian). UNI - Ente Nazionale Italiano di Unificazione. Milano – Italy; 1994.

[69] Pisello AL, Goretti M, Cotana F. A method for assessing buildings' energy efficiency by dynamic simulation and experimental activity. Appl Energy 2012;97:419–29.

[70] Regione Lazio. Official Bulletin of the Region of Lazio, Fares and Price (in Italian). <http://www.regione.lazio.it/binary/rl_infrastrutture/tbl_contenuti/BURL_28_08_2012.pdf> [last access on 10 January 2016].

[71] AEEG (Autorità Energia Elettrica e Gas). Price and rate (in Italian). <http://www.autorita.energia.it/it/prezzi.htm> [last access on 10 January 2016].

[72] ASHRAE Handbook 2012 - HVAC Systems and Equipment, SI Edition. Chapter 37, Solar energy equipment. ISBN 978-1-936504-26-8 ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329.

[73] Alimohammadisagvand B, Jokisalo J, Kilpeläinen S, Ali M, Sirén K. Cost-optimal thermal energy storage system for a residential building with heat pump heating and demand response control. Appl Energy 2016;174:275–87.

[74] Salata F, de Lieto Vollaro A, de Lieto Vollaro R, Mancieri L. Method for energy optimization with reliability analysis of a trigeneration and teleheating system on urban scale: a case study. Energy Build 2015;86:118–36.

[75] Research on Energy System - RSE SpA. Electric energy, anatomy of cost (in Italian). Milan (Italy): Alkes Publishing; 2014. ISBN 978-88-907527-7-3.

[76] Peruzzi L, Salata F, de Lieto Vollaro A, de Lieto Vollaro R. The reliability of technological systems with high energy efficiency in residential buildings. Energy Build 2014;68(PARTA):19–24.

[77] Salata F, De Lieto Vollaro A, De Lieto Vollaro R, Davoli M. Plant reliability in hospital facilities. Energy Proc 2014;45:1195–204.

[78] Lotov A, Bushenkov VA, Kamenev GK. Interactive decision maps: approximation and visualization of Pareto frontier. New York: Springer Science+Business Media; 2004 [ISBN 978-1-4613-4690-6].

[79] van den Berg E, Friedlander MP. Probing the Pareto frontier for basis pursuit solutions. SIAM J Sci Comput 2008;31(2):890–912.