University of Bergamo
&
University of Naples Federico II

PhD Program in Technology, Innovation and Management
XXXIV Cycle

PhD Thesis

ENERGY AND ENVIRONMENTAL DESIGN OF THE BUILT ENVIRONMENT: MULTI-OBJECTIVE OPTIMIZATION STUDIES, FROM THE SINGLE BUILDING TO THE DISTRICT

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> *“Anything else you're interested in is not going to happen*
> *if you can't breathe the air and drink the water.*
> *Don't sit this one out. Do something. Make it sustainable.* “

CHAPTER 1. Introduction

1.1. Background

Human political and socio-economic spheres are deeply influenced by energy consumption and polluting emissions, and thus it is universally recognized that a sustainable development and a green, low-carbon economic represent the most crucial challenges of our epoque. World energy consumption increased by just 1% in 2016, following a really weak growth during the last years (*e.g.*, 0.9% in 2015 and 1% in 2014) [1]. Referring to the European Union (EU), energy consumption is even decreasing (the 10-year average is 1.1% per year [1]) because of EU strict policy about energy conservation and efficiency [2,3] (but also of economic crisis). However, even if energy efficiency and increasing energy conversion from renewables are interested by a great focus, a big effort is still fundamental to reduce global energy needs in order to promote sustainability.

Within this context, many international agreements have been signed. The “Roadmap for moving to a competitive low carbon economy in 2050” [4] establishes the target of reducing greenhouse gas (GHG) emissions by 80–95% by 2050 in comparison with the levels of 1990. The “Paris Agreement” [5] sets out the goal of keeping the increment of the global average temperature below 2°C above pre-industrial levels, and it also aims at limiting the aforementioned increment to 1.5 °C. Moreover, it establishes to peak the most the GHG emissions and to boost their absorbance according to the best available technologies, in order to attain a balance between emissions and removals shortly after 2050. These goals cannot be reached without a substantial effort for the improvement of the energy performance of buildings. Indeed, it is well known that the main responsible of energy use, energy waste, polluting emission and thus anthropogenic negative impact of the world climate is the building construction sector. In EU countries, buildings are responsible for about 40% of the energy consumption, 36% of the CO_2-eq emissions and 55% of the electricity consumption, and the shares are really similar at global level [6, 7]. Therefore, a rapid boost of the energy efficiency of buildings is fundamental in order to reduce the global energy use and to promote the sustainability of the environment. Two are the possible key-strategies to achieve tangible results in reducing the impact of buildings on the environment:

1) designing new nearly-zero energy buildings (nZEBs), whose main characteristic is to have an almost null energy impact on the environment. The main limit of this strategy is that the replacement rate of the building stock is really low – *i.e.* it is included between 1.0 and 2.0% per year [6];
2) promoting the energy retrofitting of the existing buildings. Indeed, the stock of buildings is old – more than 90% of EU buildings was built before 1990 –, and so an adequate energy retrofit of the building stock may generate a decrement of the energy consumption of the EU of around 5-6% and of the CO_2-eq emissions of around 5% [7].

However, the path is very challenging. Indeed, it should be noted that the more and more pressing requests of comfort, according to all point of views (lighting comfort, thermal comfort, hygrometric comfort), are determining a constant increase of energy consumption, due to the active energy systems installed in our houses, so that, only as example, most of residential buildings, especially in the Mediterranean region, are now equipped with systems and equipment for cooling. Only some years ago, this energy use was absent, thus, even if the available technologies improve their energy efficiency, this increment of efficacy is partly or completely nullified by the increase of users' expectation in matter of comfort. On the other hand, when cost reasons or energy availability are not so capillary diffused, the so-called phenomenon of energy poverty occurs, with all negative impacts described, for examples, by milestone papers of Santamouris [8] and Santamouris *et al.* [9, 10] and recently by Scarpellini *et al*. [11]. About it, it should be observed that there is also a special office of the European Institution whose aim is to contrast the energy poverty [12], and that the EU is putting significant effort towards energy efficiency improvement of buildings. In fact, with the Directives "2002/91/EU" (Energy Performance of Building Directive, EPBD) [2] and "2010/31/EU" (EPBD-Recast) [3], the EU countries have started a common path with the aim to reduce the energy impact of buildings and the polluting emissions related to them. In addition, recently, an updated version of the EPBD has been released, namely the Directive

"2018/844/EU" of the European Parliament and of the Council "amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency" [13], with a view to the goal of 2050 of cutting off the CO_2-eq emissions of the EU by more than the 80% compared to 1990. In this Directive, it is highlighted that innovative strategies improving the energy efficiency of buildings should focus not only on the envelope, but also on the active energy systems and all their components, and that both their technical and economic feasibility should be guaranteed.

Several potential technologies have appeared during last years, but their economic feasibility constitutes one of the greatest obstacles to their widespread diffusion. Indeed, the energy design or retrofit of one or more buildings is a high-difficulty task, due to the different and often contrasting perspectives to be satisfied. On one hand, there is the public point of view, whose main aim is to reduce the energy and environmental impact of buildings. On the other hand, the private perspective primarily aims at maximizing the financial benefits and only secondarily at reducing the environmental impact. For this reason, aiming at combining both energy and financial objectives, the EPBD-Recast has established that among all the possible energy design/retrofit strategies, the so-called "cost-optimal" one should be implemented [14]. Several different energy efficiency measures (EEMs) that involve the passive, the active energy systems, other than renewable energy sources, should be combined and investigated, in order to find the aforementioned "cost-optimal" solution, which allows to simultaneously minimize the global cost (GC) and the non-renewable energy consumption of buildings [15].

Finally, two possible scale-level approaches can be adopted in order to investigate the EEMs that should be applied to guarantee the best trade-off between the public perspective and the private one: a) the building scale – often modeled as stand-alone – technique; b) the district/neighborhood of buildings approach, which involves all the external background. The former may be characterized by a higher level of detail, but, unfortunately, limiting the focus exclusively on the investigated building, in certain cases it may happen that the results may be inaccurate, not considering the so-called "inter-building effect" and the shadowing effect produced by the neighboring buildings. On the contrary, the district/neighborhood scale approach may be characterized by a lower level of detail – if referring to each building singularly and comparing the developed model to the same model obtained by using a stand-alone approach –, but both the inter-building effect and the shadowing one are considered, and so results should be more accurate, especially compared to stand-alone technique ones scaled to an entire neighborhood or district. Generally, district energy modeling approaches are useful because they enable to attain a satisfying integration in planning, control and management [16-18]. In addition, due to many actions implemented by national and international governments for promoting local energy communities, the accurate district energy modeling results even more crucial.

All told, reducing the energy and environmental impact of buildings is a complex and arduous task, in fact:

- it can focus on the energy design of new buildings or on the energy retrofit of existing ones;
- it involves EEMs that affect different parts of the building system – *i.e.*, the envelope and the active energy systems, considering also the implementation of renewable energy systems;
- it can be conducted considering different kind of approaches – *i.e.*, stand-alone approaches or district level ones.

Generally speaking, this task yields a series of critical, still-open questions that have aroused a heated discussion in the scientific community. The aim of this study is to provide a "general methodological approach" to face the energy and the environmental issues due to the building sector. More in detail, this general approach is fitted and "optimized" according to different situations and considering all the possible scale-levels, from the single building to the whole district. Therefore, even if in this study different multi-objective optimization approaches are presented, all are characterized by the same "primitive" metholodogy and by the same aim, which is the improvement of the energy efficiency of the building sector.

1.2. Organization of the thesis

After the present Introduction (*Chapter 1*) and before the Conclusions (*Chapter 8*), the thesis is articulated in the following *chapters*:

CH. 2. The state-of-art of scientific literature in building and district/neighborhood energy modeling and retrofitting is presented.

CH. 3. A multi-objective optimization approach for the optimization of the energy design of new buildings is presented. It is focused on the optimization of the envelope composition. Then, it is applied to a newly-built five-story residential building ubicated in different Italian cities.

CH. 4. A multi-stage multi-objective approach for the energy retrofit of existing buildings is presented. Then, it is applied to a typical office building supposed to be situated in Naples (Italy).

CH. 5. A new integrated framework for the energy modeling and retrofit planning of districts/neighborhoods of buildings is presented. Then, it is applied to an existing neighborhood ubicated in Naples (Italy).

CH. 6. The integrated framework presented in the previous chapter is detailed and enhanced. Indeed, the approach here presented investigates more energy efficiency measures, which affect all the possible components of the building system. Moreover, it considers also the implementation of PV sharing together with the other energy efficiency measures, and studies the energy, financial and environmental implications of the Italian massive public grant policy named "Superbonus 110%" too. Then, the proposed approach is applied to an existing neighborhood ubicated in Naples (Italy).

CH. 7. A novel approach to conduct analyses on the effects of energy retrofit measures on neighborhoods/districts of buildings is presented. Differently from the approaches described in the two previous chapter, this one takes into account also the stochasticity of the human behavior and the effects of the global warming when planning the energy retrofit. Then, the proposed approach is applied to an existing neighborhood in Naples (Italy).

It is noted that the description of each methodology is followed by the application to a case-study, which acts as a sort of validation procedure.

"Energy efficiency is the most
powerful renewable source"

CHAPTER 2. Roadmap for the energy efficiency of the building sector

2.1. Background

In recent years, a great effort has been made, at international level, for reducing the energy consumption of buildings. Indeed, the construction sector represents one of the main challenges to deal with, in order to guarantee a sustainable development for our sons and, more in general, compatible with a suitable common future.

At the European Union level, starting from 2002, with the entrance into force of the EPBD (Energy Performance of Building Directive – 2002/91/CE [2]), for the first time in the history, all the Member States decided to establish common guidelines for improving the energy performance of buildings, concerning both new and existing architectures. In this regard, at national level, several laws have been formulated for receiving the European mandatory trends, by taking into account the local peculiarities of the building stock, technology and construction activities.

Some years later, the EPBD-Recast (2010/31/EU [3]) has been enacted. Really, this was only a further step of a continuous process aimed at reducing, with targets increasingly more ambitious, the impact of human activity on climate change. This Directive introduces the goal of nearly zero-energy buildings (nZEB), by underlining both the high-required performance as well as the economic feasibility of the 'building system', by means of the new concept of cost-optimality.

More recently, an updated version of the EPBD has been released, namely the Directive "2018/844/EU" [13], with a view to the goal of 2050 of cutting off the CO_2-eq emissions of the EU by more than the 80% compared to 1990. In this Directive, it is highlighted that innovative strategies improving the energy efficiency of buildings should focus on both the envelope and the active energy systems, and that both their technical and economic feasibility should be guaranteed.

2.2. State of art

Many strategies have been studied, aiming at contrasting the massive impact of buildings on the environment [19-21]. In this matter, reliable energy modeling and simulations are first fundamental steps to improve building energy performance. Building modeling can be performed by considering two different scales, *i.e.*, the building scale – often modeled as stand-alone – and the district/neighborhood one, which involves all the external background. Generally, single building approaches are the most common due to their lower computational burden compared to district/neighborhood ones, but they are usually less accurate, neglecting the so-called “inter-building” effect and the shadowing produced by the neighboring buildings. On the other hand, district energy modeling approaches are useful because they enable to attain a satisfying integration in energy planning, control and management at city-scale [16-18], allowing to attain higher levels of energy efficiency. In addition, taking into account both the inter-building effect and the shadowing one, they provide more accurate results, even if the computational effort is much more important compared to the stand-alone approaches. In addition, due to many actions implemented by national governments (*e.g.,* for promoting local energy communities), the accurate district energy modeling results even more crucial. Note that also the implications due to the clinometric conditions of the surrounding landscapes should be taken into account, especially when the investigated buildings are ubicated in rural areas, where the inter-building effect and the local shadowing due to neighboring buildings is neglectable. Moreover, the clinometric shadowing results even more crucial when a rigorous and detailed analysis of the energy production of PV systems to be installed on the investigated buildings is performed. In this case, indeed, the landscape and, more precisely, the relative position of the investigated buildings to the landscape has an influence in determining the hours of insolation during a day for these buildings, and so in determining with a higher level of detail the solar irradiation feeding PV panels, thus their productivity. As predictable, also in this case, the influence due to surrounding landscapes becomes neglectable if local shadowing affects PV panels.

However, being the aim of this thesis the proposition of a general methodological approach or, more in detail, the proposition of five different techniques based on the same “primitive” approach to cope with most of the energy and environmental issues due to the building sector, and so not aiming at proposing a detailed approach for designing PV systems, as well as being considered as case studies only buildings ubicated in urban areas, where local shadowing effects are preponderant, the effects due to clinometric conditions of the surrounding landscape have been neglected.

All told, another distinction is necessary when investigating solutions in order to improve the energy performance of buildings. Indeed, the scientific community supports the necessity of acting on both newly-built and existing buildings. By acting on the former, it is possible to achieve higher results in terms of envelope quality, and so in terms of energy efficiency and thermal comfort, having the possibility to optimize each component of the stratigraphies. On the other hand, due to reduced replacement rate of buildings, the optimization of the energy efficiency measures (EEMs) – or energy retrofit measures (ERMs) – on existing buildings may allow to attain a higher impact on the collectivity, due to the low value of the actual replacement rate of the building stock.

Within this background, the current literature provides a large number of studies on the huge potentials of building energy efficiency improvement.

2.2.1. Stand-alone building approach

Aiming at optimizing the building energy performance, a distinction between newly-built buildings and existing ones should be done, as said. More precisely, for the former, the optimization results are generally better, and it is less complex to achieve nZEBs (nearly zero energy buildings) or NZEBs (net zero energy buildings) because the comprehensive optimization of the whole design is more feasible. On the other hand, the energy retrofit of existing buildings allows to attain a larger reduction of the energy impact of buildings, due to the low replacement rate of buildings.

All told, the evolution of the design and retrofit approaches, supported by the availability of new tools (*e.g.*, BIM – Building Information Modeling), promotes the achievement of successful and effective projects [22-24]. When referring to the energy design of new buildings, the attention should be focused especially on the proper design of the envelope, because the latter is crucial to strongly reduce energy consumption, enabling the designers to strongly minimize the thermal energy demand (TED). In fact, concerning a general-purpose building, over 50% of energy demand is due to the heat losses through the shell [25], thus the improvement of envelope energy efficiency is overriding. In this regard, recently, Chen *et al.* [26] showed that the optimization of the envelope design provides substantial energy savings, close to 50% compared to a common envelope. However, a global intervention on the composition of the envelope is possible only for new buildings, whilst existing ones still constitute the largest portion of buildings presently in service.

This could appear a trouble, but really this is not so, because there are many other solutions to reduce building energy consumption. In fact, while the envelope defines the TED, the primary energy consumption and the GHG emissions depend on the whole system "building + HVAC (heating, ventilating and air conditioning) system", and the designers operate on this whole system when they investigate the energy retrofit of an existing building. In this regard, the investigation of more effective energy retrofit strategies, even by implementing innovative energy efficiency measures (EEMs), is an active research field. Grillone *et al.* [27] conducted a review on innovative methods to investigate the energy retrofit of buildings. Serrano-Jiménez *et al.* [28] proposed a framework to support the designer in the decision-making process for the energy retrofit of buildings. Ballarini *et al.* [29] examined the energy implications of different EEMs – *i.e.*, the thermal insulation of the walls, the replacement of the windows, the replacement of the heat generators, and so on – applied to different typologies of Italian buildings. Aranda *et al.* [30] investigated retrofit solutions for buildings in Spain with the aim to maximize the energy savings and considered several different EEMs, such as the installation of thermostatic valves on radiators or the implementation of photovoltaic (PV) systems. PV systems are milestones in reducing the energy and environmental impact of buildings, as demonstrated in literature [31]. Ürge-Vorsatz *et al.* [32] conducted a review on the findings towards a net zero-energy buildings future. They stated that zero-energy buildings should maximize the renewable energy production, especially the PV production. Asif *et al.* [33] investigated the effects of a large-scale utilization of PV systems on the roofs of the buildings in Saudi Arabia. As case study, they examined the installation of PV systems on the buildings of the campus of the "King Fahd University of Petroleum and Minerals", finding that huge energy, financial and environmental savings could be achieved. Concerning the PV integration for buildings, in addition, the works of Shukla *et al.* [34] and Mavromatidis *et al.* [35] provided interesting insights, showing the high effectiveness of such systems.

All told, the design of new buildings can allow a comprehensive optimization of the energy performance because the constraints are significantly slighter compared to the retrofit of existing ones and the results are generally better, while, on the other hand, proper energy retrofits can allow to attain large-scale reductions in matter of energy and environmental impact of buildings. Therefore, the optimization of the design or the retrofit represents a priority to improve the energy performance of buildings, and this is the principal goal of the public stakeholders, since it allows to fight crucial issues of contemporary society such as climate change and energy poverty. However, when the optimization of building energy design or retrofit is conducted, it is fundamental to consider its cost-effectiveness and, eventually, the respect of a certain level of comfort, which are the principal aims of the private perspective. In such scenario, the optimization of building energy design or retrofit is a complex issue, which presents several potential objective functions and design variables. In this regard, thermal comfort – defined as "the order at which occupants have no intention to modify their environment" [36] – represents a crucial aspect [37], and huge attention should be paid to the indoor temperature of each thermal zone because it can cause discomfort and serious health issues [38, 39]. In addition, thermal comfort plays a fundamental influence on building energy consumption [40]. Thus, many studies were performed in this direction with the aim to better understand and quantify the extensive interaction between thermal comfort and energy performance [41, 42] as well as to investigate which are the best measures to optimize such interaction [43, 44]. Unfortunately, it is concrete the possibility that theoretical results could not be applicable to real buildings. This can occur because of the needed investment costs or, more in general, because of barriers related to economic implications. Thus, the energy design or retrofit optimization should consider all financial implications by taking into account proper economic indicators. Fan and Xia [25] proposed an approach to optimize the envelope of existing buildings, taking into account also the financial perspective. Rihsolt *et al.* [45] addressed the renovation of a Norwegian detached house using passive house components and renewable energy sources by investigating the trade-off among energy, economy and home quality indicators. Mills *et al.* [46] applied the techniques of the risk analysis to the energy efficiency design in the building sector. They described several approaches to quantify and manage the risk in order to reduce the uncertainty in energy saving assessment. Heo *et al.* [47] assessed the risks associated with investments concerning energy conservation measures for old buildings. As case study, they investigated the effectiveness of three different energy retrofit measures according to different financial indicators. Jafari and Valentin [48] proposed a decision-making framework for the selection of the energy retrofit measures to be applied to buildings considering also the financial benefits. Liu *et al.* [49] presented a framework to perform the analysis of the financial impact of the energy retrofit of existing buildings. Zheng *et al.* [50] investigated multiple energy retrofit packages for buildings, focusing especially on the financial and risk aspects. A similar study was conducted by Bleyl et al [51], who investigated in detail the financial implications of the deep energy retrofit of a building. In literature, there are many other interesting examples of energy retrofit studies and strategies that addressed the financial aspect too [52]. Moreover, many available studies considered also the public grant policies that EU Member States have adopted with the aim to increase the financial profitability of energy refurbishment [53]. Ascione *et al.* [54] optimized the energy retrofit of two different buildings, one ubicated in Italy and the other in Greece. They considered both the absence and the presence of public grant policies, outlining the importance of public funding for the energy retrofit of buildings task. Another interesting study is the one by Hong *et al.* [55], who applied a multi-objective approach based on the implementation of a genetic algorithm (*i.e.*, NSGA-II) to optimize the energy design of a university library facility located in Seoul, South Korea. The authors optimized the window type, the set point temperatures and the ventilation strategy, in order to minimize a weighted fitness function, including objectives related to energy, economic, and environmental performance. Different trade-off solutions were provided for addressing the different objectives. All told, concerning the economic aspects of building design or retrofit, there is another crucial issue related to financial availability and budget limits. Usually, designers have to limit the initial investments due to owners' constraints concerning the design budget. According to this, many researches were performed to identify optimal designs or retrofit with minimum investment cost [56]. Further important indicators to assess the economic feasibility of design or retrofit solutions are the payback period and the net present values of the investment because the private stakeholders (building occupants/owners) are quite sensitive to such metrics. For instance, Valdiserri and Biserni [57] referred to such indicators to assess the cost-effectiveness of retrofit measures of an office building located in Bologna (Italy). Several studies proposed novel techniques to help the professionals in choosing energy measures for building design and/or retrofit [58, 59].

However, even by considering financial implications and public grant policies, the results of the design or retrofit optimization still may be not transferable to real buildings, because they may be not really cost-effective when applied to the real World [60]. Indeed, in addition to the proper financial indicators, the accurate prediction of energy performance is fundamental to attain reliable and effective results for what concerns the EEMs to be applied [61]. Several techniques are available in literature for helping the designers in choosing the most appropriate EEMs for the energy design or retrofit of buildings [62]. Many of them focus on the early stage of the energy design of buildings, because, at the early stage, the optimization of building energy design is particularly arduous, being a multi-disciplinary problem involving architecture, several fields of engineering, mathematics and economics, as well as it can address several (often contrasting) objective functions. Attia *et al*. [63] found that around 93% of multi-objective optimization studies about building energy optimization referred to the early design.

More in general, many studies have been performed to find out which are the best strategies to minimize building energy needs and many other objective functions, such global costs, environmental impact, occupants' discomfort. Asadi *et al.* [64] proposed an optimization technique that makes use of a genetic algorithm, with the aim to minimize the cost, the energy consumption and the thermal discomfort hours. Those two latter objectives were the main aim also of Delgarm *et al.* in [65]. In matter of multi-objective optimization methods for building performance analysis, Nguyen *et al*. [66] provided an interesting and exhaustive literature review. Among the discussed techniques, the ones that make use of reliable simulation tools are the most suitable [67] because these allow to achieve consistent results in terms of energy and financial performance of buildings, considering most of the complex physical interactions that happen in the real World. For instance, the "parametric simulation method" approach is very common to improve building energy performance. According to it, the designer has to vary the input of each variable singularly with the aim to highlight the effect of the selected variable on the objective functions, and this procedure has to be iterated with all the variables. As predictable, the main limit is that this method often requires a huge computational time and it gives reliable results only in partial improvements because of the non-linear interactions among the different input variables. On the contrary, by means of the "simulation-based optimization" approach – or "numerical optimization" approach –, it is possible to automatically perform sequences of progressively better approximations to a solution that satisfies an “optimality condition”, previously-defined. This permits to attain the optimal solution to a problem (or a sub-optimal solution sufficiently close to the optimum [68]) with lower computational time and effort. Notably, ones of the most reliable dynamic energy simulation tools are EnergyPlus [69], TRNSYS® [70] or IDA ICE [71], allowing to achieve a dependable prediction of the design scenarios. These tools can be coupled with optimization algorithms to perform a simulation-based building energy optimization [68]. Generally, when a simulation-based approach is adopted, a simplification of the building model to be investigated should be done, but it is crucial to not over-simplify, in order to avoid the risk of inaccurate modeling of building phenomena. In addition, the convergence of the adopted optimization algorithm should be monitored. Convergence behaviors of different optimization algorithms are an extremely active research area [72, 73]. About errors, it is fundamental to say that they may occur because of infeasible combinations of variables (*e.g.*, windows areas that extend the boundary of a surface), output reading errors (as in the coupling between MATLAB® [74] and EnergyPlus), and so on. Furthermore, the entire optimization process may crash by a single simulation failure. To minimize such errors, some authors run parametric simulations to make sure that there are no failed simulation runs before running the optimization [66], or they make use of evolutionary algorithms, because even the presence of a failed solution among the population does not interrupt the optimization process. As optimization algorithms, genetic algorithms have been frequently used [63, 66, 68, 75-77]. They allow to implement both mono- or multi-objective optimization by performing the “Darwinian evolution” of a population of individuals that represent design scenarios. Multi-objective approaches include the Pareto optimization, which provides trade-off non-dominated solutions, collected on the Pareto front, which has dimensions equal to the number of objective functions. Then, the multi-criteria decision-making should be performed to pick the “best” solution – according to the used criterion – from the Pareto front.

Within this context, the following main limits to the current body of knowledge for what concerns the energy design or retrofit of buildings considering stand-alone approaches:

- limited domain of design scenarios investigated;
- huge computational effort required, and so most of the available approaches in literature are really time-consuming;

- financial implications not always are properly considered, with consequent inapplicability of the results to real world cases;
- usually, only single-objective optimization are performed, and so it is not possible to satisfy more than one category of stakeholders;
- the reduction of heat emissions is not usually considered;
- approaches may suffer from failures caused by simulation crashes.

2.2.2. District of buildings approach

In general, energy modeling and retrofit approaches at district scale permit to achieve good levels of integration in the task of planning the energy management of cities [16-18]. Deakin and Raid [16] studied smart cities and concluded that retrofit proposals should have neighborhood/district scale, also for social reasons. Van Leeuwen *et al.* [17] conducted a review on the urban energy transition in Netherlands and affirmed that, even if the integration of renewable energy in the built environment is possible by adopting both a stand-alone and a collective approach, the most interesting results are achieved mainly by means of the second one. A high scale level approach was adopted also by Salpakari *et al.* [18] with the aim to investigate the technical and financial potential of PV integration in the built environment. Generally, a high scale approach permits major improvements in lessening the impact of the building sector from the energy and the environmental perspectives [78, 79]. Rezaeiha *et al.* [78] adopted a city scale approach for studying the effects of the renewable energy integration in the built environment. Murray *et al.* [79] focused their study on the refurbishment of the Swiss buildings and districts, in order to reduce their environmental impact. They combined a simulation-based approach with a multi-objective optimization technique to minimize both CO_2 emissions and costs, and they conducted the analysis considering both the stand-alone building level and the district one. As final result, they affirmed that district level solutions are preferable to be applied to urban communities, while stand-alone ones should be applied to rural areas. Therefore, it is remarked that, in many cases, it is preferable to adopt this kind of approach – *i.e.,* neighborhood/district level scale – instead of focusing on stand-alone buildings, as often done in literature [80-82], because the neighborhood/district level scale approach permits to attain the highest improvements in terms of reduction of the impact of the building sector on the environment, other than higher levels of accuracy compared to stand-alone buildings energy modeling techniques. All told, among the neighborhood/district energy modeling approaches, two categories can be individuated: bottom-up and top-down [83, 84]. The former consists in modeling representative buildings to extrapolate the outcomes to similar buildings, while the latter handles aggregate data and implements statistical and macro-economic tools to predict future energy and cost patterns. Generally, top-down approaches do not perform accurate energy modeling and simulations on an hourly or a sub-hourly basis, but they process macro-data on a yearly or a monthly basis. Therefore, these cannot represent in detail the actual building energy behavior, which is highly dynamic. Carrión *et al.* [85] adopted a top-down approach with statistical data, and same is for Firth and Lomas [86], Wate and Coors [87] and Eicker *et al.* [88]. All these approaches are easy to be applied, but the accuracy of outcomes can be inadequate because the dynamics in building envelope inertia, transient heat transfer phenomena, energy systems’ operation and performance, building use and occupants’ behavior are not considered properly.

On the other hand, bottom-up approaches are more suitable to investigate optimal retrofit solutions for stand-alone buildings [89-91]. In this regard, Cerezo *et al.* [92] compared three different bottom-up techniques for individual buildings. They individuated a limited number of building types and scaled their investigation results to Kuwait City (Kuwait). Mastrucci *et al.* [93] used a similar approach for the city of Rotterdam. They studied only 16 buildings out of more than 300’000, and, then, they aggregated and scaled the results for the whole city. Both these approaches showed good reliability of the results in terms of building dynamics, but they did not consider the simultaneity of the energy loads. In addition, the application of a stand-alone building analysis approach to an urban scale level may result too computationally demanding, so it could be inapplicable to achieve reliable results in short time. For this reason, more efforts should be spent to identify reliable and feasible approaches for the energy modeling and analysis of districts and neighborhoods [94-96].

In this track, the literature review proposed by Reinhart and Cerezo Davila [97] is a milestone. They stressed the importance of adopting neighborhood and urban scale level approaches. In addition, they stated that a stochastic approach is crucial, aiming at reducing simulation errors, especially when proper calibration processes are not applicable due to lack of data and privacy issues. For this purpose, they affirmed that building occupants should be treated as individual agents rather than identical entities that simultaneously follow the same activities, which may be not realistic. On the district energy modeling techniques, also the review by Sola *et al.* [98] deserves to be mentioned. They compared the most common urban energy modeling frameworks and tools available in literature and highlighted once again the importance of assuming a district scale approach if the aim is to shift towards more sustainable cities. They affirmed also that one of the main challenges of the research should be to reduce the computational efforts required to create the energy models of the districts, even by using bottom-up approaches. In addition, they stated that the inter-building effect between buildings should not be neglected "a priori", as generally occurs when stand-alone building modeling approaches are applied. On the same track, Carrión *et al.* [85] addressed the energy modeling of neighborhoods and districts. They evaluated the energy consumption of buildings in Berlin (Germany) considering a long-term time horizon and concluded that the energy renovation efforts should be focused on multi-family buildings, being responsible of the highest energy demand. A similar work was proposed by Firth et. al [86], but it was focused on residential dwellings. They evaluated the effects of the implementation of ERMs on the building stock of Leicester (United Kingdom) and concluded that a high level of energy efficiency allows to cut down CO_2 emissions by 41%. However, they applied a simplified modeling approach based on archetypes. Wate and Coors [87] focused on the assessment of the thermal energy requirements for future energy demands. They proposed a framework for the evaluation of future thermal energy loads that can be applied to neighborhoods. Kaden and Kolbe [99] conducted a city-wide assessment of the yearly energy demands of buildings in the city of Berlin. They adopted a simplified energy modeling approach for their investigation, but they declared that a detailed representation of the thermal characteristics of the buildings is fundamental, having a significant influence on heat losses and energy demand. For what concerns the energy retrofit of districts, as previously seen, Mastrucci *et al.* [93] investigated the effects of ERMs on the thermal energy demand for heating of housing stocks in Rotterdam (Netherlands), with the aim to support sustainable urban planning. As specified by the authors, the proposed framework has some limits. Firstly, it is based on archetypes. Secondly, it is not possible to properly take into account different user profiles. Fonseca *et al.* [29] proposed a framework for the analysis and the optimization of energy systems in neighborhoods, in order to maximize the energy, financial and the environmental benefits, taking into account also the effects of a possible distributed generation. Once again, it is highlighted the importance of adopting a neighborhood scale level approach. Other interesting studies are the ones by Dirutigliano *et al.* [100] and Tommasi *et al.* [101]. Dirutigliano *et al.* [100] proposed a novel framework to evaluate different alternatives of building retrofitting at a district scale. As case study, they compared five different retrofit alternatives in a neighborhood located in Turin (Italy). However, as specified by the authors, the main limits are that the proposed framework is quite time-consuming and that the evaluation of the energy retrofit options needs to be improved. Tommasi *et al.* [101] developed a methodology for the generation and the evaluation of retrofit scenarios for districts, focusing on active ERMs, such as the replacement of heating, ventilating and air conditioning (HVAC) systems.

Notably, none of the aforementioned studies took into account the uncertainty in building energy demands due to the high stochasticity in occupant behavior. Actually, most of the district energy modeling and retrofit approaches available in literature are based on average energy demands, obtained by considering standardized usage profiles. Conversely, Pickering and Choudhary [102] dealt with the stochasticity of the human behavior in the energy modeling of districts, proposing a novel methodology for handling energy demand uncertainty. They examined different scenarios with the aim to minimize the cost of technology investment and operation. A single-objective approach was used, not considering the environmental impact as an additional objective function or performance indicator. In the same vein, Baetens and Saelens [103] presented a novel framework to take into account the stochasticity of the residential occupant behavior in districts' energy modeling. The limit is that the framework is focused only on the energy modeling, not considering the energy retrofit optimization task. Happle *et al.* [104] conducted a review on the occupant behavior in urban building energy models, stating that the energy demands are sensibly influenced by the behavior of the occupants. Moreover, they highlighted that there are no stochastic models available in the current state of the art considering "mixed-districts", comprising buildings with different use destinations. An *et al.* [105] developed a novel stochastic modeling method for districts of buildings that permits to take into account the diversity and the complexity of the occupant behavior. As case study, they investigated a residential district located in Wuhan (China). Results showed that neglecting the stochasticity of the occupant behavior would lead to an overestimation of the cooling loads. The main limits are that only cooling demand was assessed and energy retrofit was not addressed/optimized. As seen, most of the studies on the topic focused only on the energy modeling task, without investigating the effects of stochastic occupant behavior on the retrofit optimization process.

Another limit of the current body of knowledge consists of neglecting the effects of global warming on building energy performance. More in detail, even if one of the main aims of this research field is to reduce the impact of the building sector on the environment, few studies took into account the influence of global warming on energy, financial and environmental performance indicators in the retrofit planning of districts/neighborhoods [106-108]. In this regard, climate change cannot be neglected "a priori" when a reliable analysis of building energy performance is sought, because the increase of average temperature worldwide can produce a significant variation of energy demands for space heating and cooling. Therefore, it is crucial to consider the effects of global warming when the energy design or retrofit of a neighborhood is planned [19]. For this purpose, one can refer to the "Representative Concentration Pathways" (RCPs), which are different prevision scenarios defined by the Intergovernmental Panel on Climate Change (IPPC) on the emissions and concentrations in the atmosphere of the full suite of greenhouse gases (GHGs) [109, 110]. The use of the RCPs could enhance the quality of the analysis of the energy, financial and environmental performance of districts of buildings, with or without considering the application of ERMs, especially when the analysis is referred to a mid-term or a long-term time horizon as it should usually be [111]. Wang *et al.* [111] proposed a tool for the planning of the energy retrofit of neighborhoods or districts, taking into account the global warming effect. However, the main limits are that it is specific for the Swiss context, being based on the Swiss census data, and that it does not implement a stochastic approach for occupant behavior modeling.

Concerning the energy modeling and retrofitting of neighborhoods/districts, other important works should be mentioned. For istance, Hong *et al.* [112] presented "CityBes" for energy retrofit analysis at neighborhood or district scales. Chen *et al.* [113] used "CityBes" for the energy retrofit of buildings in San Francisco, but they examined only five retrofit solutions, affecting the HVAC (heating, ventilating and air conditioning) systems and the replacement of windows. Lobaccaro *et al.* [114] proposed an analysis approach for the assessment of the solar energy potential at neighborhood level in Trondhein (Norway). However, most studies on energy retrofit optimization of neighborhoods investigated only specific EEMs, not using a comprehensive optimization approach involving all the possible levers – *i.e.*, building envelope, HVAC systems, renewable energy systems –, and this is one of the main limits of the current body of knowledge. In addition, even if the EU Member States are promoting the creation of local energy communities, PV production sharing has not yet been studied in detail in literature, and the same is for neighborhood scale application of PV energy storages. Notably, there are many works on PV sharing at neighborhood level, but in none of them other EEMs affecting the envelope or the HVAC systems were deeply investigated. For instance, Perger *et al.* [115] investigated the effects of PV sharing in local communities. Results showed that by means of PV sharing sensible energy and financial savings could be achieved, up to 38%. Fleischhacker *et al.* [116] investigated PV sharing considering two different energy sharing models. The main result was that sharing PV energy was profitable according to both the models. Fina *et al.* [117] focused on the financial implications of PV sharing in energy communities. They conducted an optimization process to maximize the financial profitability of PV systems in four types of neighborhood and their conclusion was that PV sharing is convenient from the financial perspective. However, they also stated that more integrated studies on retrofitting measures simultaneously involving PV systems, HVAC systems and envelopes are a crucial topic for further analysis, providing important insights for future policymaking. Thus, the lack of investigations on PV sharing in coupling with other EEMs is another limit of the current state of the art.

Finally, many available studies considered also the public grant policies that EU Member States have adopted with the aim to increase the financial profitability of energy refurbishment [53]. Among them, interesting is the work by Napoli *et al.* [118], who proposed a methodological approach for appraising the cost-effectiveness of retrofit measures in buildings and took into account the Italian public grants, concluding that public funding makes profitable certain measures even in presence of low favorable market conditions. Indeed, EU Governments have commonly started to give public grants to boost the renovation of the building stock [119]. However, it may happen that the adopted policies are not the most effective ones, and so corrections are suggested. For instance, Di Pilla *et al.* [120] investigated Italian public grant policies of the last years, stating that such policies have been developed, sometimes, without robust criteria. Therefore, they proposed a framework for setting future public grant plans. Moreover, in the current body of knowledge nearly any study has considered the imponent Italian "Superbonus 110%" public grant policy [121], and so some insights may be fundamental.

