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Research article

An application of the PROMETHEE II method for the comparison of energy requalification strategies to design Post-Carbon Cities

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Abstract: A resilient, diversified, and efficient energy system, comprising multiple energy carriers and high-efficiency infrastructure, is the way to decarbonise the European economy in line with the Paris Agreement, the UN 2030 Agenda for Sustainable Development, and the various recovery plans after the COVID-19 pandemic period. To achieve these goals, a key role is played by the private construction sector, which can reduce economic and environmental impacts and accelerate the green transition. Nevertheless, while traditionally decision-making problems in large urban transformations were supported by economic assessment based on Life Cycle Thinking and Cost-Benefit Analysis (CBA) approaches, these are now obsolete. Indeed, the sustainable neighbourhood paradigm requires the assessment of different aspects, considering both economic and extra-economic criteria, as well as different points of view, involving all stakeholders. In this context, the paper proposes a multi-stage assessment procedure that first investigates the energy performance, through a dynamic simulation model, and then the socio-economic performance of regeneration operations at the neighbourhood scale, through a Multi-Criteria Decision Analysis (MCDA). The model based on the proposed Preference Ranking Organisation Method for Enrichment Evaluations II (PROMETHEE II) aims to support local decision makers (DMs) in choosing which retrofit operations to implement and finance. The methodology was applied to a real-world case study in Turin (Italy), where various sustainable measures were ranked using multiple criteria to determine the best transformation scenario.

Keywords: Post-carbon building (PCB); Multi-Criteria Decision Analysis (MCDA); co-benefit; dynamic energy simulation; decision support system (DSS); energy policy; cost-optimal analysis; DesignBuilder; EnergyPLAN; Preference Ranking Organization Method for Enrichment Evaluations II (PROMETHEE II)

1. Introduction

The importance of reducing the impact of man on the planet was underlined internationally by the introduction of the Sustainable Development Goals (SDGs). Particular attention was paid to the creation of healthy and inclusive cities and communities (SDG 11) and to the access to convenient and clean energy for all (SDG 7) through actions that limit climate change (SDG 13) [1]. To reduce energy exploitation and air pollution, European Union issued dispositions about energy saving and CO_2 emissions control. Concerning the building sector, the recast of the European Directive EPBD (Energy Performance of Buildings Directive) has introduced the concept of nearly Zero Energy Building (NZEB) as a building with very high energy performances and able to cover the residual energy demand with renewable energy sources (RES) installed on-site or nearby the building [2,3]. In 2019, the European Climate Agreement, also known as the European Green Deal, was one of the most important worldwide initiatives in terms of combating global warming and achieving carbon neutrality [4]. With this agreement, the European Commission offered a highly precise program of action, with financing sources for each action and project already identified, with a total budget of more than EUR 1 trillion in investments to be realized over the following 10 years [5]. Envisioning only public investment would be insufficient to achieve these goals. The private sector, therefore, represents a strong point for the activation of the necessary wave of energy renovation. In line with the European Green Deal, the latest proposal to recast the Energy Performance of Buildings Directive highlighted the importance of EEM in facilitating the energy transition of the construction sector by acting on the most energy-intensive stock [6]. Furthermore, climate change policy, increased energy efficiency, and investment in renewables are critical in resolving the volatility of energy costs that Europe has seen throughout the recovery phase following the COVID-19 pandemic [7]. To cope with the post-COVID-19 economic crisis, the European Commission has set up a resilience plan called Next Generation EU (NGEU) with a long-term financing plan of EUR 71 billion. Italy is the EU country that has benefited the most from NGEU funds. A large part of these funds will be spent to improve the country green transition and has been included in the Italian National Recovery and Resilience Plan (NPRR) programme. To achieve progressive decarbonisation, interventions have been planned to significantly increase the use of RES, through direct investment and the simplification of authorisation procedures for renewables, and the reduction of energy demand.

In this perspective, designing and retrofitting buildings towards Post Carbon Buildings (PCB) could be the way to reach new goals. PCB is represented by a building where the minimum energy performance is in line with national standard requirements but a great reduction of carbon emissions is expected [8]. However, specific researchers demonstrate that considering each building separately and analysing the problem at the single house level is not enough to comply with international agreements recommendations and enlarging the scale to the city represents the only feasible solution to solve the problem [9,10]. For this reason, the EU promotes the concept of Post-Carbon City (PCC). The PPC is defined as a city with low-energy and low-emission buildings, smart heating and cooling systems, renewable and shared resources, electric and hybrid cars, and sustainable public transportation [11]. The focus on the district scale and urban policies entails the inclusion of aspects not strictly related to energy exploitation, but referred to social and economic domains, such as the improvement in local energy security, the people's opinion upon different energy solutions [12–14]. Thinking about the development of policies and plans, the district scale is a convenient dimension for assessing and integrating sustainability into different urban sectors. Indeed, districts are compact and large enough to have an impact on the city and society and concentrate resources and infrastructure to improve efficiency. Moreover, districts are small parts of urban areas, where most of the current and future energy will be concentrated, and which have all the inherent characteristics of the whole urban system with high population density and representative types of buildings and infrastructure. Considering a larger scale than buildings can have a huge impact on different aspects of citizens' daily lives and shows how much benefit a society can gain from a new sustainable point of view. Moreover, it is more convenient than the building scale because the interactions between buildings with different functions and different areas of the city is more complex and can give a more efficient result. However, given the problem complexity, an integrated multi-step approach that allows for consideration of all issues that arise during the day is required. First, the energy performance of various transformation scenarios must be evaluated using simulation tools that provide not only indications of energy performance, but also other outputs that serve as cues for the formulation of alternative evaluation criteria. Following that, the results of the energy simulation must be validated using a more complex evaluation framework capable of including the problem socioeconomic sphere.

1.1. Research background

The most common approaches used in the scientific literature in the domain of energy decision problems are Life Thinking, such as Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and Cost-Benefit Analysis (CBA). Multi-Criteria Decision Analysis (MCDA) techniques have been widely used in this field over the last decade [15–17]. These evaluation tools can help with decision making in a variety of ways while taking into account various assessment principles. When dealing with complex decision-making problems, MCDA allows to combine quantitative and qualitative values. Intangible factors are frequently difficult to quantify in traditional life cycle thinking approach and CBA-based models. Moreover, MCDA is useful in complex decision-making because the methods allow for a comparative assessment of alternative projects or different measures by considering several criteria at the same time and are designed to assist DMs in integrating stakeholders' perspectives. In the context of MCDA methods, the outranking theory aims to construct a superiority relation that represents the DM's preferences given the information available to him. This theory compares two alternatives to see if "alternative *a* is at least as good as alternative *b*" [18]. The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method proposed by Brans [19] was one of the most widely used MCDA techniques, belonging to the family of outranking methods. In detail, PROMETHEE II uses the principle of overcoming to classify alternatives, combined with ease of use and reduced complexity [20–24]. PROMETHEE II also compares pairs of alternatives to classify them based on a series of criteria. But it introduces the functions of preference to measure the level of difference between the alternatives in determining the classification order and not just preferences. The method was selected because it does not necessitate prior normalization of the quantitative data of the evaluation items, which can be used in their original units. PROMETHEE II, as an outranking method, is immune from the risk of criteria offsetting. In addition, the decisions made by each stakeholder can be easily integrated through criteria weighting, preference function definition, and associated thresholds. Last but not least, the use of Visual PROMETHEE software speeds up the implementation process and allows for the visualization of the results [25].

The growing demand for multidimensional decision-making models in the energy sector has prompted energy planners to experiment with MCDA-based assessment models more frequently. In the energy context, MCDA-based models assist planners in dealing with issues that traditional models do not address. Various evaluation criteria are used in planning and selecting the best alternative from a set of alternatives. Typical questions posed in energy decision-making problems include determining the best location to build new energy conversion or transmission facilities (location issues), determining the best type of energy resource or conversion technology to use (alternative solutions or energy policies), and determining how to combine different energy sources and technologies to meet present and future energy needs (combination of alternatives). The MCDA evaluation approach is frequently used to evaluate large-scale, national and international energy interventions. The optimal location of energy generation interventions is frequently supported by analyses that consider not only technical but also economic, environmental, and social factors [26,27]. Dimitra [28], for example, applied several multicriteria evaluation approaches, including PROMETHEE II, to the problem of prioritizing and ranking the most appropriate locations for installing solar photovoltaic parks on the Greek island of Rhodes. PROMETHEE II applications have compared energy scenarios and focused on the ranking and evaluation of energy generation or exploitation alternatives at the regional and national levels. Madlener et al. considered five renewable energy scenarios for Austria [29]. The methodology investigates potential future energy pathways by combining scenario development, multi-criteria evaluation based on PROMETHEE II, and a national-level participatory process with stakeholders and energy experts [30]. Few cases have studied the potential of neighborhood renovation to promote energy efficiency in the building sector at district scale [31,32]. Dirutigliano et al. [33] investigated the role of the building sector in driving urban energy consumption and reducing greenhouse gas emissions. The authors ordered through PROMETHEE II five retrofit alternatives for a district in Turin (Piedmont Region, Italy). However, the criteria introduced in the model were purely economic in nature, not providing a comprehensive assessment of performance that included social aspects.

