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Environmental and economic implications of energy efficiency in new residential buildings: A multi-criteria selection approach

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ABSTRACT

The choice of the most appropriate technologies in buildings is often a challenge at the design stage, especially when many different criteria are taken into account. Consequently, the decision process relies often on one criterion only, such as costs or energy savings. We propose a multi-criteria approach based on multi-attribute utility theory to assess alternative energy efficiency measures, explicitly considering both environmental and economic criteria. We apply it to the design of a new residential building in Milan (Italy), with the aim to maximize CO_2 emission savings related to electricity and gas consumption, and to minimize embodied energy and investment costs. After modelling the building prototype, alternative energy efficiency measures are assessed and ranked according to the selected criteria.

The building optimized through the implementation of the best performing measures showed an overall 90% reduction in operational primary energy compared to the baseline building. The inclusion of the embodied energy altered the energy performance calculations resulting in 55–67% reduction in total energy over a 10-year period, and 77–82% over a 30-year period. Results point to the importance of a comprehensive implementation of measures, such as thermal improvements, high efficiency equipment, appliances, and renewable energy generation. The paper demonstrates the feasibility of this framework to support the decision process from a multi-criteria perspective, proposing a flexible method that can be adapted to other building types, environmental conditions, materials and technologies. It also highlights the importance of considering both environmental and economic criteria when designing a new building. It stresses how the embodied energy should be a criterion for technology selection, as current strategies to reduce operational energy often increase the amount of energy embodied into buildings with environmental consequences.

1. Introduction

Energy efficiency is recognized as one of the priorities of the Energy Union strategy [1]. Improving energy efficiency is expected to reduce greenhouse gas (GHG) emissions and energy import dependency, create jobs, boost energy security, support research, innovation and competitiveness. Accounting for approximately 40% of primary energy and 36% of greenhouse emissions, the building sector is currently the largest end-use sector in Europe [2]. In particular, the residential sector consumes more than a quarter of total energy and accounts for two thirds of building consumption.

The European Union has launched a policy framework aimed at reducing energy consumption and obtaining considerable savings from buildings. The Energy Efficiency Directive (EED) [3] and the Renewable Energy Directive (RED) [4] contain important provisions, but a major step forward is represented by the Energy Performance of Buildings Directive recast [5]. The Directive establishes the implementation of nearly zero energy buildings (NZEBs) as the building target from 2018 onwards. NZEBs are defined as buildings with a very high energy performance, where energy requirements should mostly be covered by renewable energy sources. Another important novelty is the introduction of cost-optimality. A methodology is described to derive cost-optimal levels of minimum energy performance requirements. The cost-optimal level represents the energy performance which leads to the lowest cost over the building lifecycle [6].

Combining NZEBs and cost-optimality remains challenging and often

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performed only at a research level [7]. Additionally, although different studies have highlighted that reaching the NZEBs target is achievable [8, 9], it is not always proven that the selected design choices are the most suitable from both an environmental and economic perspective.

Moreover, improving energy efficiency in buildings has been mainly focused on reducing operational emissions (e.g. linked to heating, ventilation, air conditioning systems (HVAC), domestic hot water, lighting, appliances), but it is estimated that about 30% of the energy consumed throughout the lifetime of a building is within its embodied energy [10].

1.1. Research aims

This study aims at illustrating a method able to select the technology measures that are most convenient from an economic and environmental perspective. A new residential building located in Milan (Italy) is chosen as a case study. An assessment approach based on multi-attribute utility theory (MAUT) has been developed to support a multi-criteria evaluation of selected technology measures. The study considers at the same time the minimization of embodied energy and investment costs, as well as the maximization of electricity and gas savings associated with each measure. The proposed approach allows a comparison of alternative technologies to be potentially implemented in the building prototype. The research involves the following steps:

- identification of appropriate criteria representing the different objectives of the decision and their organization into a hierarchy;
- establishment of mathematical functions to evaluate the satisfaction (utility) associated with each alternative with respect to different criteria;
- determination of a set of weights that represent the relative importance of each criterion to the overall utility;
- evaluation and ranking of the alternatives.

The baseline and the optimized building are then simulated and compared in terms of energy consumption, costs and CO_2 emissions. Finally, a sensitivity analysis is performed to assess how the outputs are affected by the uncertainty on the relative importance of the selected criteria as well as embodied energy estimations.

1.2. Literature review

A literature review is now given in relation to the main topics linked to this paper: embodied energy (Section 1.2.1), technology measures (Section 1.2.2), and multi-criteria decision-making methods (Section 1.2.3).

1.2.1. Embodied energy

Although largely ignored, the embodied energy comprises the materials used in the building and technical installations, as well as the energy consumed at the time of construction or renovation of the building [11]. In particular, it includes: the energy used to extract raw resources, process materials, assemble product components, transport between each step, construction, maintenance and repair, deconstruction and disposal [12]. The estimated embodied energy depends on factors such as building age, climate, and materials [13]. Table 1 reports the estimated percentage of embodied and operational energies in buildings as reported in the literature.

Table 1
Estimated embodied energy and operational energy in buildings.

Building type	Embodied energy		Operational energy		Reference
	min (%)	max (%)	min (%)	max (%)	
Low energy	9	46	54	91	[14]
Conventional	2	38	62	98	[14]
Conventional	10	20	80	90	[15]
NZEB	74	100	0	26	[16]
Low energy	26	57	43	74	[16]
Passive	11	33	67	89	[16]
Conventional	4	20	80	96	[16]
High performing	31	46	54	96	[17]
Conventional	10	12	88	90	[17]

The building envelope is a key element for both embodied and operational energy in buildings [22]. In more detail, the building envelope (floors, walls, roof, and finishes) contributes for about 48–50% to the overall embodied energy of a standard house. Although envelope improvements contribute to lower operational energy consumption, there are concerns about the global warming potential and other impacts that some technologies can have on the environment.

Embodied energy and costs of recycled and reused materials widely vary [18] Recent literature emphasizes standard protocols for the estimation of embodied energy [19]. Although there are standards, such as EN 15978 [20] and subsequent standards, questions on embodied energy quantification remain [21]. For instance, there is extensive uncertainty regarding the embodied energy evaluation, mainly linked to available data sources, estimation methodologies, variability of time and location [16].

Both operational energy and embodied energy are subject to performance gaps. The gap can be between simulated and monitored data in relation to the operational energy. It is subject to measurement boundaries and empirical data sources for embodied energy data. Relative to building simulation, there have frequently been performance gaps where savings from simulation have been higher than that realized in real buildings. However, there are many efforts to address these shortcomings through the use of real monitored data to guide and validate simulation inputs [23–25].

The most commonly used means to estimate embodied energy for materials or products is the Life Cycle Assessment (LCA) framework. This is a standardized environmental tool to quantify the energy, carbon or water liabilities which a product or process imposes on the physical environment [26]. This is usually carried out as life-cycle energy assessment, a form of LCA where energy consumption of the various phases is measured to account for all energy inputs over the building life. Differences in embodied energy factors arise in embodied energy estimations due to differences in scope as well as in the technology used for material production and transportation.

Besides the embodied energy, it is worth mentioning the embodied carbon which considers how GHGs are released throughout the supply chain to provide a material or service. It represents the carbon footprint of a material or process. It is an alternative metric which can be more comprehensive in accounting for the emissions intensity of the energy carrier [27–29].

To date, a number of studies consider the embodied carbon or embodied energy as a criteria for technology selection along with energy savings and costs in low energy buildings [30]. In particular, Thormark [31] and others [32] have shown that very low energy buildings typically have embodied energies that are much higher than conventional structures [33]. The additional embodied energy must be recaptured by successful reductions in operational energy. As buildings become more efficient or approach NZEBs, embodied energy can become more than half the total building energy over its useful life [34]. For the evaluation of a Passive House design, embodied energy has been found to be so high that 80 years are required to recapture through reduced operational energy [35]. Thus, to reach a useful reduction in embodied energy, a comprehensive approach is needed beyond operational energy alone [36]. Other studies have considered a multi-criteria approach to assist with measure selection [37,38]. However, none of these have used a multi-attribute utility theory approach along with operational energy, carbon or embodied energy data together.

1.2.2. Technology measures

The choice of the technologies to be implemented is not an easy task at the building design stage. In the light of the European energy policy framework, a wide range of technologies to increase energy savings have become available during the last decade [39,40], enabling more interactive buildings [41]. Generally, in efficient buildings, summer heat gains and winter heat losses are minimized, passive heating and cooling techniques are available, a rational use of daylight reduces lighting, the envelope dynamically controls the heat exchange between indoors and outdoors, renewable energy production compensates energy consumption, ICT guarantees a smarter use of energy, insulation reduces thermal losses, and systems are more efficient [42].

The envelope can considerably reduce energy needs in a building [43]. New insulation materials are able to decrease heat transfer [44]. Among them, there are fibreglass, polyurethane foam, polystyrene foam, cellulose insulation, and rock wool able to fill or coat walls, roofs, floors and façades. Nanotechnology is enabling the creation of new nanomaterials. Cool roofs can help minimize solar absorption and maximize thermal emission reducing the incoming heat flow and the energy used for cooling, in addition to reducing heat losses [45,46]. The use of natural building materials can be an effective way to reduce embodied energy [47] and in some cases can also determine a net CO_2 uptake [48].