In summary, many strategies/tools have been proposed in literature with the scope of reducing the environmental impact of buildings, as seen. The ones that permit to achieve the most interesting results and the most sensible improvements in reducing their impact are focused on neighborhoods/districts of buildings and propose ERMs to improve energy, financial and environmental performance. From the analysis of the available literature and by aiming to possible enhancements of the current body of knowledge, it is outlined that the energy modeling and retrofit planning of districts/neighborhoods present different issues that can be resumed as follows:

- top-down approaches are often easier to be applied, but the outcomes may be inaccurate when the dynamics of the building system are not properly taken into account;
- bottom-up approaches are more accurate, but the computational effort required may be too high;
- aiming at reducing the computational burden, it is common practice to study a limited number of buildings as stand-alone and then to merge and scale the results, but this may imply losses in terms of results' accuracy because the inter-building effect is neglected and the contemporaneity of the energy loads is not considered correctly;
- few integrated tools are available, but their large-scale applicability may have severe limits, due to compatibility issues of the employed tools or to the dependency on local census data;
- most strategies/tools do not consider the stochasticity in the occupant behavior that deeply affects energy demands;
- they do not consider the effects of the global warming when analyzing the ERMs to be applied to districts or neighborhoods, especially when mid-term or long-term

time horizons are considered. Thus, results obtained by the common approaches may be unreliable and not applicable to reality or, if applicable, a significant discrepancy between the assessed performance indicators and the on-site measured ones can occur today and/or tomorrow (because of climate change);

- the energy retrofit optimization of neighborhoods is usually conducted by focusing on EEMs affecting only specific components of the building system, such as the envelope or the HVAC systems or the renewable energy systems, whilst it should involve all the aforementioned components at the same time to ensure a comprehensive optimization;
- the effects of the implementation of PV sharing have not been investigated by considering the latter in coupling with other EEMs;
- the newly-adopted Italian “Superbonus 110%” public grant policy needs to be investigated more.

2.2.3. Aims and Original Contributions

The knowledge gaps that have been outlined in the two previous sections provides the following questions:

q1. How to optimize the energy design of a new building?

q2. How to optimize the energy retrofit of an existing building?

q3. How to properly perform the energy modeling and the energy retrofit planning of districts/neighborhoods of buildings?

q4. How to perform an integrated energy retrofit optimization of districts/neighborhoods?

q5. How to develop more accurate district energy models and to attain more robust results for their energy retrofit planning?

A definitive and robust answer to these questions is fundamental to overcome some of the main obstacles to the reduction of the energy and environmental impact of buildings on the environments. So far, the scientific literature did not propose a full and complete response to such critical issues. Therefore, the main aim of this thesis is to answer to these questions by providing for each of them a proper methodology approach to be used. More in detail, aiming at answering to these questions, and so, aiming at filling the knowledge gaps that have been outlined in the two previous sections, five different integrated approaches for the energy modeling and retrofit of buildings are proposed in this study. In detail, two techniques adopt the stand-alone – *i.e.*, single building – approach, while the other three the district/neighorhood one. Note that all these five approaches are detailed versions of the same "primitive" methodological approach, which has been modified and adapted according to the situations to be investigated, with the aim to cover most of the possible cases in matter of improving the energy performance of the building sector.

For what concerns the two methodologies adopting a stand-alone approach, the first – discussed in Chapter 3 – is focused on the optimization of the energy performance of new buildings, outlining the importance of choosing the most adequate envelope composition according to the climatic conditions as well as the aims of both the public and the private perspective. On the other hand, the second technique – presented in Chapter 4 – investigates the optimization of the energy retrofit of existing buildings.

In detail, the main novelties and worthy contributions of the methodology presented in Chapter 3 to the state of the art in matter of building energy design optimization can be outlined as follows:

- a huge domain of design scenarios for the building envelope is explored, without requiring a huge computational effort. This allows to achieve a comprehensive optimization of envelope energy design;
- the objective functions provide the main targets of building energy design, namely the minimization of energy needs, costs and discomfort and different optimal solutions are suggested to address the needs of different public and private stakeholders;
- making use of a properly implemented genetic algorithm as optimization algorithm, it does not suffer from failures caused by simulation crashes.

For what concerns the approach presented in Chapter 4, the main novelties consist in the following points:

- possibility to satisfy both the perspectives, the public one (by reducing the GHG emissions) and the private one (by minimizing the GC and the DH), thereby allowing to fight climate change and ensuring the design cost-effectiveness at the same time;

- the focus on the reduction of heat emissions, in addition to the assessment of energy demands and greenhouse gas emissions, is a further novel aspect as regards investigations concerning building energy efficiency;
- being the second stage conducted entirely in MATLAB®, it is no time-consuming, thus during the second stage many objective functions can be investigated and optimized without particular computational efforts;
- being based on a genetic algorithm (GA), the proposed methodology does not suffer from failures caused by simulation crashes, as in the previous technique.

Regarding the three methodologies that make use of a district/neighborhood approach, the first – presented in Chapter 5 – provides a novel integrated approach for the energy modeling and the energy retrofit of districts/neighborhoods, which couples the benefits of existing techniques. The second approach – shown in Chapter 6 – is a sort of "enhanced version" of the previous methodology. Indeed, it investigates more EEMs during the retrofit planning, affecting all the possible components of the building system. Moreover, it considers also the implementation of PV sharing together with the other EEMs, and studies the energy, financial and environmental implications of the Italian massive public grant policy named "Superbonus 110%" too. Finally, the last methodology – presented in Chapter 7 – is based on the two previous approaches, but it takes into account the stochasticity of the human behavior and the effects of global warming, in order to develop more accurate energy models and to give more robust results.

More in detail, the original contributions of the first methodology are resumed as follows:

- the adoption of a bottom-up approach provides a good accuracy of the results, which is increased by the use of EnergyPlus as dynamic energy simulator. Indeed, the latter permits to take into account also the inter-building effect and the simultaneity of the energy loads;
- the adoption of MATLAB® as post-processing engine strongly reduces the computational effort required, avoiding the operation of merging and scaling the results, which is usually one of the main causes of loss of accuracy of the results;
- the coupling between EnergyPlus and MATLAB® permits to fully automatize the data processing, and so each problem can be investigated at all the possible scale levels – from the single apartment to the entire district/neighborhood – at the same time;

- the use of well-known commercial software enables a universal compatibility, and so a widespread diffusion of the approach is possible.

For what concerns the methodology presented in Chapter 6, in addition to the innovation introduced by the previous approach, the main novelties and worthy contributions to the current body of knowledge can be outlined as follows:

- several EEMs are simultaneously investigated, by adopting an integrated retrofit optimization approach. Note that most of the examined EEMs are common measures, which have already been studied in previous years, but here the main difference is the approach. In the current body of knowledge, studies usually focus on measures that affect only specific components of the building system, especially when the target is the neighborhood or the district in spite of a stand-alone building. Conversely, in the presented methodology all the components of the building system – *i.e.*, envelope, HVAC systems, renewable energy systems – are simultaneously involved in the optimization of the energy retrofit of a district/neighborhood;
- the investigation of the effects of the implementation of PV sharing in coupling with the aforementioned measures affecting all the elements of the building system. Indeed, in the current literature, PV sharing is studied on its own, without usually taking into account the effects of its interaction with other EEMs;
- the examination of the effects of the Italian “Superbonus 110%” massive public grant policy.

Finally, the last methodology presented in this study – discussed in Chapter 7 – is characterized by the following elements of innovation compared to the current state of the art – in addition to the ones of the methodology discussed in Chapter 5:

- the consideration of the stochasticity in the human behavior, which guarantees more accurate results, closer to reality;
- the adoption of proper weather data files allows to consider the effects of global warming on the retrofit solutions.

Note that all the methodologies, adopting either the stand-alone or the district/neighborhood approach, are characterized by the possibility to simultaneously satisfy both the public and the private perspectives, even if it has not always been indicated.

How to optimize the energy design
of a new building?

CHAPTER 3. Building envelope design: a multi-objective optimization approach

3.1. Introduction

The approach presented in this chapter deals with the optimization of building energy design by proposing an optimization approach that aims at the Pareto minimization of primary energy consumption (PEC), global cost (GC) and discomfort hours (DH). A genetic algorithm (GA) is implemented by means of the coupling between the dynamic energy simulator EnergyPlus and MATLAB® in order to achieve a comprehensive optimization of envelope design. Finally, two optimal solutions are recommended: the "nZEB optimal" solution, which minimizes PEC, and the "cost-optimal" solution, which minimizes GC. These solutions represent the optimal strategies for the public and private stakeholders, respectively, which are the main actors involved in building design. Note that in this study and, more generally, in the whole thesis the acronym "nZEB" has a different meaning from the one intended by the Italian law. Indeed, for the Italian law an "nZEB building" is a building that fulfil all the requirements established by the Italian law in presence of an "important refurbishment of the first level" or in presence of a new construction, with an additional constrain also on the minimum level of use of renewable energy sources for satisfying the heating and the cooling demands and the production of domestic hot water. Moreover, there is also a constrain on the minimum size of the photovoltaic (PV) system – it is mandatory to install it for achieve the nZEB standard –, in terms of PV power peak, assessed considering the projection of the building on the horizontal plane and dividing it by 50. In general, the requirements to be satisfied concern both the envelopes and the "heating, ventilating and air conditioning" (HVAC) systems and are, for instance, that the thermal energy demand for heating and for cooling (TED_h and TED_c) evaluated for the investigated building should be lower than the same values assessed for the relative reference building, and the same is for the primary energy consumption for heating and for cooling (PEC_h and PEC_c) and for the efficiency of the heating, of the cooling and of the domestic hot water systems. The main limit is that all these requirements should be evaluated under standardized conditions and that the aforementioned values should be calculated considering steady-state conditions, which are not even close to real world buildings, being the energy behavior of a building fully changing over the time, and so being fully dynamic. On the contrary, in this thesis, the acronym “nZEB” referred to an optimal solution is used generically to indicate that the proposed solution is the one that minimizes the most the PEC among the ones examined, and so the one that allows to attain the highest reduction in terms of energy impact of the investigated building. Note that the approaches proposed in this thesis make use of a dynamic energy simulator, and so the PEC is always evaluated considering the dynamics of the energy behavior of the investigated buildings, thus it is much closer to reality, differently from the standardized conditions imposed by the Italian law. Moreover, not being constrained by the stringent requirement limits imposed by the national laws for achieving the “nZEB” standard, the proposed “nZEB” solutions or, more generally, the proposed approaches are not limited to the geographical area where the investigated buildings are ubicated, but may be easily applied everywhere, overpassing the Italian national boundaries.

All told, assuming as design variables only the ones that characterize the building envelope – the energy systems are considered fixed, assuming that the best available technologies are implemented –, it is possible to achieve a robust and comprehensive optimization of envelope design, which is fundamental because, as aforementioned, the envelope is the main responsible of building thermal energy demand. Finally, different types of optimal solutions are provided thereby addressing both the public perspective, by minimizing PEC (and thus environmental impact), and the private one, by minimizing GC and DH.

Once again, the main novelties and worthy contributions of the proposed methodology to the state of the art in matter of building design optimization are here reported:

- a huge domain of design scenarios for the building envelope is explored, without requiring a huge computational effort. This allows to achieve a comprehensive optimization of envelope energy design;
- the objective functions provide the main targets of building energy design, namely the minimization of energy needs, costs and discomfort and different optimal solutions are suggested to address the needs of different public and private stakeholders;
- making use of a properly implemented genetic algorithm as optimization algorithm, it does not suffer from failures caused by simulation crashes.

With the scope to show the potentialities of the proposed approach, a case study is presented, where it is used to optimize the design of a new residential building located in different Italian climatic zones, representative of the whole Italian territory, in order to achieve large-scale applicable results. The optimal solutions are compared to reference designs complying with Italian laws and construction practice to better outline potential energy, economic and thermal comfort benefits. Note that the application to different locations, representative of the main Italian climatic zones, allows to achieve worthy outcomes that can be applied on large-scale. In this regard, important indications concerning the energy design of new buildings are given, depending on the climatic location. Thus, guidelines are provided to rebuild most of the Italian residential stock – built after the second World War during the economic boom and the reconstruction of the European cities – with a view to energy-efficiency and cost-effectiveness. In this regard, the comparison of the optimal solutions with reference designs shows how the local construction practices can be modified and improved to achieve a more sustainable building stock. Indeed, the outcomes will show that all solutions produce huge benefits compared to the reference ones in terms of energy savings and most solutions imply comfort improvements as well as high net present values with payback times equal to zero or lower than 10 years.

3.2. Methodology

3.2.1. Framework

The early-stage energy design of a newly-built building is a crucial issue that involves two (often and unfortunately) contrasting perspectives:

- the public one, whose principal goal is to strongly reduce energy consumption and polluting emissions;
- the private one, which aims at obtaining major cost savings and indoor thermal comfort.

The methodology addresses the interests of both perspectives by performing a multi-objective optimization according to the Pareto approach. Usually, building energy optimization (BEO) requires significant computational efforts because of the high amount of possible energy-efficiency measures that have to be properly simulated by means of reliable building performance simulation tools. In order to solve this issue, the EPBD-Recast (namely, the Directive 2010/31/EU) [3] establishes that not every building should be investigated but only reference buildings. However, even considering only RBs, the robust assessment of the optimality is very time-consuming. For this reason, the use of proper BEO algorithms – which can reduce the number of explored scenarios, and so the required computational time, without affecting the robustness of the optimal solutions – is fundamental. In this study, a multi-objective optimization is performed with the aim to find optimal solutions that produce the Pareto minimization of primary energy consumption (PEC), global cost (GC) and discomfort hours (DH). Once fixed the building geometry, the occupancy profiles, the climatic conditions and the time-schedules referring to the use of the energy systems, many different energy-efficiency measures (EEMs) are investigated and optimized. These measures provide the design variables of the optimization problem and concern the building envelope (*e.g.*, building orientation, radiative properties of the plasters, thermo-physical properties of envelope components, type of windows, and so on) and the set point temperatures of space heating and cooling. The HVAC – *i.e.*, heating, ventilating and air conditioning – and primary energy systems are not considered part of the optimization problem because they are supposed to be already optimized, being set according to the best practice. In this regard, the presence of a "full-roof" photovoltaic (PV) system is considered too, already optimized as well. Indeed, the PV system is supposed to be constituted by monocrystalline PV panels installed facing South with a 30° inclination to the horizontal level. PV panels are characterized by an efficiency equal to 17%, while for the inverter the nominal efficiency is equal to 99%. PV storages are not taken into account, and so the eventual surplus of energy is fed into the grid. Note that in the whole thesis, if not differently indicated, PV panels are supposed to be installed on 90% of the gross roof area. Moreover, for each panel is always considered an area that is at least the double of its geometrical real one, with the aim to maximize the solar gain by minimizing the shadowing effects between one line of panels and the closest ones, and to guarantee easy maintenance operations.

All told, MATLAB® is used as the optimization "engine" that runs the optimization algorithm and performs the data-processing, while EnergyPlus is the dynamic energy simulation engine. Both these programs are among the most reliable in their application domain [66], thus they ensure high accuracy of the results. MATLAB® launches EnergyPlus simulations using a proper weather data file – usually available at EnergyPlus online database – and post-processes the outputs, thus the coupling of these two software permits to run automatically a huge amount of dynamic simulations. More precisely, the optimization technique implements a genetic algorithm (GA) under MATLAB® environment. The GA derives from the non-dominated sorting genetic algorithm-II (NSGA-II) and improves iteratively the building performance, aiming at finding the non-dominated solutions – namely, the Pareto front – for what concerns the envelope energy design. PEC, GC and DH are simultaneously minimized. Thus, the achieved Pareto front is investigated, and two different optimal solutions are selected, providing two recommended energy design strategies:

- the "nZEB (nearly zero energy building) solution": this is the solution that minimizes PEC among all the non-dominated ones; it is noticed, that this solution is denoted as nZEB not because it complies with a specific nZEB standard, but because it is the non-dominated solution that minimizes energy consumption, and thus it is the most sustainable one, whose performance are the closest to any nZEB standard;
- the "cost-optimal solution": this is the solution that minimizes GC over the building predicted lifecycle, among all the non-dominated ones.

Among the objective functions DH is considered, too, because the presented methodology aims not only at proposing the nZEB and the cost-optimal solutions but also at assuring comfortable and healthy indoor thermal conditions. Likely, the public stakeholders will opt for the nZEB solutions while the private ones will opt for the cost-optimal solutions. However, it is highlighted that both kinds of solutions generally produce energy, economic and comfort benefits compared to reference designs because they derive from an optimization procedure that minimizes PEC, GC and DH.

As previously said, HVAC systems, primary energy and renewable energy systems are considered fixed and set according to the best practice because, once ensured high levels of energy-efficiency of active energy systems, the major factors affecting building energy performance are related to the envelope. In addition, nowadays the installation of high-efficiency active energy systems is economically feasible even in absence of incentives by the public stakeholders, due to their large-scale diffusion, thus it is the envelope that plays the most important role even in the definition of the costs. In other words, concerning the whole concept of energy-efficiency, it is quite simple to implement high-efficiency energy systems, whereas the envelope optimization is highly more complex, given the higher number of design variables, the non-linear building energy performance as well as the different (often contrasting) effects on heating and cooling demands, respectively. Furthermore, energy systems can be easily replaced during building lifespan, whereas the energy retrofit of the building envelope is definitely more complex and expensive. For these reasons, the optimization of envelope energy design at the early-stage is greatly more complex and important – with a view to energy-efficiency, cost-effectiveness and resilience [122] – compared to the selection of energy systems. That is why the proposed optimization approach is focused on the building envelope. Finally, considering fixed the energy systems allows to reach high levels of energy-efficiency as well and enables to explore a huge domain of design scenarios concerning the envelope with feasible computational times.

3.2.2. Optimization process

Firstly, the geometrical model of the building and its subdivision into thermal zones is implemented by using DesignBuilder® [123], well-known and authoritative graphical and input/output interface of EnergyPlus. Then, the building model is completed under EnergyPlus environment (namely, the .idf editor), where it is crucial to properly define:

- the usage profiles for each thermal zone in terms of hourly schedules of people activity, occupation, etc.;
- the typology of HVAC systems, in terms of characteristics of the heating and cooling systems as well as of the distribution network and of the space conditioning terminals;
- the availability and set points of the HVAC systems;
- the typology and size of the photovoltaic system.

After the building modeling, “n” energy design measures are identified – based on the local best practice – in order to reduce PEC, GC and/or DH. A design variable is associated to each measure; thus “n” variables are introduced, each one having an assigned variability range. At this point, the optimization engine (namely, MATLAB®) starts running the GA, selecting only a limited amount of solutions within the whole domain, and so huge computational time is saved compared to exhaustive researches. When a termination criterion is satisfied, the algorithm ends and provides one three-dimensional (3D) and three bi-dimensional (2D) Pareto fronts (*i.e.*, one for each couple of objective functions). The goal would be the simultaneous minimization of all the objectives, but this is practically impossible because such functions are often in mutual opposition, and thus the GA provides trade-off non-dominated solutions included in the Pareto fronts. The implemented GA is better explained in the pseudocode reported in figure 3.1.

```
$t = 1$ (index of generations, i.e., iterations)
Create the initial population $P^{(1)} \equiv \{\underline{x}_i^{(1)}\}_{i = 1, \ldots, s}$ of s individuals
Calculate $\underline{F}(\underline{x}_i^{(1)})$ for $i = 1, \ldots, s$
Evaluate the rank value and the average crowding distance for each individual of $P^{(1)}$
DO UNTIL at least one stop criterion is satisfied
    $t = t + 1$
    Select the parents from $P^{(t-1)}$
    Generate $P^{(t)} \equiv \{\underline{x}_i^{(t)}\}_{i = 1, \ldots, s}$ from crossover and mutation of the parents: elite parents survive
    Calculate $\underline{F}(\underline{x}_i^{(t)})$ for $i = 1, \ldots, s$
    Evaluate the rank value and the average crowding distance for each individual of $P^{(t)}$
END
Return the Pareto front
```

Figure 3.1. Pseudocode of the GA

The objective functions – *i.e.*, PEC, GC and DH – are collected in the vector “F”, while the vector “x” is constituted by the bits encoding the design variables. As already specified, only a limited number of values can be assumed by the design variables. This permits to reduce the solution domain and it is much closer to the real market availability. The GA performs the iterative evolution of a population of “s” (population size) individuals (“chromosomes”). A specific combination of values of the vector x characterizes each chromosome. Vector x components are the so-called “genes” and identify a combination of building energy design measures. Numerous are the iterations through which the optimization process is performed. Each iteration constitutes a “generation”. The characteristics of the population are iteratively improved by selecting the best chromosomes as well as through the “mutation” and the “crossover” of their genes with the aim to have new individuals whose corresponding energy performance is better of the previous ones. The individuals deriving from crossover are generated by combining randomly the design variables – more in detail, the bit strings – of two parents and are named “children”. The fraction of the population originated by the crossover operation is indicated with “f_c” (the “crossover fraction”). All other individuals (“mutated children”) are generated by means of the mutation of parents – chosen randomly – by changing each bit with a probability equal to “f_m”. The best chromosomes constitute the “parents” and are selected based on the rank obtained from the corresponding values of the objective functions and from the average crowding distance among the individuals. The best parents are selected to form the “elite”, which includes “c_e” individuals surviving to each generation. The initial population is created randomly, then the described “Darwinian evolution” is performed during each generation and ends when a termination criterion is satisfied:

- there is not a significant change of the Pareto front between two following generations. Of course, a not significant variation of the Pareto front means that the variation of its spread is lower than a tolerance value "tol";
- a limit number of generations ("g_{max}") is reached.

For the case studies here considered, the GA parameters are set according to the values reported in table 3.1.

The values of s and g_{max} must be properly chosen because they crucially affect the accuracy of results, other than the needed computational efforts. Reliable s values are included between 2 and 6 times the number of design variables [124] (here it is assumed equal to 4), while setting g_{max} equal to 50 ensures a good trade-off between GA reliability and computational burden [124].

Table 3.1. Setting of the control parameters of the Genetic Algorithm

c_e	f_c	f_m	n	s	tol	g_{max}
2	0.6	0.1	16	4·n	0.001	50

The written MATLAB® code creates the vector x – that encodes a combination of energy design measures – by means of the operations of "creation", "mutation", "crossover" and "selection", and launches EnergyPlus to perform a dynamic energy simulation. Consequently, the simulation outputs – contained in a ".csv" file – are processed under MATLAB® environment and the values of PEC, GC and DH, referring to the examined combination, are obtained. More in detail, the MATLAB® code manages the hourly values of thermal energy demands for space conditioning and the ones of electricity demand for direct electric uses (*i.e.*, equipment and artificial lighting) – contained in the aforementioned ".csv" file – and converts the thermal energy demand into electricity. This conversion is carried out by means of the dynamic calculation of energy efficiency of the system through the performance curve of the selected HVAC plant (*i.e.*, a reversible air-cooled electric heat pump), which indicates its punctual efficiency as a as a function of the external temperature, the temperature of the heat transfer fluid and the load ratio. The obtained electricity demand for space conditioning is consequently summed with the electricity demand for direct electric uses, thus the hourly and the annual values of total electricity are assessed. The written MATLAB® code takes into account also the effect of the installation of a photovoltaic (PV) system. The electricity "produced" by this system is evaluated hourly – for a whole typical weather year – based on the climatic conditions provided by a proper weather data file and on the system's characteristics.

Consequently, the obtained hourly values of "produced" electricity are subtracted from the hourly values of total electricity demand in order to obtain the building electricity demand. The surplus of electricity is introduced into the electricity grid and sold. Finally, the evaluated building electricity demand is converted into PEC by means of a proper conversion factor [125]. The value of electricity demand enables to assess the annual running cost of the building. This latter and the design investment cost are handled by the MATLAB® code to calculate the value of GC according to EU guidelines [15]. Finally, regarding DH assessment, an occupied hour is classified as a "discomfort" one if the average predicted mean vote (PMV) in the considered building thermal zones is not included between -0.85 and +0.85, implying that the predicted percentage of dissatisfied (PPD) is higher than 20%.

This process is iterated until the fixed termination criterion is satisfied. Figure 3.2 shows the flowchart of the optimization process.

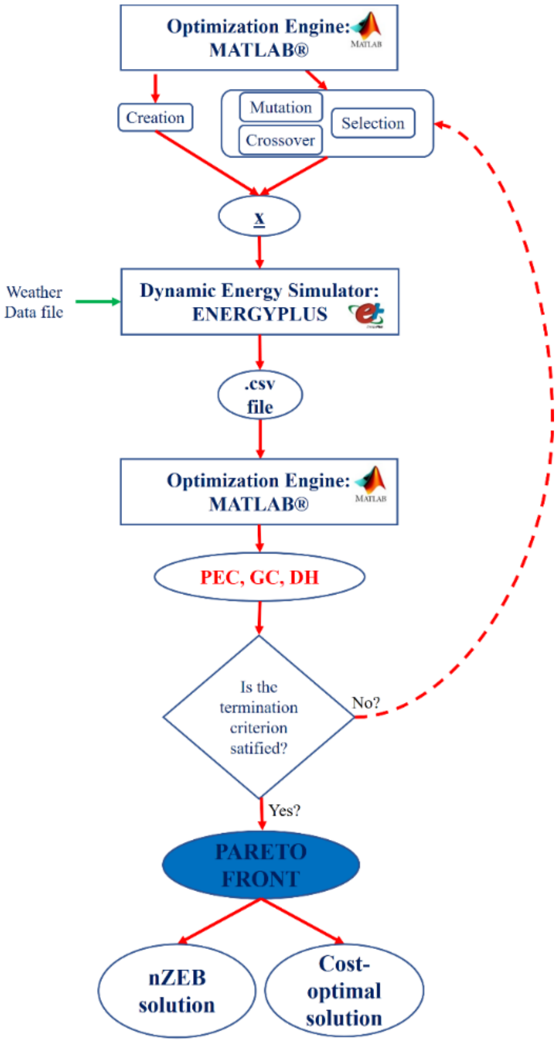

Figure 3.2. Flowchart of the optimization process

Finally, aiming at selecting one or more recommended solutions among all non-dominated ones collected in the Pareto front, the multi-criteria decision-making is performed. This task can be addressed according to different criteria because none of the solutions of the Pareto front can be "absolutely" classified as better than another. For this purpose, one or more selection criteria should be used. About the methodology here described, the chosen ones are the "energy-optimality" and the "cost-optimality", thus, when the optimization process ends, the recommended optimal solutions (*i.e.*, packages of energy design measures) are the "nZEB solution" and the "cost-optimal solution" previously defined. These two allow to produce a simultaneous improvement of building energy and economic performance compared to reference designs, satisfying both the public sphere – whose main aim is to fight energy poverty, pollution and climate change – and the private one – whose aims are the cost-effectiveness of the design and a satisfactory level of thermal comfort. About this latter, the proposed approach allows the designer to put un upper constraint to DH, which cannot be overpassed, in order to ensure satisfying thermal indoor conditions. An upper constraint can be also fixed for the other two objective functions (*i.e.*, PEC and GC), depending on wills and needs of the stakeholders.

3.3. Presentation of the case study

3.3.1. Building model description

The proposed methodology is applied to a newly-built five-story residential building, whose geometrical model is taken from [126] and it is typical of the Italian building stock (see figure 3.3). Each story is subdivided into two flats having the same extension. The gross floor area is 930 m^2 (186 m^2 per story). All façades have a glazed area equal to the 27.5% of the total external walls' surface, while shading systems are absent. The air infiltration rate is 0.7 air changes per hour (ACH). The orientation is not indicated because it is a design variable to be optimized.

50 different thermal zones are individuated, 10 per story (see figure 3.3). All thermal zones are classified into three different categories: sleeping area, living area and buffer area, which includes both the bathroom zone and the corridors. In order to properly simulate the energy and thermal behavior of the building, for each category of thermal zone, different typical schedules of building use and operation are accurately set. The occupation density is set equal to 0.05 people/m^2, according to Italian standard for residential buildings, for both the sleeping and the living areas. As predictable, sleeping

areas are supposed to be fully occupied during night hours – *i.e.*, from 22:00 to 06:00 –, while during the ranges 20:00 – 22:00 and 06:00 – 08:00 it is supposed that there is only a partial occupation, and finally during the other hours of the day these areas are unoccupied. For what concerns the living areas, these are fully occupied from 17:00 to 20:00, while they are partially occupied during the time ranges from 08:00 to 17:00 and from 20:00 to 22:00, and finally they are unoccupied during the night hours. On the other hand, the buffer areas are supposed to be unoccupied, due to the transition nature of this type of zones, thus the DH is evaluated exclusively for sleeping and living areas. However, corridors and bathrooms are conditioned because these are a sort of thermal buffer. For this reason, their conditioning could be useful during some hours of the day, aiming at reducing the heat transfer between sleeping areas and living areas (and vice versa), and so at guaranteeing a major comfort level and globally a PEC decrease. Moreover, even if the use of these areas is not continuous, thermal comfort has to be ensured also there, as part of the dwellings.

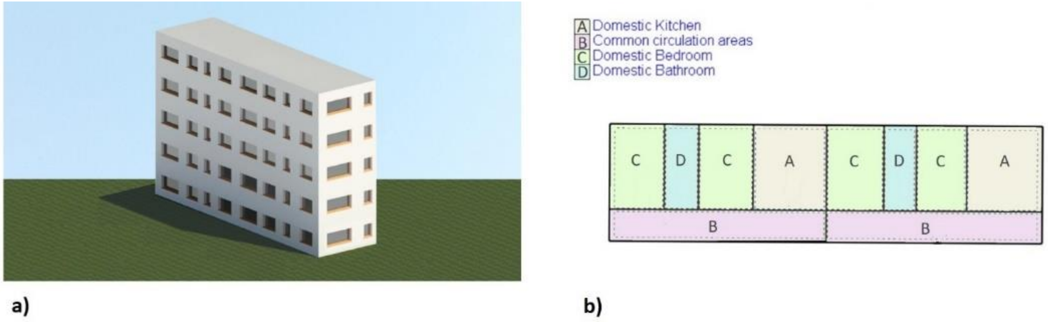

Figure 3.3. a) Overall building view; b) floor subdivision in thermal zones

Having deep implications on DH assessment, the clothing thermal resistance is accurately defined. From November 1 to April 1, it is equal to 1.3 clo during the night period (00:00 to 07:00), as it includes bed blankets, and to 1.0 clo during the rest of the day (07:00 to 00:00); from April 2 to May 1 and during October it is 0.75 clo; from May 2 to September 30 it is 0.5 clo. As previously specified, the HVAC and primary energy systems are considered fixed (*i.e.*, not included in the optimization process) and set according to the best practice. They are modeled in detail because they exert a significant influence on building performance. In this regard, all thermal zones are equipped with four-pipe fan coils, supplied with hot and cold water – hot water is at 50 °C, cold one at 6.7 °C – by a primary centralized system. The heat losses due to the distribution network are automatically taken into account by the dynamic energy simulator Energy Plus, as in the following Chapter 4. The thermal generation system is an efficient reversible air-cooled electric heat pump, which satisfies both heating and cooling demands. The nominal coefficient of performance (COP) for heating is 3.5, while for cooling it is 3.2. The used simulation procedure enables to take account of the heat pump transient performance because the actual COP value varies as a function of part load ratio and external temperature. Finally, the building is equipped with monocrystalline photovoltaic panels, which cover the 90% of the roof area (the remaining 10% is considered not occupied by panels to ensure the roof accessibility), properly modeled in EnergyPlus. By performing hourly energy balances, if the electricity produced by the PV generator is higher than the building electricity demand, the surplus is sold to the grid. In order to evaluate GC, the electricity demands of heat pump, fans, pumps, lighting and other electric equipment are taken into account, and the electricity price is assumed equal to 0.214 €/kWh$_{el}$, whilst its selling price is 0.07 €/kWh$_{el}$ [127]. Table 3.2 reports the main information about the case study building.

According to the Italian regulation [130], the whole Italian territory is subdivided into 6 different climatic zones, each one characterized by a specific range of heating degree days (HDD), as indicated in table 3.3. In each climatic zone, the heating system can be turned on only during a specific period of the year and for a maximum number of hours per day.

Table 3.2. General characterization of the building

Dimensions and Geometry			
Length (major side)	26.2 m	Length (minor side)	7.1 m
Height	17.5 m (5 floors)	Gross Floor Area	930 m^2 (net 784 m^2)
Gross Wall Area	1166 m^2	Gross Roof Area	186 m^2
Window Opening Area	321 m^2	Total Gross Volume	4650 m^3 (net 2680 m^3)
Gross Window-Wall Ratio	27.5 %	Surface to Volume Ratio	0.33 m^{-1}
Main Boundary Conditions of Energy Simulations			
Climatic data	IWEC/IGDG → EPW [128]	Occupancy	20 people (2 people per flat)
Number of thermal zones	50 (10 per level, 5 per flat)		
Building Envelope			
Shading systems	Absent	Infiltration rate	0.70 ACH
HVAC System			
HVAC typology	Reversible air-cooled electric heat pump with four pipe fan coils, no heat recovery	Sensible load control	Yes
COP for heating	3.5	Latent load control	No
COP for cooling	3.2	Investment cost	(5000+150·kWp) · 1.5 € [129]
Renewable Energy Sources: PV Panels			
Type of panels	Monocrystalline	Dimensions	0.88 m x 1.31 m
N° panels	72	Cost	430 €/m^2 [56]
Efficiency of the panels	17%	Efficiency of the inverter	99%
Peak power of the panel	196 W		
Energy Prices and Conversion Factors			
Electricity price	0.214 €/kWh	Electrical-to-primary energy conversion factor	1.95 [125]
Electricity selling price	0.07 €/kWh		

Table 3.3. Italian subdivision in climatic zones and heating period availability [130]

Climatic Zone	HDD	Heating Period	
A	< 600	1/12 to 15/3	6 hours per day
B	601 - 900	1/12 to 31/3	8 hours per day
C	901 - 1400	15/11 to 31/3	10 hours per day
D	1401 - 2100	1/11 to 15/4	12 hours per day
E	2101 - 3000	15/10 to 15/4	14 hours per day
F	> 3001	No limitations	

As case studies, the proposed design approach is applied by considering as building locations the climatic zones B, C, D and E, respectively. Climatic zone A is not taken into account because it is composed by only two municipalities, thus its outcomes are not representative at all. In addition, climatic zone F is not considered as well because its building stock composition is different from the rest of the country [126] – due to the severity of its climatic conditions – thus the results achieved by applying the described methodology to the building examined as case study are not representative of this climatic zone. In particular, one representative Italian city is identified for each considered climatic zone in order to set a specific weather data file [128] for the related EnergyPlus simulations:

- Zone B: Palermo, located in Sicily (Southern Italy);
- Zone C: Naples, located in Campania (Southern Italy);
- Zone D: Florence, located in Toscana (Central Italy);
- Zone E: Milan, located in Lombardia (Northern Italy).

These cities provide intermediate and typical climatic conditions within the related climatic zone. Therefore, they are chosen as locations of the case study in order to achieve representative outcomes that can be extended, with a satisfying approximation, on large-scale in the Italian territory.