The combination of PROMETHEE techniques with energy simulation models is another noteworthy finding from the literature review. Some authors emphasize the importance of developing integrated decision support models that incorporate investment energy performance as well as environmental, economic, and social performance. Integration with dynamic energy simulation models is critical for achieving the most reliable assessment of not only energy performance, but also comfort and LCC (investment, consumption, and maintenance) performance [34]. Vujošević and Popović [35] integrate EnergyPlus simulation software results into PROMETHEE to compare hotels in Belgrade based on a set of specific criteria. Setyantho et al. [36] rank different Semi-transparent photovoltaic (STPV) window alternatives based on different window-to-wall ratios, building orientations, and module types considering thermal, daylight, energy, and life-cycle cost performance criteria in PROMETHEE II. Pinto et al. [37] propose using PROMETHEE II to integrate the results of EnergyPlus energy simulations to order different shading solutions for an office building. Dell'Anna et al. [24] propose a multi-criteria model on PROMETHEE II based on simulated energy performance data by Barthelmes et al. [38] to evaluate alternative scenarios for the realization of a NZEB.

1.2. Paper contribution

When it comes to district-related energy investment decisions, there is no doubt that energy simulation tools are effective tools for assessing energy, environmental, and social performance. However, their application to decision support is typically limited to analyzing a single criterion at a time, with no attempt made to identify the solution that represents the best compromise between several multidomain criteria. PROMETHEE II method can be concluded to be a useful tool for assisting complex decision-making processes, particularly on a large scale. The integration of the MCDA method with modeling and energy simulation tools can help DMs identify the best alternative among the options available by calculating quantitative and qualitative criteria.

Given the complexity of the PCC, which involves several urban sectors, we concentrated solely on the construction sector and its contribution to meeting the target. The study aims to investigate the potential of the existing buildings to reach the new European goals in energy and environmental domains proposing a decision-making framework based on multi-step methodological approach, capable of coupling MCDA with energy modelling and simulation to rank different alternative retrofit scenarios at district scale. In detail, we explored the use of energy simulations based on DesignBuilder and EnergyPLAN with the PROMETHEE II method (Preference Ranking Organization Method for Enrichment Evaluations II, [19–21]). The multi-stage methodology was tested on a real-world case study of a district in Turin to address local planning on an urban scale. Starting with existing buildings, different minimum energy efficiency and carbon emission reduction requirements are combined to create alternative energy requalification strategies for achieving the PCB target first by combining DesignBuilder and the cost-optimal methodology. Once the best PCB solution has been identified, it is extended to the district area, and retrofit alternatives are evaluated integrating EnergyPLAN results in PROMETHEE II. Experts in energy and economics from Italy and Denmark are assisting in the development of weighting criteria, preference functions, and appropriate thresholds to validate the results' stability. Finally, the methodology aimed to provide guidelines and recommendations to local governments for the selected case study.

After the introduction, the paper is structured as follows; in the following section, an overview of the methodology proposed in this study is presented. In Section 3, the methodology is validated through an application to a real case study. Research results are presented in Section 4. In Section 5, conclusions follow.

2. Methods

The integration of MCDA methods with energy modelling and simulation tools can be useful to support the identification of the best alternative among the options available to DMs. Focusing on investment decisions related to the evaluation of alternative scenarios, there is no doubt that energy simulation tools are powerful tools for assessing the performance of the different sectors involved in terms of resources used and environmental impacts. However, their use to support decision-making is usually limited to the analysis of a single criterion, without identifying the solution that represents the best trade-off between different multi-domain criteria. For this purpose, energy simulation tools can be advantageously coupled with MCDA methods. In line with this, the work aims at developing a multi-step methodological proposal to support decision-makers (DMs) in the ranking of alternative scenarios for neighbourhood regeneration by considering and integrating a wide set of energy, environmental, economic, and social criteria. In particular, the methodological proposal combines dynamic energy simulations based on DesignBuilder and EnergyPLAN, to estimate the energy and environmental performance at the scale of single building and district respectively, and the PROMETHEE II method, to evaluate large scale retrofit scenarios according to indicators of different nature.

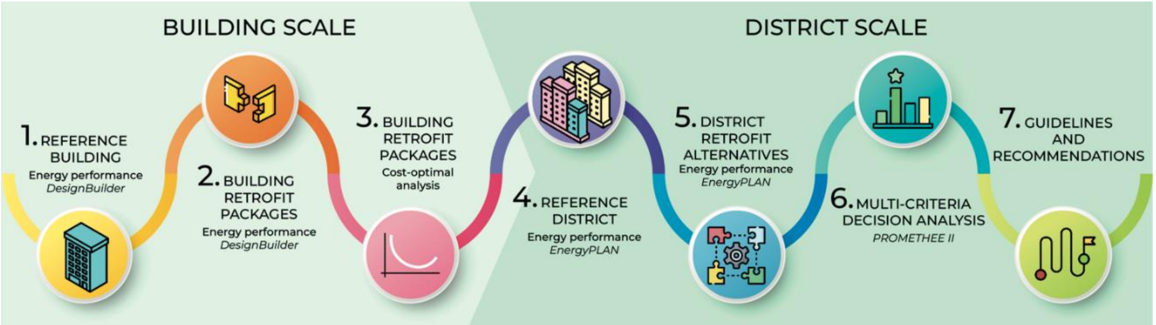

Figure 1. Methodological framework.

In detail, the research starts at the building level, studying the Reference Building (RB) energy performance and carbon emissions (Step 1), testing different retrofit solutions focusing on their environmental impact through energy simulation based on DesignBuilder (Step 2). Then, retrofit solutions are compared with their global cost (Step 3) to find the best balance (Figure 1).

To optimize the energy system, decrease both costs and carbon emissions, the research is enlarged to a district scale. First, the energy performance of the district in its current state (i.e., without any retrofit solution) must be assessed by means of dynamic energy simulations using the EnergyPLAN software (Step 4). The next step foresees that the different district retrofit alternatives are tested first from an energy point of view (Step 5), and then from an environmental, social, technical, and economic point of view, using a multi-criteria decision analysis based on PROMETHEE II, identifying the most suitable solution considering the multi-domain impacts (Step 6). Proper sensitivity analyses are developed to estimate the stability of the final ranking and to determine its changes in accordance with the variation of the relative importance of the considered criteria; specifically, weighting coefficients are changed by referring to expert opinions coming from different EU country: Italy and Denmark. This step helps to validate the stability of the results by weighting the criteria according to the energy and emission reduction policies implemented in the two countries, transposed differently. Finally, the methodology aims to provide guidelines and recommendations to local authorities (Step 7).

2.1. Energy modelling

Firstly, DesignBuilder (version 5) dynamic simulation software is used at the building level to model and assess both Reference Building and the related retrofit scenarios. DesignBuilder provides a range of environmental performance data such as energy consumption, carbon emissions, comfort conditions, daylight illuminance, HVAC (Heating, Ventilation and Air Conditioning) system components size.

For this research the software is mainly used to: estimate thermal load and energy consumption for both heating and cooling operations, evaluate different alternative solutions for the building envelope, evaluate thermal comfort conditions setting up the environmental required features, evaluate electricity consumption derived by appliances and lighting, evaluate the energy production derived by solar thermal and photovoltaic panels installed on the building rooftop. At the end of the simulation consumptions of different energy carriers are summed together using primary energy conversion factors to compare global Energy Performance Indexes (EP_{gl}) and quantities of carbon equivalent emissions of different building retrofit measures.

