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Renovating Building Groups in the Mediterranean Climate: Cost-Effectiveness of Renewable-Based Heating Alternatives in the Italian Context

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Abstract: District level approaches for the renovation of the building stock boost the implementation of energy efficiency measures (EEMs), taking advantage of the economies of scale. International Energy Agency Annex 75 aims to assess the cost-effectiveness of renovation strategies at the district level, combining EEMs and renewable energy sources. For this goal, a building energy model is simulated with the Energy Plus dynamic calculation engine for assessing the generic district of the Italian case study, representing the residential stock from 1960 to 1980, placed in two prevailing space-heating dominated climates; then, a cost-effectiveness evaluation of each scenario is conducted to support stakeholders' decision making. In particular, envelope insulation is cost-effective only in northern zones, while new decentralized thermal systems are not convenient in any case with current envelopes. Once the envelopes are insulated, decentralized low-temperature air-to-water heat pumps with PV can cover all of the buildings' energy needs, even implying a small increase in annual costs. The switch to district net scenarios is cost-effective only if coupled with PV. A rise in energy prices brings PV-based strategies under a 10-year PBT, except for solar thermal DH in northern areas, as well as non-PV-based options such as low-temperature HPs or biomass-fuelled DH in warmer and colder zones, respectively.

Keywords: cost-effective strategies; building renovation scenarios; renewables in buildings; generic district; energy efficiency measures; district heating; Mediterranean climate; Italian housing context

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1. Introduction

The building sector is the single largest energy consumer in the European Union (EU), and one of the greatest carbon dioxide emitters. Buildings in the EU are responsible for 40% of global energy consumption and 36% of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition [1]. This important energy use arises from the existence of more than 100 M residential buildings in the EU building sector, which account for only a 3% share of A-label performance examples [2]. Moreover, 75% of this stock is inefficient from an energy perspective, and recent estimations acknowledge that 75–90% of these buildings will still stand in 2050 [3].

Consequently, the building sector offers great potential for achieving energy efficiency aims. Most buildings in the EU should be renovated for energy efficiency if a decarbonized building stock is targeted by 2050. Indeed, building renovation rates are set at an annual rate of 1% [4], which poses faster and deeper energy efficiency renovation of buildings as a crucial challenge for Europe in reaching 2050 carbon-neutral goals [5].

In Italy, where natural gas is a very popular source for domestic heating [6], the residential building stock covers 28% of total national energy consumption, with 86% of these buildings having been built before 1990 [7,8]. Recent studies suggest that 41% of savings on natural gas consumption can be achieved in 2030 with respect to "business-as-usual" estimations, provided 28% of all existing flats undergo energy efficiency renovations [9]. These evaluations are calculated on a heating degree days (HDDs) model basis, stressing the high correlation of energy consumption to the contextual heat severity [10], particularly in the Italian country, which depicts a wide climate variability [11]. A recent study on the financial feasibility of interventions in terms of risk/returns highlights that in the face of uncertain market scenarios within the current post-crisis recovery, investing in resilient building models implies reinforcing the energy efficiency and comfort standards of existing stocks located in urbanized areas rather than building new properties on the city outskirts that lack a proper built-up infrastructure [12].

From the establishment of the first directives on the energy efficiency of buildings [13], mandatory requirements agreed upon within EU member states (MSs) are being continuously revised and updated to adapt to technical advances in the construction sector. So far, 70% of MS have transposed these directives into action plans to finance building renovation, such as Italy [14]. This being the case, 2010 was the first time that EU regulations included the concept of the nearly zero energy building (i.e., named after the acronym nZEB), leaving each country to freely promote the transition towards nearly zero energy scenarios. The nZEB definition dictates that part of building needs should be compensated by passive strategies adapted to the local context, and that remaining energy demands should be covered by renewable energy sources (RESs). As a result, different strategies may be accounted for in different national contexts attending to local building stock features and policies and available RESs [15].

Within the Energy in Buildings and Communities Programme (EBC) managed by the International Energy Agency (IEA), Annex 56 (*Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation* project [16]) set a methodological precedent at the building scale to the following Annex 75 (*Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables* project [17]), which aimed to investigate cost-effective strategies for reducing greenhouse gas (GHG) emissions and energy use in buildings at a district level, combining both energy efficiency measures (EEMs) and renewable energy measures. The objective is to provide guidance to policy makers, companies working in the field of energy transition, and building owners in order to cost-effectively transform the city's energy use in the existing building stock towards low-emission and low-energy solutions. Combined with other studies [18], the outcomes of this study [17] supported large-scale approaches for increasing the renovation rate of existing buildings from 1–2% to 2–3% per year by 2025 [19], taking advantage of economies of scale to reach energy efficiency goals [3].

In recent years, there has been considerable research into cost-effective assessments of measures carried out to improve the building stock towards more energy-efficient and decarbonized scenarios. Teni et al. [20] state that the building technology by construction period impacts both the energy performance and economic feasibility of interventions. The study depicts that acting on very old buildings—i.e., built before 1956—demonstrates longer investment returns than the buildings' predicted service life, which brings into debate the usefulness of renovations. On the contrary, the building stock from the seventies offers greater potential for energy improvement since these buildings often present the worst performance. In agreement with other recent research, the authors state that technological development, energy price variations, and interest rates need to be considered in studies to enhance decision-making plans on large scales. Toleikyte et al. [21] ran another study in Lithuania, reporting the need for financial incentives to boost the renovation of low-performance residential buildings and the need for a national standard regulation in line with the energy savings potential of this building stock towards 2030.

Overall, the integration of RES covering a high share of domestic energy demands is seen as an essential step towards the mitigation of CO_2 emissions and the achievement of urban decarbonized scenarios. A study on a social housing complex from 1949 in Denmark, whose aim was to accelerate stock renovations towards NZEB standards, presents a decision-making methodology supporting the selection of retrofit interventions in buildings [22], based on a previously defined cost-effectiveness parameter (CEP) that couples primary energy savings, renovation costs, and a lifetime of each renovation measure. This study was replicated in Switzerland [23]. These studies prove the CEP as useful for estimating optimal packages of interventions and conclude that implementing RES is proven cheaper than doing no renovations, with heat pumps representing the most favourable system to achieve NZEB standards. Research conducted in two case studies in Switzerland argues that, differently from common assumptions, the most cost-effective solution in buildings with low or high energy demand should imply the replacement of the existing heating system with biomass ones to decrease the GHG emissions, together with intervening over the building envelope in the worst cases [24]. The study considered the building's operation in future scenarios (i.e., climate change, material replacement, electricity mix, and occupancy behaviour) and cases related to the production of materials (i.e., life cycle assessment). However, the number of uncertainties within the definition of the research nudges the authors to state that further studies on a bigger range of energy sources, dynamic simulation tests, and more indicators for climate change scenarios would increase the robustness of results. A study on a cooperative housing neighbourhood in Norway displayed similar results [25]. By applying the method of [17], they suggest that a performing solution could include the replacement of existing windows, PV integration, and the renovation of the existing DH network fuelled by waste incineration. However, this result is superseded by the assumption that no GHG emissions are allocated to the heat production for the DH network; otherwise, this action will produce the highest emissions. Results show that the choice of different supply systems does not impact the cost-effectiveness of energy efficiency measures, but it does impact GHG emissions, highlighting the need for combined energy and environmental approaches, even if embodied emissions are considered.

A very popular solution for a more energy-efficient building sector is the implementation of district thermal systems (DTSs), which can compensate for space heating (SH), space cooling (SC), and domestic hot water (DHW) demands of buildings through a centralized approach. These technologies are more developed in Central, Eastern, and Northern Europe since they were first devoted to offset heating and DHW. However, they are becoming more and more popular in Mediterranean countries, such as Italy, where district heating covers 3% of the total share of SH which raises to 61% [26] and is expected to increase about 50% to 80% towards 2050. A review on the potentialities of DTS (i.e., heating and cooling) is reported in [27]. Alternative technologies that are under experimentation in Mediterranean countries are reported in [28,29]. DTSs present many advantages regarding the energy and thermal supply to large assets of buildings or neighbourhoods since they can integrate different RES (e.g., biomass, electricity, geothermal), can operate at low temperatures reducing CO_2 emissions [30,31], and can be coupled with energy storage systems to stabilize demand and supply of the network [32,33].