Windows are a key element for the building performance. They provide shelter from the outside while allowing for admission of natural light, visual continuity, and natural ventilation. Thermal energy, daylighting, and acoustical performances are some of the key considerations in the selection of windows. Double or triple glazed windows with low emissivity reduce energy consumption by more than 40%. Films and coatings can be used on existing glazing to limit solar gains. A frequent measure is the installation of external shading devices [49].

Innovative building façades, integrating different technologies, such as ventilated façades, solar chimneys, infra-red reflective paints, humidity control foils, solar energy absorbing thermal mass for night ventilation, contribute to the overall energy performance [50]. The usefulness of green façades and green walls is also evident to mitigate the heat island effect.

Efficient mechanical and smart systems significantly contribute to the energy performance. Heat recovery can reduce energy consumption recovering hot or cold air from ventilation exhausts and supplying it to the incoming air. Chillers can be up to three times more efficient than typical air conditioners. Condensing boilers use an additional heat exchanger to extract extra heat by condensing water vapour from combustion products.

Photovoltaic (PV) systems are becoming ubiquitous and efficient, integrated as a building material [51]. Biomass products are used in heating, and heat pumps (geo- and aero-thermal energy) are often used for ground-coupled and air-to-air heat exchange.

Control automation and smart metering devices for interaction with utilities are rapidly developing. They allow the control of the energy demand/supply through ICT technologies, allowing field data to be gathered. Control systems include daylight, presence and motion control [52,53].

The dynamic assessment of the impact of such technology measures on building energy performance is crucial, and requires the development of specific analysis and simulation techniques to select the most appropriate technologies to be implemented.

1.2.3. Multi-criteria decision-making (MCDM) methods

Multi-criteria decision-making (MCDM) methods analyse a decision process by breaking it down into different steps and assigning a relative importance to specific decision criteria [54]. The aim is to help the decision maker to deal with specific problems, compare and rank alternatives based on an evaluation of multiple, sometimes conflicting criteria [55]. Mathematical models are then used to weight criteria, score alternatives, and synthesize the final results to identify the best alternatives [56,57]. These methods have rapidly grown in research in recent years. They can clarify conflicts and trade-offs among criteria and support the selection [58,59]. The following phases can be generally distinguished [60]:

- objective identification;
- criteria development;
- generation, evaluation and selection of alternatives;
- implementation and monitoring.

As multi-criteria analysis can be affected by several sources of uncertainty, sensitivity analysis is desirable in most cases to evaluate the robustness of the results. A wide range of elements can contribute to the variability of the outcomes. The subjectivity of judgements, the imperfect knowledge of the system under investigation, the variability of the system parameters, which depend on several conditions, are some of the uncertain elements of the analysis [61]. Table 2 synthetises and describes some common MCDM methods [62,63].

MAUT relies on the idea that decision makers attempt to maximize utility with respect to a number of independent attributes [64]. Utility can be viewed as the level of satisfaction associated to a given value of a specific indicator [65]. If there are several attributes, the overall utility $\boldsymbol{U}$, representing the overall satisfaction of the decision maker, is calculated as the weighted sum of the partial utilities $\boldsymbol{u_i}$ associated to the different attributes $\boldsymbol{x_i}$ as in Equation (1):

$$U(x) = \sum_{i=1}^{n} w_i u_i(x_i) \tag{1}$$

where $u_i(x_i)$ (with $0 \leq u_i \leq 1, \forall i = 1, 2, \ldots n$) is the utility associated to the value x_i taken by the i-th attribute, and w_i is the weight associated with the utility of the i-th attribute, subject to the constraint

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

A recognized critical point of the MAUT method is the determination of the weights, as it is frequently difficult to grasp the actual preference structure of the decision makers. The hierarchical approach can be used to assign weights within the MAUT framework. Another possibility to overcome this issue is the Analytic Hierarchy Process (AHP) method [66,67], that quantifies the performances of alternative measures with respect to each decision criterion and aggregates them into a single overall score [68]. Pair-wise comparisons are performed to build a pair-wise comparison matrix that can be used to generate a ranking vector of numerical priorities representing the relative preference of each decision element compared to the other.

In the literature, MCDM methods have been used for several applications, such as procurement related regulation and environmental impact analyses [69–73]. In relation to buildings, MCDM methods have been applied with different purposes. Among them: to assist with the selection of green technologies [74], to support low carbon building design [75], to evaluate climate change mitigation policy instruments [76], to assess the thermal renovation of buildings [77], to assist with building certification [78], to optimise NZEB design [79], to compare

Table 2
MCDM methods.

Method	Description
Multi-Attribute Utility Theory or Multi-Attribute Value Theory (MAUT)	Weighted sum model (WSM): Preferable for single-dimensional rather than multi-dimensional problems Weighted product model (WPM): Applicable to single and multi-dimensional problems, but not appropriate for qualitative criteria assessment
Analytical Hierarchy Process (AHP)	Decomposes the problem into a hierarchy of alternatives and criteria weighted to generate a ranking of alternatives
Outranking (e.g. Promethee, Electre, Topsis)	Appropriate to decision problems with few criteria with several alternatives

passive and active technology options [80], to evaluate the energy supply chain [81,82], to improve thermal and energy performance [83].

However, due to a lack of confidence and established best practices within MCDM methods, designers and building managers rarely refer to decision-making tools [84]. Moreover, in relation to buildings, the decision-making process often relies only on the economic criterion, which is mainly related to the cost-benefit ratio obtained with a financial performance analysis [85]. Therefore, there is a need to investigate how MCDM methods can effectively support the decision-making process in relation to the choice of energy-efficient technology alternatives considering more criteria in the selection. In this paper, a multi-criteria decision analysis has been developed in the framework of multi-attribute utility theory (MAUT).

2. Methodology

The MCDM framework of this study was designed to evaluate the performance of energy efficiency measures based on their potential impact on selected environmental and economic criteria. From the environmental viewpoint, the consumption of both natural gas and electricity has been considered, as this is typical in the city under investigation. Electricity and gas savings derived from the implementation of different technological measures were calculated by carrying out energy simulations and making a comparison with the baseline building. The interaction of different factors including location, climate, costs, available resources and materials was also taken into account. The methodological approach is summarized in Fig. 1.

As a first step, a building prototype was defined and characterized. Energy simulations were carried out to assess the energy consumption of the baseline case. A list of technology alternatives was then selected to improve the performances of envelope, appliances and systems. To identify the most appropriate technologies to be implemented, the following criteria were considered: investment costs, electricity and gas savings, and embodied energy. More specifically, the performances of each measure were assessed in terms of the following attributes:

- increase of annual electricity savings;
- increase of annual gas savings;
- reduction of embodied energy;
- reduction of investment costs.

Therefore, for each measure, data on investment costs, embodied energy, electricity and gas savings were collected or calculated. Beyond the operational energy required to heat, cool, heat water and run appliances in the building, embodied energy considers the energy required to manufacture or obtain materials and components, as if the energy was embodied in the product itself. It is well known that many strategies to reduce operational energy, such as foam insulations or advanced windows using many plastics, can substantially increase the embodied energy required to manufacture the materials and equipment necessary to assemble the dwelling [10]. To account for this impact, the energy needed to locate, refine, manufacture and install the different energy efficiency measures was taken into account in addition to the energy saved through those measures.

The hierarchical approach was used to assign weights to the different attributes used to rank the available technologies with respect to their overall utility. A sensitivity analysis was then performed to investigate how sensitive results are to the assigned weights. After simulating the building with the selected technology measures, a comparison was made with the baseline building. Finally, a comparison was made with previous results where only investment costs and energy savings had been taken into account.

2.1. Baseline building prototype

The building prototype considered in this study is a standard new house of 120 m^2 floor area with a full cellar (Fig. 2). A similar building was used in a study by Ecofys GmbH and the Danish Building Research Institute [86], as well as in Ref. [44]. The building prototype has a rectangular footprint (9.8 × 6.1 m) with a standard height of 2.45 m and a full cellar below the structure. The roof is a conventional gable configuration, covered by terra cotta tiles with a solar absorptance of 75%. The total window area is 18 m^2, equally distributed in the four cardinal directions. A minimum air exchange at maximum occupation rate was considered, coherent with occupation levels and ventilation rates proposed by Standard EN 15251 [87] for high air quality buildings (0.5 h^{-1} for residential buildings).

