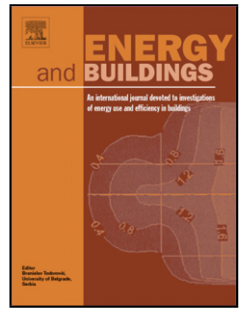

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The cost-optimal methodology for the energy retrofit of an ex-industrial building located in Northern Italy

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Highlights

- The cost-optimal methodology is here tested as a tool for evaluating energy retrofit projects
- The methodology is applied to an ex-industrial building submitted to energy retrofit
- A concrete synergy between energy and economic effectiveness issues is here achieved
- A harmonization of databases differently implemented is made
- The methodology has the potential to constitute a tool to target retrofit policy measures for both public and private investors

Abstract

The recast of the Energy Performance of Buildings Directive (EPBD) introduced a comparative methodological framework for calculating cost-optimal levels of minimum energy performance requirements. The cost-optimal methodology, conceived for national authorities, was here exploited as a decision-making tool for supporting a private investor in choosing the most viable energy scenario. The methodology was thus used to evaluate different energy efficiency measures applied to an abandoned industrial building in Turin (Northern Italy) and to identify the best retrofit solution in terms of energy and costs. Providing guidance and tools for re-designing ex-industrial areas can be useful for several similar case studies widespread not only nearby Turin, but also in other Italian regions and EU countries. The research activity here presented aims at testing the cost-optimal methodology to support energy retrofit projects starting from an early design stage. The arisen issues may be considered for future applications, with reference to specific contexts. In this perspective, this work constitutes a first step towards the definition of an "environmental and economic sustainability equilibrium", assuming that the application of models and approaches for evaluating both the energy-environmental performances and the economic ones, in many cases, may give very different results.

Keywords: environmental sustainability; economic sustainability; retrofit measures; cost-optimal methodology; ex-industrial building retrofit; urban transformation areas; dynamic simulation; global cost; energy refurbishment; project evaluation

1. Introduction

Buildings represent the largest unexploited source of energy savings and CO_2 reduction within Europe, whose potential is still unrealized [1]. In particular, existing buildings retrofit is the Europe's biggest resource in terms of energy and emission savings that can play a decisive role in fulfilling 2050 goal geared towards reducing greenhouse gas emissions by 80-95% compared to 1990 levels. To achieve this goal, significant investments need to be made in new low-carbon technologies, renewable energy, energy efficiency and grid infrastructure. Moreover, the energy infrastructures which will power citizens' homes, industry and services in 2050, as well as the buildings which people will use, are being designed, built and retrofitted now. Consequently, the definition of minimum energy performance requirements for buildings represents a key element of European policies. The recast version of the Energy Performance of Buildings Directive [2] establishes that Member States must ensure that minimum energy performance requirements are set with a view to achieving cost-optimal levels. This is defined as the energy performance level which leads to the lowest cost during the estimated economic life-cycle. Furthermore, the recast of the Directive introduced a comparative methodological framework for calculating cost-optimal levels of minimum energy performance requirements. Specifically, the cost-optimal methodology, defined in detail by EU Guidelines [3], allows evaluating the energy and economic effectiveness of different energy efficiency measures/packages/variants, which represent different retrofit scenarios. The application of this methodology represents the junction between the energy and environmental sustainability with the economic effectiveness.

The cost-optimal methodology was conceived for national authorities to develop regulations at national level to fix minimum energy performance requirements; consequently, it is used mostly at a theoretical level by government charges and scientific researchers. Therefore, at governments' level the cost-optimal methodology may be a useful tool to identify the most appropriate retrofit measures able to drive the renovation of the existing building stock and to guide national energy policies. It can also orient the supply and demand dynamics of the market towards a higher energy efficiency level [4].

Nonetheless the cost-optimal methodology is slowly spreading among professionals because, considering both energy and economic evaluations, it represents an efficient and complete decision-making tool in the preliminary design phase. Cost-optimal levels identified at national level will not be necessarily cost-optimal for every single building or private investor, so the possibility to calculate specific cost-optimal configurations could be crucial. There are numerous designing solutions and their optimality depends on boundary conditions, hence it is necessary referring to the local scale. To choose among these different optimal solutions both energy and economic effectiveness has to be taken into account. Determining an optimal solution means to find a proper combination of measures that are efficient and reliable long-term. Moreover, both designing nearly-zero energy buildings (nZEBs) and refurbishing existing ones toward nearly-zero energy buildings is not yet so viable, because high investment costs represent a significant barrier. It arises the need to have a holistic and multidisciplinary approach that permits to consider not only investment costs but also all costs that have to be supported over the building life-cycle.

This research deals with the application of the cost-optimal methodology in this second scenario as a professional tool and tests its pertinence to give clear suggestions to a private investor in the preliminary design phase.

1.1. Cost-optimality studies review

Nowadays, few studies analyze the application of cost-optimal methodology at case studies that involve hypothetical real investors; in particular, no one can be referred to an industrial building that constituted the case study of this research.

Fabbri et al. [5] identified strengths and weaknesses of the cost-optimal approach through its application to the refurbishment of a residential case study. Barthelmes et al. [6] and Becchio et al. [7, 8] highlighted the use of cost-optimal methodology as a decision-making tool for supporting architects in the energy design of some nearly-zero energy residential buildings. Similar analyses were proposed by Bonoli and Fabbri [9] that tried to apply the methodology both on new and existing buildings needed to be refurbished. Ascione et al. [10] investigated the use of cost-optimal methodology for the assessment of the refurbishment of a XV century historic building in Naples (Italy). Zacà et al. [11] exploited the cost-optimal method to evaluate high performing technical solutions for residential buildings located in the Mediterranean area. Hamdy et al. [12] introduced an efficient and time-saving simulation-based optimization method to find the cost-optimal and nZEB energy performance levels for a single-family house in Finland . Ferrara et al. [13] utilized a similar simulation-based optimization method for cost-optimal analysis applied to residential nZEBs.

Concerning office buildings, different cost-optimal analyses were developed by Becchio et al. [14, 15] and Pikas et al. [16] in order to identified the best nearly-zero energy solutions.

Stocker et al. [17] reported a study of cost-optimal building renovation arrangements regarding the heating energy performance of eight primary schools, located in the Alps and characterized by different ages and construction techniques.

1.2. Aims of the study

The purpose of this research is to simulate a real situation, in which a potential real estate developer considers the opportunity to invest into an ex-industrial building retrofit project. The focus is on the decision process which takes into account alternative investment options, each related to an alternative energy scenario, in order to select the most energy and cost effective one/s. Indeed, after the recasting of EPBD [2], private and public investors now are more and more aware of energy and financial guidelines in the construction sector, especially at the preliminary design phase, in order to find the optimal solution for their investment. Consequently, professional figures, such as architects and engineers, have to consider these new specific requests by the investors, assuming not only the role of the architectural planner, but also of the energy consultant and financial expert, who is able to identify the optimal design choice by evaluating both the energy and the financial performance of several design configurations.