Framed within the southern partners of Annex 75, [34] presents a practical validation of the proposed methodology over a Portuguese case-study neighbourhood, showing that despite being uncommon in Mediterranean areas, centralised solutions are cost-effective and energy-efficient, reducing GHG emissions and enabling the integration of RES. Nevertheless, the reported case was settled in a southern region where heating demands are not as important as that of Northern areas, concluding that further research in different climatic contexts was needed to contrast a wider range of scenarios. The authors also pointed out the importance of considering future variations in energy prices at the national level.

The choice of building renovation alternatives is not always straightforward, as several researchers report on the complexity of addressing different socio-economical contexts [35,36]. Many countries set in force the extent to which RES should cover minimum requirements, as is the case of Italy and Portugal, in which 50% of DHW production for new buildings must be supported by solar thermal systems [35].

Other related works on the building stock have been found in Mediterranean contexts. In Italy, [37] discloses a comparative study between dynamic and quasi-steady-state methods for estimating the energy consumption at the district scale, taking a social housing district in Venice as a case study, representative of historical housing buildings in the country. Authors argue that even if the simplest tool can give accurate results of energy demand estimation at the building level, it still presents a performance gap at greater extents compared to dynamic simulation tools, which are more complex and account for more parameters in the energy balance. Ref [38] presents an LCC assessment of the renovation of a reference building from the Italian public housing stock dated back to the 1960s–1970s. By using the NSGA-II method (fast elitist non-dominated sorting genetic algorithm), a multi-objective assessment with forty-one alternatives for energy efficiency measures on the envelope and thermal systems in more than 3000 combinations under two different climatic scenarios ("cold climate" with 3959 HDDs and "warm climate" with 899 HDDs) was used to reach technical-economical optimization. Authors conclude that optimal solutions are achieved with more efficient system plants rather than with energy efficiency measures on building envelopes, highlighting the renewable-integrated solution with heat pumps, and with PV generator as the most convenient in both climate contexts. Following [13], Guardigli et al. [39] develop a cost-optimal assessment of nZEB renovation strategies through a decision support system (DSS) to be applied over large publicly owned housing stocks, considering the net present value (NPV); the global cost (GC) at 10-, 20- and 30-year periods; and the building energy performance index (EP). The authors insist on the necessity of integrating local RES such as roof-integrated PV systems, to reach zero-net energy goals. Moreover, they highlight the expected increases in energy costs and the length of the study period for accurate predictions. Ferrari et al. [40] propose a method to assess housing buildings through energy performance indexes based on monitored consumption data normalized through the degree-day (DD) method. The method is applied to North-Italian public social housing assets dated from 1940 to 1993, but the authors state that the method is replicable in any other context provided that the consumption data of the buildings are available. In Portugal, [41] presents a method combining the life cycle cost assessment (LCC) and a life cycle assessment (LCA) of the renovation of a social housing building in Braga (Portugal). Authors point out that despite the energy convenience of the integration of RES, the consideration of embodied energy can hinder the aimed reductions in CO_2 emissions in a whole life-cycle approach (mainly when it regards PV and solar thermal), highlighting the importance of different energy mixes adapted for different contexts, and likewise for other researchers [42,43]. Large-scale building renovation has also been addressed by Blázquez et al. [44] in southern Spain, where standard upgrading actions—thermal insulation, windows replacement, increased airtightness, and mechanical ventilation—are tested on the social housing stock dated back to 1950–1980 in Córdoba to foresee the achievable reductions in CO_2 emissions at the urban scale. The results are transposed to a GIS platform addressed to stakeholders involved in the decision-making process to take actions on the renovation of the building stock by prioritizing the most vulnerable areas in the city [45]. Refs [46,47] present studies on the importance of the optimal insulation thickness in buildings' renovation in hot, temperate, and cold Mediterranean contexts in Spain, relying on a building energy model (BEM) representative of the built stock before 1980. In both studies, the authors place the BEMs all around the main capitals of the country under different climate zones, and state that NZEBs standards are achievable through 67 of 576 proposed energy renovation solutions. Again in Spain, the authors of [48] run an LCC study over a 30-year period on a pilot apartment building in a mild Mediterranean climate, built in 1979 in the city of Castellón. Authors define a package of optimal solutions (POS) to renovate the building, involving the building façade, windows, roof, slabs, ventilation system, infiltration improvement, thermal bridges, and domestic hot water production, providing for almost

60% primary energy savings. They also insist on the need to conduct further studies based on step-by-step interventions following private owners' way of proceeding.

So far, the identified examples in the literature on the assessment of building renovation strategies are supported by archetype energy models that are assessed at the building scale. Commonly, these studies declare that the obtained results can be extrapolated to larger scales (e.g., district, neighbourhood, urban, and national) based on simplified building models that broadly represent the existing constructive typologies throughout national building stocks. However, the direct extrapolation of building-scale results to district-scale approaches may bias the outcome when it regards the performance assessment of net-based systems (such as a DTS connecting several buildings) or when considering common expenses within the investment of a community.

In line with this, the present work aims to contribute to this research gap, by presenting an original approach at a district scale that stems from the IEA Annex 75 project, based on a generic district that arises as representative of the widely diffused housing stock from 1960 to 1980 in Italy. A set of upgrading scenarios combining energy efficiency measures (EEMs) on building envelopes and thermal systems, including centralized (i.e., district heating) and decentralized ones, is assessed in terms of primary energy consumption and annual costs.

The outcomes of the present research have a twofold aim: to evaluate the cost-effectiveness of implementing these measures from the point of view of private investors, and to provide guidance to policymakers, companies working in the field of the energy transition, and building owners, with the aim of upgrading the Italian existing building stock in a cost-effective way towards low-energy solutions and related emissions, with a focus on convenient strategies for the European Mediterranean area.

The remainder of this paper is structured as follows. Section 2 presents the methods carried out for the generation of generic district BEMs, the definition of renovation scenarios, and the cost assessment; Section 3 presents the main outputs of the research in terms of energy performance and cost-effectiveness of measures; and Section 4 discusses the main conclusions.

2. Materials and Methods

As already declared in the introduction, the present paper was framed in the Annex 75 project [17], specifically within the subtask B—work-package 1, which aimed to develop a method which can identify cost-effective strategies for urban district renovation and support decision-makers on the evaluation of the efficiency, impacts, cost-effectiveness, and acceptance of such actions.

The proposed method was applied through a set of calculations of the so-called "generic districts", which are considered the most representative district-scale archetypes of the existing housing stock of a country. According to the methodology report [34,49], "generic districts" are intended as existing or fictional urban districts, defined based on typical building typologies and district sizes in the participant countries. Starting from a reference case, a set of energy scenarios was tested on the generic district to assess their potential cost-effectiveness in terms of energy, environmental, and economic impacts.

Regarding the contribution of the Italian research group, the generic district was defined based on the analysis of the prevailing typologies of buildings in Italy [50]. The Italian fictional urban district is made up of 10 multi-family buildings with representative features of the existing 1960–1980 building stock, likely managed by a single entity.

To assess the district's hourly energy profiles of SH and SC, DHW, and electricity demands, a BEM representative of each building of the generic district was defined and simulated with the tool DesignBuilder (v.6.1.0.6) [51], with an Energy+ dynamic calculation engine [52]. Hence, all the buildings that compose the generic district share the same geometry as a common approach that was usually followed in the construction period to which they belong. Following [17], to assess the performance of the generic district under a broader climatic context, the BEM was located in three Italian cities (i.e., Milan, Rome, and Palermo) with different climate zones. The present article only reports the elaborations for the two case studies that can be compared in terms of renovation actions, placed in Milan and Rome, to narrow down the national climatic context to SH-dominated climates.