Proving that the resulting cost-optimal scenario has a low environmental impact, greenhouse gas emissions could be even reduced with new energy efficiency measures referred to the whole district. The Reference District (RD) and District alternatives are modelled with EnergyPLAN tool [39,40]. EnergyPLAN is a software developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, in Denmark in 1999 and it is still expanded continuously until now. The main purpose of this tool is to analyse the energy, environmental and economic impact of various energy strategies. The EnergyPLAN is an input/output energy system analysis model, it is deterministic and aims to identify optimal energy system designs and operation strategies using hourly simulations over the one-year period. It is usually utilized at the national level to identify the best solution for national grids, but it could be possible to employ it also at the district level to analyse the best solution for the local energy smart grid. Moreover, the model involves hourly balances of district heating and cooling as well as electricity and gas grid, also including a wide range of cross-sector technologies such as heat pumps, Combined Heat and Power plants (CHP), electric vehicles, etc.

Entering data related to energy demand obtained with DesignBuilder, EnergyPLAN gives specific consumptions in terms of fuels that can be summed by applying energy conversion factors to obtain the global Energy Performance Index (EP_{gl}) of the whole districts and relative carbon footprints.

2.2. PROMETHEE II technique

The PROMETHEE II (Preference Ranking Organization Method for Enrichment of Evaluations) method was used to solve the decision problem. Brans (1986) proposed PROMETHEE, which was later expanded by Brans et al. (1984; 1986) and Brans and Vincke (1985). The PROMETHEE is an outranking method that ranks comparable alternatives based on a pair-wise comparison of opposing criteria. The PROMETHEE II method is the most widely used of the PROMETHEE methods family because it helps the DM find a fully ranked vector of alternatives. The method necessitates two key pieces of information. The first examines the level of importance assigned to each criterion by the DM. The second piece of information indicates how much one alternative is preferred over another based on each criterion. For each criterion, a preference function is defined, which translates the difference in ratings obtained by two alternatives into a degree of preference between 0 and 1. Let us consider a set of alternatives $A = \{a_1 \dots a_2\}$ and a set of criteria $F = \{g_1 \dots g_q\}$. We suppose in the following that these g criteria have to be maximized. For each criterion g_k, the DM evaluates the preference of an alternative a_i over an alternative a_j by measuring the difference d_k of their evaluation on g_k

$$d_k(a_i, a_j) = g_k(a_i) - g_k(a_j) \tag{1}$$

This pairwise comparison allows the decision-making to quantify how alternative a_i performs on g_k compared to alternative a_j. Then, we use a preference function P_k to transform this value into a preference degree. Brans and Vincke [41] defined six types of preference functions; the usual criterion, the quasi criterion (U-shape), the criterion with linear preference (V-shape), the level criterion, the linear preference and indifference area, and the Gaussian criterion [41]. Depending on the shape of the preference function, one or two parameters that must be defined; these are known as indifference thresholds q_k and preference thresholds p_k.

$$P_k(a_i, a_j) = P_k[d_k(a_i, a_j)] \tag{2}$$

$$0 \leq P_k(a_i, a_j) \leq 1 \tag{3}$$

To quantify the global preference of a_i over a_j, we defined the notion of preference index $\pi(a_i, a_j)$. It allows to aggregate all the unicriterion preference $P_k(a_i, a_j)$ by considering the weights w_k associated to each criterion.

$$\pi(a_i, a_j) = \sum_{k=!}^{q} P_k[d_k(a_i, a_j)] \cdot w_k \tag{4}$$

$$w_k \geq 0 \text{ and } \sum_{k=1}^{q} w_k = 1 \tag{5}$$

The PROMETHEE methods' final step is based on calculating the outranking flow scores of each action. It allows the DM to quantify on average how an action a_i is preferred to all the remaining actions x of the set A and how these actions x are preferred to a_i. These two notions are respectively represented by the positive flow score Φ^+ (3)

$$\Phi^+(\mathrm{a}) = \frac{1}{\mathrm{n}-1} \sum_{X \in \mathrm{A}} \pi(a_i, x) \tag{6}$$

and negative outranking flow, calculated by (4);

$$\Phi^-(\mathrm{a}) = \frac{1}{\mathrm{n}-1} \sum_{X \in \mathrm{A}} \pi(x, a_i). \tag{7}$$

The positive and negative flow scores could be combined into the outranking net flow score Φ which is used in PROMETHEE II. Comparison of the outranking flows and definition of the complete ranking of the alternatives as follows (5);

$$\Phi(a_i) = \Phi^+(a_i) - \Phi^-(a_i) \quad . \tag{8}$$

The result of the PROMETHEE II method is the net outranking flow for each alternative and the complete ranking.

As stated before, criteria selected for the elaboration of the MCDA couldn't have the equal importance for the DM. From the different weighing techniques, the revised Simos' method (Simos-Roy-Figueira-SRF) is used to collect importance of criteria [42]. SRF method is based on the sorting a set of cards that represent the criteria from the most important to the least important. The card-play technique gave the opportunity to obtain indirectly valuable information through numerical values, transforming the ranking into importance weightings. The respondents had the possibility to differentiate subsequent criteria adding blank cards between them; if 1 blank card is introduced between 2 successive cards, the difference between the criteria is at least twice the value. The revised method introduced the z value. The analyst asked to DM how many times the most important criterion in considered more important that the least important in the ranking. From this data, the normalized weights are calculated taking in consideration criteria and blank cards positions.

3. Application

3.1. The case study

The case study analysed is a typical Reference Building representative of the existing building settled in the North of Italy (Turin) and built between 1991 and 2005 (Figures 2 and 3). It is a six-storey apartment block building (34 building units) with an unconditioned basement. It consists of a typical prebuilt concrete structure with a low level of insulation, so that the energy performances cannot comply with the actual Italian minimum energy performance requirements. The HVAC system is constituted by two gas-fired standard boilers with very low efficiency providing space heating and hot water production.

Figure 2. Photograph of the south-east elevation of the Reference Building.

Figure 3. Architectural drawing of the plan (on the left) and section (on the right) of the Reference Building.

RB energy performances are firstly tested with a DesignBuilder dynamic simulation, demonstrating the need of retrofit measures to improve its efficiency (Figure 4). The RB annual primary energy consumption is equal to 116.85 kWh/(m^{2}y) (considering space heating and cooling, ventilation and DHW as final uses) and the RB emits 40.53 $kg_{CO2}/(m^2y)$ annually, considering all building energy uses (Table 1).

Table 1. Reference Building dimension.

Building characteristic	Measurement
Gross volume	8,912.43 m^3
Heated volume	6,529.06 m^3
Gross floor area	2,970.81 m^2
Heated area	2,418.17 m^2
Primary energy consumption	116.85 $kWh/(m^2y)$
Annual CO_2 emissions	40.53 $kg_{CO2}/(m^2y)$

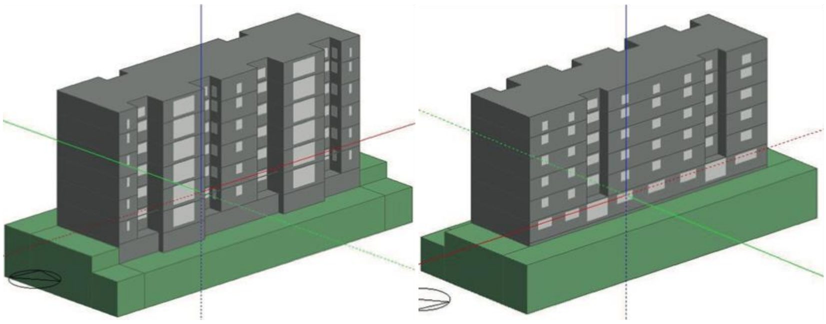

Figure 4. DesignBuilder 3D model of the Reference Building, on the left the south-east façade, on the right the north-west façade.

3.2. Energy efficiency measures and Cost-optimal application

Energy efficiency measures regarding building envelope and various configurations of heating and cooling systems are combined to create retrofit scenarios for the improvement of RB energy performances (Table 2). Retrofit scenarios also include the installation of technologies for the exploitation of RES and in some cases the installation of Controlled Mechanical Ventilation (CMV) system with heat recovery designed to deeply reduce energy ventilation losses.