Other characteristics are summarized in Table 3, where system properties, insulation levels, and airtight equipment efficiencies are also

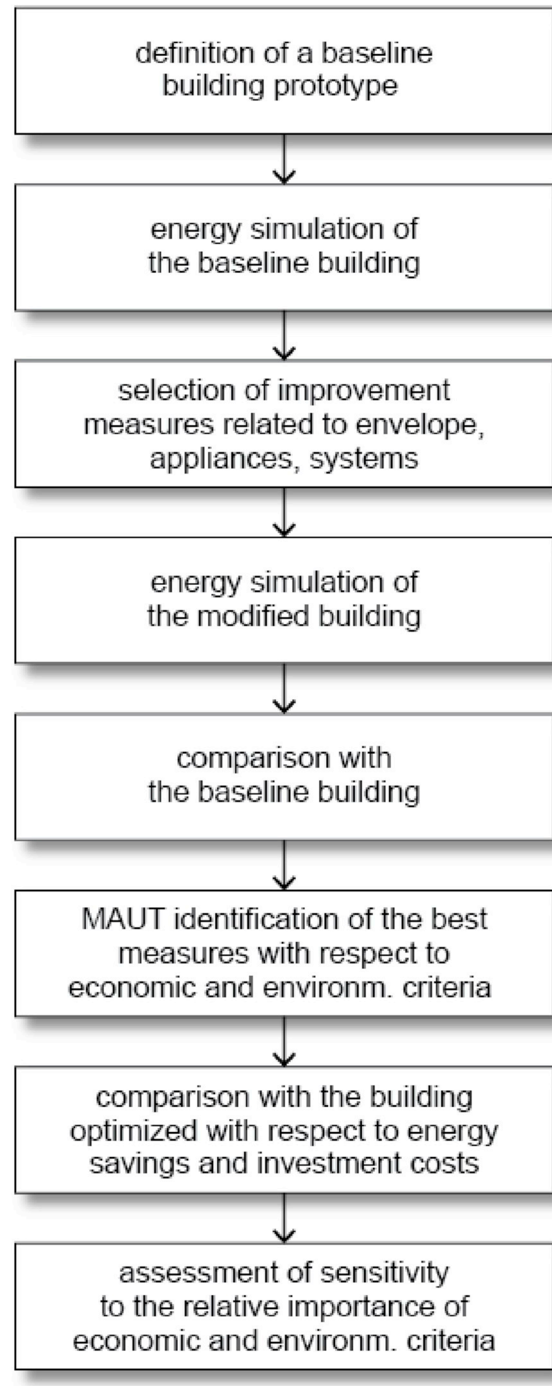

Fig. 1. The methodological approach of the research.

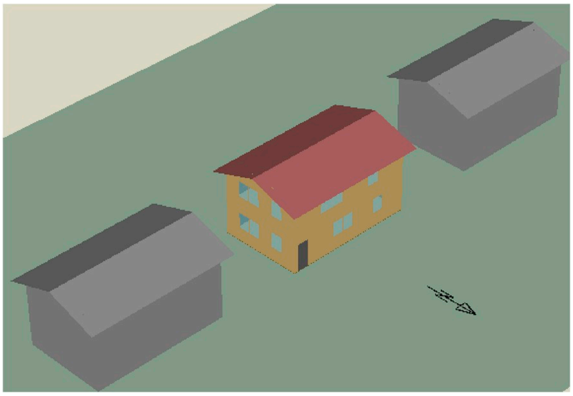

Fig. 2. The building prototype.

reported.

The single-family prototype is representative of new housing in Milan [61]. However, the authors acknowledge that this prototype cannot be representative of the overall building stock in Europe. Instead, it is used as an example for a typical building within the highly diverse stock of residential dwellings in Europe [88]. The building represents a standard energy performance building.

In relation to climate, Milan has hot, sultry summers and cold, foggy winters. The Alps and Apennine Mountains form a natural barrier that protects the city from the major circulation coming from northern Europe and the Mediterranean Sea [89]. Daily average temperatures can occasionally fall below 0 °C in winter, while in summer peak temperatures can reach 35 °C and above with high humidity levels. A graph showing monthly mean temperature, relative humidity, precipitation and sunshine hours along the year is shown in Fig. 3. Springs and autumns are generally pleasant, with temperatures ranging between 10 and 20 °C; these seasons are characterized by higher rainfall, especially in October and May. Relative humidity typically ranges between 45% and 95% throughout the year, rarely dropping below 27% or reaching 100%. In relation to degree days, Milan has 2,404 heating degree days and 380 cooling degree days: it belongs to climatic zone E based on the national classification which subdivides Italy into six zones based on degree-day intervals (from A, having less than 600° days, to F, having more than 3,000° days).

2.2. Energy simulations

Energy simulations of the baseline building were performed following the workflow of Fig. 4, where details of the model inputs, calculation and outputs are given.

Table 3
Characteristics of the baseline building.

Building type	new residential building
Building dimension	120 m^2 over a 2.5 m cellar containing heating equipment
Neighbours	similar neighbouring buildings on the two sides
Envelope	
windows	23 m^2 with double clear glass (2.2 W/m^2K)
walls	R 1.3 Insulated perlite filled masonry walls (~0.8 W/m^2K)
attic	R-5.3 insulation (~0.18 W/m^2K)
doors	insulated wood entry door (~0.8 W/m^2K)
air leakage	standard construction (4 ACH at 50Pa blower door pressure)
System	
heating	hydronic natural gas heating system, 82% efficiency
cooling	COP 4.1 mini-split cooling system
hot water	155 L insulated boiler in cellar providing 120 L per day at 55 °C
mechanical ventilation	20.3 L/s continuous with 72% efficient ERV

Dynamic simulations were carried out using the energy simulation software BEopt, developed by the U.S. National Renewable Energy Laboratory [90,91]. The calculation in BEopt uses the hourly energy simulation tool EnergyPlus developed by the Lawrence Berkeley National Laboratory and the U.S. Department of Energy [92]. The following energy uses were derived: heating, cooling, ventilation, domestic hot water, other technical systems, lighting, and appliances. EnergyPlus includes advanced features with a heat balance model of each evaluated zone. It also includes variable time steps and combined heat and mass transfer to increase simulation accuracy [93]. The results of the simulations compared to real buildings measured data verified its potential to replicate measured energy use both in cold and in hot climates [94].

Renewable energy production was evaluated using the transient simulation program TRNSYS [95]. Apart from PV, this tool predicts solar water heating performance relative to domestic hot water heating needs. TRNSYS is an hourly simulation tool that uses a set of algorithms to evaluate solar irradiance from beam and diffuse components as well as prediction of PV module temperatures that influence direct current output.

Climatic variables were derived from the IWEC weather datasets, consisting of hourly data arranged in typical weather years as a result of the ASHRAE Technical Committee 4.2 Weather Information [96]. Cost data were obtained for specific models and equipment [97]. Using similar inputs, predicted energy use and measure savings were estimated using the Passivhaus Planning Package (PHPP) software [98].

2.3. Technology alternatives

The energy efficiency measures considered in this study are related to envelope, appliances, and systems. A code is assigned to each alternative as summarized in Table 4.

2.3.1. Economic parameters

Investment costs were taken from a previous research [44], updating values where necessary, as well as using the NREL efficiency measures cost database [90]. The considered electricity price in Milan is 0.25 €/kWh, while the current natural gas price is 10 €/GJ or 0.058 €/kWh. The assumed installation and maintenance costs are different across measures: as the lifetime of building elements can be variable, a different lifetime was specified for each technology alternative and it was appropriately implemented considering data from a number of sources, including Standard EN 15459 [99]. For instance, most insulation measures were assumed to last 50 years, while appliances last 15 years. Other systems might require operation and maintenance during that time, as well as replacement before the end of the analysis period. The reference time horizon considered for the calculation is 30 years: therefore, an appliance with an expected lifetime of 15 years, such as a heat recovery unit, was considered twice in the calculation: at the beginning, as an initial investment cost, and after 15 years, as a replacement cost.

2.3.2. Impacts of energy savings on greenhouse gas emissions

The environmental impacts of electricity and gas are different. In our context it seems appropriate to refer to their contribution to greenhouse emissions. A physical evaluation of the chemical processes involved in methane or natural gas combustion shows that approximately 181 gCO_2/kWh of natural gas are released into the environment [100]. Carbon emission factors for electricity generation are more complex to assess, as they depend on the specific mix of resources used to produce each kWh. A recent evaluation showed that, in 2017, CO_2 production for electric generation averaged 447 g/kWh in Europe and 417 g/kWh in Italy [101]. This suggests that saving 1 kWh of natural gas consumption is worth about 40% of that of saving 1 kWh of electricity in terms of greenhouse gas reduction potential. Thus, we calculated impacts on global warming potential by estimating the combined savings of both

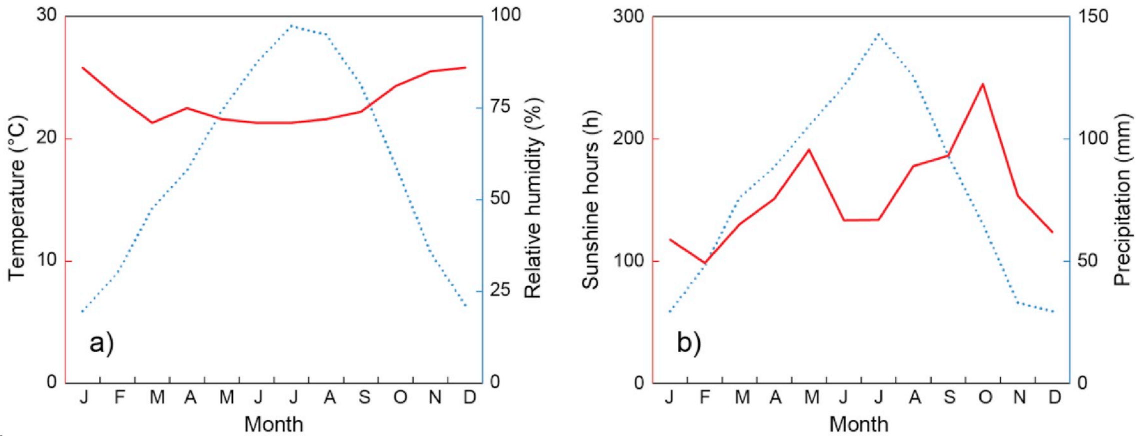

Fig. 3. Milan climate: a) monthly mean temperature and relative humidity; b) monthly mean sunshine hours and precipitation.