In detail, in this research the cost-optimal methodology was exploited as a decision-making tool for supporting the private investor in choosing the most viable energy scenario. The methodology was used to assess the energy performances and economic concerns during the whole building life-cycle for the alternative energy design scenarios. Different retrofit scenarios, consisting of Energy Efficiency Measures (EEMs) combinations, were defined for an abandoned ex-industrial building in Turin (Northern Italy, Lat. 45°07'N, Long. 07°43'E); these included different efficiency levels for both the building envelope and the HVAC (Heating, Ventilating and Air Conditioning) systems. The energy estimation was implemented by dynamic simulations using the software EnergyPlus [18]. In order to identify the measure with the lowest global cost, which represents the cost-optimal level, economic evaluations based on the global cost method from EN 15459:2007 [19] were performed for each EEM.

Coherently with the fact that this research simulates a real situation in which professionals have a limited quantity of time and money to develop the analysis, a study based on a limited amount of technically feasible combinations of energy efficiency measures, rather than a parametric study, was carried out. This is also caused by the use of dynamic simulation and the inherent calculation times, in order to accurately estimate the energy demand for heating, cooling, electric lighting, electricity from renewable sources, and especially the trade-off between heating energy and cooling energy.

Furthermore, this study is focused on an ex-factory fabricate within a vast ex-industrial area. Because of the wide diffusion of abandoned industrial areas in Turin and in the entire Italian territory, the results presented in this paper are significant. Before the economic-financial crisis involving also the real estate market and the construction sector, Turin has faced relevant urban transformations. This process led Turin to be one of the European cities which noticeably changed its structure and its urban landscape, marked by many ex-industrial areas, and pushing further this transformation from a post-industrial city to a smart city. The Third Strategic Plan for "Torino Metropoli 2025" testifies the will of the city of re-thinking and reorganizing the many abandoned industrial areas set in the urban weaving [20].

Moreover, this reskill tendency is common to many Italian cities characterized by ex-industrial areas: just to give some examples, Santa Giulia in Milano Rogoredo (ex Montedison and Redaelli factories) (120 hectares) that represents the biggest European abandoned industrial area, ex-Falck steel factories in Sesto San Giovanni (118 hectares), ex-Innocenti-Maserati (61 hectares) and ex-Alfa Romeo (38 hectares) in Milan, ex-Ansaldo mechanic (17 hectares) in Genoa, ex Molino De Cecco in Pescara (28 hectares), ex-FIAT in Florence (32 hectares), ex- Siri chemical factory in Terni (44 hectares), ex-Bertoli steel factories in Udine (32 hectares).

In this scenario, providing guidance and decision-supporting tools for the design of ex-industrial areas, also to obtain results that may be generalized to other similar Italian and foreign realities, has become crucial. For these reasons, the research aim is to test the cost-optimal methodology as a tool for supporting the assessment of this specific case study but also of other potential energy retrofit projects related to transformation of ex-industrial areas. This approach can be widen to other ex-industrial buildings subject to retrofit interventions in Italy and foreign countries.

2. Methodology

In 2012, the Commission Delegated Regulation (EU) No. 244/2012 [21], and the Guidelines [3] that accompany the Regulation, supplementing the Directive 2010/31/EU, were published. These documents report the methodological framework for calculating cost-optimal levels.

The Cost-optimal methodology, as developed in this research, consists of 4 different steps:

- Step 1: selection of the reference building (RB) that represents the baseline design scenario;
- Step 2: definition of some energy efficiency measures (EEMs) involving the improvement of the building envelope thermal performance and the systems efficiency, and combination of EEMs into packages in order to create different energy scenarios;
- Step 3: evaluation of the final and primary energy uses of the different scenarios;
- Step 4: evaluation of the costs of each scenario related to proper economic life-cycle.

Energy and economic input data (e.g. weather conditions, energy costs, initial investment cost, etc.) used in this study derive from existing databases or from specific researches done in both energy and economic fields (specifically the Turin real estate market), at urban or regional scale.

2.1. The reference building

As previously pointed out, the purpose of this research is to simulate a real situation, in which a potential real estate developer considers the opportunity to invest into an ex-industrial building retrofit project. To this purpose, a real reference building [22] was selected. As shown in Figure 1, the RB consists of a two-storey building with a tower of three floors located in the North of Turin, characterized by fairly cold winters and hot summers. This town area, the deep refurbishment of which started in the Eighty, is characterized by an industrial urban setting with many empty spaces which are, currently, object of significant enhancement interventions. The analyzed building represents a portion of an electric cables factory (INCET, Industria Nazionale Cavi Elettrici Torino), manufactured in 1888 in an area of 65’200 m² and partially listed. The building is nowadays abandoned, but the Turin Municipality reclaimed the surrounding area and a deep renovation process is undergoing in neighboring buildings. As a consequence, there is a growing interest in the building refurbishment which should include also the conversion from an industrial use to a residential and commercial one.

Figure 1. (1 column fitting image)

The building, characterized by a total floor area of about 2500 m^2, has a rectangular plan and its orientation is North-South. Nowadays, it comprises external opaque façades distinguished for historic value, roof and intermediate slabs without any interior partitions. Because the ground floor is characterized by about 8.7 m height, the building refurbishment also includes the addiction of an intermediate slab. Consequently, the total floor area amounts to 3600 m^2.

2.2. Energy Efficiency Measures

In accordance with the EPBD Guidelines [3], different energy efficiency measures were defined and applied to the RB. They regard both the improvement of the building envelope thermal insulation and the investigation of different HVAC systems configurations together with the use of renewable energy sources (RES). Several measures were examined and combined in different scenarios. Due to the high time required for modeling, simulating and carrying on the economic evaluation, only a limited number of technically feasible EEMs were investigated.

Three different EEMs aimed at improving the building envelope thermal insulation were assumed. To the purpose of not altering the external façades of the building having a historic value, the insulation layer was applied on the inside surface of the external walls. Since the RB is located in Turin, U-values for EEM_1, EEM_2 and EEM_3 were set respectively in compliance with the minimum and the optional values required by regional regulations [23], and the optional values required by the Turin regulations [24]. Table 1 lists the main U-values of the building envelope components for EEM_1, EEM_2 and EEM_3.

In relation to the residential spaces, the primary system is constituted by an air-to-water reversible cycle heat pump (Coefficient of Performance in heating = 4.9; Energy Efficiency Ratio in cooling = 3.7) or a gas condensing boiler (nominal efficiency = 0.95) coupled with a chiller (nominal efficiency = 3.2) with cooling tower with natural ventilation (NV) or controlled mechanical ventilation system (CMV) depending on the scenarios. In all the scenarios, the terminal devices for space heating and cooling are radiant floors. Regarding to commercial spaces, the hypotheses for the primary system were the same of the residential ones, whilst the terminal devices for space heating and cooling are four-pipe fan coil units.