According to the methodology of [17], the generic district is subjected to upgrading through a set of hypothetical retrofit scenarios. Starting from a *Reference case* (prior-to-retrofit state), a first action, named the *Anyway measures scenario*, involves extraordinary maintenance measures on the envelope and the common maintenance of the systems—detailed further in Section 2.2. Then, a twofold approach to upgrade the generic district through EEMs considers: (i) actions addressed to retrofit the buildings' envelopes, named *Envelope EEM scenarios*, and (ii) actions addressed to retrofit the buildings' thermal systems, named *Thermal system EEM scenarios*. According to the IEA Annex 75 methodology, in this paper, the thermal systems options were named "individual" if each flat has a different supply unit, "decentralized" if each building has a different supply unit, and "centralized" if the entire district has one supply unit. In addition to these, the integration of PV systems was also investigated for the cases in which renewable-based technologies were implemented, as a closing step under the so-called *PV system scenarios*.

To provide feasible district renovation solutions in Italy and account for the related effects, the different scenarios were compared from a cost-optimality perspective. For this purpose, the related primary energy consumption and annual costs were calculated. Moreover, the NPV of the defined scenarios was estimated to assess the related payback time (PBT).

2.1. Reference Case

The buildings of the generic district have a rectangular plan (12.40 m × 40.00 m) and four heated floors over an unheated basement (e.g., cellars, garages, warehouses, etc.). Each floor hosts 6 housing units; thus, each building accounts for a total of 24 dwellings with an average surface of 80 m^2 each. Two unheated stairwells serve 3 flats per floor.

As already mentioned, the BEM is located in two Italian cities placed in two different climatic zones according to the national classification [53]. The first is Milan (MI), in zone E with 2404 HDDs—with hot and humid summers, very cold winters, and occasional cloudiness all year round, as well as temperature fluctuations from −1 °C to 30 °C, rarely falling below −5 °C or rising above 33 °C –. The second is Rome (RO), in zone D with 1415 HDDs—with warm, dry, and mostly clear summers; long, cold, wet, and partly cloudy winters; and temperature variations between 3 °C and 31 °C, rarely dropping below −2 °C or rising above 35 °C –. According to the Köppen–Geiger classification, these climate zones can be associated with a *Cfa—warm temperate climate* and a *Csa—dry summer climate*, respectively [54].

Finally, to account for the random orientation of buildings in urban contexts, changes in the exposure of the BEM were simulated via rotation, and the average result of the performed simulations was considered. A 3D view and the geometry features of a multi-family building composing the generic district are reported in Figure 1 and Table 1, respectively.

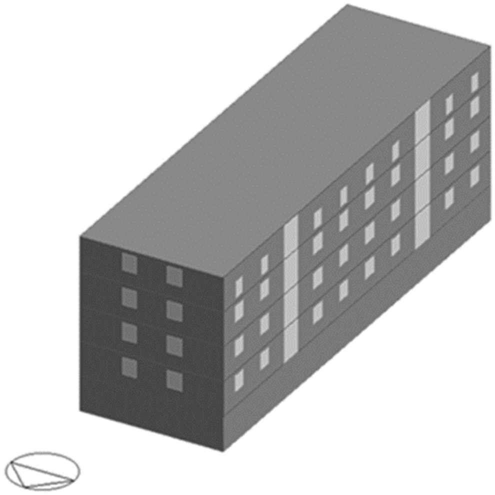


Figure 1. Three-dimensional view of a multi-family building composing the generic district.

Table 1. Geometry features of a multi-family building composing the generic district.

Feature	(u.m.)	Value
Gross-heated floor area	(m^2)	1616
Heated volume	(m^3)	4850
Façade area	(m^2)	1258
Roof area	(m^2)	496
Mean window area per façade	(m^2)	37

2.1.1. Occupation, Electric Loads, and Ventilation

Internal heat loads and the related time schedules were defined according to the standard ISO 17772 (part 1: 2017), which belongs to the package of 91 technical standards and reports concerning the calculation of the energy performance of buildings. Accordingly, different schedules for working days and weekends were adopted.

In detail, a nominal power of heat load due to occupants of 2.80 W/m^2 and an occupation rate of 0.04 people per square meter were considered. Moreover, a nominal power of heat load due to the equipment of 2.40 W/m^2 and due to the artificial lighting of 1.65 W/m^2 were considered. Hence, a mean daily internal heat load for occupants, equipment, and artificial lighting of 4.50 W/m^2 was used. Air changes per hour (ACH) were associated with the number of occupants, accounting for a mean daily ACH of 0.47 h^{-1}. Infiltration rates were kept constant at 0.2 h^{-1}.

Unconditioned spaces were modelled as buffer spaces close to the air-conditioned areas. For the vertical unconditioned cores (i.e., stairwells), internal heat loads accounted exclusively for artificial lighting, and therefore a global rate density of 1.5 W/m^2 was considered.

For SH, a comfort temperature of 20 °C with an attenuation of 18 °C was set in the periods defined by the national regulation [53], i.e., from October 15th to April 15th for no more than 14 h per day in Milan, and from November 1st to April 15th for no more than 12 h per day in Rome. Regarding the SC, a comfort temperature of 26 °C with an attenuation of 28 °C was set for the rest of the year.

2.1.2. Building Construction Characteristics

The BEMs composing the generic districts in Milan and Rome adopted typical construction characteristics in the 1960–1980 period. Vertical elements were modelled with uninsulated external cavity walls made of hollow bricks and finished with plaster and double-glazed windows with wooden frames. Horizontal elements consisted of uninsulated floors made of concrete slabs and bricks. Table 2 shows the envelope thermophysical properties assigned to the BEMs composing the generic district in the *Reference case*, as reported in the abacus of the UNI/TR 11552:2014 standard [55] and a previous study [56].

Table 2. Energy performance of the building envelope of the *Reference case* BEM.

Envelope Element	Parameter (u.m.)	Value
Walls	U value (W/m^{2}K)	0.98
Windows	U value (W/m^{2}K)	3.02
	G value (-)	0.76
First heated floor	U value (W/m^{2}K)	1.64
Roof	U value (W/m^{2}K)	0.92

2.1.3. Thermal Systems

To represent the most common practice, the following configuration was considered in both case studies. All buildings were assumed as equipped with decentralized gas-based boilers for SH, individual gas-based water heaters for DHW, and individual direct expansion (DX) multi-splits made of an external unit and 3 internal units per flat for SC. To consider the use of splits only in alternatively occupied spaces (e.g., bedrooms and living rooms), their activation and the subsequent energy consumption were set to cover 50% of the SC in reference to the entire air volume.

To simulate the systems' performance, the global seasonal efficiencies were adopted according to the regulation in force [57] by considering the contribution of each subsystem (supply, distribution, emission, and control).

2.2. Retrofit Scenarios

As previously described, the retrofit scenarios for upgrading the generic district assessed in the present paper included any, or a combination of, the following: (i) *Anyway measures*, including renovation strategies carried out to restore the functionality of the building, which do not imply an improvement of the building's energy performance and (ii) *EEMs*, considering more advanced strategies that provide improved energy performance. A summary of both approaches is described in the following section.

2.2.1. Anyway Measures

Anyway measures were first defined in the precedent project, IEA Annex 56 [16,58]. They include a set of measures addressed to the thermal envelope of the buildings and the thermal systems of the buildings. The approach is made two-fold:

- With the *Anyway measures* applied to the building thermal envelope, three actions were considered: (i) the replacement of the existing deteriorated external plaster of the walls, covering up to 30 % of the overall surface; (ii) the installation of an upper-slated finished new waterproof roof covering the old existing one; and (iii) the general repair of the existing windows (i.e., replacement of damaged hardware, sanding of the wooden windows, filling, and final painting).
- With the *Anyway measures* addressed to the building thermal systems, apart from the regular maintenance actions to keep a good functioning of the devices, the gradual replacement of the gas-based thermal plants was considered due to their lifetime expiration, spread over the 30 years of evaluation under consideration (see Section 2.3), namely the decentralized gas-based boilers, the individual gas-based DHW heaters, and the individual condensing units with a gas refill of the direct expansion cooling systems.

Hereinafter, the defined scenarios are named with a prefix derived from the city to which they refer, i.e., "MI_" for Milan and "RO_" for Rome. The refurbishment scenarios are named *"envel refurb (ExistSyst)"*.