Levels of building envelope retrofit were studied in compliance with Italian standards requirements. The first two levels are referred to the *Decreto Interministeriale* 26th June 2015, that presents which are the minimum energy performance values in force till 2015 (Level 1) and till 2021 (Level 2). More stringent thermal transmittance values are set in the municipality of Turin's *Allegato energetico ambientale* No. 2010-08963/38, where two other performance levels are indicated; in this research, the second, more stringent level of requirements is considered and referred to as Level 3. Finally, another envelope configuration, known as Level 4, is set, which combines the previous two in the following way: it sets the Level 3 thermal transmittance levels for the opaque envelope and the Level 2 thermal transmittance value for the glazing. A further step towards achieving the PCB target is the combination of the envelope measures with new systems, with higher performance and the possibility to be integrated with RES. Here again, three different configurations were designed, with different system layouts. The first (System Configuration A) consists of the installation of a condensing gas boiler; the generator is connected to the existing radiators in the flats, equipped with thermostatic valves to regulate the internal temperatures of each zone. System configuration A involves the installation of multi-splits for cooling the rooms (P1A, P2A, P3A, P4A, P3AMV). The second system configuration (Configuration B) consists of connecting the building system to the Turin district heating network, combined with radiant floors installed in the heated zones. In this configuration, cooling is provided by an air-water chiller (P1B, P2B, P3B, P4B, P3BMV). Configuration C involves an air-water heat pump capable of providing both heating and cooling, combined with the integration of radiant floors with a control device in each zone (P1C, P2C, P3C, P4C, P3CMV).

In addition, the potential energy saving due to the installation of a CVM system is tested in packages with the highest energy performances, to design, between affordable retrofit solutions, possible advanced hypothesis (P3AMV, P3BMV, P3CMV). Installing CMV system in the dwellings allows the decreasing of heating consumptions thanks to the heat recovery and a better control of indoor thermal comfort.

Finally, depending on systems configurations, different surface of panels for exploiting RES are installed on the building roof. RES consist in Solar Thermal Panels (STP) and Photovoltaic Panels (PVP) determined following the Italian Standard in force.

Table 2. Matrix of retrofit packages.

		System configuration					
		A Gas fired condensing boiler, Multisplit, RES		B District heating, Chiller, Radiant floors, RES		C Heat pump, Radiant floors, RES	
Envelope retrofit	Level 1	P1A	-	P1B	-	P1C	-
	Level 2	P2A	-	P2B	-	P2C	-
	Level 3	P3A	P3AMV	P3B	P3BMV	P3C	P3CMV
	Level 4	P4A	-	P4B	-	P4C	-
			CMV		CMV		CMV
		Controlled Mechanical Ventilation					

Following European dispositions, the European Directive 2010/31/EU required Member States to implement a standard framework based on cost-optimal approach aimed at determining the package that guarantees the amount of energy required to meet the energy demand at the lowest possible cost over the estimated economic lifecycle. According to the EBPD methodology, primary energy performances were obtained by DesignBuilder simulations. While the global cost is calculated in accordance with European Standard EN 15459-2017 and includes all investments and annual operational costs made during the calculation period (30 years). Figure 5 shows a graph combining the global cost and primary energy values of various retrofit packages. The results form a cost curve, with the lowest point representing the least expensive approach. Possible cost-effective solutions can be identified after analysing the results. The best solution is identified in package P1C, which is distinguished by Level 1 of envelope insulation, the installation of an air-to-water heat pump combined with radiant floors, and RES integration. However, P2C (Level 2 of envelope insulation, air-to-water heat pump combined with radiant floors, and RES integration) manages to provide an additional 6.2%

reduction in annual primary energy consumption at a source of 3 €/m^2 more than the P1C package; its overall costs are higher than P1C, but its energy performance is more consistent with the ZEEB definition. P2C annual primary energy consumption is 30.34 kWh/(m^{2}y), which corresponds to 19.35 kg$_{CO2}$/(m^{2}y) emitted by the building. It means that at a global cost of 280 €/m^2, it is possible to save nearly 61% of primary energy and 45% of CO_2 emitted in comparison to the RB. Given the benefits in terms of energy performance at a marginally higher global cost, the P2C package was decided to be implemented throughout the district. The choice was validated by "what if" sensitivity analyses that confirmed the consistency of the results. Sensitivity analyses revealed that as energy costs were changed, the P2C package performance improved, matching that of the P1C package; because P2C has higher investment costs and lower annual operating costs, as energy prices rise, it has less of an impact on performance than PC1, which has a higher annual cost share.

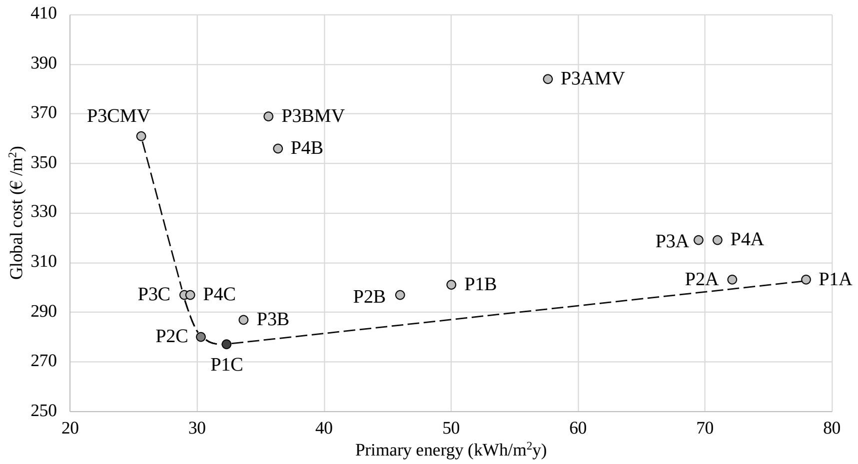

Figure 5. Cost-optimal graph.

3.3. District energy solutions

The results at the building level show that carbon emissions, even if lower than the Standard limits, do not allow for the achievement of the zero target. According to Marique and Reiter [9,43] and da Gra ça Carvalho et al. [44], expanding the analysis to the district level can reduce these quantities by introducing some additional measures.

The district chosen is the one surrounding the Refence Building from the previous calculation.

The chosen district is that one surrounding the Refence Building of previous calculation. The district, which consists of 22 buildings, is located on Turin's north-western outskirts in a suburban area (Figure 6). The district has a total land area of 94,730 m^2. For the sake of simplicity, only residential buildings are considered in this study, as they constitute the majority in the area under consideration. The total gross area of the dwellings is 89,031 m^2, and the building footprint accounts for 13% of the district area. Green spaces account for nearly 40% of the remaining land. This data shows that, despite the buildings occupying a small portion of the district total area, the district is quite dense because all of the dwellings are apartment blocks of at least 6 storeys. The building stock of the neighborhood is characterized by structures built between 1976 and 1990. Using data from the TABULA project, it is possible to divide the buildings into two construction period bands based on the stock analysis. Figure 7 depicts the building classification; there are 8 buildings constructed between 1990 and 2005 (Type A), while others date from 1976 to 1990 (Type B). The majority of the district building stock was constructed immediately following the first energy crisis (1975), which is why insulation is always present in all housing components, but the level of insulation is insufficient to achieve good performance and reduce energy demand. Buildings have different thermal transmittances and system configurations based on their age, according to the TABULA classification [45]; this data was applied to the Design Builder model to identify the different energy needs of the buildings as well as the total heating, cooling, hot water, and electricity needs of the neighborhood. The same model that was used as the RB in the previous calculation is used to determine the energy needs of building type A; the results are normalised by area and used as a reference for all dwellings built between 1990 and 2005. Because type B buildings are quite similar in size and configuration to type A buildings, it was decided to use the same model as the type A building, modifying the envelope and system performance of the reference building while maintaining the same area and size of the components as the previous model. This simplification was justified by the district's large size and the impossibility of obtaining specific requirements for each building due to the complexity of the calculation and the time-consuming dynamic simulations. Furthermore, the results of the dynamic simulation of the type B building were very similar to those developed as part of the TABULA project and can be considered quite accurate. The total district energy demand was then calculated, including annual consumption for street lighting. Various energy retrofit alternatives were developed, and the results in terms of district carbon emissions and primary energy consumptions were calculated using the EnergyPLAN tool.