Finally, about GC assessment, the EU Guidelines [3, 15] establish that the global cost should be evaluated by considering a calculation period τ of 30 years – because it is a residential building, otherwise it is 20 years – with the following equation 3.1:

$$\mathrm{GC}(\tau) = \sum_{j}\left[\sum_{i}^{\tau}(\mathrm{RC}(i) * \mathrm{R_d}(i) - \mathrm{V}_{f,\tau}(j)\right] + \mathrm{IC} \tag{3.1}$$

where:

- “RC” stands for the annual running cost. It is actualized for each year of the evaluation period by means of “Rd”, which is is the actualization factor;

- “$V_{f,\tau}$” indicates the residual value at the end of the evaluation period, using a discount rate equal to 3%;
- “IC” stands for the initial investment cost necessary to construct the building. It takes into account the construction cost of the envelope (insulation + block material), the cost of the energy systems and the cost of the PV panels. It should be noted and underlined that IC does not consider basic costs of buildings, such as foundations, structural parts, but it takes into account only energy efficiency measures that can vary among the various configurations of buildings here investigated, such as thermal insulation, active energy systems and renewables. Thus, in the proposed framework, IC represents an investment cost related to energy issues.

3.3.2. Building energy design optimization

With the aim to optimize the building energy design, 16 different design variables are considered:

1. set point temperature for space heating;
2. set point temperature for space cooling;
3. solar absorbance of the most external layer of the vertical walls;
4. solar absorbance of the most external layer of the roof;
5. position of the thermal insulation layer (polyurethane: density = 25 kg/m^3, thermal conductivity = 0.028 W/m K, specific heat = 1340 J/kg K) for vertical walls, roof and floor;
6. thickness of the insulation layer of the vertical walls;
7. thickness of the insulation layer of the roof;
8. thickness of the insulation layer of the floor;
9. thickness of the “block” material constituting the vertical walls. The term “block” is used to indicate the core material constituting the envelope element (without considering the thermal insulation layer). Indeed, in order to strongly reduce the computational efforts required by the optimization process, each element of the opaque envelope is considered to be constituted of only one material, which is characterized by values of conductance and thermal capacity that are equivalent to the ones of a multilayer structure. By setting the thickness values and the specific heat ones, the equivalent values of thermal conductivity (k) and density (ρ) are determined;

10. thermal conductivity and density of the “block” material constituting the vertical walls;
11. thickness of the “block” material constituting the roof; as aforementioned for the vertical walls, even if the roof has a mixed brick - reinforced concrete structure (reported in figure 3.4a for example purposes), it is considered to be constituted of one material with equivalent values of conductance and thermal capacity (see figure 3.4b);
12. thermal conductivity and density of the “block” material constituting the roof;
13. thickness of the “block” material constituting the floor; also in this case, the presence of one equivalent material is assumed;
14. thermal conductivity and density of the “block” material constituting the floor;
15. type of windows;
16. orientation of the building.

As told, for each component of the opaque building envelope, thermal conductivity and density are considered inter-dependent for the aforementioned reason, and therefore they provide one design variable. It is outlined that the specific heat undergoes small variations for building materials and thus it is considered fixed (for all materials of opaque envelope except for the thermal insulation) and equal to 1000 J/kg K.

Table 3.4. Characterization of the design variables

N°	Design Variables	Values
1)	Set point temperature for space heating [°C]	19; 20; 21; 22
2)	Set point temperature for space cooling [°C]	24; 25; 26; 27
3)	Solar absorbance of the vertical walls [-]	0.1; 0.25; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9
4)	Solar absorbance of the roof [-]	0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.75; 0.9
5)	Position of the insulation [-]	1 (internal); 2 (external)
6)	Insulation thickness of the vertical walls [m]	0; 0.03; 0.04; 0.05; 0.06; 0.08; 0.10; 0.12
7)	Insulation thickness of the roof [m]	0; 0.03; 0.04; 0.05; 0.06; 0.08; 0.10; 0.12
8)	Insulation thickness of the floor [m]	0; 0.03; 0.04; 0.05; 0.06; 0.08; 0.10; 0.12
9)	Block thickness for the vertical walls [m]	0.25; 0.30; 0.35; 0.40
10)	Block thermal conductivity for the vertical walls [W/m K] (*)	0.25; 0.30; 0.36; 0.43; 0.50; 0.59; 0.72; 0.90
	Block density for the vertical walls [kg/m^3] (*)	600; 800; 1000; 1200; 1400; 1600; 1800; 2000
11)	Block thickness for the roof [m]	0.25; 0.30; 0.35; 0.40
12)	Block thermal conductivity for the roof [W/m K] (*)	0.25; 0.30; 0.36; 0.43; 0.50; 0.59; 0.72; 0.90
	Block density for the roof [kg/m^3] (*)	600; 800; 1000; 1200; 1400; 1600; 1800; 2000
13)	Block thickness for the floor [m]	0.25; 0.30; 0.35; 0.40
14)	Block thermal conductivity for the floor [W/m K] (*)	0.25; 0.30; 0.36; 0.43; 0.50; 0.59; 0.72; 0.90
	Block density for the floor [kg/m^3] (*)	600; 800; 1000; 1200; 1400; 1600; 1800; 2000
15)	Type of windows [-]	1; 2; 3; 4; 5; 6; 7 (see table 3.5)
16)	Orientation of the building [°]: Angle between building North and true North	0; -45; +45; 90

(*) To each value of thermal conductivity corresponds the respective value of density (*e.g.*, to the first value of conductivity corresponds the first value of density, and so on)

The mentioned variables can assume only discrete values, which are better specified in the following tables 3.4 and 3.5. In addition, the used scheme to evaluate the investment costs necessary for the energy measures is indicated in table 3.6 – except for windows, whose investment costs are directly reported in table 3.5 – and are partly taken from suppliers’ quotations and partly from [122, 131, 132].

In order to highlight the potential benefits of the proposed methodology, the achieved optimal solutions are compared to reference designs, complying with Italian regulations [125] and construction practices. In this regard, the Italian Inter-ministerial Decree [125] provides the U-values for reference buildings related to new constructions depending on the climatic zone, as shown in table 3.7 for the investigated zones.

Table 3.5. Investigated types of windows

N°	Type	U [W/m^{2}K]	SHGC [-]	Investment Cost [€/m^2]
1	Double-glazed with air-filling, low-e coating, aluminium frame	3.09	0.69	250
2	Tinted double-glazed with air-filling, low-e coating, PVC frame	1.95	0.38	260
3	Selective double-glazed with air-filling, low-e coating, PVC frame	1.84	0.43	260
4	Double-glazed with argon-filling, low-e coating, PVC frame	1.90	0.69	260
5	Tinted double-glazed with argon-filling, low-e coating, PVC frame	1.72	0.37	270
6	Selective double-glazed with argon-filling, low-e coating, PVC frame	1.59	0.43	270
7	Triple-glazed with argon-filling, low-e coating, PVC frame	1.35	0.58	290

Table 3.6. Scheme for the evaluation of the investment cost for the considered energy measures

N°	Design Variables	Investment Cost (IC) [€]
1)	Set point temperature for space heating	-
2)	Set point temperature for space cooling	-
3)	Solar absorbance of the vertical walls	The plaster cost is taken into account in the cost
4)	Solar absorbance of the roof	of the related vertical walls or roof
5)	Position of the insulation	-
6)	Insulation thickness of the vertical walls	Insulation cost: $\mathrm{IC} = [(500 - 2000 \cdot t) \cdot t + 15] \cdot A$ [122]
7)	Insulation thickness of the roof	“A” indicates the frontal area of the building envelope component
8)	Insulation thickness of the floor	“t” denotes the thickness of the insulation layer
9)	Block thickness for the vertical walls	Block cost:
10)	Block thermal conductivity for the vertical walls	$\mathrm{IC} = \left[224.65 + \frac{(329.9 - 224.65)(\rho - 600)}{(2000 - 600)}\right] \cdot A \cdot tb$
	Block density for the vertical walls	
11)	Block thickness for the roof	→ interpolation from [133]
12)	Block thermal conductivity for the roof	
	Block density for the roof	“ρ” stands for the density of the block material
13)	Block thickness for the floor	“A” indicates the frontal area of the building envelope component
14)	Block thermal conductivity for the floor	“tb” denotes the thickness of the block material
	Block density for the floor	
15)	Type of windows	See table 3.5
16)	Orientation of the building	-

Table 3.7. U-values for new reference buildings [125] depending on the investigated climatic zone

U-Values of new Reference Buildings [W/m^{2}K]	Climatic Zone B	Climatic Zone C	Climatic Zone D	Climatic Zone E
Vertical Walls	0.45	0.38	0.34	0.30
Roof	0.38	0.36	0.30	0.25
Floor	0.46	0.40	0.32	0.30
Windows	3.20	2.40	2.00	1.80

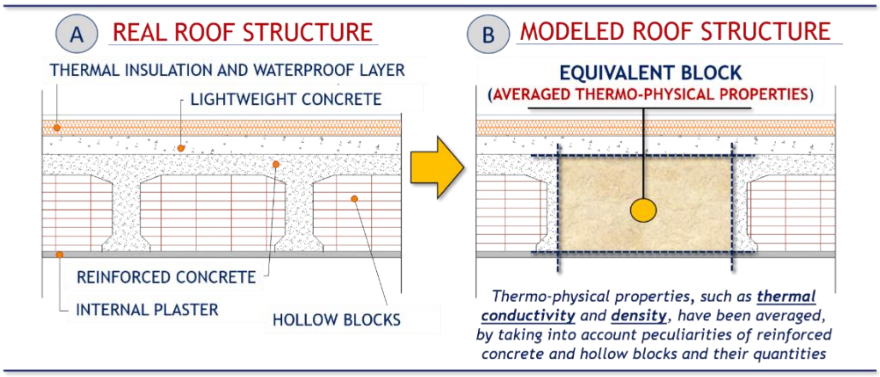

Figure 3.4. Mixed brick - reinforced concrete structure of the roof: a) Real structure; b) Modeled structure

Different reference designs are modeled for each climatic zone in order to fulfill the U-values of table 3.7 as well as local practices. In this regard, the “block” of the vertical walls is characterized by higher values of density – and thus of conductivity – moving from colder to warmer zones (from E to B) in order to achieve higher values of thermal inertia, allowing to reduce heat loads in summertime. Based on these considerations, the values given to the 16 design variables in the reference designs are reported in table 3.8 for each climatic zone. All solutions (and thus the reference ones too) are characterized by the same energy systems, set according to the best practice as previously described.

Table 3.8. Characterization of the reference designs for each location

N°	**Design Variables**	**Palermo: Zone B**	**Naples: Zone C**	**Florence: Zone D**	**Milan: Zone E**
1)	Set point temperature for space heating [°C]	20	20	20	20
2)	Set point temperature for space cooling [°C]	26	26	26	26
3)	Solar absorbance of the vertical walls [-]	0.60	0.60	0.60	0.60
4)	Solar absorbance of the roof [-]	0.60	0.60	0.60	0.60
5)	Position of the insulation [-]	Internal	Internal	Internal	Internal
6)	Insulation thickness of the vertical walls [m]	0.03	0.04	0.05	0.05
7)	Insulation thickness of the roof [m]	0.06	0.06	0.08	0.10
8)	Insulation thickness of the floor [m]	0.04	0.05	0.08	0.08
9)	Block thickness for the vertical walls [m]	0.35	0.35	0.35	0.35
10)	Block thermal conductivity for the vertical walls [W/m K]	0.36	0.30	0.30	0.25
	Block density for the vertical walls [kg/m^3]	1000	800	800	600
11)	Block thickness for the roof [m]	0.30	0.30	0.30	0.30
12)	Block thermal conductivity for the roof [W/m K]	0.50	0.50	0.50	0.50
	Block density for the roof [kg/m^3]	1400	1400	1400	1400
13)	Block thickness for the floor [m]	0.30	0.30	0.30	0.30
14)	Block thermal conductivity for the floor [W/m K]	0.50	0.50	0.50	0.50
	Block density for the floor [kg/m^3]	1400	1400	1400	1400
15)	Type of windows (see table 3.5)	1	4	4	6
16)	Orientation of the building [°]: Angle between building North and true North	0	0	0	0

In table 3.9 are reported the values assumed by the main performance indicators (*i.e.*, the three objective functions and the investment cost) for the reference designs, assessed by means of EnergyPlus simulations and MATLAB® postprocess.

Table 3.9. Performance indicators of the reference designs

Reference Designs	**Palermo: Zone B**	**Naples: Zone C**	**Florence: Zone D**	**Milan: Zone E**
PEC: primary energy consumption	84.4 kWh$_p$/m^{2}a	90.2 kWh$_p$/m^{2}a	100.7 kWh$_p$/m^{2}a	106.5 kWh$_p$/m^{2}a
GC: global cost	582 €/m^2	598 €/m^2	627 €/m^2	626 €/m^2
DH: percentage of discomfort hours	67%	51%	48%	50%
IC: investment cost	331.7 k€ (423 €/m^2)	332.6 k€ (424 €/m^2)	335.5 k€ (428 €/m^2)	327.7 k€ (418 €/m^2)

3.3.3. Results and discussion

The optimization engine (*i.e.*, MATLAB®) launches iteratively the BPS tool (*i.e.*, EnergyPlus) with the aim to find the optimal solutions for the envelope design that minimizes primary energy consumption (PEC), global cost (GC) and discomfort hours (DH). Aiming at performing an exhaustive search of the whole solution domain, more than 9.62e+11 combinations of variable should be investigated. Considering an average EnergyPlus simulation time of 2 minutes – by using a processor Intel® CoreTM i5 at 2.20 GHz – the required computational time would be around millions of years, which is obviously unfeasible. On the contrary, by means of the implementation of the genetic algorithm (GA), MATLAB® performs the evolution of a starting population of 64 individuals for 50 generations, and 3200 energy simulations are run, requiring only around 5 days, thus the optimization process is feasible. Among all the non-dominated solutions that form the 3D Pareto front, the nZEB solution and the cost-optimal one are identified. This process is carried out for the considered Italian locations, *i.e.*, Palermo (climatic zone B), Naples (C), Florence (D) and Milan (E). Finally, the resulting Pareto fronts are shown in figures 3.5 and 3.6. PEC and GC are assessed per unit of building useful area to achieve more representative outcomes, easier to be interpreted. The figures represent all 3D Pareto fronts and the 2D Pareto fronts related to the minimization of PEC and GC in order to highlight the achieved nZEB and cost-optimal solutions, respectively. Once again, it should be underlined that GC does not include the investments related to basic (and not variable) building construction categories, such as foundations, structures and so on.

In particular, figures 3.5 and 3.6 show all investigated design scenarios (gray circles) and highlight the non-dominated and optimal solutions. Figure 3.5 reports all 3D non-dominated solutions that produce the Pareto minimization of PEC, GC and DH in the 3D space of all objective functions. These solutions represent trade-off design scenarios, since there are no other solutions that improve (*i.e.*, reduce) simultaneously all three objectives. In order to better show the recommended optimal designs, the mentioned solutions are projected on the 2D plane PEC (horizontal axis) – GC (vertical axis) in figure 3.6. The latter highlights, for each location, the 2D Pareto front PEC-GC, which collects the 2D non-dominated solutions as concerns the minimization of PEC and GC. These solutions are part of the 3D non-dominated solutions, since there are no other solutions that improve (*i.e.*, reduce) simultaneously PEC and GC. However, such solutions ensure satisfying values of DH too, since this is minimized by the optimization algorithm.

The representation of the mentioned 2D Pareto fronts is particularly useful because it allows to highlight the recommended optimal solutions, namely:

- the "nZEB solution": this minimizes PEC among all the non-dominated solutions, and thus it is located on the left end of the 2D Pareto fronts of figure 3.6;
- the "cost-optimal solution": this minimizes GC among all the non-dominated solutions, and thus it is located on the right end of the 2D Pareto fronts of figure 3.6;
- the "nZEB' solution": this minimizes PEC among all the non-dominated solutions that respect un upper constraint on GC, namely the solutions that are characterized by a lower GC value compared to the reference design (see figure 3.7). This solution is introduced when the nZEB solution presents higher GC compared to the reference one in order to recommend a design strategy that is sustainable and cost-effective at the same time.

Clearly, moving from the left to the right of the 2D Pareto fronts of figure 3.6 (and thus from the nZEB to the cost-optimal solutions), the non-dominated solutions are characterized by less energy-efficient but more cost-effective design strategies. In this regard, the following tables characterize the recommended solutions, *i.e.*, the nZEB and the cost-optimal ones, respectively, for each investigated location, in terms of values assumed by the design variables (table 3.10), U-values of the envelope components (table 3.11), values of the performance indicators, *i.e.*, objective functions and investment costs (table 3.12).

About the HVAC operation, for the considered climatic zones, all optimal solutions provide the same set point temperatures for space heating and space cooling, *i.e.*, 19 °C and 27 °C, respectively – except for the cost-optimal solution for Palermo, which provides a set point temperature for cooling equal to 25 °C. This lower value can be explained by considering the need of satisfying thermal comfort levels for the occupants, in spite of the warmer climatic conditions – compared to climatic conditions affecting the other cost-optimal solutions – and the lightweight envelope provided by the same optimal solution. Indeed, the warmer external conditions in Palermo cause higher values of the mean radiant temperature of internal surfaces, which have to be balanced by lower values of indoor air temperature in order to ensure thermal comfort.

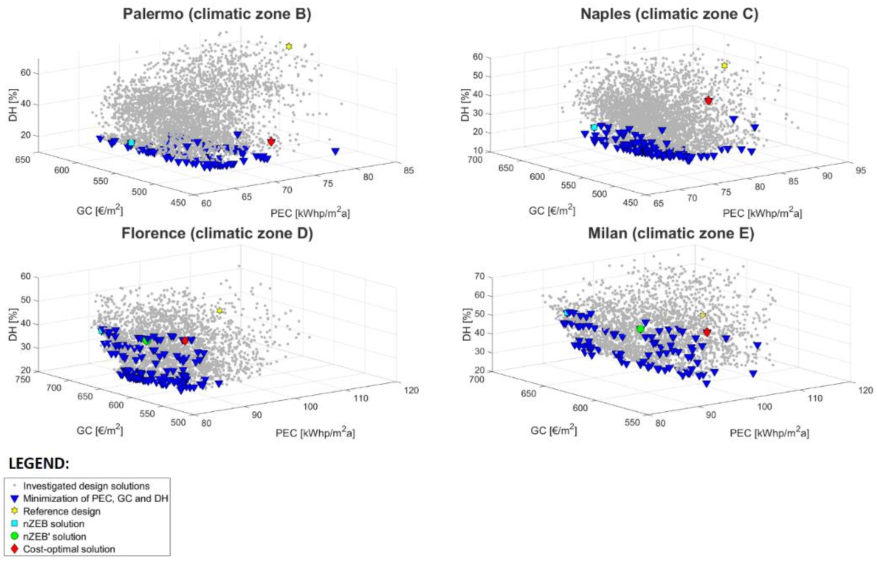

Figure 3.5. 3D Pareto fronts for all climatic zones

About the building envelope, as expected, the solar absorbance of the external surfaces of roof and vertical walls tend to increase from warmer to colder climatic zones. This occurs to maximize the exploitation of solar irradiation, which represents an issue during the cooling season especially for the warmer climatic zones, while it represents a gain during the heating season. Such gain is maximized in the colder climatic zones by means of higher values of solar absorbance because these imply minor space cooling issues in summertime.

When implemented, the thermal insulation layer is external because this allows to achieve higher values of envelope temperatures (warm walls) that improve energy performance and comfort levels. Almost all optimal solutions are characterized by the same value of insulation thickness for the external walls, which is equal to 0.10-0.12 m, except for the cost-optimal solutions for Palermo and Naples, where the vertical walls are not insulated. However, these two latter solutions are characterized by a thermal insulation thickness of 0.08 m and 0.05 m, respectively, for the floor (this partly compensates the absence of insulation on the external vertical walls), while for all other optimal solutions floor insulation is not implemented at all. The insulation thickness for the roof is always equal to 0.12 m for the nZEB solutions, while it is 0.10 m for the cost-optimal ones, apart from Florence, where the cost-optimal solution provides the installation of an insulation layer of 0.12 m. This value, which is higher than the one provided by the homologue solution related to Milan (climatic zone E), can be explained by considering the higher value of thermal conductivity for the cost-optimal block (*i.e.*, 0.36 W/m K for Florence against 0.25 W/m K for Milan) and by the need of adequate thermal comfort levels.

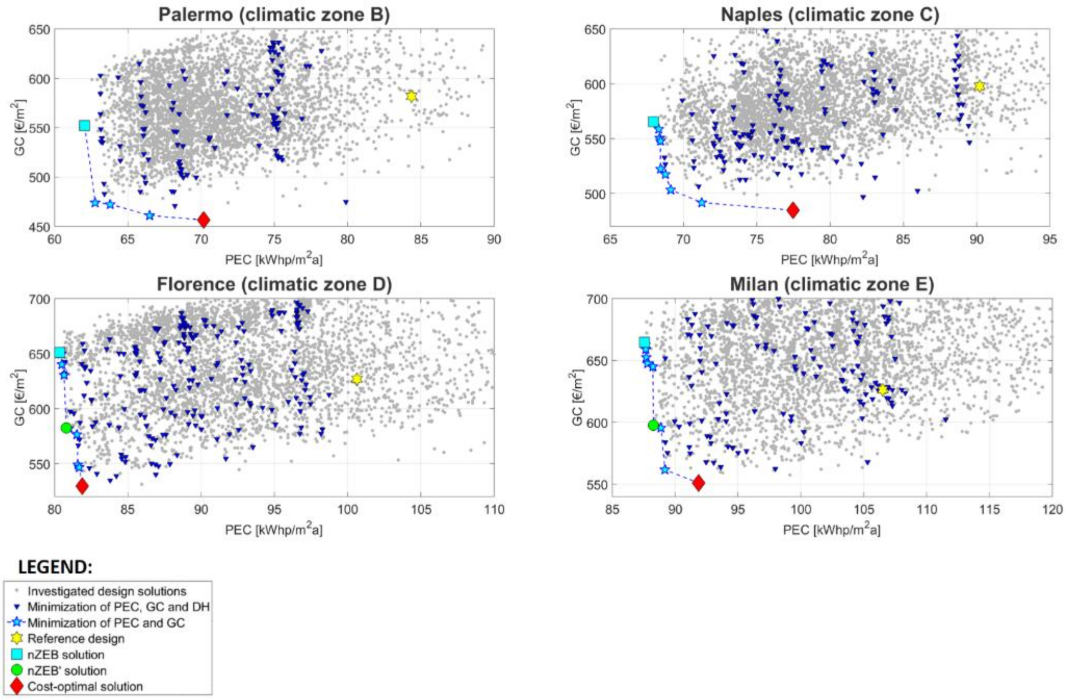

Figure 3.6. 2D Pareto fronts for all climatic zones as concerns the minimization of primary energy consumption (PEC) and global cost (GC)

Concerning the vertical envelope, firstly it should be noted that the nZEB solutions generally present more massive external vertical walls moving from warmer climatic zones to colder ones – even if the maximum density value is the one provided for Florence (unconstrained nZEB solution) – while for the cost-optimal solutions the density of the external vertical walls is always equal to 600 kg/m^3 and the thickness is always 0.25 m. The density tends to increase for colder zones because this implies higher values of thermal inertia that enables the achievement of higher levels of thermal comfort over a generic winter day (also in the hours when the heating system is switched off) in cold climates. Being the density and the thermal conductivity inter-dependent, this implies that also the conductivity tends to increase moving from warmer zones to colder ones as concerns the nZEB solutions, while it is always equal to 0.25 W/m K for the cost-optimal ones. However, taking into account the provided insulation thicknesses, the resulting thermal transmittance values (U) for the external vertical walls are similar for all the climatic zones for both types of optimal solutions (*i.e.*, nZEB ones and cost-optimal ones), but only when there is the installation of an insulation layer. In fact, when insulation is provided, the U-value varies from 0.17 W/m^2 K to 0.20 W/m^2 K, while when absent the U-value is much higher and it is equal to 0.85 W/m^2 K. This happens for the cost-optimal solutions of Palermo (climatic zone B) and Naples (C), that are characterized by temperate winter seasons. These make more cost-effective the absence of thermal insulation for the vertical walls but in presence of blocks with low values of thermal conductivity (0.25 W/m K) that ensure U-values that are not excessively high.

Table 3.10. Characterization of the optimal solutions: nZEB and cost-optimal (C-O) solutions for each location

N°	**Design Variables**	**Palermo: Zone B**		**Naples: Zone C**		**Florence: Zone D**			**Milan: Zone E**		
		nZEB(*)	**C-O(*)**	**nZEB(*)**	**C-O(*)**	**nZEB(*)**	**nZEB'(*)**	**C-O(*)**	**nZEB(*)**	**nZEB'(*)**	**C-O(*)**
1)	Set point temperature for space heating [°C]	19	19	19	19	19	19	19	19	19	19
2)	Set point temperature for space cooling [°C]	27	25	27	27	27	27	27	27	27	27
3)	Solar absorbance of the vertical walls [-]	0.40	0.50	0.80	0.80	0.70	0.90	0.90	0.40	0.40	0.90
4)	Solar absorbance of the roof [-]	0.40	0.10	0.10	0.20	0.50	0.75	0.90	0.40	0.30	0.90
5)	Position of the insulation [-]	external	external	external	internal	external	external	external	external	external	external
6)	Insulation thickness of the vertical walls [m]	0.10	0	0.12	0	0.12	0.12	0.12	0.12	0.12	0.12
7)	Insulation thickness of the roof [m]	0.12	0.10	0.12	0.10	0.12	0.12	0.12	0.12	0.12	0.10
8)	Insulation thickness of the floor [m]	0	0.08	0	0.05	0	0	0	0	0	0
9)	Block thickness for the vertical walls [m]	0.40	0.25	0.35	0.25	0.40	0.40	0.25	0.40	0.25	0.25
10)	Block thermal conductivity for the vertical walls [W/m K] (*)	0.30	0.25	0.43	0.25	0.90	0.25	0.25	0.72	0.59	0.25
	Block density for the vertical walls [kg/m^3] (*)	800	600	1200	600	2000	600	600	1800	1600	600
11)	Block thickness for the roof [m]	0.40	0.30	0.40	0.30	0.25	0.25	0.25	0.40	0.40	0.30
12)	Block thermal conductivity for the roof [W/m K] (*)	0.72	0.50	0.72	0.36	0.72	0.50	0.36	0.36	0.36	0.25
	Block density for the roof [kg/m^3] (*)	1800	1400	1800	1000	1800	1400	1000	1000	1000	600
13)	Block thickness for the floor [m]	0.35	0.40	0.25	0.30	0.25	0.30	0.30	0.30	0.40	0.25
14)	Block thermal conductivity for the floor [W/m K] (*)	0.90	0.25	0.90	0.59	0.90	0.72	0.36	0.59	0.59	0.50
	Block density for the floor [kg/m^3] (*)	2000	600	2000	1600	2000	1800	1000	1600	1600	1400
15)	Type of windows (see table 3.5)	5	3	6	7	7	6	6	7	7	4
16)	Orientation of the building [°]: Angle between building North and true North	90	90	90	90	90	90	90	90	90	90

(*) nZEB→ nearly zero energy building solution; nZEB' → constrained nearly zero energy building solution; C-O → cost-optimal solution

Concerning the roof, generally less massive blocks are provided as optimal solutions by moving from Palermo to Milan, especially for the cost-optimal solutions. This can be explained by considering that more massive roofs in warmer zones allow a better exploitation of the thermal inertia of the envelope part that is more critically invested by the solar irradiation during summer, ensuring energy savings for space cooling. More in detail, the nZEB optimal solutions provide that the density of the roof block is always equal to 1800 kg/m^3 – except for the nZEB’ solution for Florence (climatic zone D), where it is equal to 1400 kg/m^3, and for both the nZEB solutions for Milan (climatic zone E), where it is equal to 1000 kg/m^3 – while the cost-optimal ones indicate that it should be 1400 kg/m^3 for Palermo, 1000 kg/m^3 for Naples and Florence and 800 kg/m^3 for Milan. As said, since density and thermal conductivity are inter-dependent, the latter is always 0.72 W/m K for the nZEB solutions – apart from the nZEB’ for Florence and both the nZEB solutions for Milan, where it is 0.50 W/m K and 0.36 W/m K, respectively – while for the cost-optimal ones it is 0.50 W/m K for Palermo, 0.36 W/m K for Naples and Florence and 0.25 W/m K for Milan. Considering the thermal insulation layer, the U-values obtained for the roof (for both the solution types) are quite similar for the considered climatic zones, varying from 0.18 W/m^2 K for both the nZEB solutions in Milan to 0.23 W/m^2 K for the cost-optimal one in Palermo.

Table 3.11. U-values (thermal transmittance) of the envelope components for the optimal solutions

U-Values of Envelope Components [W/m^{2}K]	Palermo: Zone B		Naples: Zone C		Florence: Zone D			Milan: Zone E		
	nZEB(*)	C-O(*)	nZEB(*)	C-O(*)	nZEB(*)	nZEB’(*)	C-O(*)	nZEB(*)	nZEB’(*)	C-O(*)
Vertical Walls	0.19	0.85	0.18	0.85	0.20	0.17	0.18	0.19	0.20	0.18
Roof	0.20	0.23	0.20	0.22	0.20	0.20	0.19	0.18	0.18	0.20
Floor	1.79	0.21	2.23	0.40	2.23	1.70	0.99	1.47	1.18	1.49
Windows	1.72	1.84	1.59	1.35	1.35	1.59	1.59	1.35	1.35	1.90

(*) nZEB→ nearly zero energy building solution; nZEB’ → constrained nearly zero energy building solution; C-O → cost-optimal solution

Table 3.12. Performance indicators of the recommended solutions

Objective Functions	Palermo: Zone B		Naples: Zone C		Florence: Zone D			Milan: Zone E		
	nZEB(*)	C-O(*)	nZEB(*)	C-O(*)	nZEB(*)	nZEB’(*)	C-O(*)	nZEB(*)	nZEB’(*)	C-O(*)
PEC [kWhp/m^{2}a]: primary energy consumption	62.0	70.2	67.9	77.5	80.4	80.8	81.9	87.6	88.3	91.9
GC [€/m^2]: global cost	552	457	565	485	651	582	530	665	598	551
DH: percentage of discomfort hours	28%	35%	34%	50%	45%	46%	49%	54%	55%	58%
IC [€/m^2]: Investment cost	449	324	445	333	499	431	375	500	431	376

(*) nZEB→ nearly zero energy building solution; nZEB’ → constrained nearly zero energy building solution; C-O → cost-optimal solution

Concerning the floor, the nZEB optimal solutions indicate that less massive structures should be implemented by moving from warmer climatic zones to colder ones, while not general conclusions can be drawn for the cost-optimal ones. More in detail, the density values provided by the nZEB solutions are 2000 kg/m^3 for Palermo, Naples and Florence (unconstrained nZEB), 1800 kg/m^3 for Florence (nZEB’) and 1600 kg/m^3 for Milan, while the thickness is 0.35 m for Palermo, 0.25 m for both Naples and Florence (unconstrained) and 0.30 m for Florence (nZEB’) and Milan. Instead, for the cost-optimal solutions the density and thickness values of the floor block are, respectively, 600 kg/m^3 and 0.40 m for Palermo, 1600 kg/m^3 and 0.30 m for Naples, 1000 kg/m^3 and 0.30 m for Florence, 1400 kg/m^3 and 0.25 m for Milan. In this case, it is possible to notice how the block thickness decreases moving from Palermo to Milan. When the floor insulation is present (*i.e.*, cost-optimal solutions for Palermo and Naples), the U-value is much lower (0.21 W/m^2 K for Palermo and 0.40 W/m^2 K for Naples, respectively), otherwise it passes from 1.47 W/m^2 K (Milan) to 2.23 W/m^2 K (Naples and Florence), as nZEB solutions, and it is 0.99 W/m^2 K (Florence) and 1.49 W/m^2 K (Milan), as cost-optimal ones. However, the floor has not deep implications on thermal discomfort and on space conditioning – while it has a strong influence on the costs – due to its limited surface area compared to the vertical walls, other than the fact that it is not invested by direct solar irradiation, differently from the roof, thus high transmittance values are acceptable as well. The presence of thermal insulation for the cost-optimal solutions in Palermo and Naples can be explained by considering that vertical walls have higher U-values, which are partially compensated by the floor insulation.

Concerning the transparent envelope, triple-glazed with argon-filling, low-e coating windows are the most common, being included in the nZEB optimal solutions for Florence (unconstrained nZEB) and Milan (both the nZEB solutions), other than in the cost-optimal one for Naples. In this case, its implementation can be justified by considering the absence of thermal insulation on vertical walls, thus it is necessary to limit the heat dispersion through the envelope in order to guarantee satisfying comfort levels and to reduce energy demand for space conditioning, especially during the heating season. Selective double-glazed with argon-filling windows are implemented as nZEB solution in Naples and Florence (nZEB’) and as cost-optimal one in Florence because they provide the best trade-off among investment cost (270 €/m^2), thermal transmittance (1.59 W/m^2 K, included the PVC frame) and SHGC (0.43) for intermediate climatic zones, such as C and D. In Palermo, the nZEB solution provides the installation of tinted double-glazed with argon-filling windows, while the cost-optimal solution of selective double-glazed with air-filling ones. Both these window types are characterized by low values of SHGC (0.37 and 0.43, respectively) in order to reduce the energy demand for space cooling, being really high for Palermo the values of solar irradiation. As cost-optimal solution for

Milan, double-glazed with argon-filling windows should be implemented. These latter are characterized by the highest U-value among all the found optimal solutions (1.90 W/m^2 K), but this is “balanced” by really low U-values for both vertical walls and roof – 0.18 W/m^2 K and 0.20 W/m^2 K, respectively – as said. Furthermore, these windows are implemented because they present the highest SHGC among all the possible options taken into account, indeed it is equal to 0.69. This permits a better exploitation of the solar irradiation, strongly reducing the energy consumption for space heating, which is predominant in this climatic zone. Finally, the optimal orientation of the building is with the major façade exposed to East-West. This is due to comfort and energy reasons in order to maximize the exploitation of the solar irradiation during colder months.

The proposed design solutions are synergic with the climatic scenario and allow to maximize the benefits of involved public and/or private stakeholders. Globally, the values of all objective functions increase by moving from warmer cities, such as Palermo, to colder ones, such as Milan, as predictable because of the higher weight of heating demand compared to cooling demand for the considered use destination, characterized by low internal heat loads. More precisely, as nZEB optimal solutions the PEC is included between 62.0 kWh$_p$/m^{2}a for Palermo and 88.3 kWh$_p$/m^{2}a for Milan (nZEB’), the GC between 552 €/m^2 (Palermo) and 665 €/m^2 (Milan) – as said, the GC does not include the investments related to basic and invariable building construction categories, such as foundations and structures – and the DH between 28% (Palermo) and 55% (Milan). Concerning the cost-optimal solutions, the aforementioned values of PEC and DH are higher, as obvious, indeed PEC falls into the range 70.2 kWh$_p$/m^{2}a (Palermo) – 91.9 kWh$_p$/m^{2}a (Milan) and DH into the range 35% (Palermo) – 59% (Milan), while the GC values are lower, included between 457 €/m^2 and 551 €/m^2.

Finally, the proposed optimal solutions are compared to the reference designs related to the considered climatic locations, delineated in the previous tables 3.7-3.9. In this regard, table 3.13 shows such comparison by reporting the differences in PEC, GC, IC, DH as well as the simple payback period, the discounted payback period and the net present value. For the economic analysis, as done for GC assessment, the discount rate is set equal to 3% and the assumed calculation period is of 30 years. Figure 3.8 provides a focus on the cash flows and net present values for all proposed solutions.

Concerning Palermo, the proposed nZEB solution allows to reduce PEC of about 22 kWh$_p$/m^{2}a, GC of 30 €/m^2 and DH of 39 percentage points, compared to the reference design. However, this solution requires a higher IC – the increment is of 26 €/m^2. For this reason, the simple payback period is 9.8 years, while the discounted one rises to 11.7

years. The net present value is around 20.5 k€. Regarding the proposed cost-optimal solution, PEC and DH reductions are lower, *i.e.*, about 14 kWh_p/m^2a and 32 percentage points, respectively. Compared to the reference design, GC strongly decreases, and its reduction is equal to 125 €/m^2. This can be explained by considering the limited required IC, which is 99 €/m^2 lower than the reference one. For this reason, both the simple payback period and the discounted one are 0. Finally, for this solution the net present value is 102.5 k€.