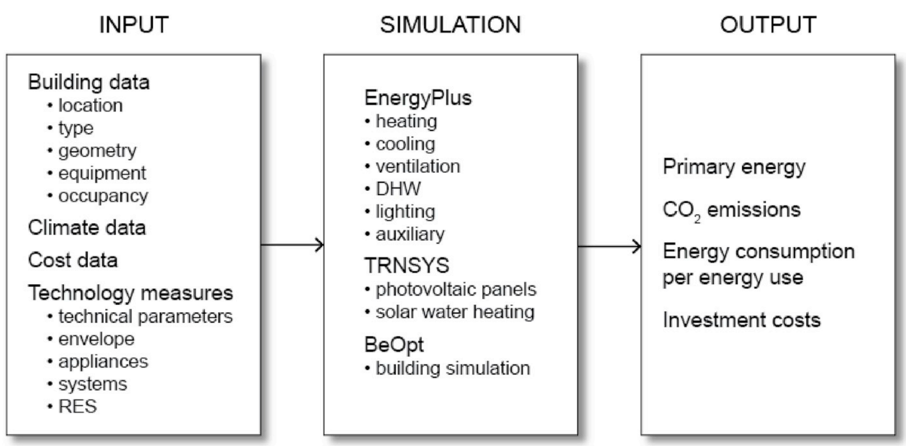

Fig. 4. The energy simulation process.

fuels on CO_2 emissions (kg/year).

2.3.3. Embodied energy

In Europe and in the city under investigation, the market of insulation materials is dominated by inorganic fibrous insulation, fibreglass, foamed plastic, and cellulose. Organic foamy materials, known as expanded and extruded polystyrene and polyurethane, account for about 27% of the market [102]. The embodied energy of insulation materials is subject to discussion, and the literature reports a wide range of estimates for different type of insulations [103].

In this research, embodied energy for materials such as concrete, wood and insulation systems was estimated from data available in the ICE (Inventory of Carbon and Energy) database by the University of Bath [104]. In our assessment, the embodied energy was determined by estimating the size, volume and weight of materials within the database and then applying it to the components of our building prototype. This is straightforward for elements such as walls and insulation. For instance, rigid foam type insulation systems have 101 MJ/kg embodied energy, while fibreglass systems have 28 MJ/kg and cellulose insulation 2 MJ/kg, the lowest of the analysed technologies. We found very large differences in embodied energy for systems promising similar performances. Considering the thickness, density and embodied energy of 1 m^2 of insulation at RSI 7.0 m^2K/W, the estimation is 619 MJ for a rigid foam insulation, 110 MJ for fibreglass, and 27 MJ for cellulose. Thus, the embodied energy for a given thickness of wall insulation can vary by a factor of twenty.

Regarding structural systems, it is estimated that foundations account for 10–15% of the embodied energy of the overall structure [105]. Concrete and steel have been compared by Ref. [106], who concluded that the embodied energy is 42 GJ for concrete and 55 GJ for steel structures in a structural bay of 7.5 m × 7.5 m. Concrete structures have been also investigated by Ref. [107]. They showed that the embodied energy can decrease by 10% with a 5% increase in costs.

To evaluate the embodied energy in advanced frame walls with high levels of insulation, an estimate of the wood content is needed. This requires carefully estimating the wood elements and their dimensions. To reach high R-walls, we assumed that double stud construction is used with either fibreglass or cellulose insulation. Hereafter, an example for the embodied energy estimation of a wall of 10 m length and 2.7 m height is reported. This requires 19 wood elements of 4.44 × 9.52 cm installed at a 0.61 m interval along the wall, or 38 elements for double construction. Two parallel sets of wood members are required with a cover of 1 cm fibreboard sheeting on the exterior. Each wood member contains 0.012 m^3 of wood so that the entire wall requires 0.44 m^3 of wood. However, allowances must be made for corners, wall plate, window, door framing such that at least 10% additional framing is needed. Thus, the final estimate for the required wood ends up at 0.48 m^3 of wood. The wood sheeting for the entire 27 m^2 wall comes up to 0.27 m^3. According to data from the University of Bath, the density of construction wood is approximately 600 kg/m^3 so that the reported example has a weight of 288 kg. The density of medium-density fibreboard averages 720 kg/m^3, as a consequence the wall contains 194 kg fibreboard. The embodied energy of timber is 8.5 MJ/kg, corresponding to an embodied energy of 2,448 MJ for the entire wall. The embodied energy of fibreboard is 11 MJ/kg, for a total of 2,134 MJ for the exterior sheathing. The total embodied energy is thus 4,582 MJ (or 170 MJ/m^2 of

Table 4
Energy efficiency measures considered in this research (in bold the technologies implemented in the baseline building).

Option code	Category	Technology description
A1	**appliance**	**dishwasher a+**
A2	appliance	dishwasher a++
A3	**appliance**	**clothes washer a+**
A4	**appliance**	**refrigerator a+**
A5	appliance	refrigerator a++
A6	appliance	clothes washer a++
A7	**appliance**	**clothes dryer a+**
A8	appliance	clothes dryer a++
L1	**lighting**	**standard incandescent**
L2	lighting	efficient LED
WH1	**water heating**	**standard water heater**
WH2	water heating	condensing water heater
MV1	**mechanical ventilation**	**base ERV (72% eff.)**
MV2	mechanical ventilation	high efficiency ERV (87%)
MV3	mechanical ventilation	highest efficiency ERV (90%)
H1	**heating**	**standard gas boiler (82% Eff)**
H2	heating	high-efficiency gas boiler (98%)
C1	**cooling**	**mini split (Standard: 7 kW capacity)**
C2	cooling	high-efficiency mini split cooling (7 kW capacity)
IC1	**insulation ceiling**	**31-cm fibreglass insulation (6.7 W/m^2K)**
IC2	insulation ceiling	40-cm fibreglass insulation (8.6 W/m^2K)
IC3	insulation ceiling	49-cm fibreglass insulation (10.6 W/m^2K)
IC4	insulation ceiling	66-cm fibreglass insulation (14.1 W/m^2K)
IC2B	insulation ceiling	35-cm cellulose insulation (8.6 W/m^2K)
IC3B	insulation ceiling	42-cm cellulose insulation (10.6 W/m^2K)
IC4B	insulation ceiling	56-cm cellulose insulation (14.1 W/m^2K)
CM1	**concrete masonry walls**	**perlite filled masonry block**
CM2	concrete masonry walls	perlite filled w/5 cm foam insulation on exterior
CM3	concrete masonry walls	perlite filled w/14 cm interior cavity w/6 cm fibrous insulation
CW1	cavity wall insulation	base: double stud, 27-cm fibreglass insulation
CW2	cavity wall insulation	double stud, 27-cm fibreglass insulation, advanced framing
CW3	cavity wall insulation	double stud, 32 cm fibreglass insulation, advanced framing
CW4	cavity wall insulation	double stud, 37 cm fibreglass insulation, advanced framing
CW5	cavity wall insulation	base: double stud, 27-cm cellulose insulation
CW6	cavity wall insulation	double stud, 27-cm cellulose insulation, advanced framing
CW7	cavity wall insulation	double stud, 32-cm cellulose insulation, advanced framing
CW8	cavity wall insulation	double stud, 37-cm cellulose insulation, advanced framing
EI	exterior insulation sheathing	RSI-0.9 foam insulation (2.5 cm)
EI2	exterior insulation sheathing	RSI-1.8 foam insulation (5 cm)
EI3	exterior insulation sheathing	RSI-2.6 foam insulation (7.5 cm)
CI1	**cellar insulation**	**base: 2.5-cm foam insulation (0.90 W/m^2K)**
CI2	cellar insulation	5.0-cm foam insulation (0.50 W/m^2K)
CI3	cellar insulation	7.5-cm foam insulation (0.35 W/m^2K)
CI4	cellar insulation	10.0-cm foam insulation (0.27 W/m^2K)
W1	**windows**	**double glass, hi-gain, low-e, standard frame, air fill**
W8	windows	double glass, low-e, low-gain, insulated frame, Ar fill
W9	windows	double glass, hi-gain, low-e, insulated frame, Ar fill
W13	windows	Passivhaus window, hi gain, insulated frame, Ar fill
W14	windows	Passivhaus window, low gain, insulated frame, Ar fill
INF1	**air leakage**	**building air leakage = 4.0 ACH @ 50Pa Press (standard building)**
INF2	air leakage	building air leakage = 2.0 ACH @ 50Pa Press (tighter)
INF3	air leakage	building air leakage = 0.6 ACH @ 50Pa (Passivhaus level)
PV1	photovoltaic panels	4 kW PV system with inverter

wall area).