For all scenarios, in order to cover 60% of domestic hot water (DHW) net energy need, twelve flat plate solar collectors were installed on the roof for a total annual production of 4.25 MWh.

National regulation [25] establishes that 35% of the demand for space heating and cooling and DHW production has to be provided by renewable sources. In compliance with this target, several hypotheses about the number of photovoltaic panels, related to different total peak power, were analyzed for the different scenarios.

The identified EEMs were combined in order to create twenty-four energy scenarios characterized by different performances in terms of both energy consumptions and costs (Table 2).

2.3. Energy model

The primary energy demand of the different scenarios was assessed by dynamic simulations using EnergyPlus (version 8.0) [18]. This software is an open-source free software, well-known in academic and commercial contexts for dynamic simulations and good enough in terms of capabilities [26]. The energy simulation was performed with reference to the current use of the building. The building was then divided into 8 thermal zones, one of them unconditioned. A detailed sub-hourly simulation of the building inserted in the urban landscape (Figure 2) was thus conducted for each scenario, using the reference IWEC (International Weather for Energy Calculations) weather file for Turin (2671 DD), retrieved from the EnergyPlus weather data files database [27].

Figure 2. (1 column fitting image)

Operational parameters were set to be consistent with the building typology. Occupancy was fixed to 0.04 pers/m² for residential spaces and 0.1 pers/m² for the commercial ones [28]. In accordance with EN 13790:2008 [29], lighting and appliances power densities were respectively set to 3.88 W/m² and 2.9 W/m² for residential use and 15.06 W/m² and 4.8 W/m² for commercial use. These densities were connected to activities scheduled in the building during weekdays and weekends. During the weekdays, the outdoor air flow rate was set to 11 l/s per person operating from 7 a.m. to 8 p.m.

In compliance with Italian regulations [30] for the climatic zone E (in which Turin is located, HDD 2639), the heating system was assumed to be active from the 15th of October to the 15th of April. The cooling system was set to operate from the 1st of May to the 30th of September. All days, the heating and cooling setpoints were set respectively to 21 °C (18°C during the remaining hours) and 26 °C (28°C during the remaining hours) from 7 a.m. to 8 p.m. in both residential and commercial spaces.

Photovoltaic and solar systems were firstly sized using Retscreen 4 [31], a software which allows to determine the technical and financial viability of potential renewable energy and to verify the energy performance of the installed systems. After their sizing, PV and solar systems were simulated with EnergyPlus, considering context and shadows generated by panels themselves, in order to calculate the actual total energy production.

2.4. Economic model

The economic evaluation was determined for the different scenarios in two steps: calculation of the global cost for each scenario and determination of the cost-optimal level.

2.4.1. Calculation of global cost

Global cost was calculated in accordance with the EN 15459:2007 [20], as specified in the Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 [3]. The calculations consider the initial investment, the sum of annual and disposal costs, from which the residual value of the components with a life-cycle longer than the building lifetime must be deducted. In this specific case, costs were defined considering only the financial perspective and not the macroeconomic one, as indicated in the Guidelines: the evaluation was made assuming the real estate developer point of view, to whom cost categories such as greenhouse gas emissions, substantial from the social and environmental point of view, are not cost effective.

The diagram in Figure 3 shows how costs are categorized according to the method used to calculate the global cost.

Figure 3. (1.5 column fitting image)

The global cost can therefore be calculated as follows in Equation (1):

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i)\right) - V_{f,\tau}(j)\right] \quad (1)$$

where:

$C_G(\tau)$ = global cost (referred to starting year τ0);

C_I = initial investment costs;

$C_{a,i}$ (j) = annual cost during year i of component j; it includes annual running costs (energy costs, operational costs, maintenance costs) and periodic replacement costs;

R_d (i) = discount rate during year i;

$V_{f,\tau}$ (j) = residual value of the component j at the end of the calculation period (referred to the starting year).

Data relating to costs must necessarily be based on market analyses; generally assessments based on comparisons with recent building projects, market-based databases or data from analyses of market prices made by operators.

Running costs and residual values of building elements must be considered for the whole of the calculation period. It is therefore particularly important to choose an appropriate calculation period, which is determined in relation to the estimated life-cycle of the building and of the considered technological components. With this regard, Commission

Delegated Regulation (EU) No 244/2012 provides guidelines regarding the time period that can be used for the purpose of this calculation, while the lifetime of the elements of the building envelope and systems can be determined using the values set out in European Standard EN 15459:2007[1].

The costs over the calculation period are discounted by means of the discount factor R_d, which is calculated as (Eq. 2):

$$R_d(p) = \left(\frac{1}{1+r/100}\right)^p \tag{2}$$

where:

p is the number of years starting from the initial period;

r is the real discount rate.

The real discount rate excludes inflation and is generally defined according to the country in which the analysis is conducted.

As far as operational and maintenance costs are regarded, development over time is set as equal to the general inflation rate, whilst concerning energy costs, the Guidelines [3] provide instructions taken from energy trend scenarios developed with the *PRIMES* model[2], and updated by the European Commission every two years.

In order to calculate the global cost of each alternative scenario, first of all it was necessary to define the various cost categories that make up the global cost.

In this research, as suggested by the methodology, the following elements were defined for each scenario:

- **Initial investment costs**, consisting of the sum of costs of each individual element of the renovation project (building envelope and internal partitions and systems). By consulting the price lists of the Piedmont Region [32], it was possible to produce an itemised cost estimation for all works. In some cases it was decided to consult the parametric values listed in the specific price list *Prezzi Tipologie Edilizie 2010* [33], as some of the items contained compared with the RB were useful in establishing the cost of certain works, in particular relating to systems.
- **Operational/running costs**, corresponding to costs of energy consumption for the whole building during the entire calculation period, set at thirty years. The overall cost corresponds to the sum of all discounted annual running costs. The running cost for year n therefore corresponds to that year's electricity and natural gas consumption multiplied by the specific costs of electricity and natural gas, all discounted. The calculation process thus required that electricity and natural gas consumption are calculated for each scenario, characterised by specific consumption of natural gas and electricity. These values were provided by the EnergyPlus simulations. Electricity and natural gas prices were assumed based on the prices set by the Italian Regulatory

[1] Annex A – Economic data for energy systems, Table A.1 - Data for lifespan and maintenance costs.
[2] PRIMES: a modelling system that simulates a market equilibrium solution for energy supply and demand in the EU28 and its Member States.