2.2.2. Envelope EEMs

The EEMs applied on the thermal envelope of the buildings go a step further in upgrading the existing constructions to improve the building's energy performance up to the targets set by the national regulation [59]. They consist of three main strategies: (i) the replacement of the existing windows with low-e triple-glazed ones in Milan and low-e double-glazed ones in Rome, both with argon-filled cavities and an aluminium frame with a thermal brake; (ii) the addition of an EPS external thermal insulation composite system (ETICS) on the existing façades; and (iii) the addition of EPS external insulating walkable panels on the building roof overlapped by waterproof covering with an upper-slated finishing.

Considering these EEMs on the envelope, different scenarios were defined. Those associated with existing systems are named *"envel insul (ExistSyst)"*; those associated with the replacement of an existing thermal system with new gas-based ones (and individual air-to-water heat pumps (AtoW HPs) installed to produce DHW [60]) are named *"envel insul + NewGasSyst"*.

2.2.3. Thermal System EEMs

This set of measures contemplated upgrading the building systems for SH and DHW, with new ones exploiting the energy from RES, in addition to some of the previously defined scenarios. None of the considered *Thermal system EEM* actions alluded to the resettlement of the tenants, i.e., the existing distribution pipes at the building level were maintained at the original state in each apartment.

Starting from a scenario in which the thermal envelope performance is that of *Anyway measures* (without thermal improvement in the envelope), the defined *Thermal system EEM* scenarios regarded two different actions: (i) the replacement of the gas-based existing systems with more efficient new ones, named *"envel refurb + NewGasSyst"*, or (ii) the substitution of the existing systems with decentralized high-temperature air-to-water heat pumps (HT-AtoW HPs) to maintain the proper level of water temperature supply to the radiators in the absence of envelope insulation and the installation of individual AtoW HPs for DHW, named *"envel refurb + DecRenSyst (HT_AtoW_HP)"*.

If the thermal envelope of the buildings was already improved through an *Envelope EEM* measure, the decentralized scenario will regard the installation of building-level low-temperature air-to-water heat pumps (LT_AtoW_HP) and will be named *"envel insul + DecRenSyst (LT_AtoW_HP)"*, together with the installation of individual AtoW HPs for DHW.

As a further step, the realization of a new district heating (DH) network was considered for renewable-based SH centralized scenarios, together with the installation of individual AtoW HPs for DHW. Different energy supply options were defined for upgrading the generic district thermal systems as follows: (i) the *"DH Biomass"* scenario considers a DH fuelled by a biomass plant with exchangers as substations; (ii) the *"DH GSHP"* scenario considers a DH fuelled by a ground source heat pump (GSHP) with vertical probes and heat exchangers as substations; and (iii) the *"DH SolTh+WtoW_HP"* scenario considers a DH fuelled by a solar system adopting seasonal thermal storage (SolTh) with water-to-water heat pumps (WtoW HPs) as substations. Again, all these scenarios included the installation of individual AtoW HPs for DHW.

2.2.4. PV System Scenarios

As mentioned before, the defined renewable-based scenarios for the generic district renovation were also upgraded by integrating solar energy production. For sizing the system, the considered PV panels have a nominal power of 250 W_P and an efficiency of 14%. They were assumed to be tilted, mounted on the roof (facing south), and properly spaced to avoid mutual shading and the shading cast by stairwell volumes, as well as to allow their maintenance, thus conservatively covering 50% of the available net building roof surface. Hence, the entire PV system has a size of 26.4 kWp and can potentially produce 68.3 MWh of electricity in Milan and 79.4 MWh in Rome, according to the PVGIS tool [61].

Therefore, whenever the previously defined scenarios consider PV integration, they are hereinafter denoted by adding the suffix "*+ PV*" to their original name.

2.3. Costs Analysis

To estimate the cost of interventions, recent building price lists for public works generally used in public tenders involving large size works were adopted for both case studies, i.e., the price list of Lombardy Region in 2020 [62] for Milan and the pricelist of Lazio Region in 2020 [63] for Rome, as already outlined in previous studies [16,58]. The southern case of Rome reveals some higher costs due to logistics and transportation matters given its further distance from the main production centres. Missing data in any of the two mentioned price lists regarding the considered interventions were supplied with costs found in other price lists available at the national level or eventually with average costs taken from scientific literature and technical documentation.

To determine work costs, no extra discounts were considered for design and administrative building process costs. The costs of *Anyway measures* and *Envelope EEMs* include the rental of the scaffolding for the period needed; the transportation and disposal of waste materials; the finishing of surfaces (e.g., wall painting); and, in the case of envelope insulation, the adaptations to the new thickness of the windowsill, balcony joints, etc.

Table 3 reports the costs of envelope measures referred to as the unit of element surface.

Table 3. Unit costs of envelope measures [EUR/m^2].

Envelope Measure	Milan	Rome
Partial restoration of walls plaster	71	83
General repair of windows	155	144
Additional roof waterproofing	23	27
ETICS on walls	130	151
New windows	639	739
Insulation of roof	47	68

Regarding the retrofit of the buildings' thermal systems in both *Anyway measures* and *Thermal system EEM* scenarios, the costs include the dismission of the existing supply units and the installation of the new ones together with proper devices to adapt them to the existing distribution and regulation system and other technical requirements (e.g., heat exchangers in DH substations, air side connections for individual AtoW DHW production, etc.). Table 4 reports the unit costs of thermal and PV system measures, referred to as the building level.

Table 4. Energy demand of current and insulated envelopes and unit costs of thermal and PV system measures [EUR/kW].

		MILAN		**ROME**	
		Reference Envelope	**EEMs Envelope**	**Reference Envelope**	**EEMs Envelope**
Annual demand [MWh]	SH	1245	405	479	112
	SC	41	7	95	46
	DHW	356		232	
Peak demand [kW]	SH	920	350	657	260
	SC	115	60	175	130
	DHW	97			
		Unit costs [EUR/kW]			
Decentralized gas-based boilers		112		222	
Individual DHW gas-based heaters		1970		1970	
Individual DX splits renovation		720		490	
Decentralized HT-AtoW_HPs		408		457	
Decentralized LT AtoW_HPs		710		775	
DH biomass		1100		1180	
DH GSHP		1600		1680	
DH SolTh+ decentralized WtoW_HP		7135		1900	
Individual DHW AtoW_HP		4930		4930	
PV system (26 kWp)		2240		2130	

In particular, the costs to build the centralized DH scenarios include 200 EUR/kW for substations and 500 EUR/m for the network realization [64], the latter determined by considering a thermal energy density of 1.5 MWh/m [65]. For the seasonal solar thermal storage, the size of 2.3 m^3 of water per m^2 of the solar collector was assumed, with a cost of 250 EUR/m^3 [66].

The cost of the different scenarios was assessed in terms of their annual cost, defined as the sum of the annual cost of building management and maintenance, the annual discounted instalment of initial costs, and the product of the cost of the initial investment and the annual discount factor. A calculation period of 30 years and an interest rate of 3%, according to the IEA Annex 75 methodology [34,49], which is in line with the EU recommendation [67,68], were considered. The calculation did not include any fiscal support instrument, such as incentives and tax deductions. Energy prices were set equal to 0.219 EUR/kWh for electricity, 0.081 EUR/kWh for natural gas, and 0.027 EUR/kWh for biomass in DH, according to real data from the third quarter of 2021 [69]. A service life of 30 years was considered for the envelope measures and 15–20 years for thermal systems, in addition to their regular maintenance.

Finally, adopting a variation trend in the cost of energy and the inflation rate characterizing the previous five years (assumed as 3% and 1%, respectively), the NPV of the extra costs for the different intervention scenarios was calculated to assess the PBT.