In relation to windows, embodied energy depends on the glass type, number of glass panes, area, and frame material type. More glass panes can improve the overall thermal resistance, but increase embodied energy. The impacts of windows have been addressed by Refs. [108–110]. Here we relied on a detailed evaluation by Kristiansen & Petersen (2016) [111] evaluating the embodied energy of standard, advanced and very advanced energy efficient windows with values of 92 MJ/m^2, 142 MJ/m^2 and 158 MJ/m^2, respectively.

Energy efficient lighting and appliance systems figure prominently in energy saving schemes [59]. Good estimates for LED versus conventional incandescent lighting sources are available in the evaluation done by Ref. [112]. The same reference also shows embodied energy estimates for appliances such as refrigerators, washing machines and dishwashers used for the purposes of this study.

In our assessment we found estimates for appliance and heating and cooling equipment embodied energy to be particularly limited. We used [113] as the source for these estimates of appliance embodied energy. Other sources available in the literature were considered for the estimation of the embodied energy of other technology measures [10, 114–118].

Table 5 shows the computed embodied energy of each option in the baseline and optimized building prototype. Values are provided for construction materials, insulation, lighting, appliances, and equipment.

The ICE database came from process-based LCA. These can suffer underestimation errors of 40–70% since they can neglect energy and carbon use in the upstream layers of the construction supply chain [119–121]. On the high end, Crawford and Stephan [35] and Chastas [144] documents up to 378% increases in LCA when using hybrid-input-output evaluations.

We compared the data we found in Ref. [104] with other databases [122,123]. While we found variation for some items, such as fiberglass insulation, the embodied energy estimates on foam insulation were

Table 5
Comparison between embodied energy (EE) in the options of the baseline and optimized buildings.

Baseline Option	Baseline EE (MJ)	Baseline EE (kWh)	Optimal building Option	Optimal building EE (MJ)	Optimal building EE (kWh)
A1	4750	1319	A2	5200	1444
A3	3900	1083	A6	4750	1319
A4	5900	1639	A5	7080	1967
A7	4000	1111	A8	5000	1389
L1	50	14	L2	900	250
WH1	4000	1111	WH2	8000	2222
MV1	5000	1389	MV3	6000	1667
H1	25000	6944	H2	35000	9722
C1	16500	4583	C2	19800	5500
IC1	6198	1722	IC2B	1864	518
CM1	22536	6260	CW8	6900	1917
E0	0	0	E1	11586	3218
INF1	0	0	INF3	3000	833
CI1	6623	1840	CI2	13246	3679
W1	29014	8059	W8	44856	12460
PV0	0	0	PV1	97680	27133
Total	**133471**	**37075**	**Total**	**270862**	**75239**

identical. The only discrepancy was the estimates for cellulose insulation (Table 6). For this material, the Ecoinvent values were higher (9.7 MJ kg vs. 2.1 MJ/kg). However, we found that there is not consistent agreement on the appropriate values to be used for cellulose insulation referring to other sources which suggest lower estimates closer to the ICE database [29]. Indeed, the recycling content of the source material and the specific application impact values to be used.

The ICE embodied energy estimates for concrete were within 20% of those for Ecoinvent (111 MJ/kg against 136 MJ/kg) (Table 5). The value we used for wood construction timber (8.5 MJ/kg) is reasonable in context of variation other LCA studies. For instance, Hammond and Jones [124] showed embodied estimates for saw wood ranging from 0.3 to 61 MJ/kg depending on wood type, drying methods and location. Bribián et al. [123] estimated kiln dried construction wood to have an embodied energy of 21 MJ/kg although an estimate for concrete (111 MJ/kg) was identical to that use in our study. Dixit et al. [125] showed such uncertainties were typical and arising from a variety of influences. Given the uncertainties, we conducted a brief sensitivity study looking at the impact of the described differences on our overall results (Section 3.5 and 3.6).

2.4. Multi-attribute technology selection

In this work, the MAUT method was used to assess the overall performances of alternative technology measures for a new residential building. First, the criteria (each one representing a specific objective of the decision, as described in section 2) were organized into a hierarchy, illustrated in Fig. 5.

For each attribute x_i, a utility function u_i was defined to map the value of each alternative measure into a range comprised between 0 (minimum satisfaction with respect to the objective) and 1 (maximum satisfaction). The utility function can be derived by identifying the range of variation, the functional form (monotonically increasing, decreasing, or non-monotonic), and the values to be associated with minimum, maximum and/or intermediate levels of utility on the basis of limit and target reference points.

In our study, we aimed at maximizing energy savings (electricity and gas), and minimizing costs and embodied energy. The following functions were hence used for the maximization (Equation (3)) and minimization, respectively, of the attributes (Equation (4)):

$$u(x) = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (3)$$

$$u(x) = \frac{x_{max} - x}{x_{max} - x_{min}} \quad (4)$$

where *Xmin* and *Xmax* are the minimum and maximum values of the evaluation indicators.

The overall utility was then derived as the weighted sum of the utilities associated to the different attributes (Equation (5)):

$$U = u_{ES} \cdot w_{ES} + u_{EE} \cdot w_{EE} + u_C \cdot w_C \quad (5)$$

where w_i is the weight associated to attribute x_i. The subscript ES stands for energy savings (encompassing electric and gas savings), EE for embodied energy, and C for costs.

Table 6
Key embodied energy (EE) values.

Material	EE values (MJ/kg)
Cellulose	2.1 [123] – 9.7 [122]
Fiberglass	28.0 [123] - 37.0 [122]
Extruded Polystyrene	101.5 [123] - 105.6 [122]
Construction Wood	8.5 [123] −21.0 [122]
Concrete	111.1 [123] −136.0 [122]
Concrete Block	0.7 [122,123]

The weights assigned in the literature to environmental, economic and social criteria vary depending on the analysis. The following ranges can be found: between 0.5 and 0.7 for the environmental criterion, between 0.5 and 0.2 for the economic criterion, and between 0.2 and 0.1 for the social criterion [126,127].

In this analysis, weights were assigned through a hierarchical approach, considering two main macro-criteria: economic and environmental performance (Fig. 5). Considering the importance of the environmental and economic perspectives within EU policies, the following weighting factors were established: 0.6 and 0.4 for the environmental macro-criterion and the economic macro-criterion, respectively (Table 7).

For energy savings and embodied energy, the assigned weights were 0.6 and 0.4. This choice gives slightly more importance to energy savings during the operational phase, but assigns a significant contribution to embodied energy as well. Electric and gas savings were first transformed into avoided CO_2 emissions and then aggregated into a single figure before calculating an overall utility value.

The final weight of the leaf criteria (the attributes) can be calculated by multiplying the weights of all the nodes connecting a leaf with the root (the general objective). For instance, the global weight assigned to embodied energy is the product of the relevant local weight 0.4 (the relative preference against energy savings) times 0.6 (the relative preference of the environmental macro-criterion against the economic one).

2.5. Sensitivity analysis

A sensitivity analysis was performed to evaluate the robustness of the results in relation to the uncertainty associated to the weights expressing the relative importance of the three main criteria used to calculate the overall performances of each alternative measure: energy savings, embodied energy and costs. The three weights (w_{ES}, w_{EE}, and w_C) were varied between 0 and 1 (under the constraint that they sum up to 1); for each triplet of values, overall utilities were recalculated and the best alternative was determined according to the corresponding ranking.

3. Results

3.1. Energy consumption of the baseline building

Simulations reveal a consumption of 3,836 kWh/year electricity and 54.5 GJ/year natural gas for the baseline building. Fig. 6 details the electricity (Fig. 6a) and gas consumption (Fig. 6b) of the building as obtained by the energy simulations. In the baseline building, the largest share of electricity consumption is related to appliances, while gas consumption is basically related to heating (Fig. 6).

3.2. Evaluation of technology alternatives

Table 8 reports the incremental investment cost, the incremental embodied energy, the electricity and gas savings, as well as the avoided CO_2 emissions, as calculated for each analysed measure in comparison with the baseline building. The overall utility of each measure, as obtained via the MAUT method, is also given.

Alternative measures based on cavity wall insulation (CW) have the lowest incremental costs, followed by mechanical ventilation (MV2), lighting (L2), and appliances (A2, A5, A6). The highest incremental costs are associated with the installation of photovoltaic panels (PV1), concrete masonry (CM4, CM5, CM2, CM3), very efficient windows (W13, W14), and exterior insulation sheathing (EI, EI3, EI2).

The highest incremental embodied energy is related to the PV system, concrete masonry walls (CM3, CM2), exterior insulation sheathing (EI3, EI2), and windows (W13, W14, W8, W9). The lowest incremental embodied energy is found in insulation ceiling measures (IC2B, IC3B, IC4B), cellar insulation (CI2, CI3), appliances (A2, A6, A5), concrete masonry (CM4, CM5), and mechanical ventilation (MV2, MV3).