Regarding Naples, the proposed nZEB solution allows to reduce PEC of about 22 kWh_p/m^2a, GC of 33 €/m^2 and DH of about 17 percentage points, in comparison with the reference design. However, as the nZEB for Palermo, this solution requires a higher IC – the increment is of 21 €/m^2. For this reason, the simple payback period is 8.1 years, while the discounted one is 9.4 years. The net present value is equal to 22.8 k€. On the other side, for the proposed cost-optimal solution, PEC and DH reductions are lower – *i.e.*, about 13 kWh_p/m^2a and 1 point, respectively – while the GC one is higher and it is equal to 113 €/m^2. As previously said, this can be explained by the limited IC, which is 91 €/m^2 lower than the reference one. For this reason, also in this case, both the simple payback period and the discounted one are 0. In conclusion, for this solution the net present value is 93.4 k€.

For Florence, two "nZEB" optimal solutions are proposed because the unconstrained one (nZEB) is not cost-effective compared to the reference design, thus a constraint on GC is set and the nZEB' solution is individuated. The unconstrained nZEB solution allows to reduce PEC of about 20 kWh_p/m^2a and DH of about 3 percentage points, while it produces an increment of GC of about 24 €/m^2, due to the significant IC – it increases of about 71 €/m^2 in comparison with the reference one. In this case, the simple payback period is 31.3 years, while the discounted one is 94.1. In addition, as predictable, the net present value is negative and it is equal to -20.8 k€, which implies that this solution is not cost-effective at all. For this reason, also the nZEB' solution is proposed. This latter produces slight lower reductions of PEC and DH while ensuring a strong decrease of GC (compared to the reference design), which is reduced by 45 €/m^2 because the required IC is almost equal to the reference one. In this second case, the simple payback period and the discounted one are between 1 and 2 years, while the net present value is 32.5 k€. On the other hand, for the cost-optimal solution, the PEC reduction is a bit lower – *i.e.*, about 19 kWh_p/m^2a, while the GC decreases of about 97 €/m^2. As for the former solution, this can be justified by considering the reduced IC, which is 53 €/m^2 lower than the reference one. Unfortunately, this solution provides an increment of DH of about 1 point. In conclusion, in this case, both the simple payback period and the discounted one are 0. The net present value is of 74.4 k€.

Finally, as for Florence, two "nZEB" optimal solutions are proposed for Milan. The unconstrained nZEB one allows to reduce PEC of about 19 kWh_p/m^2a, while it produces an increment of DH of about 4 percentage points and of GC of 39 €/m^2 because of the necessary IC – it increases of about 82 €/m^2 compared to the reference one. In this situation, the simple payback period is 39 years, while the discounted one is unreachable. In addition, the net present value is equal to -31.9 k€. For this reason, the nZEB' solution is proposed too. This one produces a PEC reduction of around 18 kWhp/m2 and a DH increase of 5 points compared to the reference design. Most notably, GC decreases by more than 28 €/m^2 compared to the reference one because the required IC is lower to the one of the former nZEB solution, even if it is 13 €/m^2 higher than the reference design. For this solution, the simple payback period and the discounted one are around 7 years – more precisely, they are 6.4 years and 7.3 years, respectively – while the net present value is 20.8 k€. On the other side, for the cost-optimal solution, the PEC reduction is a bit lower – *i.e.*, 15 kWhp/m^2a – while GC decreases of about 75 €/m^2 because of the required IC, which is 42 €/m^2 lower than the reference one. Unfortunately, also in this case, DH increases compared to the reference design (higher than 9 points). Regarding the payback periods, both the simple and the discounted ones are zero. In conclusion, for this solution the net present value is 57.2 k€.

Globally, the proposed cost-optimal solutions are much more cost-effective than the nZEB ones, as predictable, but what could surprise the most is that they are almost as energy-efficient as the nZEB solutions especially for colder climates, such as Florence and Milan, thus also the public stakeholders – and not only the private ones – could opt for this type of solutions in several situations.

Table 3.13. Comparison between the proposed optimal solutions and the related reference designs

Objective Functions	**Palermo: Zone B**		**Naples: Zone C**		**Florence: Zone D**			**Milan: Zone E**		
	nZEB$^{(*)}$	**C-O$^{(*)}$**	**nZEB$^{(*)}$**	**C-O$^{(*)}$**	**nZEB$^{(*)}$**	**nZEB'$^{(*)}$**	**C-O$^{(*)}$**	**nZEB$^{(*)}$**	**nZEB'$^{(*)}$**	**C-O$^{(*)}$**
PEC reduction [kWh_p/m^2a] $^{(**)}$	22.4	14.2	22.3	12.7	20.3	19.9	18.8	18.9	18.2	14.6
GC reduction [€/m^2] $^{(**)}$	30	125	33	113	-24	45	97	-39	28	75
IC reduction [€/m^2] $^{(**)}$	-26	99	-21	91	-71	-3	53	-82	-13	42
DH reduction [percentage points] $^{(**)}$	39	32	17	1	3	2	-1	-4	-5	-9
Simple Payback Period [years]	9.8	0	8.1	0	31.3	1.2	0	39.0	6.4	0
Discounted Payback Period [years]	11.7	0	9.4	0	94.1	1.3	0	never	7.3	0
Net Present Value [k€]	20.5	102.5	22.8	93.4	-20.8	32.5	74.4	-31.9	20.8	57.2

$^{(*)}$ nZEB→ nearly zero energy building solution; nZEB' → constrained nearly zero energy building solution; C-O → cost-optimal solution

$^{(**)}$ positive values denote that the proposed solutions induce a reduction (and thus an advantage) of the performance indicator, while negative values denote an increase (and thus a disadvantage)

The comparison shows that the optimal solutions provide some different guidelines for the construction of new buildings compared to the reference designs. The main differences are detailed below:

- concerning the HVAC operation, the set-point temperatures for heating and cooling should be set equal to 19 °C and 27 °C, respectively, in spite of 20 °C and 26 °C for all climatic zones;
- concerning the envelope in general, it should be oriented with the major side exposed to East-West;
- concerning the vertical walls, lower values of solar absorbance than 0.6 should be preferred for warmer climatic zones, while higher ones for the colder climatic zones. In addition, the insulation layer – if present – should be 0.10-0.12 m thick, much higher than for the reference buildings, where the insulation layer is 0.03-0.05 m thick. Finally, in general, less massive and less conductive vertical walls should be designed;
- concerning the roof, as for the vertical walls, lower values of solar absorbance than 0.6 should be preferred for warmer climatic zones, while higher ones for the colder climatic zones. Furthermore, the insulation layer should always be 0.10-0.12 m thick, which means that it should be thicker compared to the reference buildings, where the insulation layer is 0.06-0.10 m thick. In conclusion, more massive roofs should be preferred in warmer climatic zones, while less massive ones in colder zones;
- concerning the floor, it may be better not to insulate it, differently from the reference buildings; moreover, in general, it should be more massive;
- concerning the transparent envelope, the double-glazed windows with air/argon-filling and low-e coatings of the reference design should be replaced with selective double-glazed ones with argon-filling and low-e coatings or triple-glazed ones with argon-filling and low-e coatings.

Final remarks

Finally, the proposed methodology may be very powerful for improving the energy performance of new buildings. Indeed, it can give important indications to rebuild part of the Italian/European residential stock, innovative compared to local construction practices, taking into account both the energy-efficiency and the cost-optimality, thus satisfying both public and private perspectives. Unfortunately, the presented methodology is suitable only for new buildings, involving in the optimization process many design variables that may be varied exclusively during the early-stage of the energy design of a new construction. However, aiming at massively reducing the energy and environmental impact of the construction sector, research should focus also (or mainly) on the energy retrofit of existing buildings, due to the low value of replacement rate of the stock building – *i.e.*, around 1-2%.Therefore, a novel approach is presented in the next chapter for the optimization of the energy retrofit of existing buildings.

How to optimize the energy retrofit of
an existing building?

CHAPTER 4. A multi-stage multi-objective approach for the energy retrofit of existing buildings

4.1. Introduction

With the aim to reduce the energy and the environmental impact of the building sector, different actions need to be taken for new buildings and for existing ones. As for example, for the formers a comprehensive optimization of the characteristics of the envelope is feasible, as seen, but the same is not possible for the latter. Therefore, while in the previous chapter a study is presented concerning the optimization of the energy design of new buildings, here a novel approach for the energy refurbishment of existing buildings is proposed.

Among the numerous optimization methodologies described in literature, the methodology proposed in this chapter makes use of a genetic algorithm. As better explained in the following section, the method here applied is structured in two consequent and interdependent stages. More precisely, during the first stage, there is the implementation of the GA and, by means of the continuous coupling between MATLAB® and EnergyPlus, the thermal energy demands (TED) for heating and cooling, respectively, and the discomfort hours (DH) are minimized. Conversely, the second stage is entirely conducted under MATLAB® environment and enables to find constrained cost-optimal solutions that ensure a drastic reduction of global costs as well as of CO2-eq emissions. Finally, the effect of such solutions on building heat emissions into the external environment is assessed, in order to evaluate the contribution to the mitigation of urban overheating, which highly affects the external human comfort and the livability of our cities. This is a crucial aspect, due to constantly increasing urbanization, in fact more than the half of the world’s population (*i.e.*, the 54%) nowadays lives in urban areas [134, 135] and it is forecasted to be rising during the next few years [136, 137], with obvious implications on environmental degradation, being the cities and their inhabitants the principal players in heat wasting and CO_2 emitting [136, 138].

The main novelty of the proposed methodology consists in the possibility to satisfy both the perspectives, the public one (by reducing the GHG emissions) and the private one (by minimizing the GC and the DH), thereby allowing to fight climate change and ensuring the design cost-effectiveness at the same time. The focus on the reduction of heat emissions, in addition to the assessment of energy demands and greenhouse gas emissions, is a further novel aspect as regards investigations concerning building energy efficiency. In addition, being the second stage conducted entirely in MATLAB®, it is no time-consuming, thus during the second stage many objective functions can be investigated and optimized without particular computational efforts. Finally, being based on a GA, the proposed methodology does not suffer from failures caused by simulation crashes.

Aiming at showing the importance of the presented approach, a case study is presented. Indeed, the methodology is applied to a typical existing office building, which is representative of the Italian building stock since 1970's.

4.2. Methodology

4.2.1. Framework

This study proposes a multi-objective and multi-stage optimization technique to find a constrained cost-optimal solution that ensures the Pareto optimization of TED (thermal energy demand) for heating, TED for cooling, discomfort hours (DH), global cost (GC) and GHG emissions. Once fixed the main boundary conditions, concerning geometry, occupancy profiles and climatic conditions, several energy efficiency measures are combined and examined. The considered energy efficiency measures concern all levers of energy efficiency in buildings, *i.e.*:

- the building envelope (*e.g.*, new kind of low-emissive or selective glazing, addition of thermal insulation, particular plasters);
- the primary energy systems, considering also renewable energy sources (*e.g.*, efficient air-source heat pumps, photovoltaic generators).

More in detail, EnergyPlus is used for dynamic energy simulations, because it ensures high accuracy and reliability, while MATLAB® is used to run the optimization algorithm and to perform the data-processing, because of its large opportunities of programming. Furthermore, MATLAB® is used to launch EnergyPlus simulations. Thus, the coupling of these two software allows to run automatically a huge set of dynamic energy simulations that are managed by the optimization algorithm, developed directly in MATLAB® environment. More precisely, the methodology performs a multi-stage and multi-objective optimization by implementing a genetic algorithm (GA) – 1st stage – and running a smart exhaustive sampling – 2nd stage. The GA, born as a modification of NSGA-II, operates by iteratively improving the models of the building with the aim to identify the non-dominated solutions (*i.e.*, the Pareto front) for what concerns the building envelope design or retrofit, by minimizing TED for heating, TED for cooling and DH. Then, the smart exhaustive sampling stage allows to investigate the Pareto front solutions obtained during the 1st stage and the baseline situation, aiming at reducing GC and GHG emissions thereby conducting a constrained cost-optimal analysis. Thus, decision making is performed by providing a recommended trade-off design/retrofit solution. A similar technique was used in [132], but this study addresses different objective functions in order to provide solutions that allow to fight climate change and ensure cost-effectiveness at the same time. This represents the main worthy and original contribution of the proposed approach that enables to conciliate the private and public perspectives.

Since the 2nd stage is conducted entirely in MATLAB®, the required computational efforts are strongly reduced. The following subsections provide a description of the two methodology stages.

4.2.2. 1st Methodology stage: Optimization algorithm

In this stage, the baseline energy performance of the building ("as built") is assessed, in terms of TED for space cooling, TED for space heating and DH, respectively. The building is modeled in EnergyPlus by using the graphical interface DesignBuilder, that allows a careful definition of geometry and subdivision into thermal zones. As specified in the previous chapter, it is quite important, for the EnergyPlus model, to set:

1. the thermo-physical characteristics of the building envelope;
2. the profiles of building use for each thermal zone, in terms of hourly schedules of occupancy, people activity, ventilation need, and so on;
3. the operation of HVAC systems by setting the values of set-point temperatures;
4. the type of HVAC systems in terms of characteristics of the heating and cooling terminals as well as of the distribution network.

It should be noted that the heating/cooling primary systems are not modeled in this phase, because, during this stage, the aim is to calculate the thermal energy demand (*i.e.*, the "net requirement") and not the primary energy consumption, which is assessed later by means of MATLAB®. After modeling the baseline building (BB), an EnergyPlus simulation is run by using a proper weather data file, usually available at the EnergyPlus online database. The annual values of TED for space heating (TED_{heat}), for space cooling (TED_{cool}) per unit of conditioned area, and DH are the simulation outputs. DH provides the annual percentage of discomfort hours. As done in [139], an occupied hour is considered a discomfort one if the average predicted mean vote (PMV) in the building thermal zones is out of the range -0.85÷0.85, implying a value of predicted percentage of dissatisfied (PPD) higher than 20%.

After the investigation of the energy behavior of the BB, a set of "n" energy efficiency measures for the reduction of TED_{heat}, TED_{cool} and DH is identified, based on the current energy performance, building peculiarities and best practices. A variable is associated to each energy efficiency measure and it can be, potentially, discrete or continuous, even if in the case study presented in this chapter all variables are considered as "discrete". Finally, "n" variables are introduced, and a range of variability is assigned to each of them, by defining the sample space that should be explored with the aim to examine the energy efficiency measures' combinations. At this point, the GA carries out a smart research within the entire solution domain by investigating only a limited number of solutions, properly selected by the optimization logic. As aforementioned, a large amount of computational time is saved if the method is compared to exhaustive researches. Since three objective functions are chosen – *i.e.*, TED_{heat}, TED_{cool} and DH – the algorithm provides one three-dimensional (3D) and three bi-dimensional (2D) Pareto fronts (one for each couple of objectives), by collecting the non-dominated solutions, which represent optimal packages of the investigated energy efficiency measures. Obviously, the goal is the minimization of all targets at the same time, but this is concretely impossible, because usually the objective functions are in mutual contradiction. The GA provides trade-off solutions collected in the aforementioned Pareto fronts (for this reason we call them "non-dominated"). The used GA has been already implemented by Ascione *et al.* [139] in MATLAB® environment according to the scheme reported in the figure 4.1, where the vector F collects the objective functions ($F = [TED_{heat}, TED_{cool}, DH]$). The vector x is composed of bits that encode the design variables representing energy efficiency measures. Each design variable can assume a limited number of values, because this allows to reduce the solution domain and it is much closer to reality and availability of the market. The possible values must be carefully chosen according to best practices and experiences. The GA performs, iteratively, an evolution of a population of "s" (population size) individuals, denoted as "chromosomes", each one characterized by a set of values of the vector x, whose components are called "genes" and correspond to a combination of building energy efficiency measures. The process is performed through numerous iterations, the so-called "generations". It is required to improve the characteristics of the population by the selection of the best chromosomes as well as through the operations of mutation and crossover of their genes (*e.g.*, the bits encoding the thicknesses of thermal insulation layer) in order to have new individuals that improve the energy and thermal performance of the building. The individuals that derive from crossover, called “children”, are randomly generated by combining the design variables (*i.e.*, bit strings) of two parents. The population fraction that originates from crossover is indicated by the crossover fraction “f_c”. All other remaining individuals (“mutated children”) are originated by the mutation of random parents, more in detail by changing each bit with a mutation probability equal to “f_m”. The best chromosomes are called “parents” and are chosen based on a rank assigned from the values of objective functions and from the average crowding distance among individuals. The best parents constitute the “elite” that survives to the generation. After the random creation of the initial population, the described “Darwinian evolution” occurs during each generation and ends when one of the following termination criteria is satisfied:

- a threshold number of generations (g_{max}) is reached;
- the Pareto front does not change significantly between two following generations. Of course, a not significant variation of the Pareto front means that it is lower than a tolerance “tol”.

The used termination criterion is the first one and most GA parameters take the same values shown in table 3.1.

For what concerns the values of s and g_{max}, it is important to notice that these must be properly set depending on the complexity of the case study, because they crucially affect the reliability of the results and the required computational efforts. Ascione *et al.* [124] assessed that reliable “s” values are 2-6 times the number of design variables (in this study, it is set equal to 4), whilst reliable “g_{max}" values are included in the range 10–100 generations (in this study, this is set to 20).

More in detail, for each energy efficiency measures’ combination, which is encoded by certain values of the vector x, MATLAB® launches EnergyPlus in order to run a dynamic energy simulation. Then, the results of this simulation are post-processed for obtaining the values of the objective functions (*i.e.*, TED_{heat}, TED_{cool}, DH) with reference to each examined combination. The coupling scheme between the two software is shown in figure 4.1. The “coupling function” between EnergyPlus and MATLAB®” converts x into a new building model to be simulated (the “.idf” file) and consequently handles the output file of EnergyPlus (the “.csv” file),in order to calculate the values of the objectives contained in F. It is noticed that the energy efficiency measures are implemented and parametrized directly within the “.idf” EnergyPlus file. Moreover, in some cases also a constrain is defined, since all solutions that cause an increase of the values of one selected objective function compared to the base building configuration can be excluded. Thus, the GA implementation must be followed by the decision-making process, which aims at selecting one recommended solution from the Pareto front. This process is performed during the second stage.

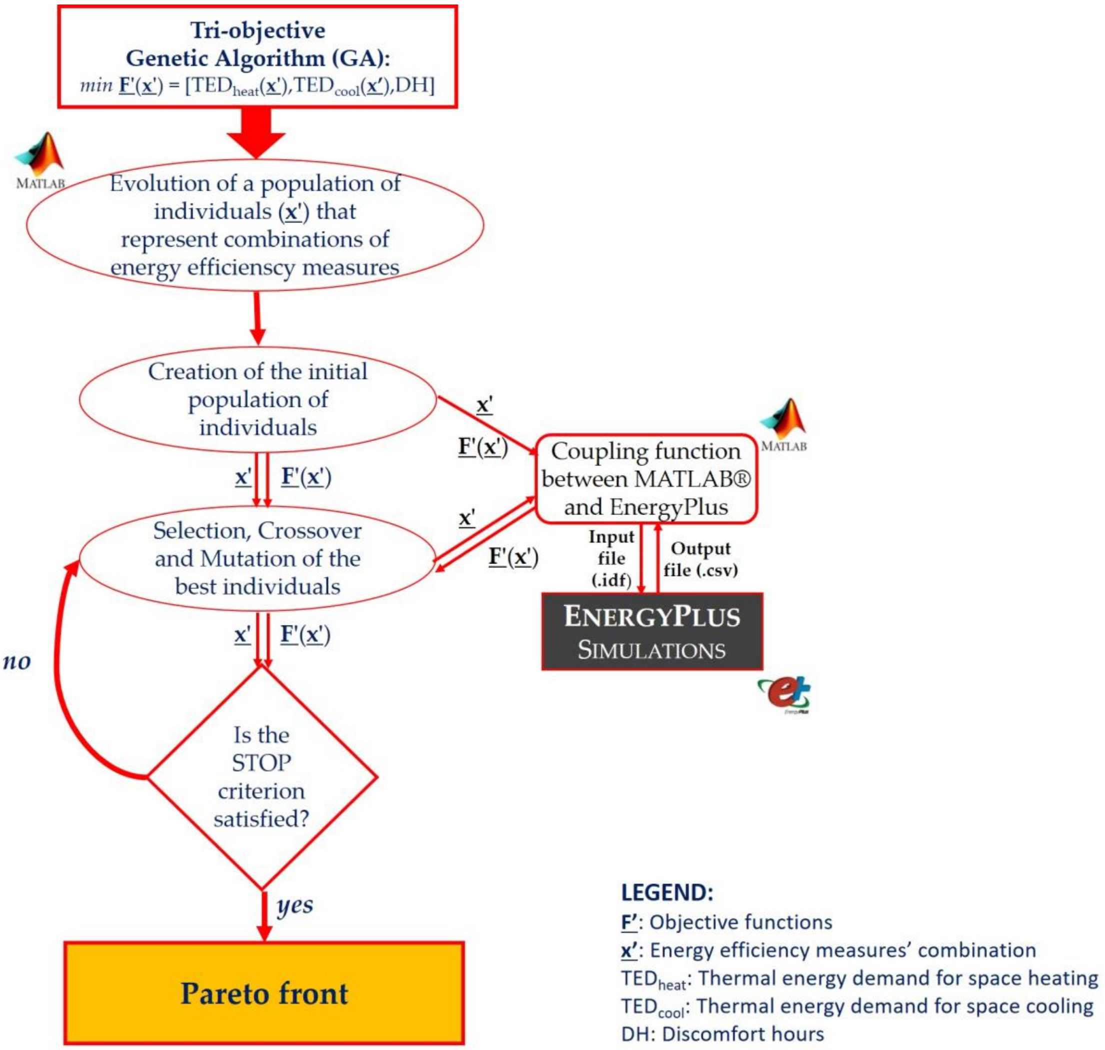

Figure 4.1. Scheme of the 1st optimization stage, which addresses the optimization of energy efficiency measures' combination (x) for the minimization of the thermal energy demand for space heating (TED_{heat}) and space cooling (TED_{cool}) and the discomfort hours (DH) – adopted from [124] and modified

4.2.3. 2nd Methodology stage: Decision-making

In this phase, the decision-making process is performed, aiming at selecting one combination of energy efficiency measures among all non-dominated configurations. It is a crucial task and it can be carried out according to different criteria. Obviously, none of the solutions of the Pareto front can be chosen "a priori", because it cannot be defined better than another. For this reason, a selection criterion is essential. For what concerns the methodology described in this chapter, the chosen criterion is the so-called “cost-optimality”, which means that, at the end of the entire optimization process, the chosen solution (*i.e.,* package of energy efficiency measures) is the one that minimizes the global cost (GC) over building predicted lifecycle. The cost-optimal analysis is applied by means of a smart exhaustive sampling. This latter permits to investigate further energy efficiency measures – addressed also to primary energy systems – besides those examined in the 1st stage, which are addressed to the envelope and to the operation parameters of the HVAC systems. It is important to notice that the GC considers the initial investment cost, the GHG emissions costs and the running costs, those latter evaluated for a certain number of years (depending on the category of the building) and actualized at the starting time.

More in detail, during this stage, a smart exhaustive sampling is carried out by investigating the energy performance of different solutions of primary energy systems, in presence of the non-dominated energy efficiency measures’ combinations selected in the first stage, and also in absence of energy efficiency measures (baseline configuration). For each combination, the GC and the GHG emissions are evaluated, and, finally, the cost-optimal solution is found. A sensitivity analysis is then performed in correspondence of different values of the discount rate, in order to investigate the robustness of the found cost-optimal solution. The major novelty introduced by this methodology is that this stage is entirely implemented in MATLAB® environment, without launching further EnergyPlus simulations. For this reason, it needs a negligible computational time compared to the first stage (*i.e.*, the order of magnitude is few seconds). The exhaustive sampling is “smart” because:

1. it is performed in MATLAB® environment, without needing further EnergyPlus simulations;
2. it explores, besides the baseline building (BB), only the packages of energy efficiency measures that are properly selected through the GA implementation.

More precisely, the chosen energy efficiency measure package represents a “constrained” cost-optimal solution, since only suitable packages are selected for the cost-optimal analysis based on the results of the 1st methodology stage. The retrofit solutions that provide higher DH values compared to the baseline situation are excluded from the 2nd stage. This allows to achieve a constrained cost-optimal solution that produces, at the same time, a substantial improvement of energy performance and thermal comfort, thereby satisfying both the private and the public perspectives. Furthermore, the impact of such optimal retrofit solution on the annual heat emissions of building HVAC systems into the external environment is assessed. This analysis aims at investigating the contribution to the mitigation of urban overheating, which significantly affects the external thermal comfort of people, and thus the liveability of our cities, as well as building energy needs.

4.3. Presentation of the case study

4.3.1. Building model description

The case study is an existing office building, typical of the Italian building stock in reinforced concrete as structural material. It is theoretical reference building, provided by an accurate ENEA study [140], which examined the national building stock and proposed many reference buildings.

The building is supposed to be situated in Naples (South Italy) and it has five floors above the ground, each one having a net height of 3 m. The building gross floor area is equal to 2400 m^2 (480 m^2 per level). It is possible to notice that the glazing area changes with the exposure. More in detail, for the west and the east façades, it is about the 55% of the whole area (*i.e.*, about 128 m^2), while, for the south exposure, it is about the 33%, and for the north side it is about the 30%. In the baseline situation, the shading systems are absent. For what concerns the air infiltration rate, according to common Italian values for existing buildings, it has been set at 0.5 air changes per hour (ACH). As for the building use, 50 thermal zones can be individuated, and thus 10 for each floor. There are three different categories of thermal zones, as shown in figure 4.3.

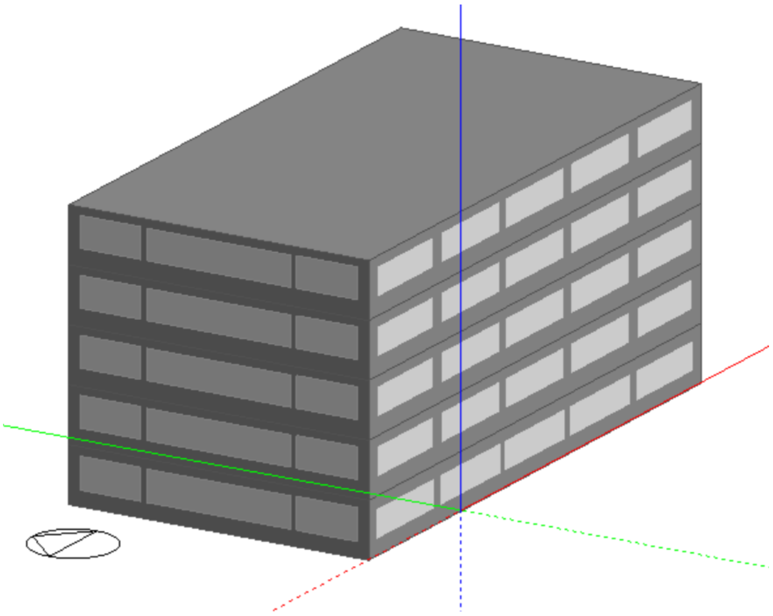

Figure 4.2. Overall building view

As for the building use, 50 thermal zones can be individuated, and thus 10 for each floor. There are three different categories of thermal zones, as shown in figure 4.3.

The following tables 4.1-4.3 show the supposed composition of the opaque building envelope components according to the standard Italian constructive practice. The attention is focused on ground floor, roof, and external walls, by considering the necessity to rigorously respect the national law limits about the thermal transmittance (*i.e.*, U-value). Moreover, table 4.4 reports the thermo-physical properties of the cited materials. As concerns the transparent building envelope, the windows are double-glazed with clear float glasses, air-filling and aluminium frames. The window U-value is equal to 3.74 W/m^{2}K while the solar heat gain coefficient (SHGC) is equal to 0.76. Finally, the U-values of all envelope components are reported in table 4.5, which provides an overview of the baseline configuration of the reference building, as concerns HVAC systems too. In this regard, there is a primary centralized system, which supplies hot and cold water to four-pipes fan coils. All building thermal zones are equipped with such terminals. The heating primary system is a traditional natural gas boiler, while the cooling one is an electric air-cooled chiller. The nominal efficiency (η) of the boiler at the LHV (Lower Heating Value) is 0.85, the nominal coefficient of performance (COP) of the chiller is 2.3. The heating load of the entire building is about 220 kW, while the cooling load is about 235 kW.

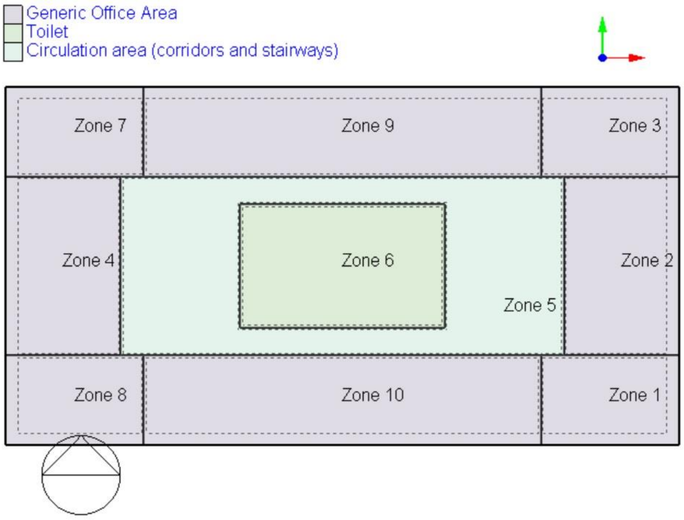

Figure 4.3. Floor subdivision in thermal zones

As concerns the economic assumptions, the considered specific prices for electricity and natural gas are the following ones:

- 0.25 €/kWh$_{el}$ for the electricity;

- 0.90 €/Sm^3 for the gas with a LHV equal to 9.59 kWh/Sm^3.

In addition, as for the discount rate (denoted with r) applied in the assessment of global cost, three different values are considered (*i.e.*, 1%, 3% and 5%). The assumed calculation period is 20 years, since the investigated building is an office [3, 15].

Finally, table 4.5 shows the explored performance indicators of the baseline building (BB), namely:

- thermal energy demand for space heating (TED_{heat});
- thermal energy demand for space cooling (TED_{cool});
- annual percentage of thermal discomfort hours (DH);
- global cost due to energy uses (GC);
- GHG emissions due to energy uses in terms of CO_2-eq emissions.

Table 4.1. Baseline building: External walls composition, from the external to the internal layer

Layer n°	Material	Thickness [m]
1	Plaster	0.025
2	Hollow bricks	0.12
3	Polystyrene	0.08
4	Air gap	0.12
5	Hollow bricks	0.08
6	Plaster	0.025

Table 4.2. Baseline building: Ground floor composition, from the external to the internal layer

Layer n°	Material	Thickness [m]
1	Pebbles	0.18
2	Slab	0.30
3	Semi-rigid panels	0.05
4	Screed	0.03
5	Tiles	0.02

Table 4.3. Baseline building: Roof composition, from the external to the internal layer

Layer n°	Material	Thickness [m]
1	Roof plaster	0.03
2	Roof slab	0.18
3	Semi-rigid panels	0.03
4	Screed	0.03
5	Cement	0.03

The GC is calculated for a long-time period τ of 20 years with the equation established by EU Guidelines [15] and reported below.

$$\mathrm{GC}(\tau) = \sum_{j}\big[\sum_{i}^{\tau}(\mathrm{RC}(i) * \mathrm{R_d}(i) + \mathrm{C_{c,i}}(j) - \mathrm{V_{f,\tau}}(j)\big] + \ \mathrm{IC} \qquad (4.1)$$

Note that the equation 4.1 presents the additional term “$C_{c,i}(j)$”compared to the equation 3.1. It stands for the cost of the GHG emissions. It is used a cost of 20 €/tCO_2-eq until the year 2025, 35 €/tCO_2-eq until 2030 and then 50 €/tCO_2-eq, as specified in [15]

Table 4.4. Thermo-physical properties of the opaque building envelope materials

Material	Density [kg/m^3]	Specific heat [J/kg K]	Conductivity [W/m K]	Material	Density [kg/m^3]
Plaster	2000	1000	1.40	Plaster	2000
Hollow bricks	2000	1000	0.90	Hollow bricks	2000
Polystyrene	1100	1450	0.037	Polystyrene	1100
Pebbles	1500	1000	0.70	Pebbles	1500
Semi-rigid panels	16.00	1660	0.046	Semi-rigid panels	16.00
Screed	1800	1000	0.90	Screed	1800
Tiles	2300	840	1.00	Tiles	2300
Roof plaster	800	1000	0.70	Roof plaster	800
Roof screed	400	1000	1.40	Roof screed	400
Cement	2000	1000	1.40	Cement	2000

Table 4.5. Characterization of the building

Dimensions and Geometry			
Length (E-W direction)	30 m	Length (N-S direction)	16 m
Height	15 m (5 floors)	Total Area	2400 m^2
Surface to Volume Ratio	0.33 m^{-1}	Total Volume	7200 m^3
Main Boundary Conditions of Energy Simulations			
Climatic data	IWEC → EPW	Design occupancy	230 people
Number of thermal zones	50		
Winter setpoint temperature	20 °C (8 am – 1 pm, 2 pm – 7 pm)	Summer setpoint temperature	26 °C (8 am – 1 pm, 2 pm – 7 pm)
Artificial lighting, lighting levels and electric equipment are diversified depending on the thermal zone use			
Building Envelope			
U_{WALL}	0.97 W/m^{2}K	$U_{GROUNDFLOOR}$	0.51 W/m^{2}K
U_{ROOF}	0.85 W/m^{2}K	$U_{WINDOWS}$	3.74 W/m^{2}K
Shading systems	Absent	$SHGC_{WINDOWS}$	0.76
Infiltration rate	0.50 ACH		
HVAC System			
HVAC typology	Four pipe fan coils, hot and cold water loops, no heat recovery	Ventilation Air	2.5 m^3/s globally
Sensible load control	Yes	Latent load control	Not
Boiler nominal capacity	250 kW	Boiler type	Hot water, Gas fired η=0.85
Chiller nominal capacity	260 kW	Chiller type	Electric air-cooled, COP=2.3
Energy Prices, Conversion Factors and Emission Factors			
Electricity price	0.25 €/kWh	Gas price	0.90 €/Sm^3
Electricity selling price	0.07 €/kWh		
Electrical-to-primary energy conversion factor	1.95	Gas-to-primary energy conversion factor	1.05
Electricity LCA emission factor	0.708 t CO_2/MWh	Gas LCA emission factor	0.237 t CO_2 / MWh
Renewable electricity LCA emission factor	0.035 t CO_2 / MWh		
Baseline Performance Indicators			
TED_{heat}	10.7 kWh/m^{2}a	TED_{cool}	62.2 kWh/m^{2}a
DH	52.4 %	CO_2-eq emissions	161.2 t/a
GC (r = 1%)	560.8 €/m^2	GC (r = 3%)	471.9 €/m^2
GC (r = 5%)	404.1 €/m^2		

The equation 4.1 permits to adopt a macro-economic approach, which is fundamental in order to choose proper energy efficiency measures’ aiming at reducing the environmental impact due to buildings. In fact, mid-polluting measures’ combinations – which could be the most efficient trade-offs between the two main objectives of this study (minimization of GC and GHG emissions) in short-midterm evaluations – result to be inefficient for a long-term period, once taken into account also the cost of the GHG emissions.

4.3.2. Energy retrofit scenarios

As concerns building energy retrofit, 11 different design variables – representing retrofit measures for the reduction of thermal energy demands and/or discomfort – are considered to perform the 1st stage of the optimization process, namely:

1. Setpoint temperature for space heating;
2. Setpoint temperature for space cooling;
3. Thermal emissivity of the most external layer of the vertical walls;
4. Solar absorbance of the most external layer of the vertical walls;
5. Thermal emissivity of the most external layer of the roof;
6. Solar absorbance of the most external layer of the roof;
7. Thickness of an additional external layer of thermal insulation for the vertical walls – polyurethane panels are considered (density = 25 kg/m^3, conductivity = 0.028 W/mK, specific heat = 1340 J/kgK);
8. Thickness of an additional external layer of thermal insulation (polyurethane) for the roof;
9. Type of windows;
10. Type of shading systems;
11. Position of the shading systems.