Authority for Electricity Gas and Water[3]; €0.30/kWh for electricity, €0.49/m^3 for natural gas [34]. Costs were discounted using a real discount rate r of 2.3%. This value was taken from "EU energy trends to 2030" [35].[4]

- **Replacement and maintenance costs** for system elements were calculated using European Standard EN 15459:2007 [20], according to the definition of the lifetime of individual building or system elements and their maintenance cost percentage share. For all measures relating to the building envelope, no replacement cost is considered, as the lifetime of the components is longer than – or, in the case of doors and windows, the same as – the calculation period. Maintenance costs, calculated for each year of the lifetime of the building, were discounted using the same procedure as described above for running costs, the only difference being the application of a real discount rate of 5%. This value, which is derived from economic market analyses and assumes that the role of promoter is played by a private investor, includes the risks that such an investment may entail.
- **Residual value** which, unlike maintenance and replacement costs, must be taken into account for both building system elements and for opaque elements, while doors and windows, which have a lifetime of thirty years – the same as the calculation period – have no residual value. In contrast, all opaque elements have a residual value, as their rated lifetime is fifty years. In order to determine this value, based on the simplified assumption that the component is used in an equal manner during each year of its lifetime, a straight-line depreciation schedule is assumed so that the purchase value of the asset is spread evenly across the years of its lifetime. The resulting residual value shall be detracted from the global cost, after having been discounted from the thirty-first year in relation to the current year ($\tau = 0$) in which the calculation is performed.

2.4.2. Identification of the cost-optimal level

Once the global cost and energy consumption of each package/scenario have been calculated, they can be represented graphically in a diagram illustrating the relationship between energy performance and global cost, as shown in figure 4.

Figure 4. (1 column fitting image)

The x axis represents primary energy (kWh/m^{2}year) while the y axis measures the global cost (€/m^2) (Figure 4).

Each energy efficiency measure is represented in the graph by a point. By interpolating these points a curve is obtained, which represents the cost curve. The minimum point on the curve represents the cost-optimal level.

As can be seen in Fig. 4, it is possible to identify the cost-optimal range, that shows the minimum values of the curve. It is useful to define this range when there are scenarios with extremely similar or identical global costs. In this case, the

[3] Documents up to date as of 1 January 2014, electricity prices: "Condizioni economiche per i clienti in maggior tutela", gas prices: "Condizioni economiche di fornitura del gas naturale per il servizio".
[4] The document, drawn up by the European Commission in 2009, contains growth or contraction forecasts for all Member States in various fields, including the economy, population and energy.

determination of the optimal level according to costs should be based on the package which exhibits the lowest primary energy demand.

In any case, it can be stated that the energy efficiency measure which represents the cost-optimal level must necessarily be identified among the measures with the lowest global costs.

3. Results

The aim of the dynamic energy assessment was to determine the annual overall energy use (including space heating and cooling, ventilation, lighting, equipment, DHW production) of the scenarios in terms of delivered energy (divided by sources) and primary energy (where the primary conversion factor for electricity was assumed 2.18 and for natural gas 1 [34]).

Figure 5 shows the energy demand in terms of primary energy for each end use and for each scenario; in particular, for each end use it is reported the sum of the energy consumptions for commercial and residential spaces. Observing the bar graph, it is evident that the consumption for lighting and equipment is constant, as the one for DHW production. Consequently, it is the energy demand for space heating and cooling the most influencing factor on the total consumption; indeed, the energy demand for fans and pumps is a direct consequence of those ones and, also, of the presence of the CMV system.

The consumption for space cooling ranges (in terms of median from the one for commercial spaces and that for residential ones) between 17 kWh/(m²year) (scenario 8 and 16) and 27 kWh/(m²year) (scenario 17 and 21). The lowest value is associated to an air-to-water heat pump in combination with a CMV system and fan coils for commercial spaces and radiant panels for the residential ones; scenario 8 and 16, in terms of envelope thermal insulation, are characterized respectively by the minimum and the optional values required by regional regulations. The highest consumption is gathered to the highest level of envelope thermal insulation and the following plants: for residential spaces and for both scenarios, to a chiller combined with natural ventilation and radiant panels while, for the commercial ones, to fan coil with CMV system with a chiller in scenario 17, and with an air-to-water heat pump in scenario 21.

The energy demand for space heating is the dominant factor; it ranges between 25 kWh/(m²year) (scenario 18 with the highest level of envelope thermal insulation, a condensing boiler combined with CMV system and fan coils in commercial spaces and radiant panels in the residential ones) and 85 kWh/(m²year) (scenario 7, with the lowest level of envelope thermal insulation, an air-to-water heat pump combined with a CMV system and fan coils in commercial spaces and with natural ventilation and radiant panels in the residential ones). Indeed, the two scenarios with the highest heating consumption (7 and 8, differing as far as the natural ventilation in residential spaces is concerned) are also the ones with the highest total energy demand. Furthermore, it is worth stressing that the conversion factors play a relevant role in the final results; indeed, the value of the one for electricity is more than double of that of natural gas and determined the fact that the generator system with the highest efficiency supplied by electricity is related to the highest primary energy consumption for space heating.

Figure 5. (2 column fitting image)

Economic calculations were performed in compliance with the global cost method previously explained. Having calculated all of the cost items for each scenario, it was possible to determine the global cost for each of them. Figure 6 illustrates the breakdown of the global cost. The investment cost has the greatest impact on global cost in absolute terms and to a similar degree across the different scenarios. It may also be noted that it is the operational/running cost, shown in red in the graph (energy cost), that changes most across the different scenarios and hence causes the greatest degree of variation among global costs. In particular, scenario 1 has the lowest global cost (€ 899.731) whereas scenario 7 has the highest (€ 1.089.468). Such substantial difference is caused by the size of the operational/running costs, respectively the lowest (€ 341.872 for scenario 1) and the highest (€ 541.190 for scenario 7) amongst the considered 24 scenarios. Conversely, the investment costs are similar: slightly lower for scenario 7 (€ 540.875) than for scenario 1 (€ 544.505). As for the investment costs on all 24 scenarios, the lowest are for scenario 15 (€ 526.696) and the highest are for scenario 18 (€ 580.380), denoting variations less substantial compared with that observed for operational/running costs. The maintenance and replacement costs and the residual values have very low bearing and size for all 24 scenarios.