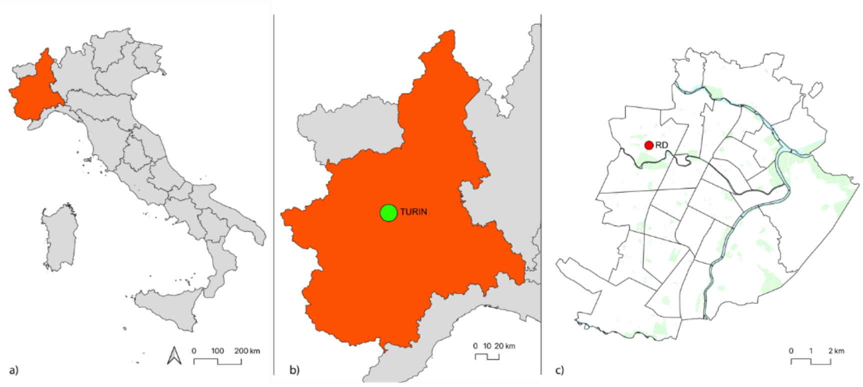

Figure 6. Location maps. The Piedmont Region is highlighted in red in Figure 6a, Turin is depicted in Figure 6b and the Reference District (RD) is shown in Figure 6c in relation to the municipal territory.

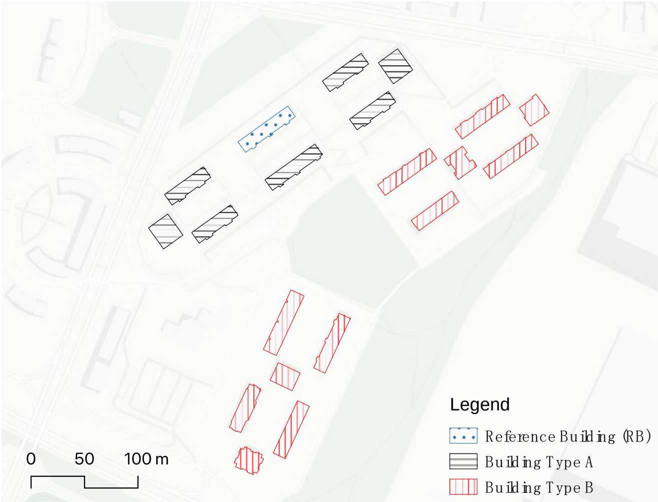

Figure 7. Classification of the buildings located in the Reference District (RD) and Reference Building (RB) location.

EnergyPLAN is structured in categories and subcategories that analyse the problem in different steps: filling EnergyPLAN tab sheet with district electricity, heating, cooling demands and local energy production, it calculates annual fuels consumptions.

District retrofit alternatives were represented by envelope structure of P2C package, previously identified as the cost-optimal solution at the building, and test systems solutions combined with local energy and electricity production: single air-to-water heat pumps, district connection to the Turin district heating grid, installation of a cogeneration system (heating and electricity production) powered by natural gas, installation of a cogeneration system powered by biomass and a trigeneration system (heating, cooling and electricity production) powered by biomass too (Table 3). Systems configurations are also combined with RES configurations: exclusively standard limits set by Italian law for STP and PVP (thus the same configuration as the P2C package), a larger share than provided for in the legislation of solar thermal panels (STP+) or photovoltaic panels (PVP+), or both (Advanced).

Table 3. Matrix of district retrofit solutions.

		RES configuration			
		Standard	STP+, Solar Thermal Panel	PVP+, Photovoltaic panels	Advanced (STP + PVP)
System configuration	Heat pump	D1A	-	-	D1D
	District heating grid	D2A	-	-	D2D
	Gas cogeneration	D3A	D3B	-	D3D
	Biomass cogeneration	D4A	D4B	D4C	D4D
	Trigeneration	D5A	D5B	D5C	D5D

Environmental results demonstrate that biomass fuels decrease in a significant way carbon emissions while primary energy consumption values are almost in line with values referred to heat pumps installations and district heating connections (Figure 8). It seems evident that gas cogeneration solutions reach worse level of both primary energy consumptions and carbon emissions.

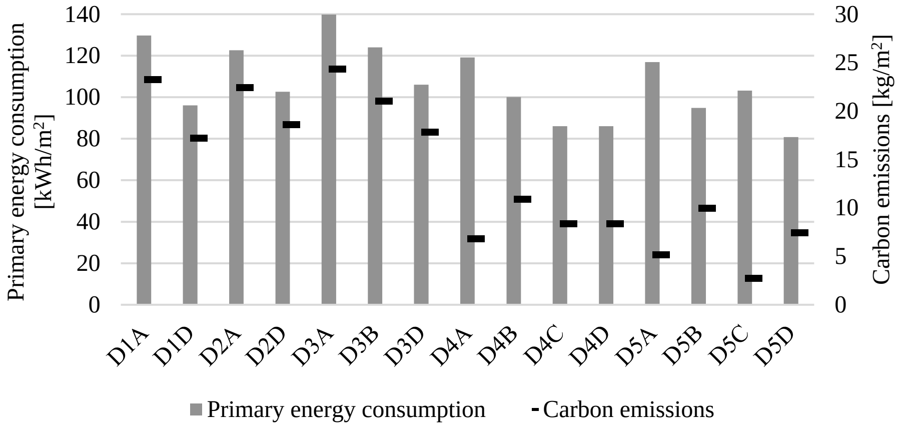

Figure 8. District environmental performances.

Defining primary energy and carbon emissions of each district alternative is only the first step of the evaluation process. Indeed, referring to a larger scale other factors must be considered to address the choice and to identify the suitable solution. For that reason, a Multi-Criteria Decision Analysis is set up.

3.4. Multi-Criteria evaluation

In decision-making, the choice of criteria to be used in evaluation is a key step. The criteria must be chosen based on the characteristics of the alternatives to be evaluated and capable of describing the input data of the model [46]. The criteria selected to address this issue could be clustered in four main families, and comprise economic, environmental, technical, and social (Table 4).

The economic criteria are usually related to the individual benefits for the users and reflect the financial savings they can achieve with the retrofit, the payback period, and the global costs. They are frequently the only way to persuade the user to carry out the retrofit and, as such, are critical, even though the evaluation cannot consider only these criteria. The second type of criteria are environmental. Environmental criteria are related to local and diffuse environmental benefits, ranging from local air pollution and visual impact reduction to conventional fuel savings and climate impact on a larger scale. They sometimes reflect the limits and objectives of national standards and are the main aspects that can guide the choice, with reference to international guidelines. The third category is technical criteria, which refer to the effectiveness of energy efficiency measures and aid in the selection of various system solutions. To quantify the effects of retrofit on a larger scale, social criteria are added to the environmental and economic assessments. Understanding what the retrofit means for the local population and society is critical, especially in the evaluation of a near-zero energy and emission district, which represents a portion of the city and aims to be a replicable pilot solution that will affect larger portions of the city. Table 5 displays the performance of each alternative, the evaluation direction, the preference functions, the function thresholds, and the units of measurement for each criterion.

Table 4. Coding, definitions, and functions of selected criteria.

Criteria family	Criteria				
	Code	Name	Definition	Unit of measure	Function and thresholds
Economic	EC1	Avoided running cost	The annual energy savings calculated by comparing the RD with the performance on new scenarios are represented by the criterion [47].	€/m^2	V-shape (p = 2)
	EC2	Cost effectiveness	It compares cost and emissions of each alternative on a common basis. The calculation of this criterion is equal to the ratio between the investment cost and the avoided CO_2 [48,49].	€/avoided kg_{CO2}	Usual function
	EC3	Payback Period	It is one of the most common investment feasibility indicators. It is calculated by dividing annual savings by total investment cost and indicates the number of years required to recover the initial investment [50,51]	years	Linear function (q = 3, p = 6)
	EC4	Global cost	The criterion is based on cost-optimal methodology, and considers investment cost, O&M costs, and residual value over 30 years [52].	€/m^2	Linear function (q = 10, p = 50)
	EC5	Normalised cost by energy	This criterion expresses the total of fixed and variable costs divided by the total amount of electricity self-produced over a 30-year period [53].	€/kWh	Linear function (q = 5, p = 8)
Environmental	EN1	Energy consumption	It is expressed in terms of Primary Energy, net of energy produced by the RES [24].	kWh/(m^2y)	Usual function
	EN2	Equivalent CO_2 emissions	It is calculated using consumption data; for each energy carrier, carbon conversion factors are calculated using the Italian Standard UNITS 11300-4 [24,52,54]	kg_{CO2}/(m^2y)	Usual function
	EN3	New green areas	The criterion considers the square meter of trees in each scenario to reduce carbon emissions, improve quality of life, and building market value [55].	m^2	Usual function
	EN4	Visual impact	It expresses people's preference for integrated solutions on a qualitative scale ranging from 1 to 5, with 1 indicating the worst performance and 5 indicating the best [53].	1 to 5	Level function (q = 1, p = 2).