The values that the mentioned variables can assume are all discrete as shown in the following tables 4.6-4.8, where the acronym BB denotes the value of the baseline building configuration. It should be noted that our target was to propose a methodology. In future studies, the possible ranges and values that can be assumed by the variables can be better defined, according to the real availability of some solutions in the market of energy efficiency measures and building components. In particular, this may concern reflectance and emissivity of building external coatings that should comply the fact that emissivity is high for almost all non-metal materials and that the soiling affects largely the solar absorptance.

Concerning the 2nd stage of the optimization process, 4 heating primary systems and 2 cooling primary systems are taken into account, as shown in tables 4.9 and 4.10. When the air-source electric heat pump and the high-efficiency electric air-cooled chiller are implemented together, the installation of only one reversible heat pump is considered.

Table 4.6. Characterization of the design variables of the 1st optimization stage

Design variables	Values
Setpoint temperature for space heating [°C]	19; 20 (BB); 21; 22
Set-point temperature for space cooling [°C]	24; 25; 26 (BB); 27
Emissivity of the vertical walls [-]	0.1; 0.25; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9 (BB)
Absorbance of the vertical walls [-]	0.1; 0.25; 0.4; 0.5; 0.6 (BB); 0.7; 0.8; 0.9
Emissivity of the roof [-]	0.1; 0.25; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9 (BB)
Absorbance of the roof [-]	0.1; 0.2; 0.3; 0.4; 0.5; 0.6 (BB); 0.75; 0.9
Additional insulation thickness of the vertical walls [m]	0 (BB); 0.03; 0.04; 0.05; 0.06; 0.08; 0.10; 0.12
Additional insulation thickness of the roof [m]	0 (BB); 0.03; 0.04; 0.05; 0.06; 0.08; 0.10; 0.12
Type of windows [-]	1 (BB); 2; 3; 4; 5; 6; 7; 8 (see table 4.7)
Type of shading systems [-]	0 (BB); 1; 2; 3; 4; 5; 6; (see table 4.8)
Position of the shading systems [-]	1 (internal); 2 (external)

Table 4.7. Investigated types of windows

N°	Type	U [W/m^{2}K]	SHGC [-]
1	Double-glazed with air-filling. Aluminium frame (BB)	3.74	0.76
2	Double-glazed with air-filling and low-e coating. PVC frame	2.12	0.69
3	Tinted double-glazed with air-filling and low-e coating. PVC frame	1.95	0.38
4	Selective double-glazed with air-filling and low-e coating. PVC frame	1.84	0.43
5	Double-glazed with argon-filling and low-e coating. PVC frame	1.90	0.69
6	Tinted double-glazed with argon-filling and low-e coating. PVC frame	1.72	0.37
7	Selective double-glazed with argon-filling and low-e coating. PVC frame	1.59	0.43
8	Triple-glazed with argon-filling and low-e coating. PVC frame	1.35	0.58

Table 4.8. Investigated shading systems

N°	Type	Solar Transmittance	Solar Reflectance	Visible Transmittance	Visible Reflectance
0	Shading system is absent (BB)	/	/	/	/
1	Low reflect – Low trans shade	0.1	0.2	0.1	0.2
2	Low reflect – Medium trans shade	0.4	0.2	0.4	0.2
3	Low reflect – High trans shade	0.7	0.2	0.7	0.2
4	Medium reflect – Low trans shade	0.1	0.5	0.1	0.5
5	Medium reflect – Medium trans shade	0.4	0.5	0.4	0.5
6	High reflect – Low trans shade	0.1	0.8	0.1	0.8

Table 4.9. Investigated heating primary systems

Heating system	Efficiency
Traditional boiler (BB)	$\eta = 0.85$
High-efficiency natual gas boiler	$\eta = 0.95$
Condensing natual gas boiler	$\eta = 1.05$
Air-source electric heat pump	COP = 3.5

Table 4.10. Investigated heating primary systems

Cooling system	COP
Air-cooled electric chiller (BB)	2.3
High-efficiency electric air-cooled chiller	1.2

Furthermore, the 2nd optimization stage considers the installation of photovoltaic (PV) panels. Two different solutions are investigated – monocrystalline panels (more efficient) and polycrystalline ones – installed on the roof in order to satisfy the electricity needs of lighting, equipment and HVAC systems. In detail, 10 different roof coverage percentages are considered, from 10% to 100% by means of increments of 10%. The PV panels are installed facing South with an inclination equal to 30°. The inverter has a nominal efficiency equal to 99%, as in the previous chapter, and it is the same for both the type of PV panels. No batteries for PV energy storage are considered, and so the eventual surplus of energy is fed into the grid. In this case, the price assumed for the electricity sold to the greed is 0.07 €/kWh_{el} according to current Italian tariffs.

As concerns the cost-optimal analysis, the assumed values of investment costs for the energy retrofit measures are reported in table 4.11. These values are taken partly from previous studies [129] and partly from quotations of suppliers. Finally, the conversion factors adopted to evaluate the GHG emissions due to the electricity and the gas needs are those reported in table 4.5.

Regarding the evaluation of GC, proper incentives are taken into account for each energy efficiency measure to be adopted, as established in the Italian economic balance law [141].

Aiming at fighting the urban overheating too, the heat emissions into the external environment due to HVAC systems are finally evaluated, with reference to both the heating and the cooling seasons. More in detail, only the direct thermal energy contributes are taken into account and thus merely the waste heat of the generators, namely:

- the thermal emissions of the gas boiler due to the smokes and the heat losses through the boiler metal box;
- the heat discharged into the ambient by the condenser of the cooling system.

For the BB, the heat emissions into the external environment are shown in figure 4.4.

With reference to figure 4.4, it should be noted that the heat loss emitted into the external environment due to the hot water gas fired boiler is much lower than the one due to the air-cooled chiller, *i.e.* for the heating season it is equal to 6.10 MWh, whilst for the cooling one it is around 189 MWh. In the intervals between 2000 – 3000 hours and between 7000 – 8000 hours, there are periods with no heat emissions, because during this mid-season climates both the heating and the cooling systems are supposed to be turned off.

Table 4.10. Investment costs of the energy retrofit measures

ENVELOPE		
Energy efficiency measure	**Characterization**	**Investment Cost [€/m^2]**
Use of an additional insulation layer (roof, external walls) of thickness:	0.03 m	30
	0.04 m	35
	0.05 m	40
	0.06 m	45
	0.08 m	55
	0.10 m	65
	0.12 m	75
Replacement of the windows	Double-glazed with air-filling and low-e coating. PVC frame	250
	Tinted double-glazed with air-filling and low-e coating. PVC frame	260
	Selective double-glazed with air-filling and low-e coating. PVC frame	260
	Double-glazed with argon-filling and low-e coating. PVC frame	270
	Tinted double-glazed with argon-filling and low-e coating. PVC frame	280
	Selective double-glazed with argon-filling and low-e coating. PVC frame	280
	Triple-glazed with argon-filling and low-e coating. PVC frame	320
Installation of shading systems	Each type of considered shading system	50
HVAC SYSTEM + RES		
Energy efficiency measure	**Characterization**	**Investment Cost**
Replacement of the primary heating/cooling system*	High-efficiency natural gas boiler	12390 €
	Condensing natural gas boiler	21260 €
	Air-source electric heat pump	41300 €
	High-efficiency electric air-cooled chiller	43775 €
	Reversible air-source electric heat pump	65662 €
Installation of PV panels	Polycrystalline PV panels – nominal efficiency = 14%, peak power = 91 W, dimensions = 0.66 m x 0.98 m	250 €/m^2
	Monocrystalline PV panels – nominal efficiency = 17%, peak power = 196 W, dimensions = 0.88 m x 1.31 m	430 €/m^2

**All the HVAC systems are oversized by considering an oversizing factor equal to 1.1.*

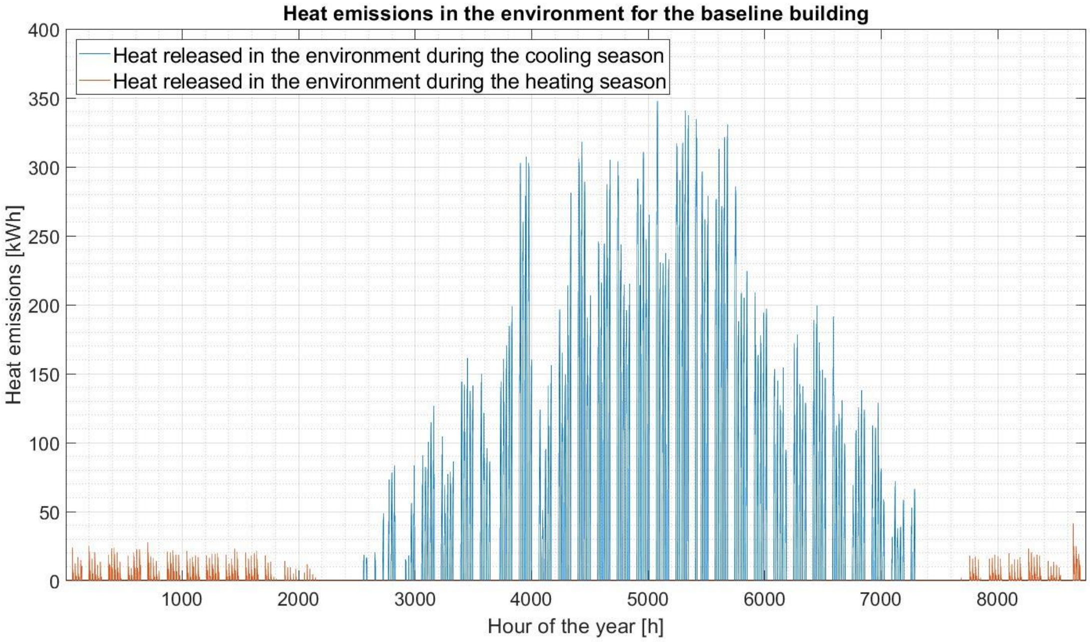

Figure 4.4. Heat emissions into the external environment for the baseline situation

4.3.3. Results and discussion

During the 1st stage of the optimization process, the genetic algorithm (GA) is implemented in order to find optimal solutions for the building energy retrofit as concerns the minimization of thermal energy demands and discomfort hours. A starting population of 44 individuals is considered and 20 generations are set as termination criterion of the GA. Considering also the randomly generated starting population, more than 900 different dynamic energy simulations (through the automatic coupling between EnergyPlus and MATLAB®) are run in order to achieve the Pareto minimization of TED_{heat}, TED_{cool} and DH. In order to have a more general framework of the results obtained by means of the GA, the three mono-objective solutions, which minimize the TED_{heat}, the TED_{cool} and the DH singularly, are reported. About the energy efficiency measures' combination that reduces the TED_{heat} the most, it provides the following operations:

- Installation of a 0.12 m-thick external thermal insulation layer on vertical walls;
- Installation of a 0.10 m-thick external thermal insulation layer on roof;
- Installation of plasters with particular radiative properties, *i.e.* thermal emissivity (e) and solar absorptance (a). For the roof the provided values of e and a are 0.1 and 0.75, respectively, while for the vertical walls optimal values of e and a are 0.8 and 0.1, respectively;
- Replacement of the windows with triple-glazed with argon-filling and low-e coating ones;
- Installation of external low reflection – medium transmittance shading system;

Finally, the set-point temperatures for heating and for cooling should be set equal to 19 °C and to 25 °C respectively. It should be noticed that this combination of retrofit measures produces simultaneously the following effects:

- TED_{heat} passes from 10.7 kWh/m^2a (BB, baseline building) to 5.6 kWh/m^2a;
- TED_{cool} increases from 62.2 kWh/m^2a (BB) to 74.5 kWh/m^2a;
- discomfort hours: DH passes from 52.4%(BB) to 37.1%.

The adoption of a high insulated envelope strongly reduces the TED_{heat} and the DH, but the TED_{cool} is higher of about 20% in percentile terms, thus it is not minimized, as clear. Regarding the minimization of the TED_{cool}, the retrofit measures to be adopted are the following:

- Installation of a 0.05 m-thick external thermal insulation layer on roof, while for the vertical walls no additional insulation is provided;

- Installation of plasters with particular values of e and a. For both the vertical walls and the roof the optimal values of e and a are 0.8 and 0.1, respectively. Therefore, it is recommended the use of cool plasters;
- Replacement of the windows with tinted double-glazed with argon-filling and low-e coating ones;
- Installation of an external medium reflection – medium transmittance shading system;

In this case, the set-point temperatures for heating and for cooling should be set higher than the previous ones, more precisely they should be set equal to 21 °C and to 27 °C respectively. For this second retrofit measures' combination, the effects produced are the followings:

- TED_{heat} softly increases from 10.7 kWh/m^2a (BB) to 11.8 kWh/m^2a;
- TED_{cool} decreases from 62.2 kWh/m^2a (BB) to 32.1 kWh/m^2a;
- DH passes from 52.4%(BB) to 53.0%.

As it is possible to notice, the energy efficiency measures provided to minimize the TED_{cool} seem not to have significant effects on the other two objective functions, differently from the previous examined solution. However, this solution will be cut off during the 2nd optimization stage of the multi-objective optimization process because of the increase of the DH from the BB situation.

The last mono-objective optimal retrofit measures' combination resulting from the applied GA is the one that minimizes the DH, and it provides the following interventions:

- Installation of a 0.12 m-thick external thermal insulation layer on both the vertical walls and the roof;
- Installation of plasters with particular values of e and a. For the vertical walls the optimal values of e and a are 0.9 and 0.9, respectively, while for the roof the optimal values of e and a are 0.1 and 0.5, respectively;
- Replacement of the windows with triple-glazed with argon-filling and low-e coating ones;
- Installation of an internal low reflection – high transmittance shading system;

In this final mono-objective case, the set-point temperatures for heating and for cooling should be set equal to 19 °C and to 24 °C respectively. By means of this third energy efficiency interventions' combination, the following effects are obtainable:

- TED_{heat} strongly decreases from 10.7 kWh/m^2a (BB) to 5.7 kWh/m^2a;
- TED_{cool} increases from 62.2 kWh/m^2a (BB) to 83.7 kWh/m^2a;

- DH passes from 52.4%(BB) to 32.5%.

The installation of high-thick insulation layers and triple-glazed windows allow to reduce the TED_{heat} and, obviously, the DH, whilst the TED_{cool} increases by the 35% in percentile terms, mainly because of the summer overheating.

Finally, the resulting Pareto fronts (one 3D and three 2D) for the multi-objective optimization are shown in figures 4.5-4.8.

The achieved Pareto non-dominated solutions are 224, most of which implies a significant improvement of occupants' thermal comfort compared to the baseline building (BB). Only twelve Pareto solutions cause an increase of DH compared to BB, and thus they are excluded in the 2nd methodology stage. This latter is implemented by conducting the smart exhaustive sampling. Thus, also the replacement of primary energy systems is considered, and globally 32802 different energy retrofit scenarios are investigated by assessing GC and GHG emissions (see figure 4.9). More in detail, the differences in global cost (dGC) and GHG emissions (dCO_2-eq) compared to the baseline are evaluated in order to obtain more representative results.

For a discount rate (r) equal to 3%, the resulting cost-optimal solution provides the following energy retrofit measures:

- Installation of a 0.12 m-thick external thermal insulation layer on roof and vertical walls;
- Installation of plasters with particular radiative properties, *i.e.* thermal emissivity (e) and solar absorptance (a). For the roof the optimal values of e and a are 0.7 and 0.1, respectively, while for the vertical walls optimal values of e and a are 0.8 and 0.1, respectively. Therefore, the optimization procedure recommends the use of cool plasters;
- Replacement of the windows with tinted double-glazed with argon-filling and low-e coating ones;
- Installation of the reversible electric heat pump for both space heating and cooling;
- Installation of PV monocrystalline panels covering the 100% of the usable roof area.

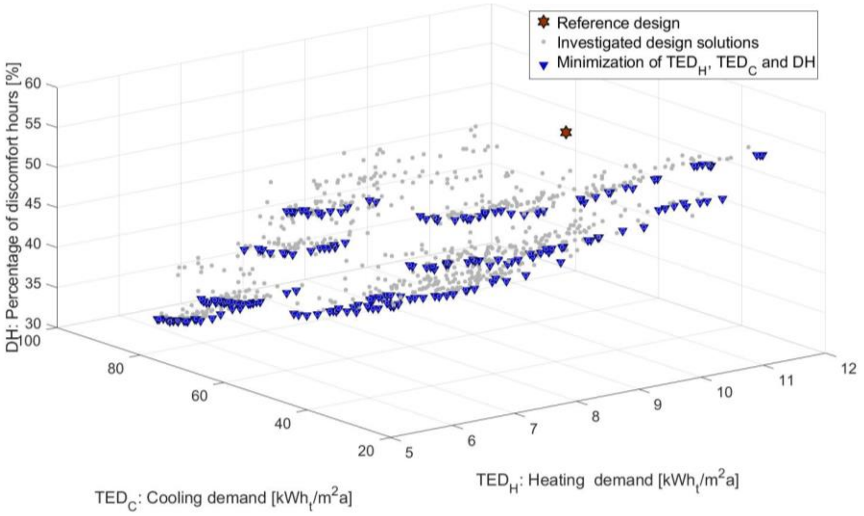

Figure 4.5. 3D Pareto front

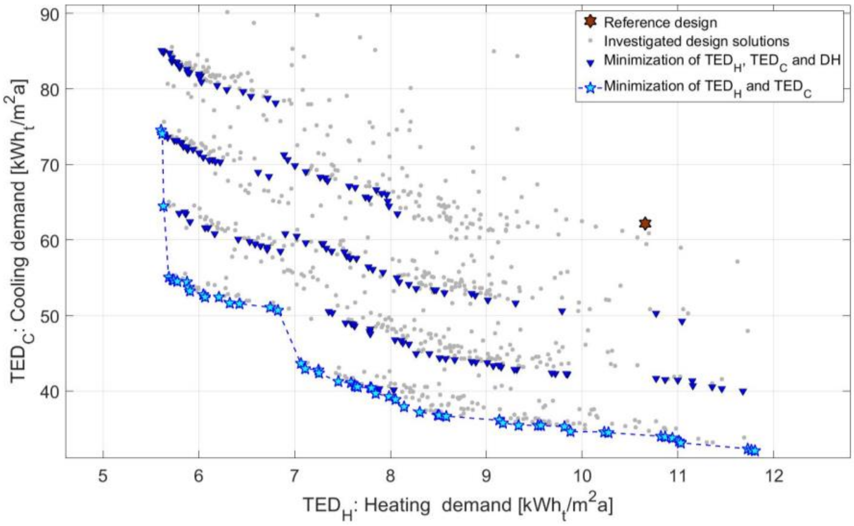

Figure 4.6. 2D Pareto front $TED_{heat} – TED_{cool}$

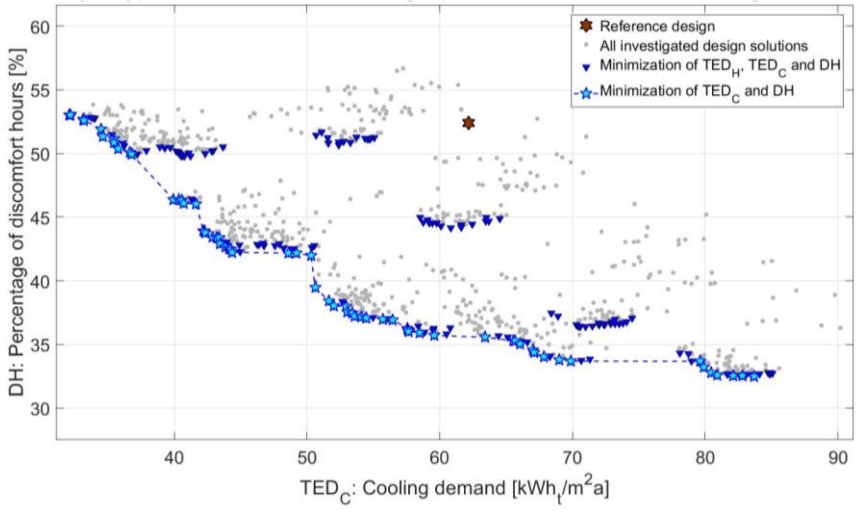

Figure 4.7. 2D Pareto front $TED_{cool} – DH$

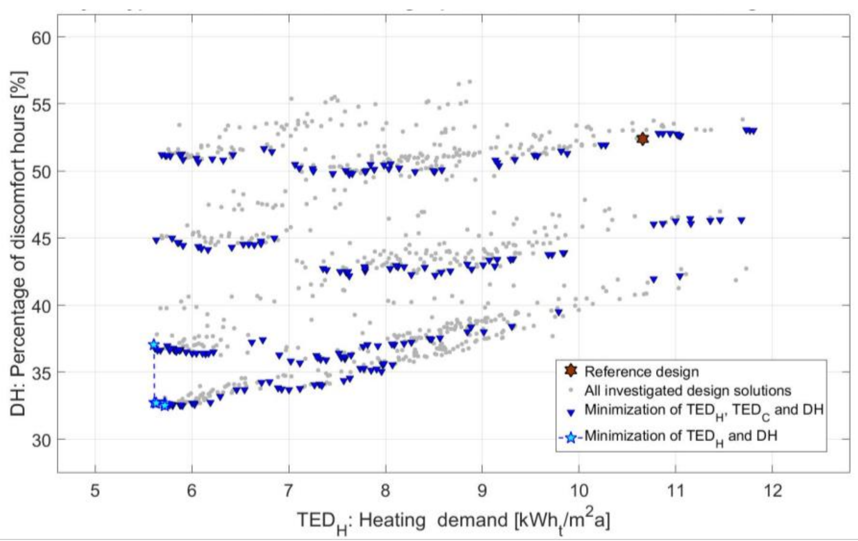

Figure 4.8. 2D Pareto front–TED$_{heat}$ - DH

Finally, the set-point temperatures for heating and for cooling should be set equal to 20°C and to 27 °C respectively. It should be noticed that the combination among envelope thermal insulation, cool plasters, tinted windows and high-efficiency primary systems is highly synergic and produces simultaneously reductions of:

- TED$_{heat}$ which passes from 10.7 kWh/m^{2}a (BB) to 8.5 kWh/m^{2}a;
- TED$_{cool}$ which passes from 62.2 kWh/m^{2}a (BB) to 36.8 kWh/m^{2}a;
- discomfort hours: DH passes from 52.4%(BB) to 49.9%;
- global cost: dGC = -119.3 €/m^2;
- GHG emissions: dCO2-eq = -25.3 kg/m^{2}a;
- annual heat emissions into the external environment, which pass from 195 MWh (BB) to 105 MWh (in percentile terms, this means that the reduction is around 46%).

About this last result, it is fundamental to highlight that the beneficial effect on heat emissions due to the installation of the air-source electric heat pump (which “removes” heat from the external environment) is not considered in order to avoid the overestimation of the goodness of the cost-optimal solution found in terms of urban overheating mitigation too. Hourly heat emissions into the external environment for the cost-optimal solution are reported in figure 4.10.

The robustness of the solution is examined by assessing the cost-optimal solution for other two values of the discount rate r (*i.e.*, 1% and 5%). More in detail, when the discount rate is varied the cost-optimal solution remains the mentioned one. Clearly, only the value of dGC changes and it is equal to -153.2 €/m^2 for r=1% and to -93.2 €/m^2 for r = 5%.

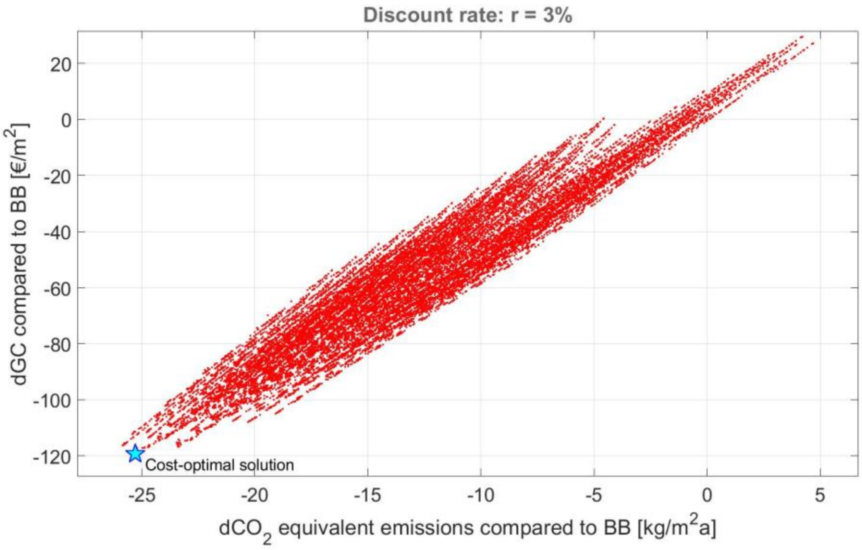

Figure 4.9. dGC vs dCO$_2$-eq emissions for all the investigated energy retrofit scenarios for r = 3%. The cost-optimal solution is highlighted by a bigger marker

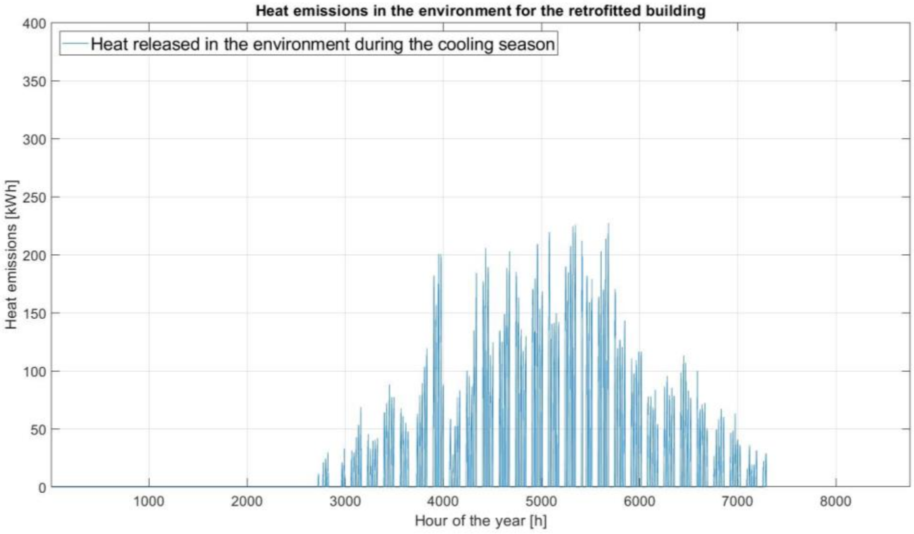

Figure 4.10. Heat emissions into the external environment in presence of the cost-optimal solution

Final remarks

The study discussed in this chapter proposes an optimization methodology for building energy design/retrofit based on two main objective functions, and thus the reduction of global costs and GHG emissions, in order to perfectly conjugate the two involved perspectives: the private one (minimization of financial expenditure) and the public one (minimization of pollution and environmental impacts of buildings).

The importance of the application of the proposed optimization methodology is that the reduction of the CO_2-eq emissions can enable the different countries to respect the limits imposed by the international agreements on polluting emissions for fighting climate change, while the minimization of the GC makes the adoption of proper energy efficiency measures more appealing to building owners, letting them play also an important role for the community.

Finally, the applied methodology enables to reach more than satisfying results not only in fighting the climate change under a macroscopic approach, but also in contrasting the urban overheating by adopting a local-limited approach.

All told, most of the techniques available in literature for facing the energy and environmental impact of buildings focus on stand-alone buildings. However, investigating more than one building at the same time may be more appropriate aiming at achieving high integration levels in planning the management of cities [135]. Therefore, a novel approach is presented in the next chapter for the modeling of districts/neighborhoods of buildings and for the optimization of their energy retrofit.

How to properly perform the energy modeling
and the energy retrofit planning
of districts/neighborhoods of buildings?

CHAPTER 5. A comprehensive approach for the energy retrofit of neighborhoods and districts

5.1. Introduction

As seen, from the analysis of the available literature and by aiming to possible enhancements of the current body of knowledge, it is clear that the energy modeling and retrofit planning of districts/neighborhoods present different issues that can be resumed as follows: 1) top-down approaches are often easier to be applied, but the outcomes may be inaccurate when the dynamics of the building system are not properly taken into account; 2) bottom-up approaches are more accurate, but the computational effort required may be too high; 3) aiming at reducing the computational burden, it is common practice to study a limited number of buildings as stand-alone and then to merge and scale the results, but this may imply losses in terms of results' accuracy because the inter-building effect is neglected and the contemporaneity of the energy loads is not considered correctly; 4) few integrated tools are available, but their large-scale applicability may have severe limits, due to compatibility issues of the employed tools or to the dependency on local census data.

Therefore, the aim of the study presented in this chapter is to propose a new integrated framework for the energy modeling and retrofit planning of districts/neighborhoods of buildings, which tries to couple all the benefits of existing techniques, overpassing the aforementioned limitations. In detail, it is based on a bottom-up approach combining a GIS tool – *i.e.*, CADMapper® [142] –, a proper dynamic energy simulator – *i.e.*, EnergyPlus – and a well-known versatile post-processing engine – *i.e.*, MATLAB®. The presence of the GIS tool enables the designer to effortlessly develop the geometrical model of the district. The adoption of the bottom-up approach guarantees good accuracy of the results, which is increased by the presence of EnergyPlus that enables to consider the inter-building effect and the contemporaneity of the energy loads. The use MATLAB® as post-processing engine allows to deeply cut down the computational burden, preventing the operation of merging and scaling the results, and so avoiding losses in terms of accuracy. In addition, through the interaction between EnergyPlus and MATLAB®, simulations and data processing are totally automatized, enabling to perform comprehensive retrofit optimizations, examining the problem at all the possible scale levels – *i.e.*, from a single apartment to the whole district/neighborhood as an entity –, and so enabling different possible energy investigations at once. Finally, the use of common commercial software guarantees a universal compatibility, and, consequently, a widespread diffusion of the framework is possible.

As a case study, part of an existing neighborhood located in Naples (Italy) and representative of the Southern Italy building stock from 1961 to 1975 is addressed, and two optimal retrofit solutions are proposed: the “nZEB” (nearly Zero-Energy Building) and the “cost-optimal” ones.

5.2. Methodology

5.2.1. Framework

The energy modeling and the consequent retrofit planning of existing districts or neighborhoods is an involved issue that has energy, financial and environmental implications. Generally, as for the stand-alone approaches, the involved perspectives are the public one, which aims at facing energy and environmental criticalities, and so it aims at reducing the energy consumption and the polluting emissions due to buildings, and the private one, which mainly aims at achieving financial benefits, even if the sensibility of the society towards sustainable solutions is increasing nowadays, and so environmental issues are partially considered by this perspective too.

The proposed framework may be applied by both these perspectives and can even ensure the best trade-off between them, since more objectives can be addressed simultaneously to guarantee a good satisfaction level for both spheres.

The provided methodology consists of two subsequent main phases, as follows (see figure 5.1):

1) energy modeling of the district/neighborhood (“Energy Modeling of the District” or “EMD” phase);
2) planning/optimization of the energy retrofit measures to be applied (“Energy Retrofit Planning of the District” or “ERPD” phase).

An accurate energy modeling – performed during the EMD phase – is strictly necessary to achieve reliable results during the ERPD phase.

5.2.2. Energy Modeling of the District/Neighborhood

The first step required by an accurate energy modeling of the district/neighborhood is to perform the most accurate geometrical modeling of the buildings. For this scope, two programs are used: CADMapper® and SketchUp® [143]. The former is a Geographical Information System (GIS) software that easily imports the geometrical shapes of investigated buildings, by converting data from OpenStreetMap and National Aeronautics and Space Administration (NASA) into nearly organized "*.dxf*" files – *i.e.*, CAD files. On the other hand, SketchUp® is a well-known 3D geometrical modeling software, characterized by an inference engine that assists the designer from a graphical viewpoint. More in detail, the geographical location of the district/neighborhood is individuated in CADMapper® and the relative 2D geometrical model is exported as a "*.dxf*" file. This file is then imported in SketchUp®, where it is converted into a 3D geometrical model. Subsequently, a distinction occurs between the buildings under investigation and the neighboring buildings. The formers have to be energy modeled during the next steps, while the latter are considered only as shading polygons in order to avoid a significant increase of the computational effort.

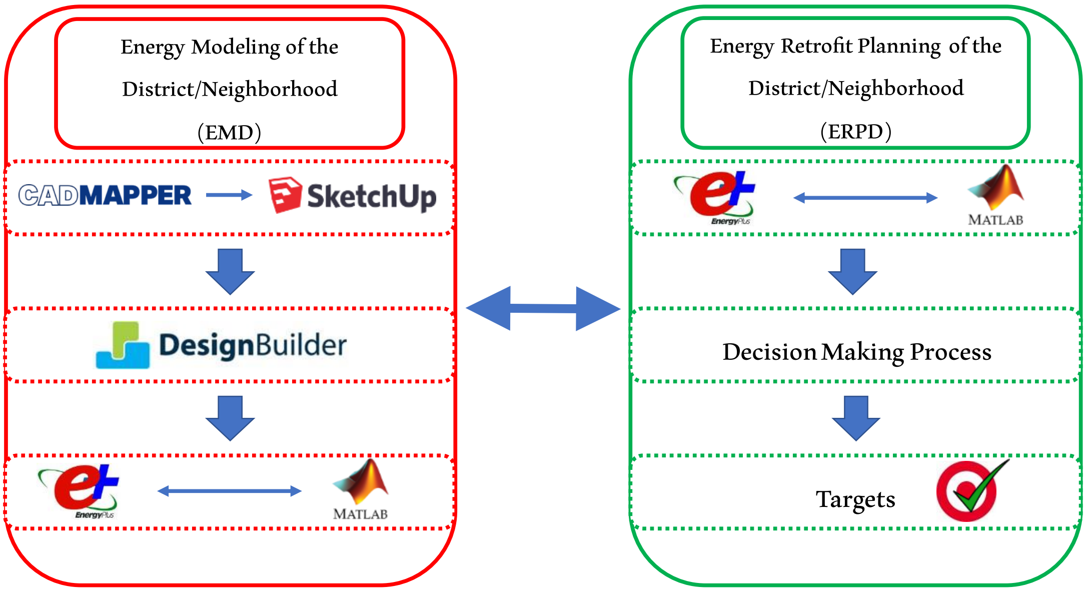

Figure 5.1. Framework of the proposed methodology. The first phase consists in the energy modeling of the district/neighborhood, while the second one is the retrofit planning

The following step consists in importing the geometrical model realized in SketchUp® in DesignBuilder® to refine it, achieving a higher detail level. DesignBuilder® is an authoritative graphical interface of EnergyPlus that enables to perform the preliminary energy modeling of the investigated buildings. In detail, in DesignBuilder® the stratigraphy of each component of the building envelopes is defined. This operation must be conducted with high care, because the accuracy of the results depends on it and huge information is required – *i.e.*, number of layers of each stratigraphy, thickness of each layer, materials employed and their thermophysical properties, type of windows and frames. Consequently, after the definition of the stratigraphies, the subdivision of each building into thermal zones is performed.

Once completed the preliminary energy modeling in DesignBuilder®, an *".idf"* file is exported. This is the input file for EnergyPlus, where the detail level of the energy model of the district/neighborhood is enhanced by defining:

1) the usage profiles for each thermal zone in terms of hourly schedules of people activity, ventilation need and occupancy, lighting levels, equipment load and use;
2) the operation of the Heating, Ventilation and Air Conditioning (HVAC) systems, in terms of availability periods and set-point temperatures.

Notably, these could be defined also in DesignBuilder®, but EnergyPlus offers higher possibilities of customization. Once performed the definition of the usage profiles for each thermal zone and the operation of the HVAC systems, ideal HVAC systems are implemented in EnergyPlus in order to assess the ideal thermal energy demand for space heating (TEDh) and for space cooling (TEDc). In fact, the "real" generation systems for both heating and cooling and the relative distribution systems – *i.e.*, distribution networks, regulation systems and emitting systems – are not modeled in EnergyPlus, but directly in MATLAB® environment, deeply reducing the computational burden of the dynamic energy simulations.