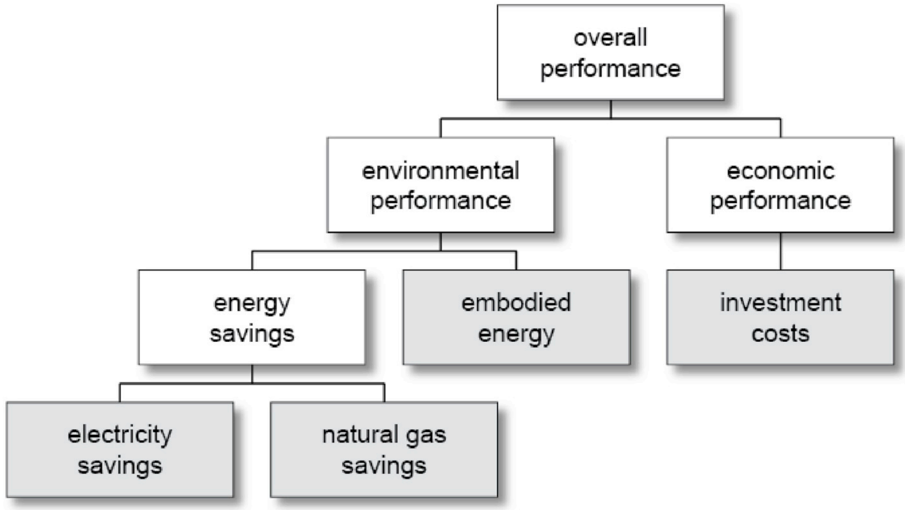

Fig. 5. The hierarchy of decision criteria considered in this study. Boxes highlighted in grey indicate leaf criteria, i.e. those used as attributes for the assessment.

Table 7
Weighting factors for MAUT analysis.

Criteria	Weighting Factor
Environmental performance	0.6
Economic performance	0.4
Energy savings	0.6
Embodied energy	0.4

The highest electricity savings in comparison with the baseline building derive from the installation of PV (PV1), concrete masonry walls (CM5, CM4), lighting (L2) and appliances (A8, A6, A5), while the lowest are linked to cellar insulation (CI3, CI4), windows (W13, W8), and mechanical ventilation (MV2). In relation to gas savings, CW and CM groups of measures guarantee the highest savings, while the lowest are obtained from lighting (L2), appliances (A5, A8, A2, A6) and PV (PV1).

3.3. *Multi-criteria analysis*

As described in Section 2.4, the MAUT method was applied to rank the technology alternatives in order to minimize embodied energy and investment costs and maximize energy savings. The overall utility of each alternative obtained for the Milan case study is shown in Table 8.

At the top of the ranking there is cavity wall insulation (CW group), a group of measures having low embodied energy and costs. The best options are those implementing a wood frame wall insulation system. In particular, the very best one is CW8, which corresponds to double stud, 37-cm cellulose insulation with advanced framing, thanks to its lower cost and embodied energy. After this group of measure there are building air tightness (INF3) and exterior insulation sheathing (EI), cheap options with low embodied energy, followed by lighting and efficient appliances (A6, L2, A8). Ceiling insulation (IC2B) and efficient heat recovery ventilators (MV3) show an intermediate position in the ranking, followed by high efficiency heating (H2), hot water (WH2) and cooling (C2) equipment. Cellar and ceiling insulations (CI3, CI4, IC3, IC4) have a low position in the ranking. Very efficient windows (W13, W14, W9) and concrete masonry walls (CM2, CM3) are among the last measures, mainly due to their high cost despite good energy reductions. Photovoltaic panels (PV1) are the very last option, due to their high embodied energy.

3.4. *Energy consumption of the optimized building*

A new building implementing the technologies with the highest rank for each category (e.g. walls, window, systems) was simulated. All CM (concrete masonry) measures were ignored, since the CW group (cavity frame wall with cellulose) had a better ranking. Similarly, all EI (exterior sheathing walls insulation) measures were ignored because they compete with CW and have a worse ranking than all the CW measures. In particular, the technology measures implemented in the new building, which will be indicated as "optimized building" hereafter, are the following (see Table 4 for option codes):

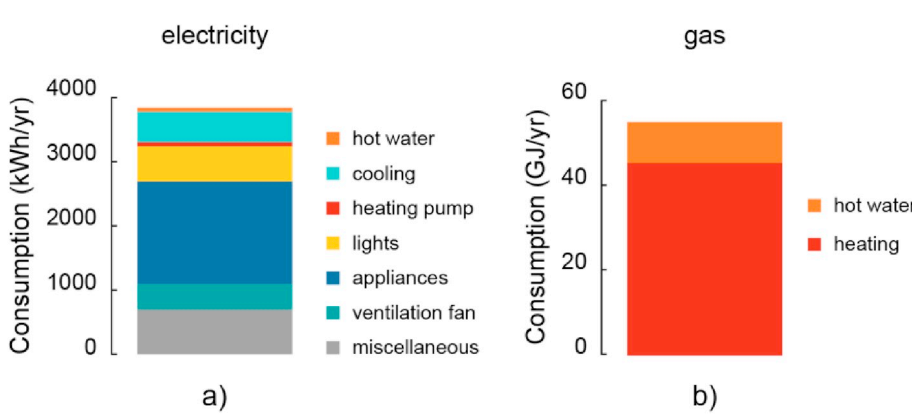

Fig. 6. Energy consumption of the baseline building: a) electricity; b) gas.

Table 8
Incremental investment cost, incremental embodied energy, electric and gas savings, and avoided CO_2 emissions with respect to the baseline case for the energy efficiency measures considered in this research (see Table 4 for option codes). Measures already included in the baseline building are not reported.

Option code	Incremental Cost (€)	Incremental Embodied energy (MJ)	Electric savings (kWh/year)	Gas savings (MJ/year)	Avoided CO_2 emissions (kg/year)	Overall utility (−)
A2	160	450	46	84	89	0.500
A5	150	850	252	802	551	0.529
A6	160	1,180	152	−348	182	0.504
A8	120	1,000	284	−105	438	0.522
L2	32	34	407	−844	502	0.532
WH2	419	4,000	0	1,382	250	0.493
MV2	21	500	0	1,245	225	0.513
MV3	41	1,000	29	1,340	289	0.515
H2	1,567	10,000	2	6,202	1,126	0.498
C2	1,092	3,300	211	760	340	0.479
IC2	282	1,799	11	812	165	0.498
IC3	564	3,599	14	1,023	208	0.487
IC4	999	6,997	14	1,192	238	0.466
IC2B	396	−4,333	14	992	202	0.511
IC3B	678	−3,930	14	1,234	246	0.503
IC4B	1,222	−3,173	17	1,477	295	0.487
CM2	3,424	23,172	76	11,445	2,194	0.475
CM3	1,589	64,883	102	15,527	2,974	0.487
CW1	−3,306	4,245	111	16,877	3,233	0.807
CW2	−3,306	4,245	111	16,919	3,241	0.808
CW3	−2,956	5,012	117	17,573	3,369	0.803
CW4	−2,423	5,779	120	18,069	3,464	0.790
CW5	−3,763	1,141	111	16,877	3,233	0.830
CW6	−3,763	1,141	111	16,919	3,241	0.830
CW7	−3,397	1,347	117	17,573	3,369	0.826
CW8	−3,397	1,553	120	18,069	3,464	0.832
EI	1,671	11,586	76	9,135	1,776	0.533
EI2	2,458	23,172	105	13,248	2,567	0.530
EI3	3,227	34,759	120	15,590	3,015	0.507
CI2	459	6,623	−15	844	129	0.478
CI3	927	13,246	−27	1,350	201	0.452
CI4	1,395	19,869	−36	1,719	253	0.424
W8	1,103	15,842	−24	2,964	498	0.459
W9	1,103	15,842	73	2,036	486	0.458
W13	4,109	20,968	−56	7,932	1,346	0.403
W14	4,109	20,968	96	5,580	1,164	0.391
INF2	182	1,450	2	3,059	557	0.527
INF3	378	3,000	2	5,179	941	0.542
PV1	8,409	97,680	3,528	0	5,677	0.360

- CW8
- INF3
- EI
- L2
- A6
- A8
- MV3
- IC2B
- A5
- A2
- H2
- WH2
- C2
- CI2
- W8
- PV1

Fig. 7 shows the simulated electricity (Fig. 7a) and gas consumption (Fig. 7b) of the optimized building. Electric consumption is equal to 2,436 kWh/year, which compared to the consumption of the baseline building (3,836 kWh/year) represents a 37% reduction obtained through the implementation of the most performing technological measures. When the contribution of PV panels is considered (3,573 kWh/year), the net energy balance results in a surplus of 1,137 kWh/year; electric energy savings become hence greater than 100%. Gas consumption in the optimized building was equal to 22.7 GJ/year, down from 56.6 GJ/year, a 60% reduction compared to the baseline building. Also in the optimized building, the main contributions in energy consumption are those related to the operation of appliances for electricity and to heating for gas (Fig. 7).