Figure 6. (2 column fitting image)

Once established the global cost for each scenario, it was possible to analyse the packages not only from an energy perspective but also in economic terms, which have a significant influence on the stakeholders' choice of retrofit measures. Table 3 summarises the primary energy demand for the entire building and the global costs for all 24 scenarios, and also sets out the energy classes, that the two different building uses achieve as a result of the different retrofit scenarios according to the energy classification adopted by the Piedmont Region. In particular, the assessment of the energy classes for each scenario was performed considering exclusively the energy demand for space heating and DHW production (expressed in terms of primary energy) according to the Regional Regulation (D.G.R. 43-11965, art 6.3) [36]. This Regulation establishes nine energy classes, from the highest A+ to the lowest "not classified". All scenarios are classified in class from A+ to C. The class A+ is characterized by an annual primary energy consumption minor than 27 kWh/m^2 for residential buildings and minor than 9 kWh/m^3 for the commercial ones; the class A ranges for residential buildings and for the commercial ones, respectively, from 27 kWh/m^2 to 44 kWh/m^2 and from 9 kWh/m^3 to 14 kWh/m^3, the class B from 44 kWh/m^2 to 82 kWh/m^2 and from 14 kWh/m^3 to 27 kWh/m^3, and the class C from 82 kWh/m^2 to 143 kWh/m^2 and from 27 kWh/m^3 to 46 kWh/m^3.

It was possible to represent the obtained data in a graphical form, making the results and differences among the various scenarios easier to be communicated to the stakeholders involved in the retrofit process.

Figure 7. (2 column fitting image)

The cost-optimal graph, in the Figure 7, shows the global costs of the different scenarios expressed in €/m² (y-axis), in function of the primary energy consumption expressed in kWh/m²·year (x-axis). The data were divided into the three categories of intervention related to the envelope thermal insulation (EEM 1, EEM2 and EEM3) and represented with different shapes; the energy efficiency classes are reported only for the scenarios that are on the cost curve. This one represents the curve connecting the outer points closest to the abscissa axis and the ordinate axis. The minimum value lying on the curve represents the cost-optimal level. The scenario with the lowest global cost specified in the graph also shows the optimal level of energy performance in relation to the costs, which thus represent the cost-optimal level of energy performance.

The range, in which global cost values of all scenarios are situated, is restrained (from 989 €/m² of scenario 1 to 1197 €/m² of scenario 7) while that of primary energy consumption is quite significant (from 132 kWh/(m²·year) of scenario 17 to 168 kWh/(m²·year) of scenario 7).

Scenario 1 has the lowest global cost, indeed it lays at the lowest point of the curve. According to the methodology, this one may be considered as the best retrofit scenario, and it can be defined the cost-optimal level. Also the scenario 9 can be taken into account, although it presents a slightly higher specific global cost. However, it provides lower primary energy consumption, reduced by about 15 kWh/(m²·year). The reduced need for energy demand in scenario 9 determines a better energy class. The residential building switches from a class B to a class A, while for commercial building rises from class A to an A +. Both scenarios present the same primary energy systems; radiant floor, condensing boiler and chiller with natural ventilation for residential use; fan-coil units, condensing boiler and chiller with CMV for commercial spaces. The thermal solar and photovoltaic systems consist of the same number of panels. The only difference between the two scenarios, which determines the increasing cost and the decreasing consumptions, is constituted by the thermal insulation level of the building envelope. Building envelope of scenario 1 is less performing than that of scenario 9.

Scenario 17 is the best performing in terms of primary energy with the same energy classification of scenario 9, that has also the same HVAC and RES system features. Its global cost is higher than that of scenario 9 of 30 €/m² due to a more expensive investment related to an increasing in the thickness of envelope thermal insulation and to a consequent higher space cooling energy demand. Since the increasing of global cost and the reduction of primary energy of 2 kWh/(m²year) respect to scenario 9 that does not determine a change in energy classification, it is clear that scenario 17 is not the most viable and scenario 9 is preferable.

Scenario 7 represents the worst performing solution in terms of both cost and energy effectiveness. As above-mentioned, it is because this scenario presents the highest consumption for space heating and the highest running costs.

The fact that scenarios 5 and 17 have almost the same global cost highlights that nowadays is possible to realize high-performing retrofit interventions with the same economic effectiveness valued on the whole building life-cycle. Indeed, scenario 17 is characterized by a primary energy consumption of 132 kWh/(m²year), while that of scenario 5 is equal to 155 kWh/(m²year). This has a significant impact also on energy classification moving from class A for residential spaces and A+ for the commercial ones to class B for both the space uses.

A sensitivity analysis was carried out in order to assess the outcomes in global cost calculations for scenarios 1 and 9. In particular it was considered the sensitivity of outcomes to variability in specific input parameters, such as energy costs and discount rates. As illustrated in Figure 8, the steeper curves in spider graphs represents the more critical variables (for both scenarios the variation of electric energy costs and the discount rate on energy costs).

Figure 8 (2 column fitting image)

The final choice between the two scenarios will therefore depend on the stakeholders' propensity to invest resources to get the best energy performance and, consequently, lower running costs.

4. Conclusions and future developments

Throughout the research some issues correlating physical data to estimative ones were detected. With the aim to apply the cost-optimal methodology on a concrete local context, a preliminary reasoning about the criticalities listed below is necessary.

- The lifespan of building elements used for redevelopment and upgrading energy efficiency. Lifespans proposed by the guidelines of EN 15459:2007 [20], or by other Italian rules are reflected in the UNI 11156/2006 [37], are reliable, but must be adapted to each specific case. Also in the mentioned above documents, a relevant number of systems are not dealt with.
- The estimation of the evolution of energy prices. The information, that the guidance accompanying the Delegated Regulation (EU) No. 244/2012 provides, are taken from energy trend scenarios, elaborated with the Prime model [38]. However, if the predictions differ much from reality, the results, and therefore the scenarios, would be greatly affected.

Moreover the methodology based on the concept of global cost, when used to evaluate the economic sustainability of alternative retrofit measures and planning solutions, allows to give more weight to the energy performances of the technological components rather than taking into account only financial aspects. Therefore it represents a useful tool yet in the planning and design phases, suitable to identify the optimal energy design choice by evaluating both the energy and the financial performances of several design configurations that can be also very similar to each other.

This work is expected to represent the starting point for other researches, which could further deepen the aspects here studied. In particular the relationships between the Real Estate Appraisal and Project Evaluation issues and the energy and comfort related aspects, which has to be faced during a renovation process, would be increasingly studied together in order to strengthen their synergy. Indeed, nowadays very often the energy-environmental sustainability and the economic effectiveness are debated separately and during different design stages [39].

This research, moreover, constitutes an application of the methodology on a concrete case study in which input data deriving from various sources are harmonized. For this reason it represents a starting point for a comparison among different operational modalities finalized to the integration of databases differently implemented.

Finally an interesting direction to address the research could be the use of the proposed methodology as a tool to support public authorities in defining planning strategies, policies of operation on heritage and existing buildings, including the case of listed assets, at urban and territorial scales.

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Figure captions

Figure 1. The ex-industrial building

Figure 2. The energy model constituted by the building and the urban landscape.