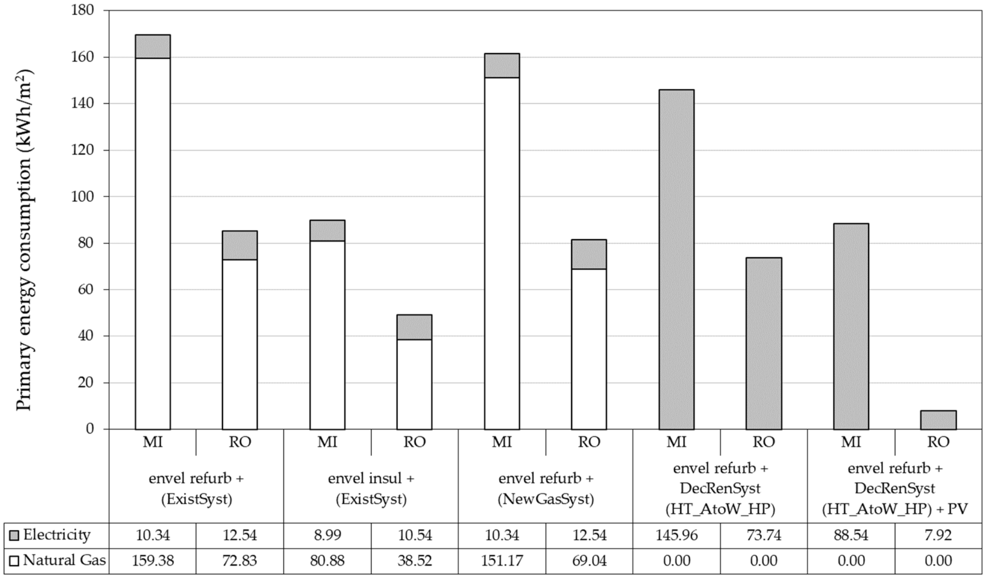
3. Results

This section presents the results stemming from the different evaluations of the upgrading scenarios proposed for implementing the generic district case studies in Milan and Rome. First, Section 3.1 reports the evaluation in terms of the energy performance of the generic districts under different upgrading scenarios, followed by a cost-effectiveness assessment of the same proposed scenarios and their PBT included in Section 3.2. Finally, the cost-effectiveness of the proposed scenarios was also assessed regarding the rise in energy prices taking place from the third trimester of 2021 to the first trimester of 2022.

3.1. Primary Energy Consumption of Retrofit Scenarios

The next figures show the primary energy consumption stemmed from the defined retrofit scenarios (Section 2.2). The primary energy conversion factors adopted were taken from the Italian inter-ministerial decree [57] (i.e., 1.05 for natural gas, 2.42 for electricity, and 1.0 for biomass).

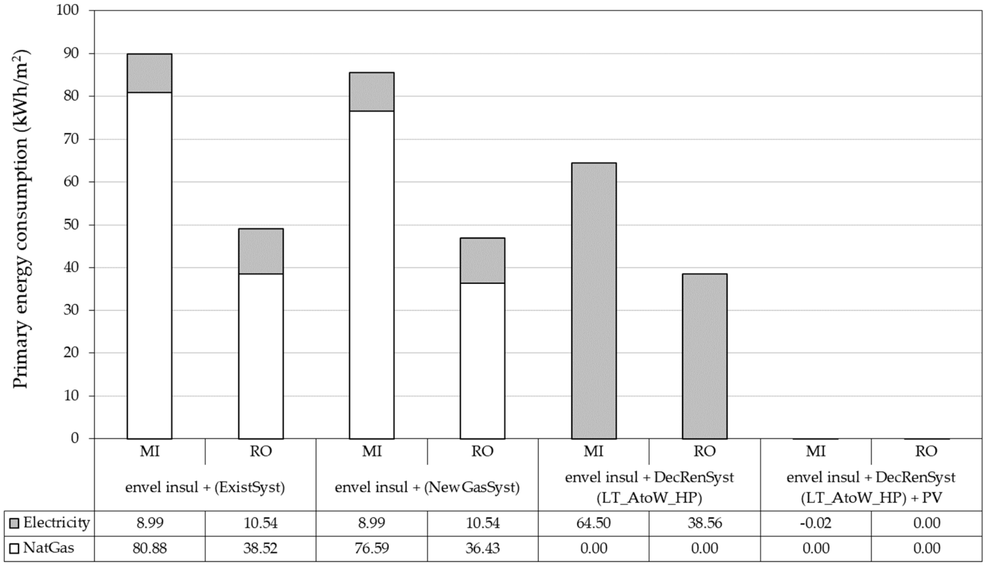
Figure 2 presents the primary energy consumption clustered by energy source (natural gas or electricity) obtained in five different scenarios built on the *Reference case*. Taking an *Anyway measures scenario* as a referent, the chart shows that replacing the existing thermal systems with more efficient gas-based technologies or even adopting a renewable-based implementation through air source HPs would imply a slight decrease in primary energy in both cities (4.8% and 4.4% less in the first scenario and 14% and 13.6% less in the second one, for Milan and Rome, respectively). On the contrary, insulating the buildings' thermal envelopes would bring strong reductions (47.1% in Milan and 42.5% in Rome). If the replacing air source HPs are integrated with a supporting PV system instead, a similar reduction would be obtained to that of the envelope insulation in the case of Milan (47.8% less), while in Rome, due to a warmer climate context, the amount of electricity produced by the PV can bring the primary energy consumption near to zero (90.7% less).



	MI	RO	MI	RO	MI	RO	MI	RO	MI	RO
	envel refurb + (ExistSyst)		envel insul + (ExistSyst)		envel refurb + (NewGasSyst)		envel refurb + DecRenSyst (HT_AtoW_HP)		envel refurb + DecRenSyst (HT_AtoW_HP) + PV	
▨ Electricity	10.34	12.54	8.99	10.54	10.34	12.54	145.96	73.74	88.54	7.92
☐ Natural Gas	159.38	72.83	80.88	38.52	151.17	69.04	0.00	0.00	0.00	0.00

Figure 2. Primary energy consumption (kWh/m^2) of the generic district in Milan and Rome through five upgrading scenarios, making the buildings undergo *Anyway measures*.

Figure 3 represents the primary energy consumption obtained in four different scenarios that upgrade the thermal systems by adopting a decentralized approach. This set of scenarios considers the buildings' already-insulated thermal envelope.

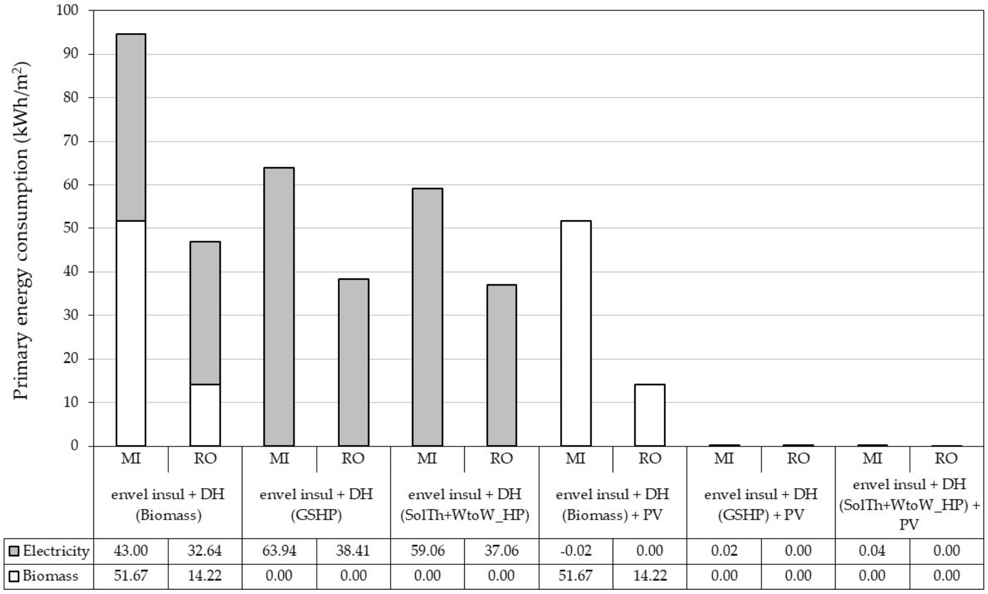


	envel insul + (ExistSyst)		envel insul + (NewGasSyst)		envel insul + DecRenSyst (LT_AtoW_HP)		envel insul + DecRenSyst (LT_AtoW_HP) + PV	
	MI	RO	MI	RO	MI	RO	MI	RO
▨ Electricity	8.99	10.54	8.99	10.54	64.50	38.56	-0.02	0.00
☐ NatGas	80.88	38.52	76.59	36.43	0.00	0.00	0.00	0.00

Figure 3. Primary energy consumptions (kWh/m²) of the generic district in Milan and Rome through four decentralized upgrading scenarios with the buildings’ envelope insulated.