Overall, the optimized building achieves a 50% reduction in operational primary energy consumption compared with the baseline building, from 27,805 kWh/year (101.1 GJ/year) to 13,987 kWh/year (50.35 GJ/year), which decreases to 2,732 kWh/year (11.9 GJ/year), equivalent to a 90% reduction, when considering the contribution of PV panels (Fig. 8a and b). It should be noted that the baseline building was already fairly well insulated, but featured concrete masonry walls, the most common design solution in the city under investigation. However, the optimized building differed from the baseline in many ways, particularly for walls and the insulation materials chosen for the roof elements.

Firstly, although glass wool insulation is commonly used, its replacement with a cellulose insulation provides advantages, both with respect to embodied energy and cost. Thus, in all locations where its use is feasible, such as ceilings/roofs and walls, its use seems superior to other options. Secondly, although concrete masonry is popular, the results of the multi-criteria assessment also indicated cavity wall insulation with wood construction (and minimized thermal breaks) and cellulose insulations as potentially better performing solutions with lower embodied energy.

This type of wall has a lower cost, lower embodied energy, and yields similar performances. Exterior sheathing insulations (usually extruded polystyrene) also provide good performances, although a relatively high embodied energy prevents them from being ranked high in the multi-

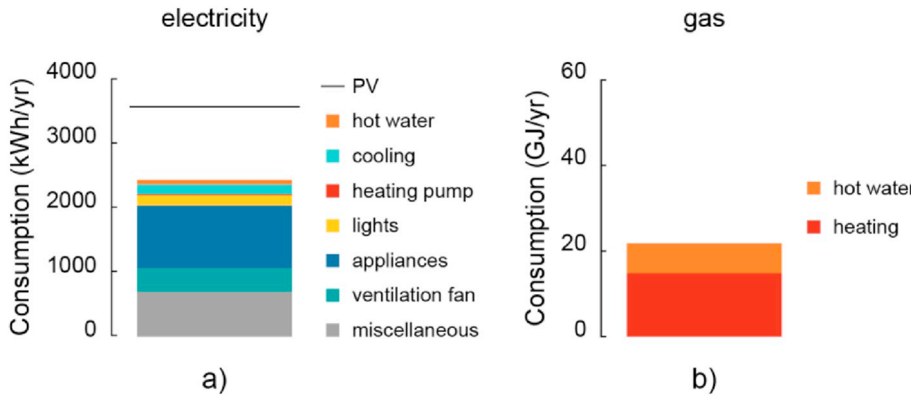

Fig. 7. Operational energy consumption of the optimized building: a) electricity; b) gas. Scale intentionally left as in Fig. 6 for comparison. The black horizontal line indicates the total electric production by PV panels.

criteria assessment. This indicates, however, that wood sheathing products with high insulation value (some of which have been developed for Passivhaus applications) are potentially desirable.

The performances of the baseline and the optimized building were compared also in terms of CO_2 emissions (Fig. 8c and d) and costs of utility bills (Fig. 8e and f). CO_2 emissions decrease from 6.0 t/year for the baseline building to 3.1 t/year in the optimized one, further decreasing to 0.6 t/year if the contribution of PV panels is taken into account. Fig. 8c and d details the origin of CO_2 emissions in the building. Most savings are obtained in relation to heating, going down from 2.7 t/year to 0.9 t/year of CO_2 emissions.

Utility bills decrease from 2,387 €/year (baseline building) to 1,365 €/year (optimized building), showing an important reduction both for electricity (−414 €/year) and gas (−608 €/year). Further savings (−1,058 €/year) can be achieved thanks to the electricity production ensured by the PV panels (Fig. 8e and f).

3.5. Discussion

The application of the multi-criteria approach led to the selection of energy efficiency measures allowing a 60% reduction of natural gas use for heating and hot water, and a >100% reduction of net electricity use. The impact on net source energy use drops from 27,805 kWh/year (100.1 GJ) to 2,732 kWh/year (11.9 GJ), representing a 90% reduction in operational primary energy. However, the embodied energy of the optimized building, which included PV, was twice as high as the baseline building at the time of construction (baseline 37,075 kWh vs optimized 75,239 kWh). This difference is in line with the literature on low energy and NZEBs covered by Chastas [21]. Although the optimized building in our case starts off with higher embodied energy, it recovers this over time reducing its operational energy.

Considering that LCA estimates for embodied energy may underestimate in the range from 40% to 70%, we re-evaluated our range of savings when operational and embodied energy are taken into account with this allowance.

These reductions amounted to a 55–67% reduction (from 190 to 215 MWh) in total energy over a ten year period after construction. Evaluated over a 30-year period, the reductions were 77–82%. We also investigated differences in values found for insulation systems, wood and concrete. These numbers reduced the embodied energy advantages of wood versus concrete block construction. We found that the newer values increased the embodied energy by 23% and the optimized building by 27%. This reduced the total energy savings over 10-year period to 47–62%. Savings over a 30-year period were then 73–80%. When evaluated over a 50-year period, the total energy savings would be even more favourable to our evaluation, even assuming our process-based estimates remain biased low.

The authors also note that much of the loss in embodied energy advantage of wood against concrete block construction in our re-evaluation stems from embodied energy intensive fibreboard. This is used as sheathing in wood construction. Also, for cellulose insulation, increasing the use of recycled wood products could be important to re-establishing the large embodied advantage initially seen.

The selection of the criteria used in the multi-criteria analysis has been based on their relevance and the availability of relevant data and information. The establishment of the hierarchy of criteria and their weighting are important steps of the method, with relevant implications on the results. Both environmental and economic criteria should be taken into account when designing a new building. With respect to environmental criteria, we considered both embodied as well as operational energy in the optimization. While the assessment of operational energy is a well-established research field, with a vast body of literature reporting rigorous data produced by means of sound methodologies, research on embodied energy is a relatively new field. Methodologies are often inconsistent and poorly described, causing scarce research repeatability and data quality, and consequently limiting the ability to extend results beyond their original context.

In addition to those we considered in our analysis, other criteria can play a role in the decision process. For example, the inclusion of social criteria, such as health and safety, job creation, occupant behaviour, wellbeing or satisfaction, can have important implications in the choice. Technical criteria, such as the feasibility of technology integration, the maturity and reliability of technologies could also be investigated. The inclusion of additional criteria in the analysis may impact the relative priority given to the different aspects of the problem and affect the ranking of the candidate measures. However, the complexity of collecting data and information related to these criteria prevent their inclusion and represents an open research challenge.

3.6. Sensitivity analysis

The ranking of the different technology measures reflects the desirability of the alternatives with respect to the considered decision criteria. In turn, the relative importance of the different criteria is reflected by the values assigned to the associated weights. The ternary plot in Fig. 9 shows the very best performing technology measure as a function of the weights assigned to energy savings (w_{ES}), embodied energy (w_{EE}) and costs (w_C).

If energy savings are given low to moderate relevance (w_{ES}<0.7), cavity wall insulation measures (CW6 and CW8) are the best choice. In particular, CW6 ranks first when higher importance is given to minimizing embodied energy, while CW8 is preferred when higher priority is given to minimizing costs. On the other hand, if energy savings are given high relevance (w_{ES}>0.7) then the preferred option becomes the installation of PV panels. Finally, if the highest priority is given to the minimization of embodied energy (w_{EE}>0.9), the best choice becomes