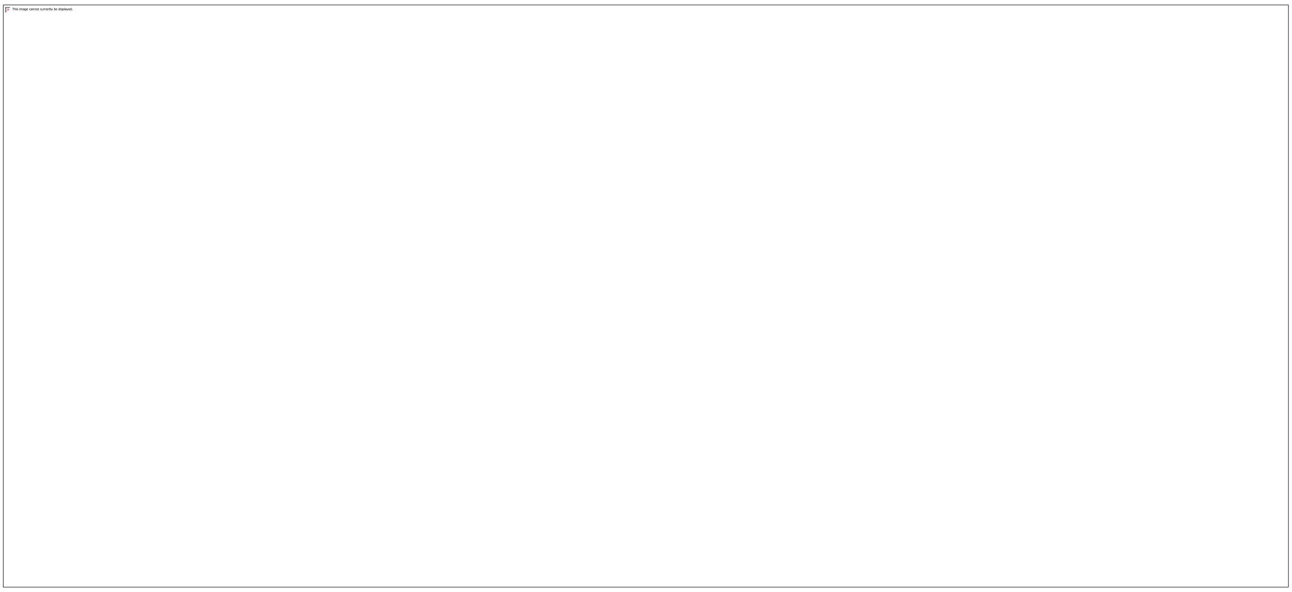


Figure 3. (Simplified) categorization of costs according to applicable legislation (source: drawn from the guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU of the European Parliament and of the Council (2012/C 115/01).

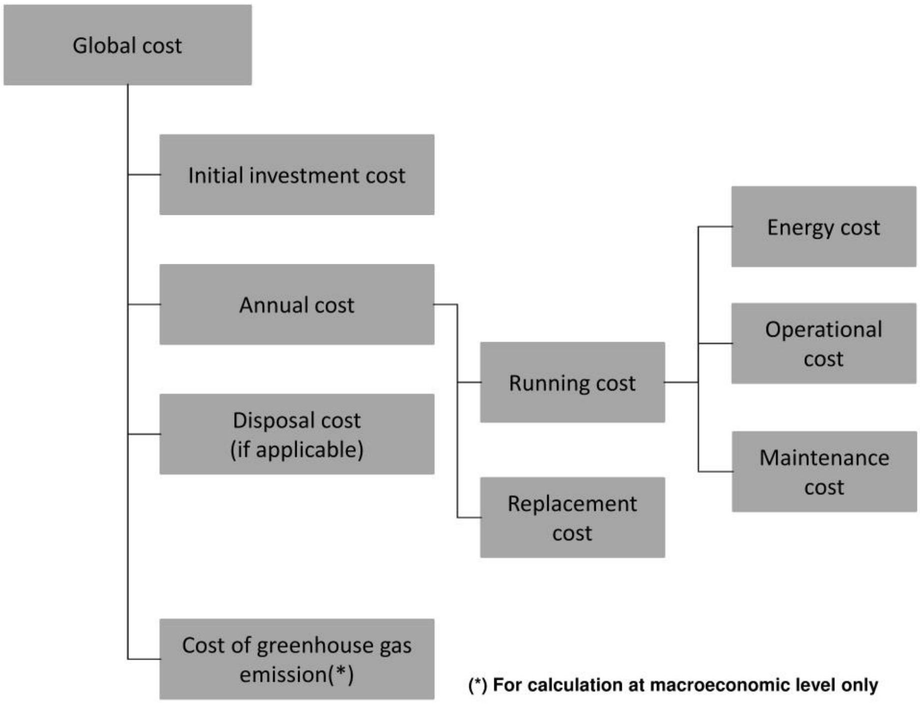


Figure 4. Graphical representation (schematic example) of cost-optimal level (source: developed from Guidelines accompanying Delegated Regulation (EU) No 244/2012 of 16 January 2012, p. 25).

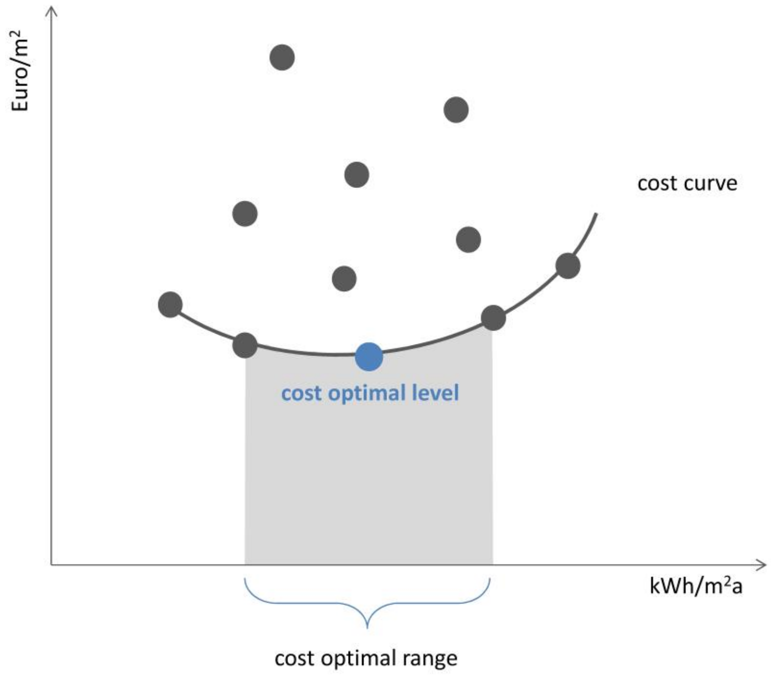


Figure 5. Primary energy demand subdivided for the different end uses for the different scenarios.