Finally, a "coupling function" is implemented in MATLAB® to automatize the interaction between EnergyPlus and MATLAB® itself [128, 131]. In detail, the latter automatically runs EnergyPlus simulations and handles the output ".csv" files. Hence, MATLAB® performs the post-processing of the results by:

- implementing the "real" HVAC systems – *i.e.*, generation, distribution, regulation and emission systems;
- implementing possible renewable energy systems, such as photovoltaic (PV) systems. If local energy communities are present in the examined neighborhood, these can be implemented too;
- assessing the objective functions and other possible performance indicators. Note that the selection of such functions/indicators depends on the stakeholders' needs and wills. Thus, the approach ensures high flexibility.

More in detail, starting from the output file of an EnergyPlus simulation, the hourly values of TEDh and TEDc are assessed. Consequently, the hourly values of fuel and electricity are evaluated by using dynamic performance curves, for what concerns the generation systems, and efficiency values provided by the Italian standard UNI/TS 11300 [144], for what concerns the distribution systems – *i.e.*, distribution networks, regulation systems and emitting terminals. An analogous process is performed for the implementation of the renewable energy systems too. This approach is used with the aim to reduce the computational effort required, without suffering from relevant losses in terms of accuracy of the results.

Besides, thanks to the aforementioned coupling function, the whole post-processing of the results is conducted entirely in MATLAB®, and this permits to investigate each district or neighborhood considering all the possible scale levels – *i.e.*, from a single apartment to the whole district/neighborhood as an entity – simultaneously, enabling different possible energy investigations at once. This is one of the main potentialities of the proposed framework. It makes the approach suitable for different types of users – *i.e.*, designers, single private citizens, families, condominiums, local Administrations and even Governments. In addition, a post-process phase entirely in MATLAB® allows to easily assess the desired performance indicators and objectives, strongly reducing the computational effort required, especially in the next ERPD phase, when different energy retrofit measures are investigated [131]. For instance, the primary energy consumption (PEC), the running costs (RC) or the equivalent emissions of CO_2 can be assessed directly in MATLAB® after EnergyPlus simulations.

5.2.3. Energy Retrofit Planning of the District/Neighborhood

A detailed energy model of the district/neighborhood is crucial for the Energy Retrofit Planning of the District (ERPD) phase. During the retrofit planning, the aim is to optimize the energy retrofit measures (ERMs) to apply to the district/neighborhood, according to the different wishes and needs of the involved stakeholders. For this reason, like the EMD phase, the ERPD can be conducted by considering all the aforementioned viewpoints, with the possibility of taking into account both the public and the private perspectives. For this purpose, the selection of the objective functions and of the retrofit variables is fundamental and depends on the situation to be studied. However, being the aim of this study to provide a new integrated framework for the energy modeling and retrofit planning of districts/neighborhoods of buildings that is versatile and applicable to all possible situations, no general methodological assumptions are made on which should be the objective functions or the retrofit parameters. Nevertheless, for what concerns the case study of the next section, the objectives are the reduction of PEC and GC, while the ERMs involve both the envelopes and the primary energy systems.

During the ERPD phase, "n" ERMs are investigated, according to the designer experience and the most common local practices. The aim is to minimize/maximize the values of the selected objective functions, which are collected in the vector "F". A design variable "xi" is associated with each measure, and so "n" variables are introduced. Each variable has a proper variability range and is adequately parametrized in the EnergyPlus input file. An in-house-developed MATLAB® script permits to encode every combination of the ERMs in the vector "x". The coupling function between EnergyPlus and MATLAB® transforms the vector x into a new energy model of the district to be simulated (the ".idf" file) and launches the dynamic energy simulation in EnergyPlus. Then, it manages the ".csv" file containing the simulation outputs to assess the values of the objectives contained in F, referring to the examined combination. This process is iterated until all the desired ERMs' combinations are examined. Finally, aiming at selecting one or more combinations, the decision-making phase occurs. This task can be performed according to different criteria, depending on stakeholders and situation. Once again, no general methodological assumptions are made on the decision-making criteria. However, for what concerns the case study of the next Section, the chosen ones are the "energy-optimality" and the "cost-optimality", as previously done by the authors in [145]. The former provides the so-called "nZEB" (nearly Zero-Energy Building), which minimizes the PEC, while the latter provides the so-called "cost-optimal" solution, which minimizes the GC. Besides, also other performance indicators are assessed in order to have a more complete overview of the examined ERMs in terms of energy, financial and environmental implications.

5.3. Presentation of the case study

5.3.1. Neighborhood model description - Baseline (as built)

The case study is part of an existing neighborhood located in a highly populated zone of Naples (South Italy, Mediterranean climate). The same neighborhood was investigated in [146], but with different purposes. In detail, here the aim is to outline the benefits introduced by the presented integrated framework, while in [146] the aim was to only introduce the methodology – here detailed and enhanced – to optimize the solar energy exploitation in the neighborhood, considering the effects of the implementation of a local energy sharing community.

The investigated neighborhood is composed of four buildings in reinforced concrete. These have from five to nine stories above the ground, each with a net height equal to 3.1 m. The gross floor areas vary from 4394 m^2 to 6417 m^2 per building, while the glazing areas from 552 m^2 to 986 m^2. Shading systems are absent because the closest buildings to the investigated ones produce significant shadowing effects. Therefore, in addition to the four buildings under investigation, also the shadowing buildings are geometrically modeled – as shown in figure 5.2 –, to consider the mentioned shading phenomena properly. The latter are automatically handled by EnergyPlus, thanks to its “Shading Module”. More in detail, a shadow algorithm based on coordinate transformation methods and on the shadow overlap method of Walton is used to compute sunlit areas, with the aim to assess heat gains due to solar radiation. Shadowing calculations are performed considering timesteps of the order of days – *i.e.*, 5 or 10 days –, and so the solar position values are averaged over the considered time period. The solar position is individuated by three direction cosines, which are necessary to assess the incidence angle of solar rays on building surfaces. The cosines of the incidence angle are the result of the dot product of surface and sun direction cosines. Once assessed the incidence angle, shadows are easily obtained by the shadow algorithm and are transformed onto the plane of the receiving surface. Finally, the area of the overlap between the polygons representing the shadows and the ones representing the receiving surfaces is determined, and so the solar gains are evaluated.

Concerning the use destinations, these buildings are mostly residential, even if few offices are present – they are situated in apartments – and the presence of shops mainly characterizes all the ground stories. Globally, 227 thermal zones are individuated, and 157 of them are space conditioned – the unconditioned ones are the common circulation areas between one apartment and the other or between one shop and the other. More in detail, there are four categories of thermal zones, which are distributed as follows (see figure 5.2, where buildings are denoted by the numbers 1, 2, 3 and 4):

- 111 apartments – 30 in building 1, 29 in building 2, 23 in building 3, 29 in building 4;
- 42 shops – 11 in building 1, 12 in building 2, 9 in building 3, 10 in building 4;
- 4 offices – 2 in building 1, 0 in building 2, 1 in building 3, 1 in building 4;

- 70 common circulation areas – 21 in building 1, 16 in building 2, 15 in building 3, 18 in building 4.

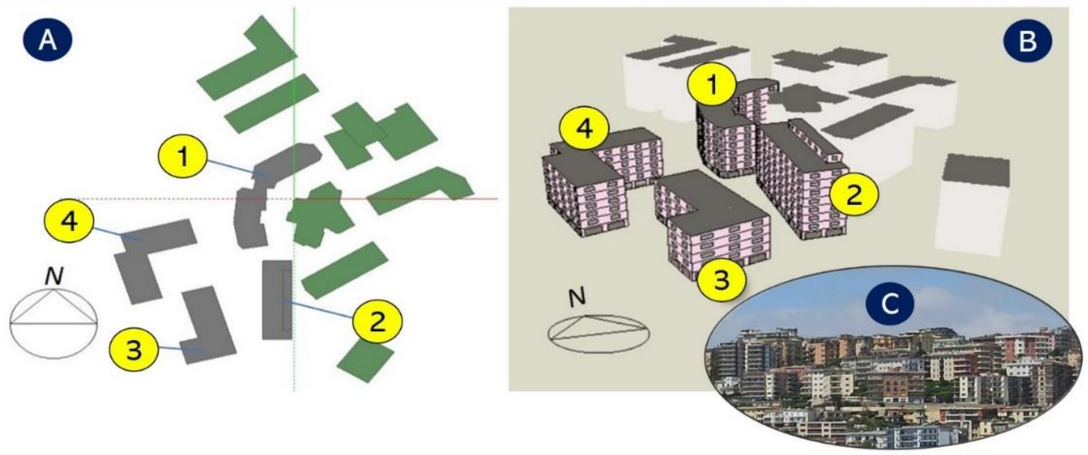

Figure 5.2. A: Aerial view of the neighborhood. Grey buildings are investigated, while the green ones are the neighborhood buildings. B: 3D rendering. C: urban context and density

According to the Italian standard construction technology, all buildings are characterized by the same composition of the envelope, as detailed in tables 5.1-5.3 for external walls, roof and ground floor. Concerning the transparent envelope, windows are all single-glazed, but with different types of frames, according to the use destination. More precisely, residential apartments, common circulation areas and offices have wooden frames, while shops have aluminum frames with thermal break. Besides, for shops, a wider glazing area is considered – *i.e.*, 60% of the respective gross wall area –, while this percentage is around 20% for all the other zones. For residential apartments, common circulation areas and offices, the window U-value is equal to about 5.89 W/m^{2}K and the solar heat gain coefficient (SGHC) is equal to 0.86. For shops, these parameters are equal to around 5.44 W/m^{2}K and 0.86, respectively.

Table 5.1. External walls composition, from the external to the internal layer

Layer n°	Material	Thickness [m]	Density [kg/m^3]	Specific heat [J/kg K]	Conductivity [W/m K]
1	External plaster	0.03	2000	670	1.40
2	Hollow bricks	0.12	2000	1000	0.90
3	Air gap	0.12	-	-	-
4	Lapillus block	0.08	1000	880	0.38
5	Internal plaster	0.02	2000	670	1.40

Table 5.2. Ground floor composition, from the external to the internal layer

Layer n°	Material	Thickness [m]	Density [kg/m^3]	Specific heat [J/kg K]	Conductivity [W/m K]
1	Urea-formaldehyde	0.13	10	1400	0.04
2	Concrete	0.10	2000	1000	1.13
3	Screed	0.07	1800	1000	0.90
4	Wood floor	0.03	650	1200	0.14

Table 5.3. Roof composition, from the external to the internal layer

Layer n°	Material	Thickness [m]	Density [kg/m^3]	Specific heat [J/kg K]	Conductivity [W/m K]
1	Asphalt	0.01	2100	1000	0.70
2	Urea-formaldehyde	0.08	10	1400	0.04
3	Concrete	0.06	2000	1000	1.13
4	Reinforced Concrete	0.20	2400	1000	2.50
5	Plaster	0.02	2000	670	1.40

Table 5.4. General characterization of the neighborhood

DIMENSIONS AND GEOMETRY			
BUILDING 1			
Height	22.40 m (7 floors)	Gross Floor Area	6416.97 m^2
Gross Wall Area	4082.60 m^2	Gross Roof Area	916.71 m^2
Window Opening Area	986.09 m^2	Total Gross Volume	20534.54 m^3
Gross Window-Wall Ratio	24.15 %	Surface to Volume Ratio	0.33 m^{-1}
BUILDING 2			
Height	28.80 m (9 floors)	Gross Floor Area	5211.36 m^2
Gross Wall Area	3316.42 m^2	Gross Roof Area	631.57 m^2
Window Opening Area	771.52 m^2	Total Gross Volume	16676.37 m^3
Gross Window-Wall Ratio	23.26 %	Surface to Volume Ratio	0.31 m^{-1}
BUILDING 3			
Height	16.00 m (5 floors)	Gross Floor Area	4394.46 m^2
Gross Wall Area	2081.97 m^2	Gross Roof Area	732.41 m^2
Window Opening Area	551.95 m^2	Total Gross Volume	11718.72 m^3
Gross Window-Wall Ratio	26.51 %	Surface to Volume Ratio	0.34 m^{-1}
BUILDING 4			
Height	19.20 m (6 floors)	Gross Floor Area	5373.06 m^2
Gross Wall Area	3086.09 m^2	Gross Roof Area	895.81 m^2
Window Opening Area	779.58 m^2	Total Gross Volume	17199.77 m^3
Gross Window-Wall Ratio	25.26 %	Surface to Volume Ratio	0.325 m^{-1}
WHOLE DISTRICT			
Gross Floor Area	21395.85 m^2	Gross Roof Area	3176.51 m^2
Gross Wall Area	12567.08 m^2	Total Gross Volume	66129.41 m^3
Window Opening Area	3089.13 m^2		
MAIN BOUNDARY CONDITIONS OF ENERGY SIMULATIONS			
Climatic data	IWEC/IGDG → EPW [147]	Occupancy	4 people per thermal zone
Number of thermal zones	227 (conditioned 157)		
BUILDING ENVELOPE			
Shading systems	Low reflect – Low trans shade	Infiltration rate	0.70 ACH
U walls	1.01 W/m^{2}K	U ground	0.37 W/m^{2}K
U roofs	1.09 W/m^{2}K	U windows-residential	5.89 W/m^{2}K
U windows-office	5.89 W/m^{2}K	U windows-shop	5.44 W/m^{2}K
U windows-common areas	5.89 W/m^{2}K		
HVAC SYSTEM			
HVAC typology	Natural gas-fired water boiler (heating) Air-cooled electric chiller (cooling)	η distribution (heating)	0.96
η generation (heating)	0.80	η emission (heating)	0.95
COP (cooling)	2.50	η regulation (heating)	0.94

Table 5.4 reports the U-values of all the envelope components and a general overview of the baseline configuration of all examined buildings as concerns the HVAC systems. In this regard, each conditioned thermal zone has its heating and cooling primary systems. The heating primary system is a natural gas-fired water boiler, which provides hot water at 80 °C to baseboards. Furthermore, the cooling primary system is an air-cooled chiller, which feeds split air conditioners. All thermal zones are equipped with such terminals, except for the common circulation areas. The nominal efficiency (η) of the boiler at the LHV (Lower Heating Value) is 0.80, the nominal coefficient of performance (COP) of

the chiller is 2.5. For the heating system, also the effects of the whole distribution network – to be intended as distribution pipes, regulation system and emission system – are considered in terms of efficiencies. However, differently from the studies presented in Chapters 3 and 4, in this study as well as in the studies discussed in Chapters 6 and 7 the heat losses due to the distribution network are not automatically assessed by Energy Plus, where ideal systems are considered, but in MATLAB® by means of the efficiencies reported in the national standard UNI-TS 11300. This choice is due to the intention of reducing the computational effort required for simulating the entire neighborhood, without having relevant losses in terms of the assessed performance indicators.

5.3.2. Energy Retrofit Measures

A crucial step for an accurate energy retrofit planning is the identification of the targets and of the energy retrofit measures (ERMs) to be addressed and optimized. In this case, the aim is to reduce the primary energy consumption (PEC) and the global cost (GC), to guarantee the satisfaction of both the aforementioned perspectives – *i.e.*, the public and the private ones. Once defined the objectives, the following common ERMs are investigated:

1. insulation of the external walls – thickness equal to the minimum value that permits to comply with the law limit [125];
2. insulation of the roof – thickness equal to the minimum value that permits to comply with the law limit [125];
3. replacement of windows – the investigated options are reported in table 5.5. When windows are replaced, the infiltration rate passes from 0.7 air changes per hour to 0.3 because the building airtightness is improved.
4. replacement of the HVAC primary systems – the investigated options are reported in table 5.6;
5. installation of photovoltaic (PV) panels on building roofs. Note that, as in the previous cases, panels are supposed to be installed facing South with an inclination equal to 30° to the horizontal level.

These are chosen based on the local most common retrofit practices and on the Italian policies [148] aimed at promoting, also through public funding, the energy efficiency of the existing building stock. All examined ERMs fulfill the minimum energy requirements set by the Italian Law [125], except for the window type n°2, which is characterized by a U-value higher than the allowed one. Such value is considered to show if this window type is not effective also from a financial viewpoint. For what concerns the replacement of the HVAC primary systems, when heat pumps are installed, these are based on the direct expansion technology (*i.e.*, air-to-air systems, multi-split or low-size variable refrigerant flow). The considered coefficients of performance for heating (COPh) and cooling (COPc) are the results of an investigation on several different manufacturers catalogs [149], suitable for the case study here investigated, in term of technology (*e.g.*, compressor type) and size (cooling and heating capabilities at rated conditions).

Table 5.5. Investigated window types

N°	Type	U [W/m²K]	SHGC [-]	Investment Cost [€/m²]
1	Single-glazed, aluminum frames (*Baseline, currently installed*)	5.89	0.86	0
2	Double-glazed with air-filling, PVC frame	3.12	0.76	250
3	Double-glazed with argon-filling and low-e coating, PVC frame	1.49	0.56	280

** The Investment Cost for Single-glazed windows is null because they are already present in the baseline neighborhood.*

Table 5.6. Investment costs of energy retrofit measures

ENVELOPE		
Energy retrofit measure	**Characterization**	**Investment Cost [€/m^2]**
Additional insulation layer (external walls)	Thickness of 0.07 m	50.1
Additional insulation layer (roof)	Thickness of 0.08 m	30.1
HVAC SYSTEM + PHOTOVOLTAICS (PV)		
Energy retrofit measure	**Characterization**	**Investment Cost [€/m^2]**
Replacement of the primary heating/cooling system*	Condensing natural gas boiler – nominal efficiency 1.05 (referred to LHV) Reversible air-source DX electric heat pump – COPh = 4.5, COPc = 4.0	1380 € 23
Installation of PV panels	Monocrystalline PV panels – facing South and inclined at 30° to the horizontal level, efficiency of a panel = 19%, peak power of a panel = 330 W, dimensions of a panel = 1.016 m x 1.686 m, efficiency of the inverter = 99%	520 €/m^2

**All the HVAC systems are oversized by considering an oversizing factor equal to 1.1.*

The scheme to evaluate the Investment Cost (IC) necessary for the ERMs is indicated in tables 5.5 and 5.6. The costs are partly taken from previous papers [131, 145] and partly from recent suppliers' quotations. According to the Italian Law in the matter of energy efficiency in buildings [125], energy retrofit operations can be carried out at different levels:

- Major Renovation of the First Level;
- Major Renovation of the Second Level;
- Energy Requalification.

More in detail, a Major Renovation of the First Level of a building includes interventions that affect the building envelope with an incidence of more than 50% of the total gross dispersing area of the building, together (or not) with the replacement of HVAC components. On the other hand, a Major Renovation of the Second Level consists in interventions affecting the building envelope with an incidence of more than 25% – but less than 50% – of the total gross dispersing area of the building and may affect the HVAC system too. Finally, an Energy Requalification of a building includes interventions that are not related to previous cases but still impact the building's energy performance. Therefore, these interventions involve an area less than or equal to 25% of the total gross dispersing area of the building and/or consist in the new installation or replacement of the HVAC system or other partial interventions, including the replacement of the heat generator. According to the intervention level, it is possible to receive higher or lower incentives by the Italian Government: finally, the more profound is the retrofit (and thus the improvements of energy performances), the higher are the incentives.

In this case, 10 packages (*i.e.,* combinations) of ERMs are considered with the aim to reduce the PEC and the GC: three can be classified as Energy Requalification, three as Major Renovation of the Second Level and four as Major Renovation of the First Level. For all of them, the effect of both the absence and the presence of monocrystalline PV panels – installed on 90% of the useful roof areas – are considered. Finally, a nZEB solution and a cost-optimal solution are chosen for each level of retrofit. Incentives from 50% to 75% of the IC required – they depend on the retrofit measure – are accorded in 10 years to all the ERMs considered, according to the Italian Law [148]. Really, in the summer/autumn 2020, exceptionally, the incentives were raised to 110% in special cases, here not considered because of different and many constraints and requirements are requested to fulfill.

The ERMs are supposed to be applied simultaneously on all the four buildings of the neighborhood, even if future studies may consider different combinations of ERMs for each building or thermal zone. Therefore, the results of the energy retrofit are presented considering a “macro-scale” approach.

5.3.3. Objective Functions and Performance Indicators

In the presented case study, the considered objective functions are the PEC and the GC in order to satisfy both the public and the private perspectives. Besides, other performance indicators are assessed, with the aim to have a complete overview of the energy, financial and environmental implications due to the examined ERMs. In detail, from an energy viewpoint, in addition to the PEC, also the thermal energy demand for space heating (TEDh) and for space cooling (TEDc) are assessed. From a financial viewpoint, besides the GC, the running cost (RC), the simple payback period (SPB) and the discounted payback period (DPB) are evaluated. Finally, from the environmental viewpoint, the CO_2-eq emissions are assessed.

Table 5.7. Main factors for the assessment of the performance indicators [131]

ENERGY PRICES, CONVERSION FACTORS AND EMISSION FACTORS			
Electricity price	0.23 €/kWh	Gas price	0.90 €/m^3
Electricity selling price	0.07 €/kWh	Natural Gas LHV	9.59 kWh/m^3
Electrical-to-primary energy conversion factor	1.95	Gas-to-primary energy conversion factor	1.05
Electricity CO_2-eq emission factor	0.708 kg CO_2-eq/kWh	Gas CO_2-eq emission factor	0.237 kg CO_2-eq/kWh

For what concerns the energy aspect, the considered conversion factors are indicated in Table 5.7 and are the same as in [131]. The TEDh and the TEDc are obtained directly from the “.csv” file – *i.e.*, the output file of the EnergyPlus simulations –, which is post-processed by MATLAB®. On the other hand, the PEC is assessed as follows:

$$\mathrm{PEC} = \mathrm{E_{el}} * \mathrm{fp_{el}} + \mathrm{E_{gas}} * \mathrm{fp_{gas}} \tag{5.1}$$

where:

- E_{el} is the non-renewable electricity consumed per year;
- fp_{el} is the electrical-to-primary energy conversion factor;
- E_{gas} is the energy consumption due to gas. It is obtained by dividing the gas consumption by the LHV;
- fp_{gas} is the gas-to-primary energy conversion factor.

For what concerns the financial aspect, the considered specific prices for natural gas and electricity are indicated in table 5.7. The gas price is intended for natural gas with a LHV equal to 9.59 kWh/m^3.

The RC per year due to energy uses is assessed through equation 5.2:

$$\mathrm{RC} = \mathrm{E_{el}} * \mathrm{C_{el}} - \mathrm{G_{el}} * \mathrm{S_{el}} + \mathrm{Vol_{gas}} * \mathrm{C_{gas}} \tag{5.2}$$

where:

- C_{el} is the electricity price;
- G_{el} is the electricity obtained by renewable energy sources that is not self-consumed and, so, it is sold to the grid;
- S_{el} is the electricity selling price;
- Vol_{gas} is the volume of gas consumed per year;
- C_{gas} is the gas price.

The GC due to energy uses is assessed through equation 5.3 – indicated in EU Guidelines [15] – using a discount factor *d* equal to 3% and an assessment period τ of 20 years. The latter is explained because the neighborhood provides both residential and non-residential use destinations, characterized by a different assessment period according to [15] – *i.e.*, 20 years for the tertiary sector and 30 years for the residential one – and thus the shortest assessment period is considered. Note that the equation 5.3 is the same as the 3.1, but here is reported again to make the entire section clearer for the reader.

$$\mathrm{GC}(\tau) = \mathrm{IC} + \sum_j \left[\sum_i^{\tau} (\mathrm{RC}(i) * \mathrm{R_d}(i)) - \mathrm{V}_{f,\tau}(j)\right] \tag{5.3}$$

where:

- IC is the Investment Cost. This term is zero when no energy retrofit measures (ERMs) are considered, as in the as-built baseline configuration. Concerning the photovoltaic, a light increment has been considered for taking into account maintenance and replacement of inverter after 10-15 years.
- R_d is the actualization factor and depends on the discount factor *d*. It permits to actualize RC for each year of the assessment period;
- $V_{f,\tau}$ is the value that is residual at the end of the assessment period. In GC assessment, the residual value of the ERMs [15] is neglected because the explored measures have a lifespan of around 20 years and after this period, the residual value can be ignored, in a conservative approach, being poorly significant.

When ERMs are applied, in equation 5.3 a subtractive term near IC is present, in order to take into account the incentives (IN), estimated according to the Italian Government policy [148].

Other financial indicators are the SPB and the DPB. The latter are evaluated exclusively for the considered retrofit packages, not for the neighborhood as built. More in detail, they are assessed as follows:

$$\mathrm{SPB} = \frac{\mathrm{IC} - \mathrm{IN}}{\Delta\mathrm{RC}} \tag{5.4}$$

$$\mathrm{DPB} = -\frac{\log(1 - \mathrm{SPB} \cdot \mathrm{d})}{\log(1 + \mathrm{d})} \tag{5.5}$$

Finally, for what concerns the environmental performance indicator, the CO_2 equivalent emissions are evaluated according to equation 5.6:

$$CO_2\text{-eq} = \mathrm{E_{el}} * \mathrm{fc_{el}} + \mathrm{E_{gas}} * \mathrm{fc_{gas}} \tag{5.6}$$

where:

- fc_{el} is the electricity CO_2-eq emission factor;
- fc_{gas} is the gas CO_2-eq emission factor.

5.3.4. Results and discussion

According to the methodology described in Section 5.2, the first phase consists in the development of the district/neighborhood energy model. The main energy, financial and environmental indicators are presented in table 5.8. The baseline results in terms of the considered objective functions and performance indicators at district level are the same as in [146], as predictable. However, here the results are reported in detail for each building.

The TEDh (thermal energy demand for space heating) varies from 17.9 kWh/m^{2}a for building 4 to 21.0 for building 1 (see the previous figure 5.2 for the building numbers). The higher values for buildings 1 and 2 (19.5 kWh/m^{2}a) are due to the lower values of direct solar radiation because of neighboring buildings' shadowing effect. For the same reason, buildings 1 and 2 are characterized by the lowest TEDc (thermal energy demand for space cooling) values – *i.e.*, 26.2 kWh/m^{2}a and 28.3 kWh/m^{2}a, respectively. More in detail, the TEDc varies from 26.2 kWh/m^{2}a for building 1 to 29.2 kWh/m^{2}a for building 3. Considering the effects of the HVAC systems and the energy consumption due to lights and electric facilities, the PEC (primary energy consumption) values can be obtained. The PEC is equal to 115.1 kWh/m^{2}a for both buildings 3 and 4, while it is slightly higher for building 2 (116.6 kWh/m^{2}a) and building 1 (119.4 kWh/m^{2}a).

Table 5.8. Main neighborhood indicators

	Building 1	**Building 2**	**Building 3**	**Building 4**	***District***
TEDh [kWh/m^{2}a]	21.0	19.5	18.4	17.9	19.4
TEDc [kWh/m^{2}a]	26.2	28.3	29.2	28.5	27.9
PEC [kWh/m^{2}a]	119.4	116.6	115.1	115.1	116.8
RC [€/m^{2}a]	12.6	12.4	12.2	12.3	12.4
GC [€/m^2]	187.9	183.9	182.0	182.3	184.4
CO_2-eq [kg/m^{2}a]	36.1	35.4	35.1	35.2	35.5

For what concerns the RC (running cost), it is quite similar for all buildings, except for building 1, which also has the highest PEC, as seen. More in detail, the RC passes from 12.2 €/m^{2}a for building 3 to 12.6 €/m^{2}a for building 1. It means that, considering a flat of 100 m^2, the annual bills can be in the range 1223 – 1263 €/a, and these costs are a kind of validation, being quite common in this location. The GC (global cost) is included between 182.0 €/m^2 for building 3 and 187.9 €/m^2 for building 1, as predictable, being the GC assessed from the RC. Finally, the CO_2-eq emissions are nearly the same for all buildings and vary from 35.1 t/a for building 3 to 36.1 t/a for building 1. At a higher scale, the values for the whole district are presented. These are the results of a weighted sum of the aforementioned results, where the weights are the conditioned areas of each building. The TEDh and the TEDc for the district are 19.4 kWh/m^{2}a and 27.9 kWh/m^{2}a, respectively, while the PEC is equal to 116.8 kWh/m^{2}a.

Concerning the financial aspect, the RC is equal to 12.4 €/m^{2}a and the GC is equal to 184.4 €/m^2. In conclusion, the value of CO_2-eq emissions for the whole district is 35.5 kg/m^{2}a.

Figure 5.3 shows the monthly values referred to a unitary conditioned floor area of PEC. The higher values refer to January and December, followed by July and August – the latter is warmer than the former – during which the HVAC systems have to satisfy higher demands of space heating or cooling. High values of PEC are assessed also in February and March, where the heating system is still allowed to be turned on according to Italian Law [130], even if the heating demand is lower compared to January and December. Even if the TEDc is sensibly higher than the TEDh, the PEC is higher during the heating season than during the cooling period. This can be explained by considering the efficiencies of both the heating and the cooling systems in the baseline, resulting the latter much more efficient in the energy conversion process.

Once the district has been modeled and simulated, ten combinations of energy retrofit measures (ERMs) are investigated, organized as specified in Section 5.3.2:

- Energy Requalification: **1)** replacement of the existing windows – *i.e.*, single-glazed windows with wooden frames – with double-glazed windows with air-filling and PVC frames; **2)** replacement of the existing windows with double-glazed ones with argon-filling, low-e coating and PVC frames; **3)** insulation of the roofs;
- Major Renovation of the Second Level: **4)** replacement of the windows with double-glazed ones with air-filling and PVC frames combined with the replacement of the heating boilers with more efficient condensing boilers; **5)** insulation of the roofs combined with the replacement of the heating boilers with condensing ones; **6)** insulation of the roofs combined with the replacement of the existing HVAC systems for both heating and cooling supply with reversible air-source electric heat pumps;
- Major Renovation of the First Level: **7)** insulation of the external walls together with the replacement of the existing HVAC systems with reversible air-source

electric heat pumps; **8)** the same as in 7) but, in addition, the replacement of the windows with double-glazed ones with air-filling and PVC frames is considered; **9)** the same as in 7) but it is applied an insulation layer also on the roofs; **10)** as in 9) but with also the replacement of the windows with double-glazed ones with argon-filling, low-e coating and PVC frames.

All the aforementioned ERMs are summarized in table 5.9. For each retrofit package, both the absence and the presence of monocrystalline photovoltaic (PV) panels installed on 90% of the useful roof area of each building are taken into account.

The performance of the three Energy Requalification packages (**n°1**, **2** and **3**) is shown in figure 5.4, as concerns the monthly PEC. Table 5.10 concerns the other main energy, financial and environmental indicators, and the differences with the baseline are reported to show potential reductions/savings (denoted with positive values).

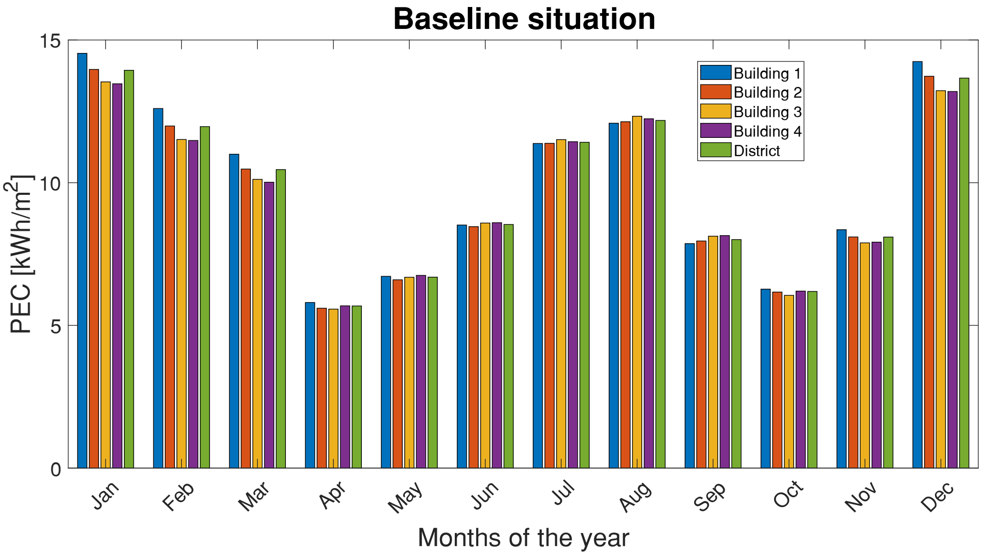

Figure 5.3. Monthly PEC values for the baseline. District values result from a weighted sum, where the weights are the conditioned areas of each building

Table 5.9. Investigated retrofit packages organized according to Italian normative [125]

	N°	**Double-glazed Windows, air-filling, PVC frames**	**Double-glazed Windows, Argon-filling, Low-e coatings, PVC frames**	**Insulation of the roofs (0.08 m)**	**Insulation of the external walls (0.07 m)**	**Condensing boilers**	**Reversible air-source electric heat pumps**
Energy Requalification	1	•					
	2		•				
	3			•			
Major Renovation of the Second Level	4	•				•	
	5			•		•	
	6			•			•
Major Renovation of the First Level	7				•		•
	8		•				•
	9			•	•		•
	10		•	•	•		•

Package n°1 (windows' replacement), as predictable, implies a sensible reduction of the TEDh during the cold months compared to the baseline – *i.e.*, 13.9 kWh/m^{2}a less at district level – but also a significant increase of the TEDc during the warm periods – *i.e.*, 9.5 kWh/m^{2}a more. The higher values of TEDc are due to the lower values of the thermal transmittance of the double-glazed windows and the lower values of the infiltration rate. Globally, the replacement of the windows implies a substantial PEC reduction by 15.0 kWh/m^{2}a at the district scale (see also figure 5.4). However, for the aforementioned reasons, the monthly values (see figure 5.4) during summer months can be higher compared to the baseline, and this can also happen when an insulation layer is added to the opaque envelope. Unfortunately, even if the RC is reduced by 1.2 €/m^{2}a for the whole district, this intervention is not cost-effective from a financial viewpoint. In fact, the GC is incremented by 4.3 €/m^2 and the SPB (simple payback) and the DPB (discounted payback) are 18.4 and 27.2 years, respectively, due to the excessive investment cost required, albeit the incentives' policy. Since a 20-years assessment period is considered, a DPB higher than 20 years implies that the GC is incremented compared to the baseline resulting in an investment that is not cost-effective. Finally, from an environmental perspective, at district level, the CO_2-eq emissions are reduced by 2.7 kg/m^{2}a.

If PV systems are installed, all the aforementioned indicators are improved, except for TEDh and TEDc that are not affected. More in detail, at district scale, the PEC is reduced by 35.9 kWh/m^{2}a, the RC by 4.3 €/m^{2}a, the GC by 33.3 €/m^2 and the CO_2-eq emissions by 10.3 kg/m^{2}a, resulting the installation of PV panels much more effective from the energy, financial and environmental perspectives. Besides, SPB and DPB are sensibly reduced and are 7.0 and 8.0 years, respectively.