Continued on next page

Criteria family	Criteria				
	Code	Name	Definition	Unit of measure	Function and thresholds
Technical	T1	Efficiency rate	It denotes the relationship between the energy delivered and the energy acquired by the system [56].	0 or 1	V-shape function (*p* = 0.5)
	T2	Energy independence	It is related to energy self-production and the potential for renewable energy production and storage systems. It is expressed as the ratio of self-energy produced to total energy consumed [57].	%	Linear function (*q* = 0.5, *p* = 0.45)
	T3	Maturity of the technology	It reflects the dependability of the measures used in the various scenarios. It is expressed in five levels, with 1 indicating that the technology has only been tested in the laboratory and 5 indicating that the solution has a solid market position [58–60].	1 to 5	Level function (*q* = 1, *p* = 2)
	T4	Service life	It defines the lifetime of the energy system [61].	years	V-shape function (p = 10)
	T5	Energy smart grid	It is expressed as a binary criterion, with 1 indicating the presence and 0 indicating the absence of a local smart energy network [13,62].	0 or 1	Usual function
Social	S1	External cost	The criterion expresses the societal harm caused by the use of electricity supplied by the national grid. ExternE was used to calculate the performance of the alternative according the criterion [63,64].	€	V-shape function (*p* = 0.5)
	S2	Green jobs	It quantifies the new employment impacts by counting the number of jobs created by each alternative [65,66].	No	Usual function
	S3	People acceptance	This criterion reflects public perception of different energy systems. It is expressed on a 5-point scale, with 1 indicating complete discordance and 5 indicating total compliance [67].	1 to 5	Level function (*q* = 1, *p* = 2)

Table 5. Performance matrix.

	EC1	EC2	EC3	EC4	EC5	EN1	EN2	EN3	EN4	T1	T2	T3	T4	T5	S1	S2	S3
	Avoided running cost	Cost effectivness	Payback period	Global cost	Normalized cost by energy	Energy consumption	Equivalent CO2 emission	New green areas	Visual impact	Efficiency rate	Energy independence	Maturity of the technology	Service life	Energy smart grid	External cost	Green jobs	People acceptance
	€/m²	*€/kgCO₂*	*years*	*€/m²*	*€/kWh*	*kWh/m²*	*kgCO₂/m²*	*m²*	-	*%*	-	-	*years*	-	*€cent/kWh*	*No*	-
Ranking sense	max	min	min	min	min	min	min	max	max	max	max	max	max	max	min	max	max
Function	V-shape	Usual	Linear	Linear	Linear	Linear	Usual	Usual	Level	V-shape	Linear	Level	V-shape	Usual	V-shape	Usual	Level
q	-	-	3	10	5	6	-	-	1	-	0.5	1	-	-		-	1
p	2	-	6	50	8	30	-	-	2	0.5	0.45	2	10	-	0.50	-	2
D1A	6.82	8.12	30.00	296.81	64.00	129.75	23.22	0	5	2.13	0.44	5	38.00	0	2.19	239	1
D1D	7.93	8.86	37.00	383.97	15.00	96.09	17.19	0	3	1.52	1.06	5	32.00	0	1.69	336	5
D2A	3.42	6.15	90.00	303.92	44.00	122.61	22.43	0	5	1.00	0.00	5	43.00	0	2.35	188	2
D2D	6.38	6.56	41.00	312.91	55.00	102.54	18.61	0	3	0.69	1.63	5	38.00	0	1.34	236	5
D3A	3.74	8.28	56.00	381.20	7.00	139.82	24.34	19341	5	0.61	0.23	4	40.00	1	3.50	219	2
D3B	4.90	8.58	52.00	397.29	14.00	124.03	21.03	19341	4	0.58	0.55	4	36.00	1	2.69	268	2
D3D	5.31	9.65	59.00	473.02	12.00	106.06	17.81	19341	3	0.55	0.65	4	32.00	1	2.54	346	3
D4A	5.87	7.66	54.00	462.07	18.00	119.14	6.79	19341	5	0.74	0.18	3	31.00	1	2.63	391	3
D4B	5.66	9.75	52.00	507.92	52.00	100.10	10.88	19341	4	0.55	1.29	3	30.00	1	1.68	445	4
D4C	6.73	8.40	59.00	529.03	16.00	105.09	4.28	19341	4	0.71	0.24	3	29.00	1	2.51	460	4
D4D	7.00	10.42	57.00	574.87	31.00	86.05	8.37	19341	3	0.52	1.45	3	28.00	1	1.55	513	5
D5A	5.70	7.28	54.00	457.65	17.00	116.91	5.15	19341	5	0.71	0.18	2	31.00	1	2.63	338	3
D5B	6.04	9.42	51.00	501.50	51.00	94.87	9.95	19341	4	0.49	1.57	2	30.00	1	1.57	441	3
DC5	11.26	8.02	58.00	524.80	15.00	103.18	2.70	19341	4	0.68	0.24	2	29.00	1	2.52	456	3
D5D	11.81	10.09	55.00	568.46	31.00	80.82	7.43	19341	3	0.46	1.73	2	28.00	1	1.45	510	4

3.5. Multi-actor analysis

The last step includes the evaluation of a sensitivity analysis providing information on the stability of the ranking with respect to the applied criteria weights. A sensitivity analysis of the criteria could be a promising starting point to facilitate a final decision and successful implementation [68]. In detail, a multi-actor analysis was performed to highlight the reception of energy policies regarding the abatement of emissions in two European countries; Italy and Denmark. Indeed, the common path at the European level in the context of post-carbon buildings in recent years links the adoption of renewable energies and energy efficiency. Denmark has thus been among the EU countries driving towards a sustainable energy transition for some time. It consistently ranks high in the Energy trilemma index of the World Energy Council (WEC) for its performance in terms of energy equity, environmental sustainability, and energy security. Furthermore, the International Energy Agency (IEA) ranks Denmark as the most advanced country in the integration of so-called variable renewable energies, with wind and solar providing 50% of gross electricity consumption in 2020. Alternative solutions based on Danish guidelines may push Italian energy policy in the same direction.

The criteria were then weighted by interviewing two economic and two energy experts, one from each country. As described above, the weights of the criteria were determined using the SRF technique. Figure 9 shows the experts' preferences.

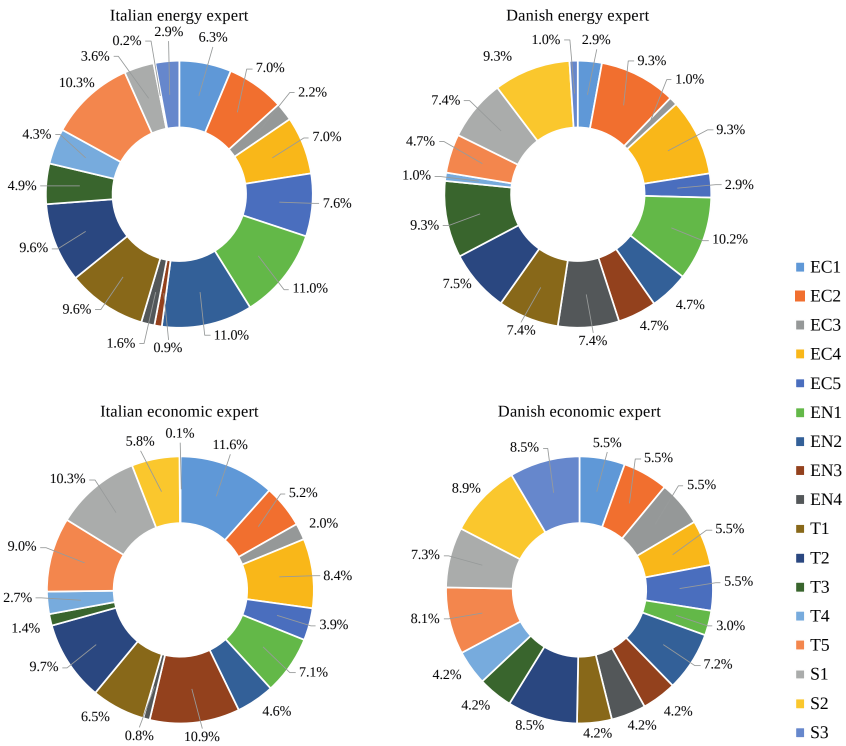

Figure 9. Weights of the criteria according to the four experts.