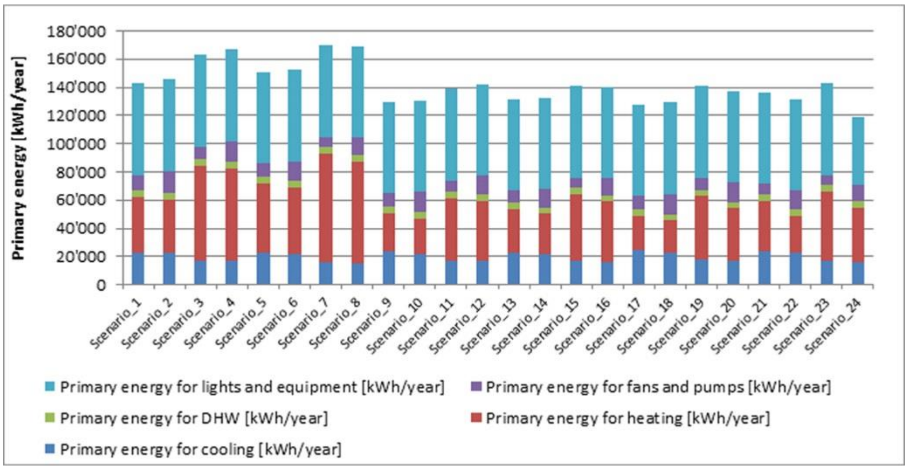


Figure 6. Breakdown of global cost of the entire building for each scenario.

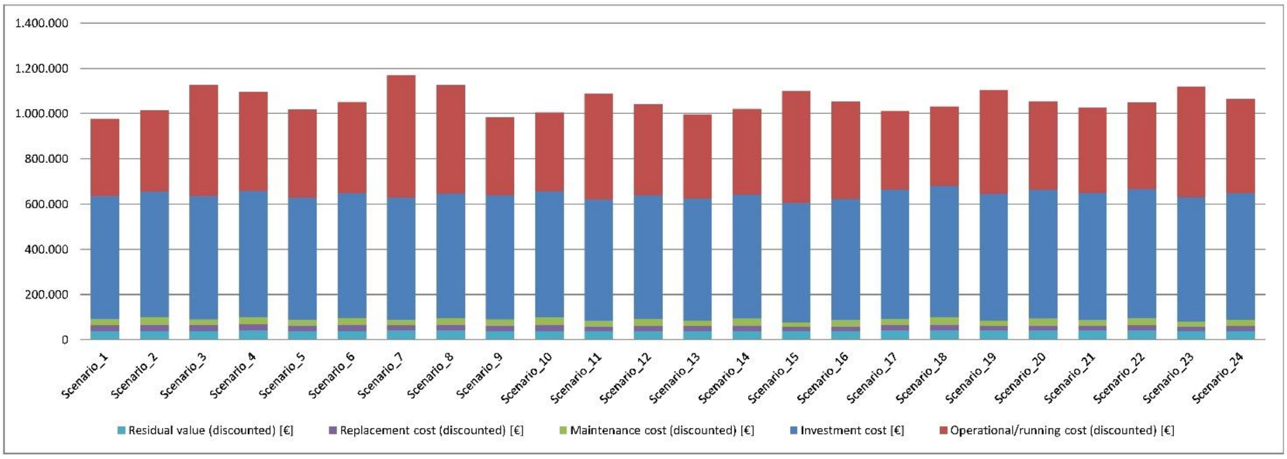


Figure 7. Global cost versus Primary Energy of each EEM.

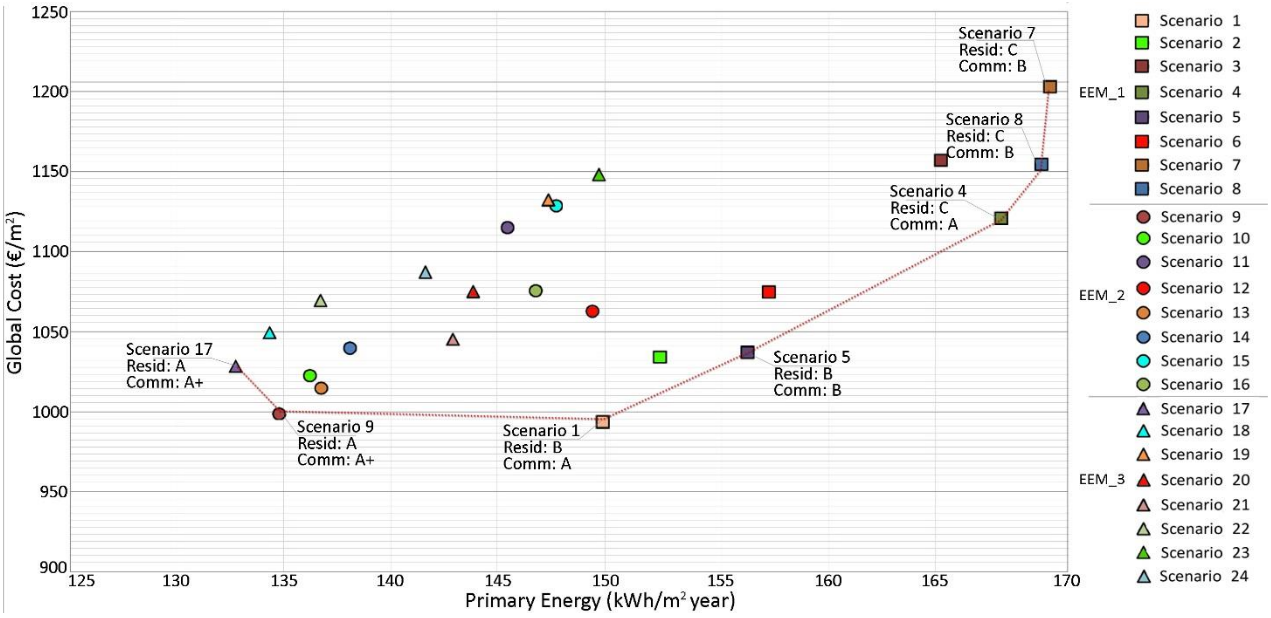
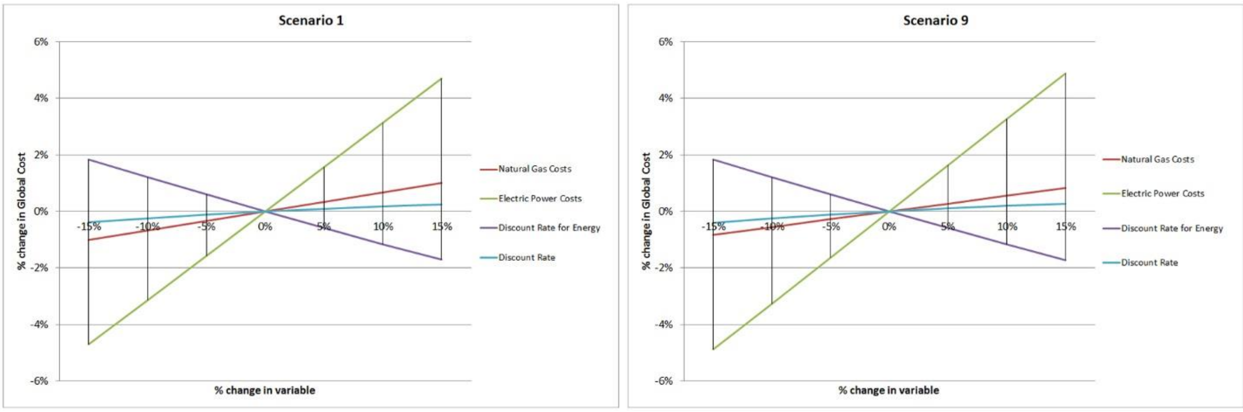