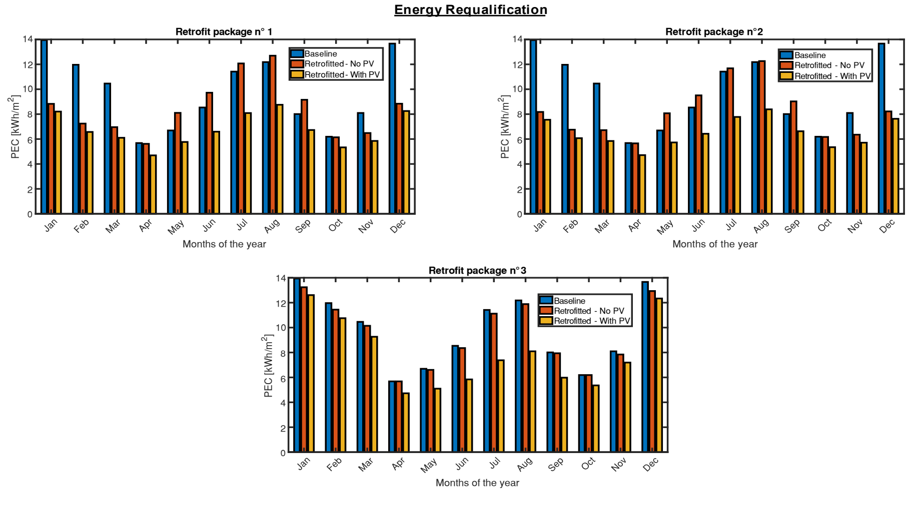

Figure 5.4. Monthly PEC at district level: baseline vs Energy Requalification Packages with and without the installation of photovoltaic (PV) systems

Package n°2 provides the installation of windows with lower U-value, thereby implying a more significant TEDh reduction, *i.e.*, 15.5 kWh/m^{2}a at district level, while the TEDc increment is lower, *i.e.*, 7.4 kWh/m^{2}a, because of the different radiative characteristics of installed glasses (lower SHGC compared to Package n°1). This package allows PEC and RC reductions of 18.2 kWh/m^{2}a and 1.5 €/m^{2}a, respectively, while the GC rises by 2.2 €/m^2, due to the significant investment cost required. For the same reason, the SPB and DPB periods are quite long and are 16.3 years and 22.7 years, respectively. Finally, the CO_2-eq emissions are reduced by 3.6 kg/m^{2}a.

If the PV systems are installed, this package provides higher energy, financial and environmental benefits, as predictable. Indeed, it permits to reduce the PEC of 39.0 kWh/m^{2}a and the RC of 4.6 €/m^{2}a. Therefore, for the GC, a decrement of 35.2 €/m^2 occurs. The SPB and the DPB are almost the same compared to package 1) – *i.e.*, 7.2 and 8.2 years, respectively. Finally, the equivalent emissions are reduced by 11.2 kg/m^{2}a.

Table 5.10. Main energy, financial and environmental indicators for the Energy Requalification packages with and without the installation of photovoltaic (PV) systems

		ENERGY REQUALIFICATION									
		without PV systems					**with PV systems**				
		**B. 1	B. 2	B. 3	B. 4	*District*	B. 1	B. 2	B. 3	B. 4	*District*
Retrofit Package **n°1**	*dTEDh [kWh/m^{2}a]	14.3	14.2	13.4	13.5	*13.9*	14.3	14.2	13.4	13.5	*13.9*
	dTEDc [kWh/m^{2}a]	-8.8	-10.4	-9.7	-9.4	*-9.5*	-8.8	-10.4	-9.7	-9.4	*-9.5*
	dPEC [kWh/m^{2}a]	15.8	14.8	14.1	14.6	*15.0*	37.7	27.4	40.6	38.9	*35.9*
	dRC [€/m^{2}a]	1.3	1.2	1.1	1.2	*1.2*	4.4	2.8	5.2	4.8	*4.3*
	dGC [€/m^2]	-1.3	-13.6	-2.2	-0.3	*-4.3*	37.4	8.0	47.3	43.6	*33.3*
	SPB [years]	15.9	26.5	16.8	15.1	*18.4*	6.4	12.1	5.8	5.7	*7.0*
	DPB [years]	21.9	53.4	23.8	20.4	*27.2*	7.3	15.2	6.5	6.4	*8.0*
	dCO_2-eq [kg/m^{2}a]	3.0	2.6	2.5	2.7	*2.7*	10.9	7.2	12.1	11.5	*10.3*
Retrofit Package **n°2**	dTEDh [kWh/m^{2}a]	16.3	15.8	14.8	14.8	*15.5*	16.3	15.8	14.8	14.8	*15.5*
	dTEDc [kWh/m^{2}a]	-6.9	-7.9	-7.4	-7.4	*-7.4*	-6.9	-7.9	-7.4	-7.4	*-7.4*
	dPEC [kWh/m^{2}a]	19.5	18.3	17.2	17.4	*18.2*	41.2	30.9	43.3	41.4	*39.0*
	dRC [€/m^{2}a]	1.6	1.5	1.4	1.5	*1.5*	4.8	3.2	5.5	5.0	*4.6*
	dGC [€/m^2]	1.5	-12.2	0.1	1.5	*-2.2*	40.0	9.4	49.2	45.2	*35.2*
	SPB [years]	14.0	22.9	14.9	13.8	*16.3*	6.5	11.9	5.9	5.9	*7.2*
	DPB [years]	18.4	39.4	20.0	18.0	*22.7*	7.3	15.0	6.6	6.6	*8.2*
	dCO_2-eq [kg/m^{2}a]	3.9	3.6	3.4	3.4	*3.6*	11.8	8.2	12.9	12.2	*11.2*
Retrofit Package **n°3**	dTEDh [kWh/m^{2}a]	1.6	1.5	2.4	2.0	*1.8*	1.6	1.5	2.4	2.0	*1.8*
	dTEDc [kWh/m^{2}a]	1.2	0.9	2.0	1.6	*1.4*	1.2	0.9	2.0	1.6	*1.4*
	dPEC [kWh/m^{2}a]	3.1	2.7	4.7	3.8	*3.5*	22.7	14.5	27.8	25.3	*22.2*
	dRC [€/m^{2}a]	0.3	0.3	0.5	0.4	*0.3*	3.3	1.8	4.3	3.7	*3.2*
	dGC [€/m^2]	2.4	2.0	3.7	3.0	*2.7*	38.3	22.6	49.3	43.6	*37.6*
	SPB [years]	7.1	7.3	6.8	6.7	*6.9*	3.1	2.6	3.4	3.2	*3.1*
	DPB [years]	8.1	8.4	7.7	7.6	*7.8*	3.3	2.8	3.6	3.4	*3.4*
	dCO_2-eq [kg/m^{2}a]	0.8	0.7	1.2	1.0	*0.9*	7.9	5.0	9.7	8.8	*7.7*

** d stands for difference with the baseline: Positive values denote a reduction (i.e., a saving), negative values an increment.*
*** B. stands for building*

Package n°3 consists in the insulation of the roofs of all four buildings. As predictable, the PEC decreases during the cold months due to the TEDh reduction. However, the PEC is reduced also during the warm periods because the insulation layer reduces the peak cooling loads and postpone them during colder hours of the day, with benefits in terms of efficiency of the HVAC systems. More in detail, the TEDh is reduced by 1.8 kWh/m^{2}a, while the TEDc by 1.4 kWh/m^{2}a. In terms of PEC, the reduction is 3.4 kWh/m^{2}a, while it is 0.34 €/m^{2}a for the RC and 2.7 €/m^2 for the GC. Considering the payback periods, the SPB and the DPB are 6.9 years and 7.8 years, respectively. Finally, 0.9 kg/m^{2}a of CO_2-eq emissions are avoided.

If the PV systems are installed, the PEC reduction is much higher and is equal to 22.2 kWh/m^{2}a. A substantial decrement compared to the baseline is obtained also for the RC – *i.e.,* 3.2 €/m^{2}a – and for the GC – *i.e.*, 37.6 €/m^2. This implies short SPB and DPB periods, and thus 3.1 years and 3.4 years, respectively. Finally, the attained reduction of CO_2-eq emissions is equal to 7.7 kg/m^{2}a.

Among the ERMs considered in the Energy Requalification, the stand-alone replacement of windows with ones characterized by lower U-values is not cost-effective, though significant reductions of PEC are assessed. The solution is to couple these measures with the installation of PV panels to make the overall retrofit cost-effective and guarantee short payback periods. For what concerns the insulation of the roof, this allows to reduce the PEC without resulting too costly. However, the combination with PV panels results fundamental to achieve significant reductions of PEC values and higher financial benefits too.

The performance of the three Major Renovation of the Second Level packages (**n°4**, **5** and **6**) is shown in figure 5.5, as concerns the PEC on a monthly basis, and in table 5.11 as concerns the other main energy, financial and environmental indicators.

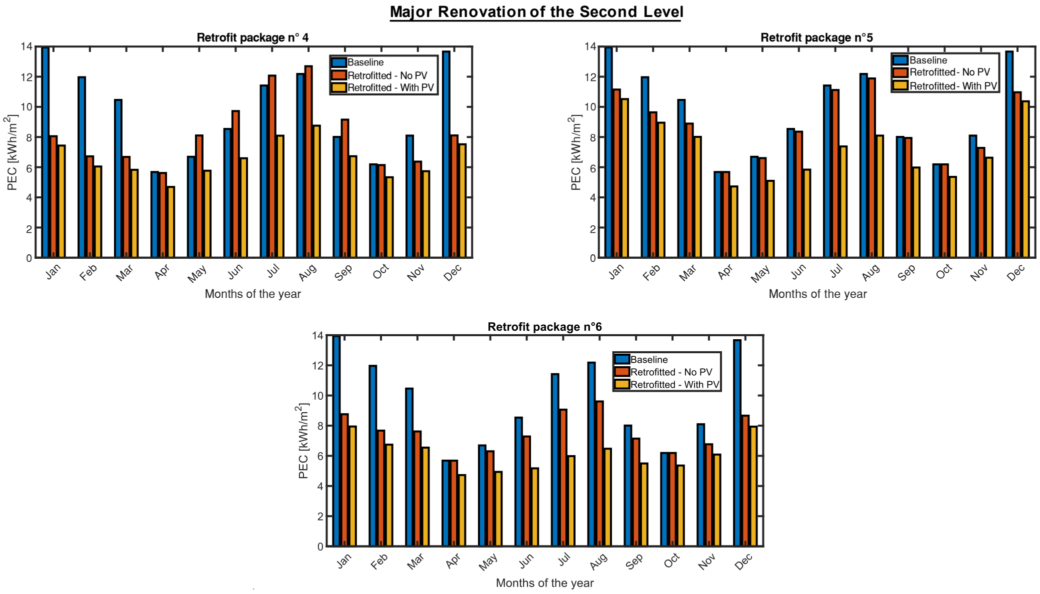

Figure 5.5. Monthly PEC at district level: baseline vs Major Renovation of the Second Level packages with and without the installation of photovoltaic (PV) systems

Table 5.11. Main energy, financial and environmental indicators for the Major Renovation of the Second Level Packages with and without the installation of photovoltaic (PV) systems

		MAJOR RENOVATION OF THE SECOND LEVEL									
		without PV systems					with PV systems				
		**B. 1	B. 2	B. 3	B. 4	*District*	B. 1	B. 2	B. 3	B. 4	*District*
Retrofit Package **n°4**	*dTEDh [kWh/m^{2}a]	14.3	14.2	13.4	13.5	*13.9*	14.3	14.2	13.4	13.5	*13.9*
	dTEDc [kWh/m^{2}a]	-8.8	-10.4	-9.7	-9.4	*-9.5*	-8.8	-10.4	-9.7	-9.4	*-9.5*
	dPEC [kWh/m^{2}a]	18.8	17.2	16.4	16.6	*17.4*	40.6	29.8	42.8	40.8	*38.3*
	dRC [€/m^{2}a]	1.6	1.4	1.3	1.4	*1.4*	4.7	3.0	5.4	5.0	*4.5*
	dGC [€/m^2]	-3.2	-17.5	-7.3	-4.4	*-7.8*	35.5	4.1	42.2	39.5	*29.8*
	SPB [years]	17.0	27.5	20.4	18.0	*20.3*	7.3	13.5	7.1	6.9	*8.2*
	DPB [years]	24.1	59.0	32.1	26.3	*31.9*	8.4	17.6	8.1	7.8	*9.6*
	dCO$_2$-eq [kg/m^{2}a]	3.6	3.2	3.0	3.1	*3.3*	11.6	7.7	12.6	12.0	*10.9*
Retrofit Package **n°5**	dTEDh [kWh/m^{2}a]	1.6	1.5	2.4	2.0	*1.8*	1.6	1.5	2.4	2.0	*1.8*
	dTEDc [kWh/m^{2}a]	1.2	0.9	2.0	1.6	*1.4*	1.2	0.9	2.0	1.6	*1.4*
	dPEC [kWh/m^{2}a]	11.5	10.5	11.7	10.8	*11.1*	31.1	22.3	34.9	32.4	*29.9*
	dRC [€/m^{2}a]	1.1	1.0	1.1	1.0	*1.0*	4.0	2.6	4.9	4.4	*3.9*
	dGC [€/m^2]	7.7	5.4	5.0	5.7	*6.1*	43.6	26.1	50.6	46.2	*41.1*
	SPB [years]	7.6	9.3	10.3	9.2	*8.9*	4.0	4.6	4.6	4.3	*4.3*
	DPB [years]	8.8	11.0	12.5	10.9	*10.4*	4.3	5.1	5.0	4.7	*4.7*
	dCO$_2$-eq [kg/m^{2}a]	2.7	2.5	2.8	2.6	*2.6*	9.8	6.8	11.2	10.4	*9.4*
Retrofit Package **n°6**	dTEDh [kWh/m^{2}a]	1.6	1.5	2.4	2.0	*1.8*	1.6	1.5	2.4	2.0	*1.8*
	dTEDc [kWh/m^{2}a]	1.2	0.9	2.0	1.6	*1.4*	1.2	0.9	2.0	1.6	*1.4*
	dPEC [kWh/m^{2}a]	17.6	17.1	18.1	17.1	*17.4*	35.7	28.8	39.0	36.6	*34.8*
	dRC [€/m^{2}a]	2.4	2.3	2.3	2.2	*2.3*	5.2	3.9	6.0	5.4	*5.0*
	dGC [€/m^2]	22.6	21.7	21.4	20.3	*21.6*	56.8	42.3	64.2	58.5	*54.8*
	SPB [years]	5.3	5.3	5.7	5.7	*5.5*	3.9	3.9	4.2	4.1	*4.0*
	DPB [years]	5.8	5.9	6.4	6.4	*6.1*	4.3	4.2	4.5	4.5	*4.4*
	dCO$_2$-eq [kg/m^{2}a]	5.8	5.6	5.9	5.6	*5.7*	12.4	9.9	13.5	12.7	*12.0*

** d stands for difference with the baseline: Positive values denote a reduction (i.e., a saving), negative values an increment.*
*** B. stands for building*

Package n°4 consists in the replacement of the existing windows with double-glazed ones, with air filling and PVC frames, coupled with the installation of natural gas-fired condensing boilers to cover the thermal demands for space heating. The performance in terms of TEDh and TEDc is the same as Package n°1, but by means of the condensing boilers, the PEC is sensibly reduced, as shown in figure 5.5. In particular, the package allows a reduction of PEC equal to 17.4 kWh/m^{2}a and of RC equal to 1.4 €/m^2, mainly because of the higher efficiency of the condensing boilers compared to the existing traditional boilers. However, the GC is incremented by 7.8 €/m^2, mainly because of the investment cost required for windows, and so the SPB and the DPB periods are longer than the evaluation period (20 years), *i.e.*, they are 20.3 years and 31.9 years, respectively. If the PV systems are installed, an important reduction of the PEC equal to 38.3 kWh/m^{2}a is obtained, combined with sensible reductions of RC and GC, which are of 4.5 €/m^{2}a and of 29.8 €/m^2, respectively. The SPB is equal to 8.2 years, while the DPB to 9.6 years. Finally, the CO$_2$-eq emissions are cut down by 10.9 kg/m^{2}a.

Package n°5 consists of insulating the roofs and replacing the existing boilers with condensing ones. As predictable, coupling these two ERMs reduces the PEC sensibly, as shown in figure 5.5. More in detail, the PEC decrement is equal to 11.1 kWh/m^{2}a, while the RC reduction is of 1.0 €/m^{2}a. The GC is slightly reduced by 6.1 €/m^2. The SPB and the DPB are respectively equal to 8.9 years and 10.4 years. From an environmental perspective, the CO$_2$-eq emissions are cut down by 2.6 kg/m^{2}a.
If the PV systems are installed, the situation profoundly changes. The PEC decrements of 29.9 kWh/m^{2}a and the RC of 3.89 €/m^{2}a. The GC is reduced by 41.1 €/m^2. For what

concerns the CO_2-eq emissions, a decrement of 9.4 kg/m^{2}a is attained. Finally, SPB and DPB are 4.3 years and 4.7 years.

Package n°6 is characterized by the insulation of the roofs, as in the previous case, and the replacement of both the heating and cooling HVAC systems with a much more efficient reversible air-source electric heat pump. In this case, the PEC reduction is 17.4 kWh/m^{2}a, as for Package n°4, but higher compared to Package n°5, where the insulation of the roofs is coupled with the installation of condensing boilers (see figure 5.5 again). The RC decrement is equal to 2.3 €/m^{2}a and the GC is sensibly reduced by 21.6 €/m^2. Therefore, satisfactory short payback periods are obtained – the SPB is equal to 5.5 years, while the DPB is equal to 6.1 years. Finally, the CO_2-eq emissions are decreased by 5.7 kg/m^{2}a.

If the PV systems are installed, all aforementioned energy, financial and environmental indicators are strongly improved. In fact, the PEC is reduced by 34.7 kWh/m^{2}a, the RC by 5.0 €/m^{2}a, the GC by 54.8 €/m^2 and the CO_2-eq emissions of 12.0 kg/m^{2}a. Besides, the SPB and DPB periods are very short and equal to 4.0 years and 4.4 years, respectively.

Finally, among the ERMs considered as Major Renovation of the Second Level, once again the replacement of single-glazed windows with double-glazed ones does not result cost-effective, even if coupled with the replacement of the existing boilers for space heating with more efficient condensing ones. Indeed, this combination is energy-effective and environmentally-friendly, but it is not convenient from a financial viewpoint. Therefore, it is fundamental to combine the replacement of windows with the installation of PV panels and, additionally, with the replacement of the existing boilers with condensing ones. Differently, the insulation of the roofs simply coupled with the installation of condensing boilers permits to improve the energy, financial and environmental benefits. If this package is combined with the PV systems, the aforementioned savings are notably increased. However, the best way to maximize the energy, financial and environmental performance consists in the installation of reversible air-source electric heat pumps, more effective than condensing boilers, in order to maximize the usefulness of the electricity produced by the PV systems, and so the deployment of the renewable energy sources.

The performance of the four Major Renovation of the First Level packages (**n°7**, **8**, **9** and **10**) is shown in figure 5.6, as concerns the PEC on a monthly basis, and in table 5.12 concerning the other main energy, financial and environmental indicators.

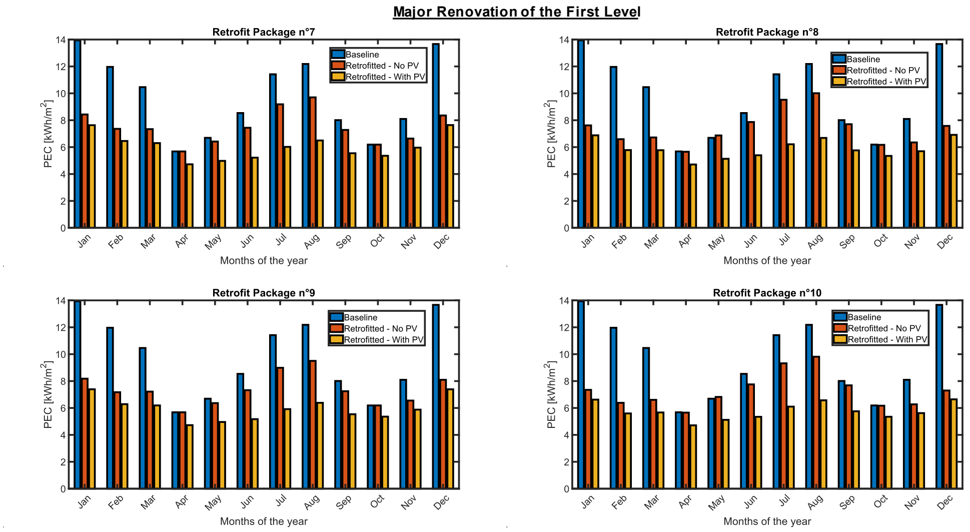

Figure 5.6. Monthly PEC at district level: baseline vs Major Renovation of the First Level packages with and without the installation of photovoltaic (PV) systems

Table 5.12. Main energy, financial and environmental indicators for the Major Renovation of the First Level Packages with and without the installation of photovoltaic (PV) systems

		MAJOR RENOVATION OF THE FIRST LEVEL									
		without PV systems					**with PV systems**				
		**B. 1	B. 2	B. 3	B. 4	*District*	B. 1	B. 2	B. 3	B. 4	*District*
Retrofit Package **n°7**	*dTEDh [kWh/m^{2}a]	5.3	5.2	4.0	4.3	*4.8*	5.3	5.2	4.0	4.3	*4.8*
	dTEDc [kWh/m^{2}a]	-0.6	-0.4	-0.3	-0.4	*-0.4*	-0.6	-0.4	-0.3	-0.4	*-0.4*
	dPEC [kWh/m^{2}a]	20.3	20.0	18.7	18.5	*19.5*	38.7	31.9	40.2	38.4	*37.2*
	dRC [€/m^{2}a]	2.5	2.4	2.3	2.3	*2.4*	5.3	4.0	6.0	5.5	*5.2*
	dGC [€/m^2]	13.8	13.0	12.6	11.8	*12.9*	48.4	33.7	56.0	50.4	*46.5*
	SPB [years]	9.3	9.5	9.5	9.7	*9.5*	5.8	6.5	5.6	5.7	*5.9*
	DPB [years]	11.1	11.4	11.3	11.6	*11.3*	6.5	7.3	6.2	6.4	*6.5*
	dCO$_2$-eq [kg/m^{2}a]	6.2	6.1	5.8	5.7	*6.0*	12.8	10.4	13.6	13.0	*12.4*
Retrofit Package **n°8**	dTEDh [kWh/m^{2}a]	12.3	12.1	10.3	10.5	*11.4*	12.3	12.1	10.3	10.5	*11.4*
	dTEDc [kWh/m^{2}a]	-5.9	-6.6	-6.0	-6.0	*-6.1*	-5.9	-6.6	-6.0	-6.0	*-6.1*
	dPEC [kWh/m^{2}a]	25.2	24.7	23.0	22.8	*24.0*	44.4	36.9	45.3	43.5	*42.4*
	dRC [€/m^{2}a]	2.7	2.6	2.5	2.4	*2.5*	5.6	4.2	6.2	5.7	*5.4*
	dGC [€/m^2]	-6.4	-19.6	-6.5	-6.0	*-9.7*	29.1	1.5	38.0	33.6	*24.8*
	SPB [years]	17.3	22.5	17.5	17.3	*18.7*	9.7	14.5	8.8	9.0	*10.3*
	DPB [years]	24.8	38.0	25.3	24.8	*27.7*	11.6	19.4	10.3	10.6	*12.4*
	dCO$_2$-eq [kg/m^{2}a]	6.7	6.6	6.3	6.2	*6.5*	13.7	11.0	14.4	13.7	*13.2*
Retrofit Package **n°9**	dTEDh [kWh/m^{2}a]	7.1	6.8	6.6	6.4	*6.8*	7.1	6.8	6.6	6.4	*6.8*
	dTEDc [kWh/m^{2}a]	0.8	0.6	1.8	1.2	*1.0*	0.8	0.6	1.8	1.2	*1.0*
	dPEC [kWh/m^{2}a]	22.5	21.9	21.9	21.2	*21.9*	40.6	33.7	42.7	40.6	*39.2*
	dRC [€/m^{2}a]	2.6	2.6	2.6	2.5	*2.6*	5.5	4.2	6.2	5.7	*5.3*
	dGC [€/m^2]	14.5	13.5	13.7	12.7	*13.6*	48.6	34.2	56.4	50.7	*46.9*
	SPB [years]	9.4	9.6	9.5	9.7	*9.5*	6.0	6.6	5.8	5.9	*6.1*
	DPB [years]	11.2	11.5	11.4	11.7	*11.4*	6.7	7.5	6.5	6.6	*6.8*
	dCO$_2$-eq [kg/m^{2}a]	6.6	6.5	6.6	6.3	*6.5*	13.2	10.8	14.1	13.4	*12.8*
Retrofit Package **n°10**	dTEDh [kWh/m^{2}a]	14.1	13.8	12.9	12.6	*13.4*	14.1	13.8	12.9	12.6	*13.4*
	dTEDc [kWh/m^{2}a]	-4.7	-5.8	-3.9	-4.4	*-4.8*	-4.7	-5.8	-3.9	-4.4	*-4.8*
	dPEC [kWh/m^{2}a]	27.4	26.6	26.3	25.5	*26.5*	46.3	38.8	47.9	45.7	*44.6*
	dRC [€/m^{2}a]	2.8	2.7	2.7	2.6	*2.7*	5.7	4.3	6.4	5.9	*5.5*
	dGC [€/m^2]	-5.7	-19.1	-5.3	-5.1	*-8.9*	29.4	2.0	38.3	33.9	*25.2*
	SPB [years]	16.9	21.9	16.9	16.8	*18.1*	9.7	14.4	8.9	9.1	*10.3*
	DPB [years]	23.9	36.3	23.9	23.7	*26.5*	11.7	19.2	10.5	10.8	*12.5*
	dCO$_2$-eq [kg/m^{2}a]	7.2	7.0	7.0	6.8	*7.0*	14.1	11.4	14.9	14.2	*13.6*

** d stands for difference with the baseline: Positive values denote a reduction (i.e., a saving), negative values an increment.*
*** B. stands for building*

Package n°7 consists in the insulation of the external walls combined with the installation of reversible air-source electric heat pumps for both space heating and cooling. As predictable, this measure allows to slightly reduce the TEDh without strongly affecting the TEDc. More in detail, the TEDh is reduced by 4.8 kWh/m^{2}a compared to the baseline, while the TEDc is increased by 0.4 kWh/m^{2}a. However, thanks to the presence of the heat pumps, in terms of PEC, the situation is favorable during the cold months as well as the warm ones (see figure 5.6), with the exception of months characterized by intermediate outdoor temperatures, and thus April and October, during which the PEC is slightly higher compared to the baseline. During the heating and the cooling periods, the PEC is lower than the baseline because of the higher efficiency of the reversible heat pumps. On a yearly basis, the PEC reduction is equal to 19.5 kWh/m^{2}a. With reference to the financial implications, the RC is reduced by 2.4 €/m^{2}a and the GC by 12.9 €/m^2. The SPB and DPB are acceptable, *i.e.*, 9.5 and 11.3 years, respectively. Finally, the CO_2-eq emissions are cut down by 6.0 kg/m^{2}a.

If the PV systems are installed, all aforementioned indicators are sensibly improved, with the exception, obviously, of TEDh and TEDc. In detail, the PEC, RC and GC reductions are equal to 37.2 kWh/m^{2}a, 5.2 €/m^{2}a and 46.5 €/m^2, respectively. The payback periods are much shorter, *i.e.,* 5.9 years for the SPB and 6.5 years for the DPB. The CO_2-eq emissions are reduced by 12.4 kg/m^{2}a.

Package n°8 is the same as n°7, by including also the replacement of the existing windows with double-glazed ones, with argon filling, low-emissive coatings and PVC frames. As expected, the TEDh reduction is more than doubled compared to the previous package and is equal to 11.4 kWh/m^{2}a, while the TEDc increases by 6.1 kWh/m^{2}a. The PEC is lower than the baseline during all the months of the year, with the exception of May, during which is slightly higher. However, as predictable, the obtained reduction is much higher during the cold months compared to the warm ones. On a yearly basis, the PEC reduction is equal to 24.05 kWh/m^{2}a. Considering the financial indicators, the RC is reduced by 2.5 €/m^{2}a, but the GC increases by 9.7 €/m^2, due to the significant investment cost for replacing the windows. The GC increment implies long payback periods: the SPB is 18.7 years and the DPB is 27.7 years. Finally, the reduction of the equivalent emissions is equal to 6.48 kg/m^{2}a.

If the PV systems are installed, the situation is largely improved, and the package becomes effective also from a financial perspective. In detail, the reduction of PEC is equal to 42.4 kWh/m^{2}a, of RC is 5.4 €/m^{2}a, of GC is 24.8 and of CO_2-eq emissions is 13.15 kg/m^{2}a. The SPB and DPB are 10.3 years and 12.4 years.

Package n°9 consists of replacing the existing HVAC systems for both heating and cooling with more efficient reversible air-source electric heat pumps combined with the insulation of the roofs and the external walls. Differently from Package n°7, where insulation layers are posed only on walls and the TEDc increases, both TEDh and TEDc are reduced. More in detail, these decrements are of about 6.8 kWh/m^{2}a and 1.0 kWh/m^{2}a, respectively. In terms of PEC, the situation is quite similar to Package n°7. Thus substantial reductions are attained during the cold periods of the year, while only slight improvements occur during the warm months, while in the intermediate months (April and October) the PEC is higher compared to the baseline. Globally, the PEC reduction is equal to 21.9 kWh/m^{2}a. For what concerns the financial implications, the RC is reduced by 2.6 €/m^{2}a and the GC by 13.6 €/m^2. The SPB and DPB are almost the same as Package n°7, namely 9.5 years and 11.4 years. The CO_2-eq emissions have a decrement of 6.5 kg/m^{2}a.

As for all the previous cases, if PV systems are installed, considerable improvements in energy, financial and environmental indicators are reached. More in detail, the PEC has a decrement equal to 39.2 kWh/m^{2}a compared to the baseline, the RC equal to 5.3 €/m^{2}a and the GC equal to 46.9 €/m^2. The payback periods are much shorter than the same package without PV panels, and they are equal to 6.1 years and 6.8 years, respectively. Finally, the CO_2-eq emissions are reduced by 12.8 kg/m^{2}a.

Package n°10 consists in the combination of all the possible ERMs investigated in the three previous cases. Thus, this is replacing the existing HVAC systems for both heating and cooling with more efficient reversible air-source electric heat pumps combined with the insulation of the roofs and the external walls and the replacement of the windows with double-glazed ones with argon filling, low-emissive coatings and PVC frames. As predictable, the TEDh has a deep decrement – *i.e.*, 13.4 kWh/m^{2}a – while the TEDc is increased by 4.8 kWh/m^{2}a, due to overheating phenomena that can happen especially during the warm months. However, the PEC does not suffer from these phenomena because of the reversible electric heat pump, except for the month of May. Compared to the baseline, the PEC is reduced by 26.5 kWh/m^{2}a. Despite the important improvements obtained in energy indicators, the package is not cost-effective, mainly because of the high investment cost for windows. Indeed, even if the RC is reduced by 2.7 €/m^{2}a, the GC has an increment of 8.9 €/m^2. This implies payback periods that are equal to 18.1 (SPB) and 26.5 years (DPB). In terms of environmental impact, the CO_2-eq emissions are cut down by 7.0 kg/m^{2}a. Once again, the package is coupled with the described PV systems. All aforementioned indicators are strongly improved, except for TEDh and the TEDc as previously explained. The PEC results largely cut down compared to the baseline during all months of the year and, globally, it is reduced by 44.6 kWh/m^{2}a. In terms of RC and GC, these are respectively 5.5 €/m^{2}a and 25.2 €/m^2 lower than the baseline. For what concerns the payback periods, the SPB is 10.3 years and the DPB is 12.5 years. The CO_2-eq emissions are reduced by 13.6 kg/m^{2}a.

Finally, the results of energy, economic and environmental study show that, among the Major Renovation of the First Level packages, the ones that provide the replacement of single-glazed windows with double-glazed ones are the most efficient from an energy perspective, even if these are not cost-effective, due to the high investment required. On the contrary, from the financial perspective, the installation of reversible air-source electric heat pumps together with the insulation of the external walls and, eventually, of the roofs is the most suitable combination of ERMs. This can represent the most adequate trade-off between energy savings and financial benefits. Finally, once again, the importance of coupling the aforementioned packages with a PV system should be outlined. Indeed, with a PV system, both the energy performance and the financial benefits are profoundly improved.

A further investigation, among all the investigated packages with reference to all retrofit levels, identifies two optimal solutions: the one that minimizes the PEC, denoted as nZEB solution (A), and the one that minimizes the GC, denoted as cost-optimal solution (B).

- (A) the first one is **Package n°10** coupled with monocrystalline PV panels installed on 90% of useful roof areas of all the buildings constituting the district. This package allows the highest PEC reduction and, for this reason, is the most environmental-friendly one. This is the retrofit solution that may be chosen by the public hand, aiming at minimizing the energy and the environmental impact of the district.
- (B) Concerning the economic perspective, several packages provide acceptable trade-offs between energy and financial benefits, but there is a cost-optimal one, namely **Package n°6** coupled with the installation of PV panels again. This is the most suitable retrofit solution from the private perspective because it provides the best financial indicators – highest GC savings, SPB of 4.0 years, DPB of 4.4 years – ensuring, at the same time, a significant reduction of the district energy and the

environmental impact. Therefore, it can be an effective solution for the private sphere too.

Final remarks

The study presented in this chapter aims at providing a novel comprehensive approach to face the complicated issues related to the reliable energy modeling of districts/neighborhoods and to guide professionals during the retrofit planning. The approach is based on a bottom-up technique that makes use of a Geographic Information System (GIS) tool to realize accurate geometrical models. EnergyPlus is used as dynamic energy simulator, while MATLAB® is the external post-processing engine, which makes the approach versatile and easy to be used.

In summary, the proposed approach allows to achieve reliable and detailed results at different scale levels – *e.g.,* single apartment, single building, whole district – without requiring excessive computational burden thanks to the automatic interaction established between MATLAB® and EnergyPlus. Therefore, it can be a precious tool for different stakeholders, from the single citizen for achieving financial benefits from building retrofit to public institutions for addressing and optimizing the energy policies aiming at reducing the energy and environmental footprint of the exciting building stock.

However, its main limit is that it investigates only a limited number of energy efficiency measures. Therefore, in the next chapter, a further integrated framework is presented. The latter is a sort of "enhanced version" of the methodology here discussed. In fact, it investigates much more energy efficiency measures, affecting all the possible components of the building system. Among them, it takes into account also the effects due to the implementation of a local energy community that shares the PV production in coupling with the other energy efficiency measures. Indeed, the lack of investigations on PV sharing in coupling with other energy efficiency measures is one of the limits of the current state of the art, especially considering that EU Member States are promoting the creation of local energy communities [150]. Moreover, the approach presented in the next chapter considers also the Italian massive incentivation policy "Superbonus 110%".

How to perform an integrated
energy retrofit optimization
of districts/neighborhoods?

CHAPTER 6. Comprehensive analysis for the energy retrofit of a neighborhood – optimizing the solar energy exploitation

6.1. Introduction

In matter of energy retrofit planning for districts/neighborhoods the literature is plenty of studies, as seen, and many knowledge gaps can be outlined. Among them:

- not always all the proper financial performance indicators to assess building energy retrofit are taken into account;
- the energy retrofit optimization of neighborhoods is usually conducted by focusing on EEMs affecting only specific components of the building system, such as the envelope or the HVAC systems or the renewable energy systems, whilst it should involve all the components at the same;
- the effects of the implementation of PV sharing have not been investigated by considering the latter in coupling with other EEMs;
- the newly-adopted Italian “Superbonus 110%” public grant policy needs to be investigated more.

The methodology here presented aims at filling such gaps. A comprehensive analysis is performed with the scope to reduce the energy and the environmental impact of neighborhoods of buildings, addressing the financial implications as well. A wide range of EEMs is investigated, considering both the most common EEMs and innovative ones. The examined EEMs are combined in order to involve all possible components of the building system at the same time, *i.e.,*: envelope, HVAC systems, renewable energy source systems. In addition, the PV sharing is studied in coupling with all the other EEMs. Finally, the analysis takes into account the effects of the massive public grant policy introduced in Italy to promote building energy efficiency, *i.e.*, the “Superbonus 110%”.