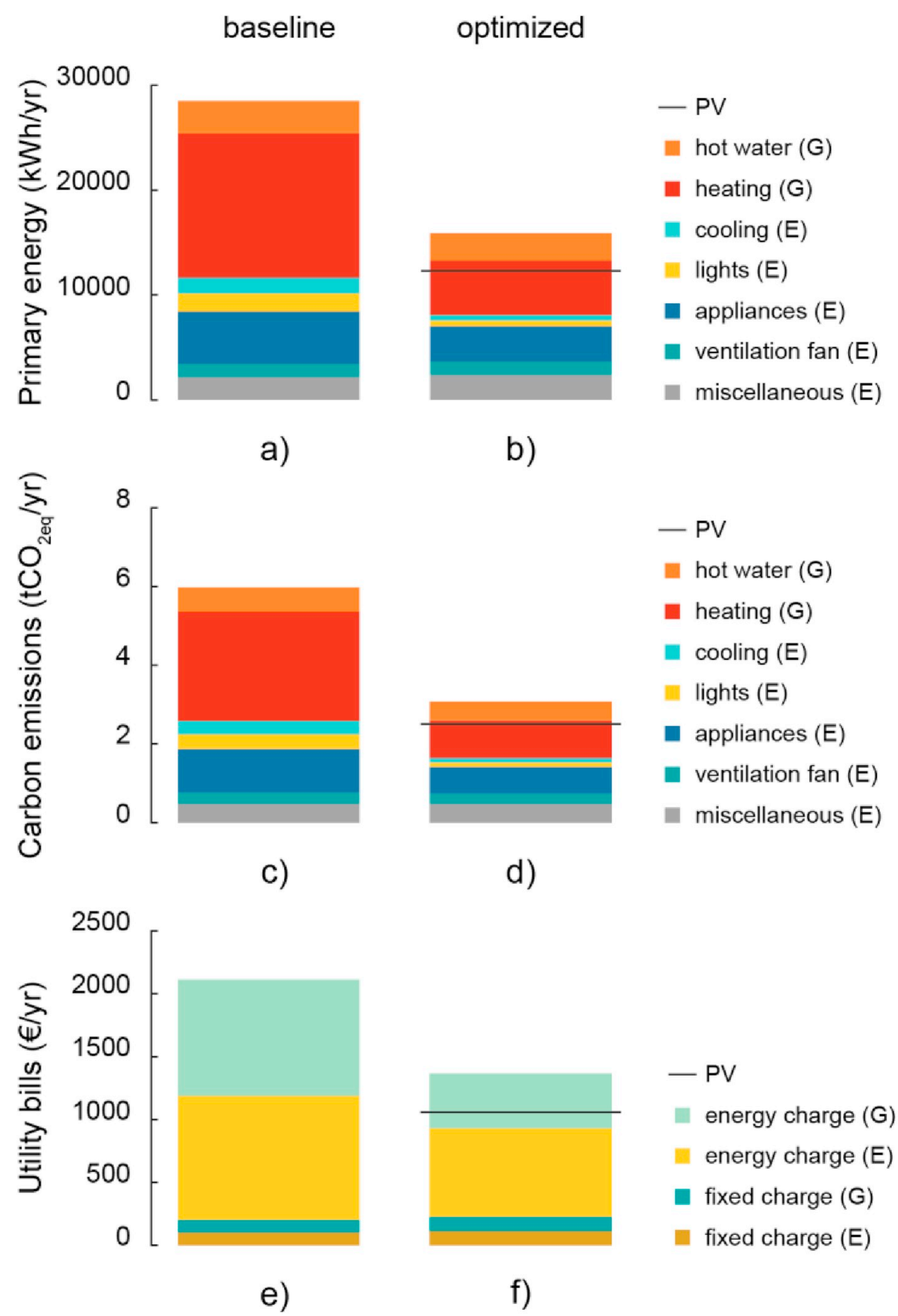

Fig. 8. Primary energy use, CO_2 emissions and utility bills of the baseline (a,c,e) and optimized (b,d,f) building. The black horizontal lines indicate energy (b), CO_2 (d) and monetary (f) savings ensured by the electric production of PV panels. G: gas; E: electricity.

the substitution of the fibreglass ceiling with a 35-mm cellulose ceiling (IC2B).

3.7. Comparison with previous research

The performances of the building optimized through the multi-criteria framework can be compared with those of a building optimized in a previous work by Ref. [44], whose aim was to maximize energy savings at the lowest investment cost. Both studies considered the same building prototype and the same technology measures, and computations were performed with the same software. Starting from the same baseline, D'Agostino et al. [44] proposed the implementation of energy efficiency measures leading to an annual consumption of 2,424 kWh/year of electricity and 16.0 GJ/year of gas, allowing a net saving of primary energy equal to 95%. The building optimized through the multi-criteria approach achieves a slightly lower improvement (88%) with respect to the baseline operational energy.

It is interesting also to contrast the ranking of the alternative measures obtained in the two studies (compare Table 9 in Ref. [44] with Table 8 in this paper). The main difference in the methodology of the two papers is the inclusion of embodied energy in the set of attributes on which the ranking is based. When considering only costs and energy savings, efficient appliances and lighting are the best performing measures, followed by wall insulation and high-performance windows. Mechanical ventilation and heating measures are at the bottom of the ranking. In this research, wall insulation measures are the first of the

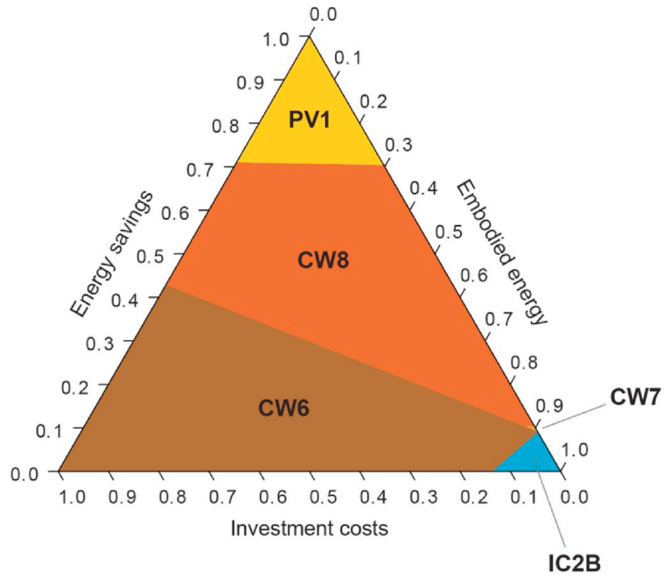

Fig. 9. Best performing energy efficiency measures as a function of the weights assigned to energy savings (w_{ES}), embodied energy (w_{EE}) and costs (w_C). See Table 4 for option codes.

ranking, while windows are the last. Enhancements to mechanical ventilation and heating are mid-way along the ranking, after measures such as improving lighting and air leakage. The PV system is the very last measure in this study, due to its high embodied energy.

This research points out that the way in which energy efficiency is pursued should account for embodied energy. In this respect, results confirm the importance of efficient appliances and lighting, showing how their inclusion can result in different solutions when combined with high-efficiency technologies and renewable energy production.

In comparing results including embodied energy, we reached conclusions similar to other investigations examining low-energy buildings. While finding appropriate efficiency measures can be successful for insulation elements considering operational energy and embodied energy [30], other parts of the building remain more difficult. For instance, although we found wood construction with cellulose insulation potentially superior from an embodied energy perspective to concrete block construction, the advantages can be reduced by exterior fibreboard sheathing. This is commonly used construction element for wood walls, but with a high embodied energy content.

Large amounts of embodied energy can be also found in energy efficient equipment, advanced appliances and thicker insulations. As example, Thormark [31] also found that low energy buildings typically have higher levels of embodied energy—often such that embodied energy can be 45% of total life-cycle energy. Others have also documented how NZEBs face an embodied energy challenge since the PV element often considerably increases embodied energy. While the operational savings from such systems is large, the embodied energy remains considerable.

4. Conclusions

Building technology offers large potential to improve the energy performances of new and existing buildings. However, the choice of the technologies to be implemented is challenging, and the selection process often rests only on a single criterion, usually the economic one. This paper proposes a multi-criteria approach relying on multi-attribute utility theory (MAUT) to evaluate energy efficiency alternatives and rank them according to a set of selected criteria. The method allows a comparative assessment of alternative technology measures with the aim to improve electricity and gas savings, and reduce embodied energy and investment costs.

The paper demonstrates the feasibility of the proposed method to integrate a range of information representing the impacts of design choices from multiple perspectives and to support the selection process. Our work provides a case study of energy-related decision making for a new residential building in Milan to illustrate the proposed multi-criteria analysis method. We considered technologies related to envelope, appliances and system, but the method may be applied to drive the decision process for a specific building part only, such as the envelope.

A reduction of 90% in operational primary energy was achieved from the baseline to the optimized building. Including embodied energy, the reduction dropped to 55–67% in total energy over a 10-year period after construction, and 77–82% over a 30-year period. Uncertainty regarding embodied energy factors was shown to potentially reduce this advantage to 73–80%.

The inclusion of embodied energy in the analysis is therefore crucial, as current strategies to reduce operational energy often increase substantially the amount of energy embodied into buildings, partially nullifying the benefits coming from improved thermal efficiency. Examples are metal or concrete overhangs in the South façade to reduce heat gain, extensive use of thermal insulation to reduce heat transfer through the envelope, and multi-glazed efficient windows.

The MAUT method was used to rank the relative performances of the analysed technologies. These can vary significantly depending on climate, materials, and local conditions. Although wool insulation is common in the city under investigation, the method indicates cavity wall insulation with wood construction and cellulose insulation as the most performing technology, a choice confirmed by the sensitivity analysis. This wall has a lower cost and embodied energy, and yields similar performances. In general, locally available, recyclable, and renewable technologies should be preferred while selecting the measures to be implemented at the design stage. Selected technologies for Milan show a combination of good insulation, building airtightness as well as efficient appliances, and lighting. PV is selected as the last measure to be implemented due to their high impact in terms of embodied energy, but can provide a substantial contribution to the energy balance of the building and to decreasing utility bills.

In future research, indicators for embodied carbon in addition to embodied energy are recommended. This is because embodied carbon may better capture the related emissions associated with the construction materials and processes being evaluated. There is rationale for this conservative approach as the embodied energy impact happens immediately upon construction. Little can be done after the energy is consumed with construction and the carbon emitted. This is contrary to the operational energy of the building which occurs over many years.

The method can support stakeholders in the formulation of the problem, to investigate opportunities and limits of adopting specific technologies, as well as to facilitate the screening of unsuitable choices. A large-scale diffusion of affordable and easy to implement decision-making methods at the design stage is therefore desirable. Results can be also useful for the development of future energy policies in the light of the European Roadmap 2050 of reducing greenhouse gas emissions by at least 80% by 2050 compared to 1990 levels.

Data availability

Delia D'Agostino, Danny Parker, Paco Melià, Environmental and economic data on energy efficiency measures for residential buildings, Data in Brief, submitted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100412.

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