Figure 8. Sensitivity analysis: spider graph.



Tables

Table 1. Thermal transmittance for EEM_1, EEM_2 and EEM_3.

Building envelope component	EEM_1 U-value [W/m^{2}K]	EEM_2 U-value [W/m^{2}K]	EEM_3 U-value [W/m^{2}K]
External walls	0.33	0.25	0.15
Roof / Ground slab	0.30	0.23	0.15
Windows	2.00	1.50	1.20
Slab VS unconditioned spaces	0.30	0.26	0.17
Walls VS unconditioned spaces	0.33	0.30	0.20

Table 2. The twenty-four energy scenarios.

Scenario	Building Envelope EEM	Systems EEM for commercial spaces	Terminal devices	Generation system	Ventilation type	Systems EEM for residential spaces	Terminal devices	Generation system	Ventilation type	Technologies for renewable sources
Scenario 1	EEM_1	EEM_8	Fan coil	Condensing boiler and chiller	CMV	EEM_4	Radiant panel	Condensing boiler and chiller	NV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 2	EEM_1	EEM_8		Condensing boiler and chiller		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (4,92 kW_p)**
Scenario 3	EEM_1	EEM_8		Condensing boiler and chiller		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (7,08 kW_p)**
Scenario 4	EEM_1	EEM_8		Condensing boiler and chiller		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (7,56 kW_p)**
Scenario 5	EEM_1	EEM_9		Air-to-water heat pump		EEM_4		Condensing boiler and chiller	NV	**n° 12 solar panels + PV (5,64 kW_p)**
Scenario 6	EEM_1	EEM_9		Air-to-water heat pump		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (5,76 kW_p)**
Scenario 7	EEM_1	EEM_9		Air-to-water heat pump		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (7,92 kW_p)**
Scenario 8	EEM_1	EEM_9		Air-to-water heat pump		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (7,8 kW_p)**
Scenario 9	EEM_2	EEM_8	Fan coil	Condensing boiler and chiller	CMV	EEM_4	Radiant panel	Condensing boiler and chiller	NV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 10	EEM_2	EEM_8		Condensing boiler and chiller		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 11	EEM_2	EEM_8		Condensing boiler and chiller		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 12	EEM_2	EEM_8		Condensing boiler and chiller		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 13	EEM_2	EEM_9		Air-to-water heat pump		EEM_4		Condensing boiler and chiller	NV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 14	EEM_2	EEM_9		Air-to-water heat pump		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 15	EEM_2	EEM_9		Air-to-water heat pump		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (4,8 kW_p)**
Scenario 16	EEM_2	EEM_9		Air-to-water heat pump		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (4,8 kW_p)**

Scenario 17	EEM_3	EEM_8	Fan coil	Condensing boiler and chiller	CMV	EEM_4	Radiant panel	Condensing boiler and chiller	NV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 18	EEM_3	EEM_8		Condensing boiler and chiller		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 19	EEM_3	EEM_8		Condensing boiler and chiller		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 20	EEM_3	EEM_8		Condensing boiler and chiller		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 21	EEM_3	EEM_9		Air-to-water heat pump		EEM_4		Condensing boiler and chiller	NV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 22	EEM_3	EEM_9		Air-to-water heat pump		EEM_5		Condensing boiler and chiller	CMV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 23	EEM_3	EEM_9		Air-to-water heat pump		EEM_6		Air-to-water heat pump	NV	**n° 12 solar panels + PV (4,8 kW$_p$)**
Scenario 24	EEM_3	EEM_9		Air-to-water heat pump		EEM_7		Air-to-water heat pump	CMV	**n° 12 solar panels + PV (4,8 kW$_p$)**

Table 3. Summary table of primary energy consumptions, global cost and energy efficiency classes subdivided for commercial and residential uses.

Scenario	Building Envelope EEM	Systems EEM for commercial spaces		Systems EEM for residential spaces		Primary energy demand (kWh/m²y)	Global cost (€/m²)	Energy class for commercial spaces	Energy class for residential spaces
Scenario 1	EEM_1	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	149	989	A	B
Scenario 2	EEM_1	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	151	1030	A	B
Scenario 3	EEM_1	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	164	1151	A	C
Scenario 4	EEM_1	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	166	1115	A	C
Scenario 5	EEM_1	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	155	1032	B	B
Scenario 6	EEM_1	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	156	1070	B	B
Scenario 7	EEM_1	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	168	1197	B	C
Scenario 8	EEM_1	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	168	1148	B	C
Scenario 9	EEM_2	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	134	995	A+	A
Scenario 10	EEM_2	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	136	1019	A+	A
Scenario 11	EEM_2	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	144	1111	A+	B
Scenario 12	EEM_2	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	148	1059	A	B
Scenario 13	EEM_2	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	136	1011	A	A
Scenario 14	EEM_2	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	137	1036	A	A
Scenario 15	EEM_2	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	146	1125	A	B
Scenario 16	EEM_2	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	146	1072	A	B
Scenario 17	EEM_3	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	132	1024	A+	A
Scenario 18	EEM_3	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	134	1045	A+	A
Scenario 19	EEM_3	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	146	1127	A+	B
Scenario 20	EEM_3	EEM_8	Fancoil; condensing boiler + chiller; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	143	1070	A	B
Scenario 21	EEM_3	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_4	Radiant panels; condensing boiler+chiller; NV	142	1041	A	A
Scenario 22	EEM_3	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_5	Radiant panels; condensing boiler+chiller; CMV	136	1065	A	A
Scenario 23	EEM_3	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_6	Radiant panels; Air-to-water heat pump; NV	148	1144	A	B
Scenario 24	EEM_3	EEM_9	Fancoil; air-to-water heat pump; CMV	EEM_7	Radiant panels; Air-to-water heat pump; CMV	141	1083	A	B