The greatest reductions are observed by switching to a RES-based system. Having insulated the buildings' envelopes, replacing the existing gas-based systems with low-temperature HPs for SH provides a primary energy consumption decrease of 28.2% in Milan and 21.4% in Rome. Implementing a PV-supporting system brings primary energy consumption to zero.

Lastly, Figure 4 shows the primary energy consumption of generic district case studies if the existing thermal systems were upgraded through a centralized approach in which the buildings were connected to a RES-based DH network for SH. As in the previous assessment, the building envelopes were considered insulated.



	envel insul + DH (Biomass)		envel insul + DH (GSHP)		envel insul + DH (SolTh+WtoW_HP)		envel insul + DH (Biomass) + PV		envel insul + DH (GSHP) + PV		envel insul + DH (SolTh+WtoW_HP) + PV	
	MI	RO	MI	RO	MI	RO	MI	RO	MI	RO	MI	RO
▨ Electricity	43.00	32.64	63.94	38.41	59.06	37.06	-0.02	0.00	0.02	0.00	0.04	0.00
☐ Biomass	51.67	14.22	0.00	0.00	0.00	0.00	51.67	14.22	0.00	0.00	0.00	0.00

Figure 4. Primary energy consumptions (kWh/m²) of the generic district in Milan and Rome through six centralized upgrading scenarios with RES-based DH networks with the buildings' envelope insulated.

Amongst the proposed scenarios, the greatest reduction in primary energy consumption can be obtained through the implementation of DH fuelled by a solar thermal system, coupled with seasonal thermal storage and water-to-water HP substations (37.6% less in Milan and 20.9% less in Rome), closely followed by the scenario that considers a GSHP to supply the DH network (32.5% less in Milan and 18.1% in Rome). Again, integrating PV would zero the primary energy consumption in all cases, but for the biomass-based system, the energy consumption for biomass exploitation will remain.

3.2. Cost-Effectiveness of Retrofit Scenarios

The next figures show a cost-effectiveness assessment of the defined scenarios to upgrade the generic districts in Milan and Rome, according to the economic criteria predefined in Section 2.3.

Figure 5 shows the cost-effectiveness assessment of measures to upgrade the buildings of the generic districts, making them undergo *Anyway measures*. In other words, it was investigated whether investing in the envelope insulation or directly installing new more efficient thermal systems was cost-efficient, considering the energy performance of a *Reference case*. Amongst all the considered strategies, only the case in Milan reports the insulation of building envelopes as a cost-effective strategy, not only reducing annual costs (from an initial value of 21.10 EUR/m^2 to 19.32 EUR/m^2), but also decreasing the primary energy consumption up to 47%.

In the case of Rome, insulating the building envelopes has a lower impact on energy consumption due to lower heating demands, without a reduction in annual costs compared to making the building undergo *Anyway measures* (Figure 5).

The most energy-efficient strategies (i.e., switching to a RES-based system through HPs coupled with PV) would eventually bring a 13% increase in annual costs in Milan and a 9% increase in Rome (Figure 5).

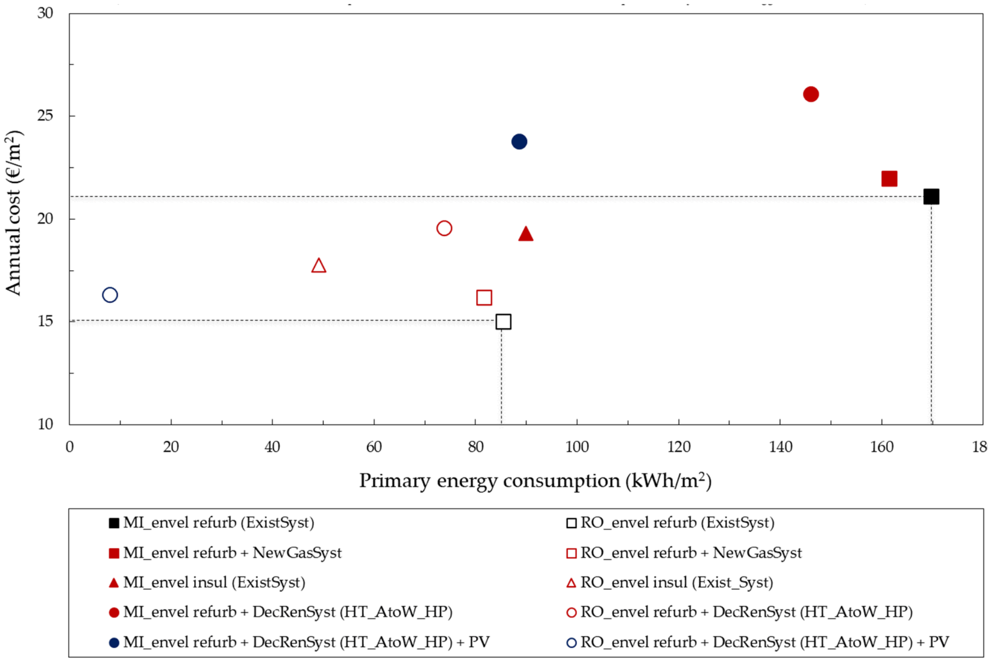


Figure 5. Cost-effectiveness of the five upgrading scenarios for the generic district in Milan and Rome making the buildings undergo *Anyway measures*.

Figure 6 shows the cost-effectiveness of adopting decentralized solutions to upgrade the existing thermal systems once the building envelopes are insulated. The chart shows that none of the proposed decentralized systems would bring further benefits in terms of cost-effectiveness. Again, the RES-based approach with HPs and PV would be the most energy-efficient strategy, covering all the energy needs of the building, but still implying a small increase in annual costs of around 0.04% in Milan and 0.03% in Rome.

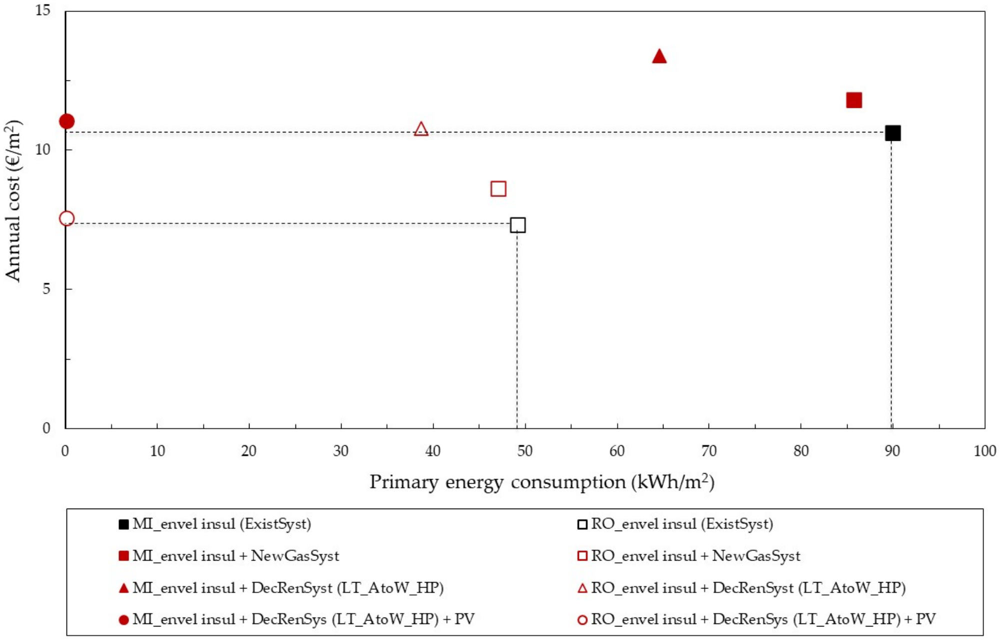


Figure 6. Cost-effectiveness of the four decentralized upgrading scenarios for the generic district in Milan and Rome with the buildings' envelope insulated.