The opinions of the economic experts concurred in the same direction; both emphasised the importance of social, rather than technological or environmental criteria. In particular, the Danish economic expert emphasised the importance of the creation of new green jobs as a driver for investment in energy research, in line with the European energy policies of recent years [66]; he also put people's acceptance first, because he believes that the community must play a very significant role in the energy transition. The Italian economist also emphasized the significance of social factors such as the social cost (S1). However, he also emphasized the importance of individual cost savings in order to quickly solve the problem, even though he believes that cities also require long-term energy strategies to reduce energy dependency through innovative and high-performance systems.

The Italian energy expert give more attention to technical aspects compared with Danish one. She gives less attention to social criteria, looking specifically to environmental criteria. The Danish expert also stresses the attention on economic aspects, highlighted their correlation with energy consumption. He thinks that economic savings could be a driving way to convince people on making a renovation.

Grouping experts by country, Danish experts give more importance to social criteria than Italian ones; the reason could be found in different approaches that Italy and Denmark have referred to energy planning. Considering local energy policy, Denmark is trying to reach the complete decarbonisation of the electricity grid at the national level, in that sense it is expected that impacts on society will play an important role in the decision assessment [69]. Italian experts give the same importance to Energy independence and Energy smart grid, in this case, the reason could be the opposite; Italy does not promote a national energy plan, so be independent at the local level and able to manage local production in order not to sell it to the grid could be a good solution for neighbourhoods.

In conclusion, interviews' results are quite different; therefore, the multi-actor analysis could be a useful method to prove the value of different neighbourhood retrofits. Criteria in the first positions are not always the same, so in the case that some alternatives will score best preference levels for all scenarios it proves that the alternative is sufficiently valuable both from an economic, technical, social, and environmental point of view.

3. Results and discussion

The Visual PROMETHEE 1.4 software aggregates the leaving and the entering flows of the alternatives ranking the 15 different retrofit solutions proposed for the case study. The alternatives are ranked based on the opinions of the experts interviewed. According to Figure 10, trigenerational alternatives are always preferred over other solutions. All experts agree that D5D is the best scenario. D5D is a retrofit option that combines a trigeneration system with with STP and PVP (Advanced). It performs very well in terms of energy independence (T2) and energy consumption (EN1), significantly reducing CO_2 emissions (EN2), criteria that are important to all experts. Some experts rank other alternatives higher than others, ranking some alternatives in very different ways. According to an Italian economic expert, one of the best alternatives is D5B, which is represented by trigeneration combined with STP+; this alternative performs exceptionally well in External Cost (S1) and Avoided Running Cost (EC1).

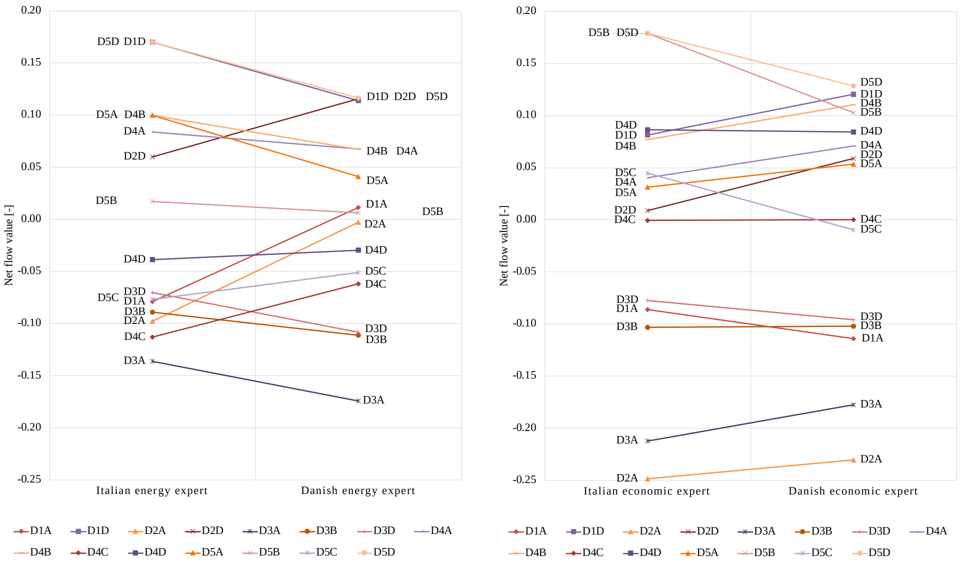

Figure 10. Ranking of the alternatives according to energy experts (on the left) and economic experts (on the right).

The D1D alternative is also very suitable for the Italian and Danish energy experts, as well as the Danish economic expert; this finding was somewhat predictable given that D1D has a short return period (37 years), a minimal visual effect, and a high level of people acceptance. It is, however, a solution that does not take into account district-scale solutions for electricity and heat supply. The heat pump system configuration, in fact, excludes Energy smart grid (T5), which is important for the Danish economic expert. However, the Danish economic expert ranks the D1D alternative second due to its excellent performance in the economic criteria, as Danish policy [70] aims to introduce solutions with high cost-effectiveness and short payback periods by 2050. According to the Danish energy expert, the second place is taken by D2D, which combines district heating with RES; the D2D solution is in line with a fairly frequent situation in Denmark, where most houses are connected to district heating implemented with RES. As said before, the Danish national energy grid is currently developing a national framework to supply the national grid only with RES beyond 2050, which differs greatly from the Italian framework, which focuses more on individual building efficiency to reduce energy demand. Italy is characterized primarily by a building stock in need of energy retrofit, with one of the priorities being to improve performance by acting on the envelope and system building solutions rather than adopting grid solutions. One other important consideration can be done among alternatives based on cogeneration powered by natural gas (D3A, D3B, and D3D). These alternatives present always negative net flows in all scenarios and for both energy experts they are ranked in the very final positions; in fact, retrofit solutions based on gas cogeneration are very badly performing referring to environmental and social criteria so all experts agree with their ineffectiveness in improving district conditions. When combined with STP, biomass CHP alternatives always have positive net flows (D4A and D4B). While D4D (biomass CHP + Advanced STP and PVP) only achieves a positive net flow for both economic experts, even ranking third for the Italian one, this is due to excellent performance in all social family criteria, reduction of Energy dependency (T2), and Energy consumption (EN1). Finally, all experts are in general agreement that the operational solution for the neighborhood can be referred to alternative D5D, though there are other viable alternatives. This alternative produced very low carbon emissions (7.43 kgco_2/m^2), which is consistent with the primary goal of this research.

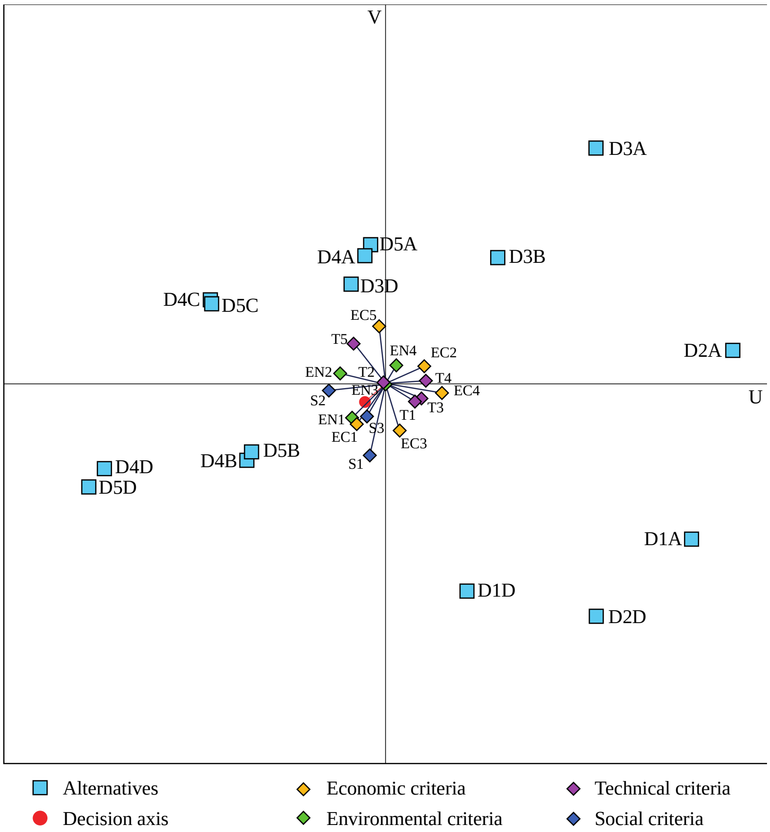

Figure 11. Criteria vs Alternatives GAIA plane considering the average weights.