Figure 7 shows the cost-effectiveness assessment of centralized scenarios by connecting the buildings to a RES-based DH network, also considering the buildings' envelopes as already insulated. In both cities, biomass seems to be the most convenient source to fuel a DH network, both integrating PV systems and not. Biomass-based solutions are however the strategies that bring the greatest primary energy consumption to the point that whenever PV systems are considered, the other two approaches—GSHP and solar thermal with seasonal thermal storage—bring energy consumption to zero. The solutions that consider solar thermal systems coupled with seasonal thermal storage always show the least convenience from an economic point of view, especially in Milan, in the absence of PV integration.

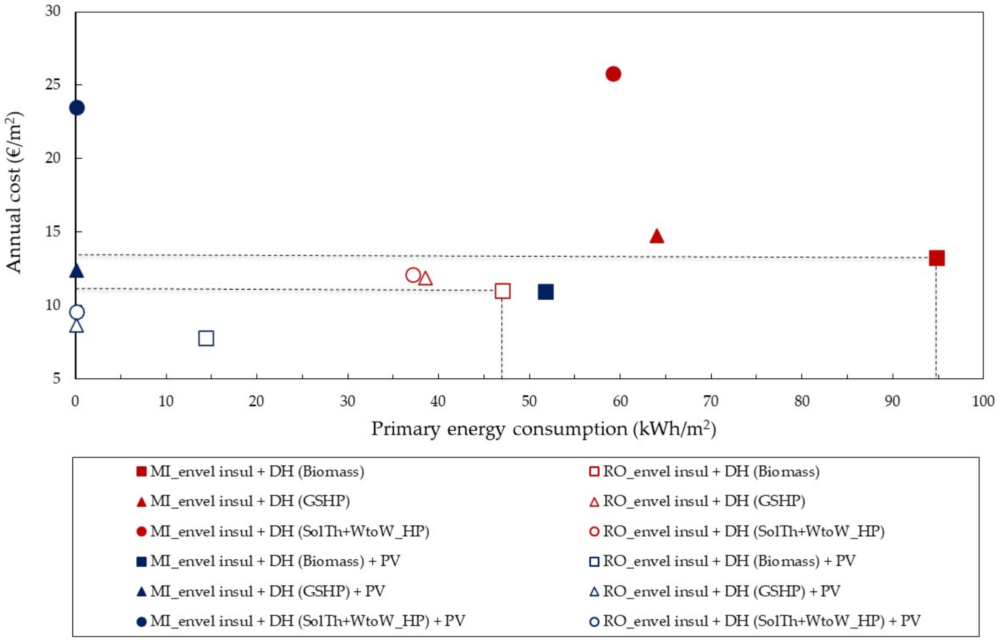


Figure 7. Cost-effectiveness of the six centralized upgrading scenarios with RES-based DH networks for the generic district in Milan and Rome with the buildings' envelope insulated.

In the following charts, the NPV and PBT of the different intervention strategies are presented. Only the scenarios revealing a useful PBT within 30 years are reported.

Figure 8 presents an assessment of the extra costs that would imply insulating the building envelopes and/or upgrading the thermal systems, taking an already-refurbished building through *Anyway measures* and new gas-based plants as a starting point. The insulation of the building envelopes implies a PBT of 13 years in Milan, while that in Rome sets a PBT pf 30 years. Adopting decentralized solutions through high-temperature HPs would bring a PBT of 21 years in Milan and 15 years in Rome, while insulating and adopting low-temperature HPs with PV integration reports 13-year and 19-year PBTs for Milan and Rome, respectively. Low-temperature HPs without PV integration are not convenient in any case: Milan would suppose a greater PBT rather than considering the PV addition (16 years), while the PBT based on the adoption of this scenario in Rome would imply no reports since it presented a 38-year PBT.

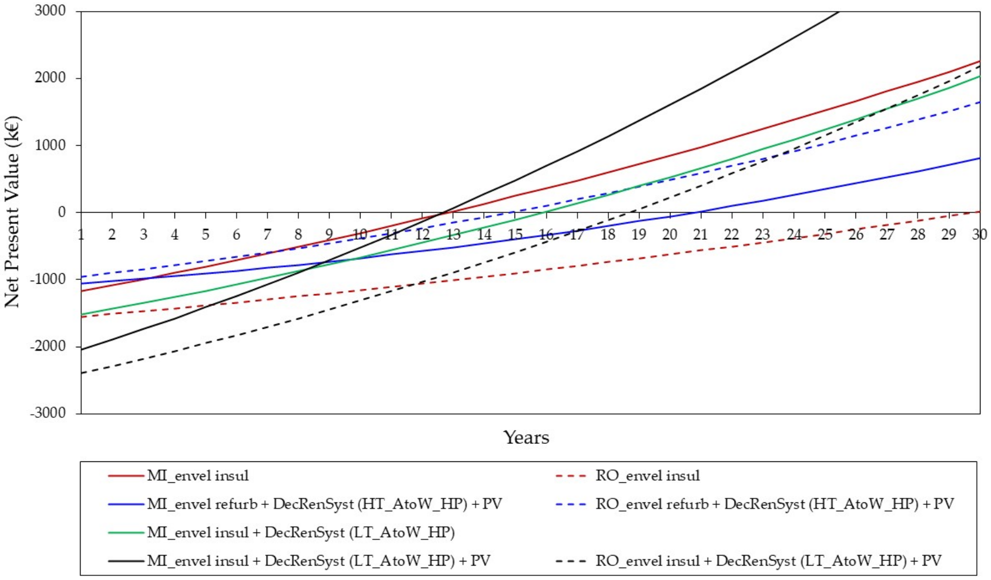


Figure 8. NPV (k/EUR) and PBT (years) for different scenarios to upgrade the buildings' envelopes and/or implement decentralized solutions, as extra costs from a reference case with the buildings' envelopes refurbished through *Anyway measures* and existing thermal systems replaced with new gas-based ones.

Figure 9 presents the extra costs that would arise from upgrading the thermal systems to RES-based ones with PV integration, taking already-insulated building envelopes and new gas-based plants as a starting point. The PBTs of the upgrading solutions for thermal systems that did not integrate PV systems have not been reported as they all presented PBTs greater than 30 years. For instance, biomass-fuelled DH networks in Milan reported a 31-year PBT, highlighting the convenience of adopting PV-integrated solutions in both cities. The PBT of the reported solutions ranges between 12 and 17 years, except for the scenario that considered a solar thermal DH with seasonal thermal storage in Milan, which was not reported due to a PBT of 41 years.

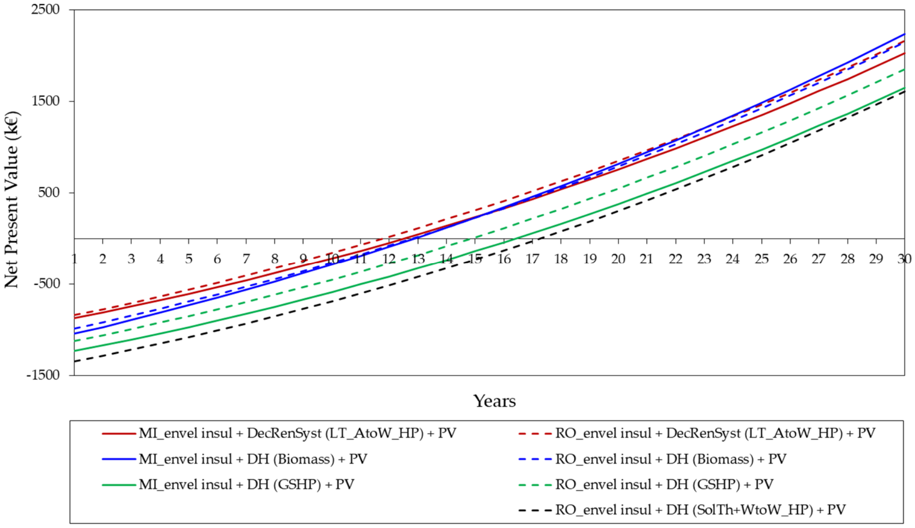


Figure 9. NPV (k/EUR) and PBT (years) for different scenarios to upgrade the buildings' thermal systems with RES-based thermal systems with PV integration, as extra costs from a reference case with the buildings' envelope insulated and existing thermal systems replaced with new gas-based ones.