The Visual PROMETHEE allows representing results graphically through to the GAIA Visual Analysis (Geometrical Analysis for Interactive Aid) [21]. GAIA is a tool that shows a 2D graphic illustration of the alternatives' ranking in a four-quadrants plan. In this application, the results were firstly visualized according to the different criteria considering their average weights (Figure 11). The average weight of the criteria was considered in order to obtain an all-inclusive assessment of the opinion of all experts involved. Each criterion is represented by a rhombus linked to an axis drawn from the centre of the plane. The alternatives are represented with squares. The red axis indicates the decision PROMETHEE stick. The alternatives are placed within the quadrant in correspondence with the criteria in which they are most performing. Moreover, the orientation of criteria axes indicates how strictly criteria are allied to each other. If criteria express comparable preferences, the axes are close to each other. On the other hand, criteria ride in opposite directions of the contradictory criteria. For example, alternatives that are performing from the point of view of the Payback period criterion (EC3) are equally valid for the Global cost criterion (EC4). Similarly, alternatives that provide for measures at the district level, such as the implementation of green areas (EN3), will also perform in terms of reducing health impacts (S1) and will be well accepted by people (S3). Besides, alternatives that generate substantial quantities of CO_2 (EN2) provide solutions characterized by low energy efficiency (T1) and low technological maturity (T3).

GAIA plane is also a useful tool to understand the point of view of each actor involved in the decision process. In Figure 12, the points represent the experts, while the squares are the alternatives. Analogous opinions are represented by points located close to each other and in the same quadrant. The energy experts, which defend the same criteria preference, are represented by axes oriented in approximatively the same direction. On the contrary, the opinion of the economic experts runs in the same direction in a contrasting way with the other actors.

In the case of this research, the analysis shows that Italian economic and Danish energy experts have very different positions, but differences are in any case limited as the preferences are oriented to the plan, since all experts' axes are oriented in the same direction of the decision axis.

Summarizing, it is possible to confirm the position of alternative D5C and state that the alternative base on trigeneration combined with PV installation is the most suitable one for the retrofit project of the district of Turin.

The results highlight the advantages of using the PROMETHEE method to support complex decision processes and compare alternative scenarios considering different criteria. The Visual PROMETHEE software facilities users in the decision-making process. GAIA Visual Analysis was extremely advantageous for exploring the diverging criteria and represents the alternatives about the different criteria and experts' points of view in the energy field.

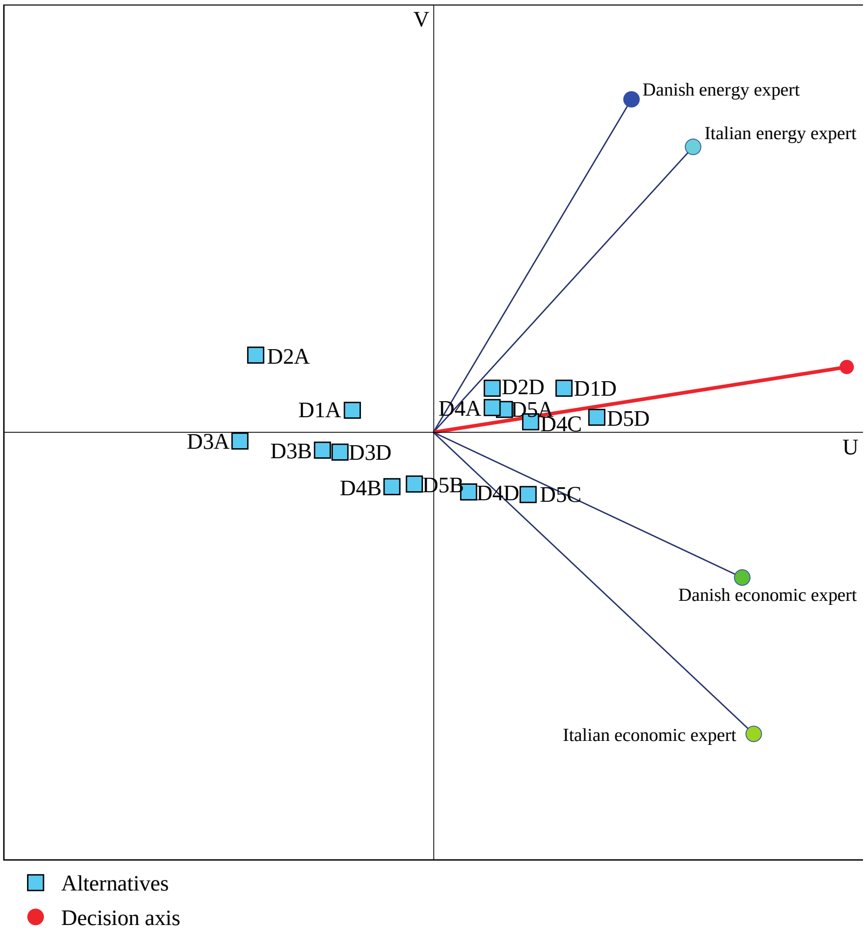

Figure 12. Alternatives vs experts GAIA plan.

4. Conclusions

Cities are at the centre of the current context research to create liveable, resilient, and healthy places (SDG 11). Within the urban context, buildings have a central role in the retrofit of existing settlements to achieve the new European goals in terms of the post-carbon city. Decision problems in this domain have been poorly investigated. A multi-dimensional approach is needed to face the fragmentation of the district scale. The paper aims to address this issue by proposing a multi-step evaluation model to support the decision considering the different points of view of the various stakeholders. The model foresaw different phases starting from the identification of the optimal solution in terms of costs and emissions. Subsequently, an evaluation model based on the PROMETHEE II method was set up to identify how to integrate the cost-optimal solution on a neighbourhood scale. The evaluation framework was applied in a district located in Turin (North Italy) to compare 15 alternative retrofit scenarios and identify the best solution. To face the different points of view of DMs, four experts were involved. The multi-actor analysis highlights how the different perspectives can influence the evaluation outcomes. PROMETHEE II results identify alternative D5C as the most suitable one. It refers to a trigeneration central plant powered by biomasses and combined with the installation of photovoltaic panels on rooftops of buildings. D5D is well-performing from an environmental point of view but, at the same time, it is one of the most expensive solutions. It reaches sufficient levels of performance referring to both technological and social domains. Considering the rankings of different experts, it is possible to notice that D5D first position is not so strong and other alternatives can represent valid retrofit solutions. The paper demonstrates how the cost-optimal approach-based method is insufficient in the evaluation of district-scale projects and how multi-criteria approaches are more suitable. Furthermore, it highlights how post-carbon building targets can be an excellent solution to answer new energy and environmental questions stated both at the European and international levels.

Since the PCC encompasses a complex city concept, with several urban sectors coming into play, in this paper we focus only on the construction sector and its contribution to achieving the goal. As one can learn from the paper, already a multitude of criteria are considered for this sector. Expanding the analysis with further tools to support the decision can be experimented in next steps. In terms of future developments, referring mainly to the district scale, it will be even more interesting to include in the analysis different types of buildings that add office buildings, shops, and others to homes, and which complicate the composition of the district. In this way, the role of intelligent energy grid monitoring will become even more important and the discrepancy in energy production and consumption can be easily overcome. Another possible implementation is represented by the introduction of electric accumulators for the storage of energy from photovoltaic panels at the district level. This technology may not yet be very common, but it is developing rapidly and will represent another solution to overcome energy misalignment.

Conflict of interest

The authors declares no conflict of interest.

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