Additionally, the present research aims to highlight the effect of increased energy prices, such the one experienced in the first quarter of 2022 [25], on the convenience of different investigated scenarios.

Figure 10 shows the PBT after the strategies' increase in energy prices, which implied insulating the building envelopes and/or upgrading the thermal systems, taking an already-refurbished building through *Anyway measures* and new gas-based plants as a starting point. Compared to the previous assessment, as reported in Figure 8, all PBTs are reduced, even setting below 10 years. In this case, Rome deserves special attention, as low-temperature HPs without PV support presented greater PBTs than 30 years, and now they are set at 10. On the contrary, the PBT of low-temperature HPs with PV integration would

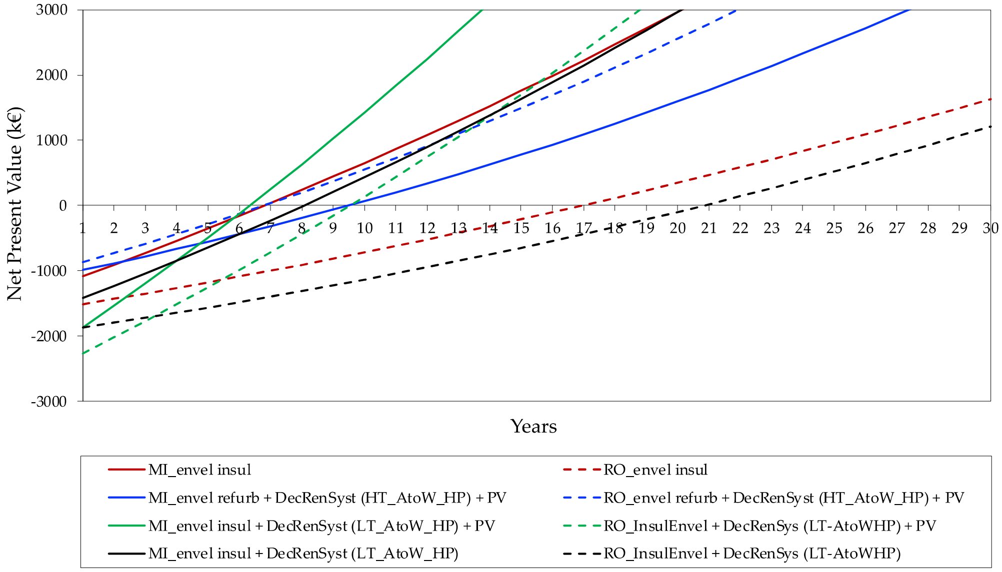


Figure 10. NPV (k/EUR) and PBT (years) for different scenarios to upgrade the buildings' envelopes and/or implement decentralized solutions, as extra costs from a reference case with the buildings envelopes refurbished through *Anyway measures* and existing thermal systems replaced with new gas-based ones, after the increase in energy prices.

Figure 11 shows the second set of strategies: upgrading the thermal systems to RES-based ones with PV integration, taking already-insulated building envelopes and new gas-based plants as a starting point. In this case, the PBT reduction in all PV-integrated solutions is set between 5 and 8 years, but for solar thermal systems with seasonal thermal storage and PV support, a PBT of 21 years is still presented, despite becoming a convenient strategy in Milan after the prices rise. Biomass-fuelled DH now shows a 10-year PBT in Milan, while it arrives until 30 years in the case in Rome (not reported in the chart). The least convenient scenarios are those that consider low-temperature HPs without PV, presenting a 21-year PBT in Milan and a PBT higher than 30 years in Rome; as a result, the latter is not reported in the chart.

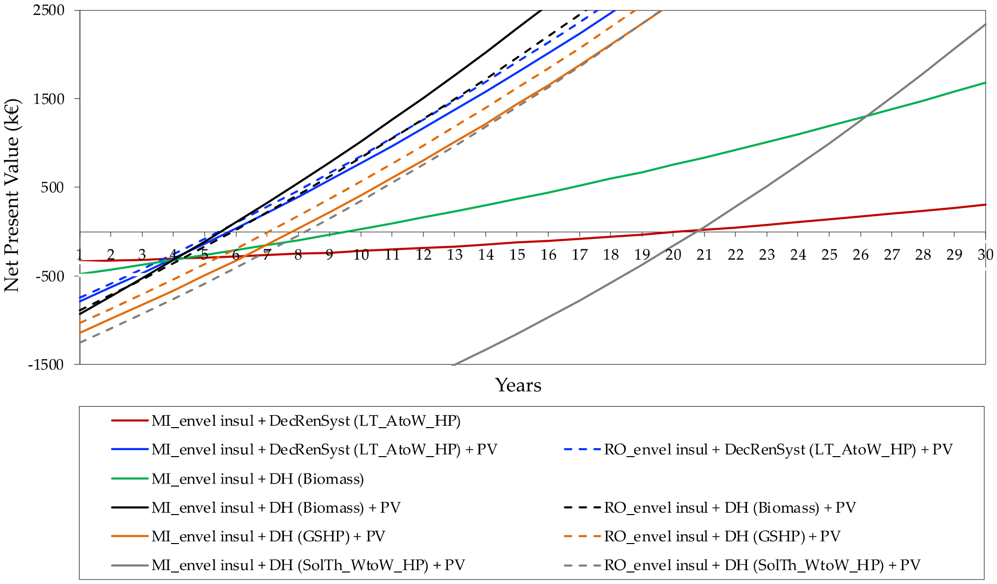


Figure 11. NPV (k/EUR) and PBT (years) for different scenarios to upgrade the buildings' thermal systems with RES-based thermal systems with PV integration, as extra costs from a reference case with the buildings' envelope insulated and existing thermal systems replaced with new gas-based ones, after the increase in energy prices.

4. Conclusions

Within the framework of the International Energy Agency Annex 75 project, the present study aimed to assess the cost-effectiveness of building renovation scenarios at the district scale, considering prevailing SH-dominated climates in Italy as a representative area of Southern Europe Mediterranean countries. A series of building renovation strategies are investigated and compared through a generic district approach, with BEMs being representative of the Italian housing stock from the period 1960–1980, placed in Milan and Rome. For each generic district, a set of energy efficiency scenarios (based on measures used to improve the building envelopes) and a set of feasible improved energy supply scenarios are assessed, including centralized and decentralized systems with the integration of RES, seasonal thermal storage, and PV support, from the perspective of primary energy consumption and global cost.

In general, insulating the building envelopes is only cost-effective in the northern areas of Italy. In addition to this, decentralized systems at the building level through low-temperature air-to-water heat pumps, coupled with PV support, bring primary energy consumption to zero but are a less convenient strategy from the economic point of view, as this implies a higher investment than just insulating the building envelopes remaining within the existing gas-based thermal systems. Due to the wider availability of solar radiation in the case of Rome, a combination of these two strategies would have a shorter PBT (19 years) than just insulating the envelope (30 years).

In the case of an insulated building envelope, the switch to district net scenarios based on biomass or GSHP is always cost-effective if coupled with PV systems. Moreover, the PV system makes DH solar thermal cost-effective in the case of Rome. Otherwise, implementing these DH technologies without PV integration would generate greater annual costs and PBTs greater than 30 years, which are not convenient.

A further step in the investigation highlights that some scenarios could improve the convenience following a hypothetical rise in energy prices, such as the one taking place in recent months. As such, decentralized and centralized strategies with PV show PBTs smaller than 10 years, except for the solar thermal-based DH with PV in Milan. On the contrary, implementing low-temperature HPs without PV support in Rome, which presented more than a 30-year PBT before the rise in energy prices, sets a 10-year PBT after the increase, which is even shorter than the PBT for the same strategy integrating PV. The only centralized strategy without PV integration that benefits from the price increase is the biomass-fuelled DH in Milan.

This study aims to guide policymakers, companies working in the field of energy transition, and building owners in upgrading existing Italian building stock in a cost-effective way towards low-energy solutions and related emissions. Moreover, given that the considered context partially shows warm-climate features, i.e., in the case of Rome, the research outputs can provide insights on building energy by upgrading to those European areas, thus presenting a low SH energy demand and the large availability of solar energy resources.

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