More in detail, the first element of novelty consists in taking into account different financial indicators, which are not innovative themselves, but innovative is the fact that they are simultaneously assessed for planning the energy retrofit of an existing neighborhood. Indeed, only one or two financial indicators are usually assessed when studying neighborhoods. Moreover, another element of novelty consists in simultaneously investigating several EEMs by adopting an integrated retrofit optimization approach. Indeed, most of the examined measures are common measures, which have already been studied in previous years, but here the main difference is the approach. In the current body of knowledge, studies usually focus on measures that affect only specific components of the building system, especially when the target is the neighborhood or the district in spite of a stand-alone building. Conversely, in the presented study all the components of the building system – *i.e.*, envelope, HVAC systems, renewable energy systems – are simultaneously involved in the optimization of the energy retrofit of a neighborhood. In addition, another novelty introduced by this study is the investigation of the effects of the implementation of PV sharing in coupling with the aforementioned measures affecting all the elements of the building system. Indeed, in the current literature, PV sharing is studied on its own, without usually taking into account the effects of its interaction with other EEMs. Finally, the last contribution to the current body of knowledge consists in examining in detail the effects of the newly-adopted Italian "Superbonus 110%" massive public grant policy on the energy retrofit planning of neighborhoods.

6.2. Methodology

6.2.1. Framework

The individuation of the energy efficiency measures (EEMs) to be applied to existing neighborhoods is a crucial task, having serious implications on many different levers. Once again, it is reminded that in general the two opposite stakeholders involved are the public stakeholder, whose main aim is to fight environmental issues, and so its action is finalized at reducing the energy consumption of buildings and the relative emissions of greenhouse gases, and the private stakeholder, whose main aim is to gain financial benefits, and so its decisions are addressed to the maximization of the financial savings. However, nowadays, the attention of the collectivity towards sustainability is growing, and so in many cases also the private stakeholder may desire to achieve sustainable goals in coupling with the financial ones.

The methodology adopted in this work permits to attain a good satisfaction level of both the aforementioned perspectives, ensuring the best trade-off among them. In fact, more objective functions are addressed simultaneously, and, in addition, other significative performance indicators are examined to have a comprehensive overview of the investigated problem.

In detail, the comprehensive analysis conducted is structured in the following three subsequent phases:

1. energy modeling of the neighborhood;
2. implementation of the EEMs to apply to the neighborhood, involving the envelopes, the heating, ventilating and air conditioning (HVAC) systems and the photovoltaic (PV) systems, considering also innovative solutions;
3. selection of the most adequate combinations of EEMs to apply to the neighborhood, assuring the best possible tradeoff between the public perspective and the private one.

The study of the effects of the actual Italian "Superbonus 110%" public grant policy is one of the main aims of this investigation, so that the analysis is conducted considering both the absence and the presence of public grants in order to better outline the effectiveness (or not) of the aforementioned policy.

Performing accurately the phases here mentioned permits to achieve reliable and interesting results for the energy retrofit of neighborhoods in general.

Figure 6.1. Framework of the adopted analysis approach

6.2.2. Energy modeling of the neighborhood

For what concerns the energy modeling phase, this procedure is the same as in the methodology previously presented – see Chapter 5. Indeed, the main novelties introduced by the approach here discussed are exclusively focused to the energy retrofit planning phase. However, in order to make the entire section clearer for the reader, the energy modeling phase is here presented again briefly. For more detail, see Section 5.2.2.

As seen, in order to realize an accurate energy modeling of the neighborhood, as first step, two software are used: CADMapper® and SketchUp®. The first is a Geographical Information System (GIS) tool that imports ".dwg" or ".dxf" files – *i.e.*, CAD files – of 2D satellite street maps from OpenStreetMap [151] servers. The second allows to easily handle the CAD files to create the 3D geometrical model. Moreover, it permits to individuate the shadowing buildings, which are not energy modeled and, in detail, are defined only as empty 3D polygons that produce shading effects. This attention to characterize the unnecessary building structures without energy modeling them strongly cuts down the computational effort required, but with no losses in terms of results' accuracy.

Once completed the geometrical model of the neighborhood, this is exported from SketchUp® and imported in DesignBuilder®, the well-known graphical interface for EnergyPlus. Here, both opaque and transparent envelopes of each building are defined in detail. This operation requires high accuracy because the reliability of the results strongly depends on it. Then, the thermal zoning is performed, and so the internal subdivisions for each building are defined and the use destinations are assigned. Consequently, the "raw" energy model of the neighborhood is exported from DesignBuilder® under the ".idf" file form. The latter is imported in EnergyPlus, which is the software employed to run dynamic energy simulations. In EnergyPlus, the raw energy model is refined by implementing:

1. the detailed usage profiles on hourly or sub-hourly basis for every energy service in each thermal zone;
2. the detailed operation schedule for the HVAC systems;

These schedules may be defined also in DesingBuilder®, but EnergyPlus has been preferred due to its unbounded possibilities of customization.

Once performed this definition, directly in EnergyPlus, ideal HVAC systems are implemented, with the aim to assess ideal thermal energy demands for heating (TEDh) and for cooling (TEDc). In fact, the heating and the cooling generation subsystems together with their own distribution, regulation and emission subsystems are modeled directly in MATLAB® in order to deeply cut down the computational burden. Note that in EnergyPlus also the energy consumption due to electric facilities is evaluated excluding the electricity for HVAC systems.

Under MATLAB® environment, in-house-developed codes are used to automatize the coupling between EnergyPlus and MATLAB® itself. In fact, EnergyPlus simulations are launched by MATLAB®, which, subsequently, postprocesses the outputs contained in ".csv" files. During the postprocessing, MATLAB® applies the HVAC systems, implements the renewable energy sources systems – if available –, such as PV, and, finally, assesses the objective functions and other fundamental performance indicators. More in detail, the objective functions are the primary energy consumption (PEC) and the global cost (GC). These are selected according to the aims of the actors involved in the decision-making process. Indeed, the public perspective mainly aims at minimizing the

PEC, while, on the other hand, the private perspective mainly aims at minimizing the GC. In addition to the PEC and the GC, other performance indicators are assessed to have a comprehensive overview of the investigated problem, and so, once the whole analysis is finished, to have the certainty to choose the most adequate combinations of EEMs, knowing clearly their effects in terms of energy, financial and environmental performance. The other performance indicators are the aforementioned TEDh and TEDc, the simple payback (SPB) and discounted payback (DPB) periods and, finally, the equivalent emissions of CO_2 (CO_2-eq). For what concerns the TEDh and the TEDc, the values assessed by means of EnergyPlus are ideal values, which are "corrected" in MATLAB® by considering the efficiencies of the HVAC subsystems, with the exclusion of the generation ones. The efficiencies of the distribution, regulation and emission subsystems are assessed according to the Italian standard UNI-TS 11300. Concerning the efficiencies of the heating and cooling generation subsystems, these are evaluated by using dynamic performance curves, which have been encoded in proper MATLAB® scripts. These curves, in coupling with the aforementioned efficiencies of the other subsystems, allow to easily assess the hourly demand of fuel and electricity due to HVAC systems. These hourly shares, together with the hourly values due to other energy services – *i.e.*, lights and electric facilities in general –, are converted:

- in PEC, by the application of conversion factors;
- in running cost (RC) (the RC is necessary to assess the GC and, in presence of EEMs, the SPB and DPB), by the application of specific electricity and gas prices;
- in CO_2-eq emissions, by the application of specific emissions factors.

Finally, analogous dynamic performance curves are used to implement PV systems, if available. On an hourly basis, the self-consumed PV energy and the stored one constitute subtractive terms in PEC and RC assessments, while, on the other hand, the exceeding electricity is fed to the grid, being paid or for free, according to the absence or presence of a public grant policy.

6.2.3. Energy retrofit of the neighborhood

When the detailed energy model of the neighborhood is finished and the values of the objective functions and all the other performance indicators are assessed for the baseline configuration – *i.e.*, neighborhood "as built" – it is necessary to select and investigate the EEMs to apply in order to minimize the PEC and the GC, by satisfying both the public stakeholder and the private one. At this purpose, a wide range of EEMs is considered, affecting the envelope, the HVAC systems and the PV systems. Being one of the aims of this work the optimization of the solar energy exploitation by using PV systems, the effects of innovative solutions for the latter are examined, by considering measures such as PV sharing, which implies the creation of a local energy community, or the installation of distributed PV energy storages in all the buildings' units of the neighborhood. The EEMs investigated and the related characteristics are reported in detail in Section 6.3.2.

All told, once selected the EEMs to consider, a limited number of scenarios is individuated for what concerns the combinations of EEMs to apply to the envelope – *i.e.*, neighborhood as built and various retrofit scenarios – because these combinations require EnergyPlus simulations. Once obtained the outputs of the dynamic energy simulations, an exhaustive search is performed, aiming at minimizing the objective functions. The exhaustive search is performed entirely under MATLAB® environment, consisting in the application of the EEMs affecting the HVAC systems and the PV ones, which are implemented directly in MATLAB®, as specified in Section 6.2.2.

When the exhaustive search is finished and the values of PEC, GC and all the other performance indicators are assessed, the Pareto multi-objective approach is adopted in order to minimize both the objective functions at the same time. Finally, the decision-making process is performed, and three suboptimal solutions are picked among all the non-dominated solutions collected in the Pareto Front. In detail, the suboptimal solutions are the following:

- the "nZEB solution": It is the one minimizing the PEC, and so it is the combination of EEMs that would be preferred by the public perspective;
- the "cost-optimal solution": It is the one minimizing the GC, and so it is the combination of EEMs that would be picked by the private perspective;
- the "utopia solution": It is the best tradeoff between PEC and GC, respectively, and so it can satisfy both perspectives. This configuration is selected according to a geometrical criterion applied in the normalized plane PEC – GC. In fact, it is the Pareto solution that presents the lowest distance from the "utopia point", which is an ideal solution that has, as coordinates, the PEC value of the nZEB solution and the GC value of the cost-optimal one.

The EEMs' application is investigated twice, once considering the absence of public grants, the other applying the Italian "Superbonus 110%" policy, with the aim to achieve important indications for the Italian Government concerning the adoption of public grants to boost the sustainability of the building sector. In Section 6.3.3, such policy is better described by referring to the examined EEMs (characterized in Section 6.3.2).

6.3. Presentation of the case study

6.3.1. Baseline configuration of the neighborhood ("as built configuration")

The case study is an existing neighborhood located in Naples (Southern Italy), which is representative of the Southern Italy stock built in the period 1960-1970. The same neighborhood was studied in [146, 152], but for different scopes. More in detail, a preliminary methodology framework to energy investigate neighborhoods or districts of buildings was presented in [146], with the further aim to optimize the solar energy exploitation, and the framework was refined in [152], enhanced by considering further energy efficiency solutions, and, in addition, the importance of a proper public grant policy was outlined.

The investigated neighborhood is constituted by four buildings in reinforced concrete. Buildings have from five to nine stories above the ground, each one with a net height equal to 3.1 m. Concerning the gross floor area, it is included between 3662 m^2 and 6417 m^2 per building, while the glazing area varies from 552 m^2 to 986 m^2. For what concerns the use destinations, buildings are mainly multi-family residential ones, even if the entire ground floors are characterized by the presence of commercial units and, in addition, few offices are present at the first floors. Finally, there are also common circulation areas, as predictable. Globally, 227 thermal zones are individuated, but only 157 are equipped with emitting terminals of the respective HVAC systems because the common circulation areas are not climatized. In detail, the distribution of the aforementioned thermal zones among the four buildings is the following (see figure 6.2):

- building 1: 30 apartments, 11 commercial units, 2 offices, 21 common circulation areas;
- building 2: 29 apartments, 12 commercial units, 0 offices, 16 common circulation areas;
- building 3: 23 apartments, 9 commercial units, 1 office, 15 common circulation areas;
- building 4: 29 apartments, 10 commercial units, 1 office, 18 common circulation areas.

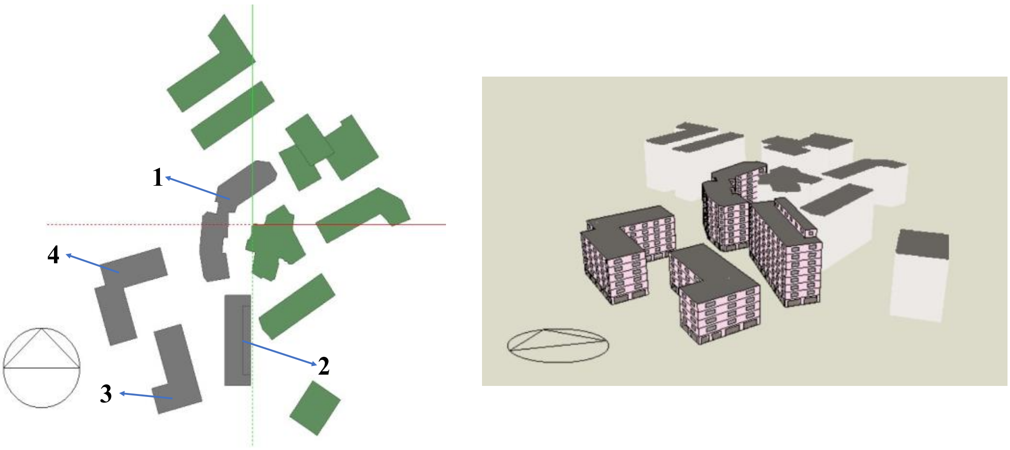

Figure 6.2. On the left: Aerial view of the small neighborhood. The investigated buildings are the grey ones, while green buildings are considered for their shadowing effect. Numbers identify each building. On the right: 3D rendering of the neighborhood. Pink buildings are the investigated ones

Each building of the neighborhood is characterized by the same opaque and transparent envelope, according to the Southern Italy construction practice of the 60s-70s. For what concerns the opaque envelope, the layer sequence and composition of the external walls, the roof and the ground floor are detailed in tables 6.1-6.3. Note that the ground floor is the only envelope structure that is already characterized by the presence of an insulation layer. The U-value of each structure is indicated in table 6.4.

Table 6.1. Composition of the external walls (from the internal to the external layer)

Layer n°	Material	Density [kg/m^3]	Conductivity [W/m K]	Specific heat [J/kg K]	Thickness [m]
1	Plaster	2000	1.40	670	0.02
2	Block of lapillus	1000	0.38	880	0.08
3	Air gap	-	-	-	0.12
4	Hollow bricks	2000	0.90	1000	0.12
5	Plaster	2000	1.40	670	0.03

Table 6.2. Composition of the roof (from the internal to the external layer)

Layer n°	Material	Density [kg/m^3]	Conductivity [W/m K]	Specific heat [J/kg K]	Thickness [m]
1	Plaster	2000	1.40	670	0.02
2	Hollow-core Concrete	800	0.51	1000	0.20
3	Reinforced Concrete	2400	2.50	1000	0.06
4	Concrete	2000	1.13	1000	0.15
5	Asphalt	2100	0.70	1000	0.01

Concerning the transparent envelope, single pane windows with different types of frames are installed in each building according to the use destinations. In detail, commercial units present aluminum frames (with thermal break), while the other thermal zones present wooden ones. In addition, the glazing area is variable with the use destination and it is equal to 20% of the respective gross wall area for residential units, offices and common circulation areas, while it rises to 60% for commercial units. The U-value of the windows is 5.44 W/m^{2}K for shops and 5.89 W/m^{2}K for all the other thermal zones.

Table 6.3. Composition of the ground floor (from the internal to the external layer)

Layer n°	Material	Density [kg/m^3]	Conductivity [W/m K]	Specific heat [J/kg K]	Thickness [m]
1	Wood floor	650	0.14	1200	0.03
2	Screed	1800	0.90	1000	0.07
3	Concrete	2000	1.13	1000	0.10
4	Urea-formaldehyde	10	0.04	1400	0.13

For what concerns the HVAC systems, each conditioned thermal zone is equipped with its own heating and cooling generation systems, which are respectively natural gas fired hot water boilers for heating and air-to-air heat pumps for cooling. More in detail, boilers are characterized by a nominal efficiency (η) at the LHV (lower heating value) equal to 0.80 and feed baseboards with hot water at 80 °C. On the other hand, air-to-air heat pumps present a nominal coefficient of performance (COP) equal to 2.5. HVAC emitting terminals are installed in all thermal zones of the buildings, with the exclusion of the common circulation areas. Note that the effects of the efficiencies of the regulation subsystems, the emitting subsystems and the distribution subsystems are assessed according to the Italian technical standards (namely, the UNI TS-11300, info at: https://www.cti2000.eu/la-uni-ts-11300/) and taken into account during the investigation. More in detail, the aforementioned efficiencies are evaluated by means of in-house developed MATLAB® scripts, which encode the UNI TS-11300. The efficiency values are not fixed, they vary according to many factors. For what concerns the efficiency of the regulation subsystems, it depends on the type of emitting terminals in addition to the type of regulation. For the baseline situation it is assumed equal to 0.94, because it is supposed that baseboards are the emitting terminals and that the regulation is "only for thermal zones" – *i.e.*, the latter is a definition taken by the considered technical standard, which implies that the HVAC system can be regulated only at thermal zone level, and in the investigated case study each space conditioned thermal zone constitutes an apartment – and the regulation happens by means of a proportionality band equal to 2 °C. For what concerns the efficiency of the emitting subsystem, it depends on the type of the emitting terminals, on the height of the thermal zones, on the mean value of the annual heating load per volume – *i.e.*, W/m^3 – and on the presence or not of insulation on the external walls. For instance, for the baseline situation, it is assumed that the emitting terminals are baseboards installed on the external walls, which are not insulated. According to the level of each apartment and to its exposition, the efficiency of the emitting subsystems varies from 0.91 to 0.94. For what concerns the efficiency of the distribution subsystems, it depends on the presence or not of insulation on the distribution pipes, on the type of HVAC system – *i.e.*, centralized or autonomous – and on type of distribution. For the neighborhood as built, being present autonomous HVAC systems, the presence or not of an insulation layer on the pipes is irrelevant according to the considered technical standard, and so the efficiency of the distribution subsystem is assumed equal to 0.99. For what concerns the efficiencies of the aforementioned subsystems in presence of EEMs on the envelope and/or on the HVAC systems, they need to be assessed case per case, as done in the investigated case study, and so no general assumptions can be made, safe that generally speaking these efficiencies are quite higher compared the homologous values of the neighborhood as built.

Table 6.4. Main geometrical and thermal characteristics of the neighborhood

Geometry			
Building 1			
Gross Floor Area	6417.0 m^{2}	Gross Wall Area	4082.6 m^{2}
Gross Roof Area	916.7 m^{2}	Height	22.4 m (7 floors)
Window Opening Area	986.1 m^{2}	Total Gross Volume	20534.5 m^{3}
Gross Window-Wall Ratio	24.2 %	Surface to Volume Ratio	0.33 m^{-1}
Building 2			
Gross Floor Area	5211.4 m^{2}	Gross Wall Area	3316.4 m^{2}
Gross Roof Area	631.6 m^{2}	Height	28.8 m (9 floors)
Window Opening Area	771.5 m^{2}	Total Gross Volume	16676.4 m^{3}
Gross Window-Wall Ratio	23.3 %	Surface to Volume Ratio	0.31 m^{-1}
Building 3			
Gross Floor Area	3662.1 m^{2}	Gross Wall Area	2082.0 m^{2}
Gross Roof Area	732.4 m^{2}	Height	16.00 m (5 floors)
Window Opening Area	552.0 m^{2}	Total Gross Volume	11718.7 m^{3}
Gross Window-Wall Ratio	26.5 %	Surface to Volume Ratio	0.34 m^{-1}
Building 4			
Gross Floor Area	5373.1 m^{2}	Gross Wall Area	3086.1 m^{2}
Gross Roof Area	895.8 m^{2}	Height	19.2 m (6 floors)
Window Opening Area	779.6 m^{2}	Total Gross Volume	17199.8 m^{3}
Gross Window-Wall Ratio	25.3 %	Surface to Volume Ratio	0.33 m^{-1}
Whole district			
Gross Floor Area	20663.6 m^{2}	Gross Wall Area	12567.1 m^{2}
Gross Roof Area	3176.5 m^{2}	Total Gross Volume	66129.4 m^{3}
Window Opening Area	3089.2 m^{2}		
Main Boundary Conditions of Energy Simulations			
Climatic data	IWEC → EPW	Occupancy	*Depending on the destination of use*
Number of thermal zones	227 (conditioned 157)		
Building Envelope			
U walls	1.01 W/m^{2}K	U windows-shop	5.44 W/m^{2}K
U roofs	1.09 W/m^{2}K	U windows-all other	5.89 W/m^{2}K
U ground	0.37 W/m^{2}K		
HVAC Systems			
Heating generation systems	Natural gas-fired hot water boilers	η generation (heating)	0.80
Cooling generation systems	Air-to-air heat pumps	COP (cooling)	2.50

6.3.2. Energy Efficiency Measures

Once defined the neighborhood as built, the next phase consists in the selection and the consequent investigation of the energy efficiency measures (EEMs) to apply. The aim is to reduce simultaneously the primary energy consumption (PEC) and the global cost (GC), thereby achieving a good satisfaction level for both the public perspective and the private one – due to the heterogeneity of the latter, the effects of the EEMs on the thermal comfort are not investigated. In detail, the following EEMs on the envelope are examined:

1. insulation of the external walls – it is applied an insulation layer having the lowest thickness that permits to respect the thermal transmittance limit imposed by the Italian building regulation [125];
2. insulation of the roof – as above, it is applied an insulation layer having the lowest thickness that permits to respect the thermal transmittance limit required by Italian building regulation [125];
3. replacement of existing windows with double-glazed ones with argon-filling, low-emitting coating and PVC frames. In this case, the infiltration rate passes from 0.7 air changes per hour (h^{-1}) to 0.3 air changes per hour.

In table 6.5 are reported the current requirements of thermal protection of buildings in Italy, in terms of maximum allowable value of thermal transmittance for a retrofitted component of the building envelope. Note that, when an EEM affects the envelope, it should respect also the “minimal environmental requirements” – in Italian, “Criteri Ambientali Minimi (CAM)” –, established by the Italian Laws [153-155]. The CAM are requirements that impose in the building sector the use of materials that are composed by a minimum aliquot of recycled material, which varies according to the material. In this study, it is supposed that the CAM as well are verified.

Table 6.5. Thermal transmittance limits for all the Italian thermal zones, according to [125]

Thermal Transmittance Limits [W/m^{2}a]						
Envelope Component	**Zone A**	**Zone B**	**Zone C**	**Zone D**	**Zone E**	**Zone F**
External walls	0.43	0.43	0.34	0.29	0.26	0.24
Groundfloors	0.44	0.44	0.38	0.29	0.26	0.24
Roofs	0.35	0.35	0.33	0.26	0.22	0.20
Windows	3.00	3.00	2.20	1.80	1.40	1.10

All told, the aforementioned EEMs on the envelope are combined as indicated in table 6.6, and so eight different scenarios are individuated, namely the neighborhood as built (with no EEMs on the envelope) and seven retrofit scenarios.

Table 6.6. Scheme of the investigated scenarios

Investigated Retrofit Solutions on the Envelope								
EEMs	*Scen 1 (as built)*	*Scen 2*	*Scen 3*	*Scen 4*	*Scen 5*	*Scen 6*	*Scen 7*	*Scen 8*
Additional insulation layer on the external walls				X	X	X	X	
Additional insultation layer on the roofs			X			X	X	X
Replacement of windows		X			X		X	X

With reference to each scenario, various EEMs for primary energy systems are investigated, each one respecting the limits imposed by the Italian law [125]. More in detail, these EEMs are:

1. the installation of photovoltaic (PV) panels on building roofs, covering different percentages of each useful roof area – *i.e.*, as useful roof area 90% of the gross roof area of each building is considered, with the exception of building 2, whose useful roof area is supposed to be equal to 50% of the relative gross roof area – and investigating different types of panels, each one with its own extension and efficiency. Note that the value 90% is chosen because it is the real useful area of each roof. In detail, the existing parapets are in metal bars, so the shadowing effect is supposed neglectable. Moreover, staircase wells are not present, because the access to the roofs is guaranteed by roof hatches. For what concerns the chimneys, these are not ubicated on the roofs, because the HVAC systems are autonomous ones, and so each apartment has its own chimney. Finally, there is only one centralized antenna per building, therefore, as for the parapets, its shadow on the PV panels is considered neglectable. All told, for what concerns the technical characteristics of the proposed PV systems, the nominal peak power, the efficiency and the geometrical dimensions of each panel are reported in Table 6.7. These are ones of the most common commercial panels available in the regional market of the neighborhood, according to the expertise of the authors. Aiming at dimensioning the PV systems, the methodology consists in performing an exhaustive search among all the possible combinations of types of PV panels and roof covering percentages. Once defined the type of panel, its geometrical dimensions are note. Assumed a specific roof covering percentage, which may vary from 0% to 100% (of the useful roof area), the number of panels, and so the size of the PV system, is obtained by considering for each PV panel an area that is about the double of its geometrical real one, with the aim to minimize the shadowing effects between one line of panels and the closest ones, and to guarantee an easy inspection during maintenance operations – *e.g.*, the considered

polycrystalline PV panels have an area equal to 1.67 m^2, but for each of them is considered a 3.35 m^2;

2. the implementation of PV energy production sharing, by means of the creation of a local energy community regrouping all the four buildings constituting the neighborhood. In theory, this measure should maximize the self-consumption of the on-site converted energy;
3. the installation of distributed or centralized PV energy storages, considering different sizes according to the configuration. In the distributed configuration, PV batteries are installed in each residential, office or commercial unit, with the exclusion of the common circulation areas, and each of them serve only one unit. On the other hand, in the centralized configuration, PV energy storages are installed all together and serve the whole neighborhood as an entity. The former configuration is supposed to be possible only when PV sharing is not implemented, while the latter when PV sharing is implemented;
4. the replacement of the existing HVAC systems, considering interventions on the generation subsystems and on the emitting terminals.

Note that, being different the aim of the studies presented in this thesis, the attention of the author has not been focused on the development of an optimized framework for the creation of a local energy community and, moreover, on the constraints established by electricity distributors and by the standards, which strongly depend on the country where the local energy community should be installed – e.g., in Italy all the buildings of the community have to be connected to the same medium voltage substation and the maximum size of the PV system of the community has to be lower than 200 kW. When PV sharing is implemented in the presented studies, the hourly balance between the electricity produced by all the installed PV systems and the electricity need at the neighborhood level is assessed. This approach permits to achieve a preliminary overview on the possible effects of the implementation of a local energy community on the considered performance indicators in really short time and with a satisfying level of accuracy. Moreover, not taking into account the different requirements imposed by national laws, it is possible to adopt the same approach for preliminary analysis beyond national boundaries. However, it is undoubtful that the achieved results are preliminary results, as said, and so further analysis should be conducted if the stakeholders decide to realize a local energy community.

For analogous reasons, also PV storages have not been modeled in detail. Indeed, as for the PV sharing, in presence of PV storages an hourly balance is performed between the energy stored and the surplus/demand of electricity, assuming as the only constrain the capacity of the batteries. The latter are supposed to be fully chargeable and dischargeable, to reduce the computational effort required for their implementation in this phase. A discharging factor equal to 0.9995 is assumed for each hour. This implies that the battery, if not used for an hour – the demand is null as well as the surplus of PV produced, for instance during night hours –, would reduce its state of charge by 0.05%. On a single hour it may appear a low reduction, but considering a day or a week, this reduction in terms of state of charge is close to commercial batteries. Finally, it is supposed that batteries have a 95% charging efficiency, and this value is due for safety reasons, with the aim not to overestimate the energy, financial and environmental benefits of implementing PV storages in presence of the simplifications conducted.

All told, the investigated EEMs are chosen according to the local most common retrofit practice and are reported in detail in table 6.7. Each EEM is intended to be applied to all the buildings of the neighborhood, even if in future studies there may be the possibility to consider variable EEMs for each building. Table 6.7 indicates the unit investment cost (IC) required for each EEM, which is partially the result of previous studies [131, 145], partially the result of market analysis [156].

Note that the capacity of the distributed energy storages is chosen according to the experience of the authors and on the common local practice. Indeed, these are the sizes of ones of the most common commercial domestic PV batteries available in the regional market of the investigated neighborhood. Moreover, these commercial units are characterized by content overall dimensions, which is crucial for a large-scale distributed configuration, because differently it may happen that someone may refuse to install it in its apartment. In future studies, it is intention of the authors to optimize also the capacity of the batteries in the distributed configuration, and so to consider a variable range of PV battery sizes, as already done for the centralized configuration.

Moreover, it is undoubtful that in certain situation the realization of underfloor heating systems in multistorey apartment buildings may be unfeasible, especially due to the cost and to the invasiveness of the intervention compared to other solutions. However, it is not impossible to realize underfloor heating systems in existing buildings and, mainly, their implementation could not be neglected, because it is really effective from the energy perspective, even if it is not the easiest and the most common one. The implications on the energy efficiency are explained by considering the lower temperature of feeding hot water of the underfloor systems compared to the ones of the fan-coils and of the baseboards, which allows the generation subsystem to work in conditions that are closer to the ones of maximum efficiency, with consequent higher benefits on the energy performance.

Table 6.7. Characteristics of the examined EEMs

Envelope		
Energy Efficiency Measure	*Characteristics*	*Investment Cost*
Insulation of the external walls	Insulation layer: conductivity of 0.030 W/mK, thickness of 0.07 m	50.1 €/m^2
Insulation of the roofs	Insulation layer: conductivity of 0.030 W/mK, thickness of 0.08 m	30.1 €/m^2
Replacement of existing windows	Double-glazed windows with argon-filling, low-emitting coating and PVC frames. U=1.49 W/m^{2}K, SHGC=0.56	280 €/m^2
Primary Energy Systems (HVAC + PV)		
Energy Efficiency Measure	*Characteristics*	*Investment Cost*
Installation of PV panels facing South and inclined at 30° to the horizontal level	Polycrystalline PV panels. Efficiency equal to 16%. Nominal peak power equal to 270 Wp. Dimensions: 1.67 m x 1.00 m	377.5 €/panel (1400 €/kWp)
	Mid-level monocrystalline PV panels. Efficiency equal to 19%. Nominal peak power equal to 325 Wp. Dimensions: 1.69 m x 1.02 m	520 €/panel (1600 €/kWp)
	High-level monocrystalline PV panels. Efficiency equal to 23%. Nominal peak power equal to 400 Wp. Dimensions: 1.69 m x 1.05 m	760 €/panel (1900 €/kWp)
Implementation of PV energy production sharing	Creation of a local energy community that maximizes the self-consumption of the energy produced by means of PV systems	/
Installation of PV batteries	Distributed energy storages: 3.3 kWh capacity	4070 €
	Distributed energy storages: 6.5 kWh capacity	5370 €
	Centralized energy storage: capacity variable from 54 kWh to 216 kWh (groups of 4 batteries, each one with a 13.5 kWh capacity)	(1500+6900·capacity/13.5)·1.1 €
Replacement of the heating generation subsystems	Natural gas-fired condensing water boilers. η=1.05 at LHV	1380 €/unit
	Reversible air-source electric heat pumps*. COPh=4.5, COPc=4.0	23 €/m^2
Replacement of the heating emitting terminals	Water-based fan-coils. Temperature of feeding hot water of 55 °C	35 €/m^2
	Radiant underfloor heating. Temperature of feeding hot water of 35 °C	115 €/m^2

** Note that when "Reversible air-source electric heat pumps" are installed, the cooling generation subsystem too is replaced.*

All told, for each of the examined scenarios – neighborhood as built and seven retrofit scenarios considering EEMs on the envelope – an exhaustive search for what concerns the EEMs affecting the primary energy systems is conducted, excluding only measures on the HVAC systems that are known to be energy ineffective and that may present operative issues – *i.e.*, the combination of heat pumps with traditional baseboards. Obviously, it is neglected also the possibility to install PV energy storages in absence of PV panels, because it does not provide any benefit from the energy perspective – considering differentiated electricity prices during the day, it may produce benefits from the financial point of view, but in this case study the electricity price is not variable during the day. All the other combinations are investigated with the aim to conduct a comprehensive analysis of all the EEMs that can minimize the PEC and the GC by optimizing the solar energy exploitation.

As previously specified, the objective functions are the PEC and GC in order to simultaneously satisfy both the public and the private perspective. However, to have a complete overview of the implications of all the adopted EEMs, further performance indicators are assessed, such as the thermal energy demand for space heating (TEDh) and for space cooling (TEDc), the simple payback (SPB) and the discounted payback (DPB) periods as well as the emissions of CO_2-eq. Table 6.8 indicates the main factors for the assessment of the PEC, the GC and the CO_2-eq. Note that all the objective functions and the performance indicators are assessed as previously indicated in Chapter 5, with the exception of the GC. In fact, here it is present the term relative to the public grant. However, as done for Section 6.2.2, the equations are reported again in order to make the section easier to be read.

Table 6.8. Main factors for the evaluation of the performance indicators

ENERGY PRICES			
Electricity price	0.23 €/kWh	Gas price	0.90 €/m^3
Electricity selling price	0.07 €/kWh		
CONVERSION FACTORS			
Electricity-to-primary energy conversion factor	1.95	Gas-to-primary energy conversion factor	1.05
EMISSION FACTORS			
Electricity CO_2 emission factor	0.708 kg CO_2/kWh [131]	Gas CO_2 emission factor	0.237 kg CO_2/kWh [131]

All told, the PEC is assessed according to the following equation 6.1:

$$\mathrm{PEC} = \mathrm{E_g} * \mathrm{fp_g} + \mathrm{E_e} * \mathrm{fp_e} \tag{6.1}$$

where:

- "E_g" is the yearly energy consumption due to gas;
- "fp_g" is the gas-to-primary energy conversion factor.
- "E_e" is the yearly energy consumption due to electricity purchased from the grid;
- "fp_e" is the electrical-to-primary energy conversion factor.

For what concerns the GC, it is evaluated according to the EU Guidelines [15]. The assessment period τ is supposed to be equal to 20 years instead of 30 years to properly take into account the presence of both commercial/office and residential units. In addition, around 20 years is the useful lifespan of modern PV panels and batteries. Finally, note that in presence of public grants for PV, the electricity that is not self-consumed is not sold to the grid, but it is fed into the grid for free. All told, the GC is assessed as follows:

$$\mathrm{GC}(\tau) = \mathrm{IC} + \sum_{j}\left[\sum_{i}^{\tau}(\mathrm{RC}(i) * \mathrm{R_d}(i) - \mathrm{V_{f,\tau}}(j)\right] - \mathrm{IN} \tag{6.2}$$

where:

- "IC" is the initial Investment Cost required for the application of the EEMs;

- “RC is the Running Cost per year. This share is actualized for each year of the assessment period thanks to “R_d”;
- “R_d” is the actualization factor. In this case the discount factor d is equal to 3%;
- “$V_{f,\tau}$” is the residual value at the end of the assessment period. It is supposed to be null in order to not overestimate the cost-effectiveness of certain EEMs combinations;
- “IN” stands for the incentives. This term is not present in the expression indicated in the EU Guidelines, but it is fundamental to be considered in order to achieve reliable results. Concerning the incentives, two different analysis are performed: in the first one, any possible public grant policy is ignored; in the other one, on the contrary, the most recent Italian 110% public grant policy [157] is taken into account.

Concerning the SPB and the DPB, they are evaluated according to equations 6.3 and 6.4, respectively:

$$\mathrm{SPB} = \frac{\mathrm{IC} - \mathrm{IN}}{\Delta \mathrm{RC}} \tag{6.3}$$

$$\mathrm{DPB} = -\frac{\log(1 - \mathrm{SPB} \cdot \mathrm{d})}{\log(1 + \mathrm{d})} \tag{6.4}$$

Finally, the CO_2-eq emissions are evaluated according to equation 6.5:

$$CO_2\text{-eq} = E_g * fc_g + E_e * fc_e \tag{6.5}$$

where:

- fc_g is the CO_2-eq emission factor for the gas;
- fc_e is the CO_2-eq emission factor for the electricity.

It is important to clarify that an integrated environmental analysis is not performed, being different the aims of this work. The environmental impact of the neighborhood is assessed by evaluating the equivalent emissions of CO_2 due to the energy consumptions by means of conversions factors reported in table 6.8. It is undoubtful that this approach may be trivial compared to more advanced techniques, such as the evaluation of the carbon footprint or the lifecycle assessment (LCA), but this work is mainly focused on the energy and the financial implications of the energy retrofit of a neighborhood. Indeed, the objective functions to minimize are the primary energy consumption and the global cost, whilst the equivalent emissions of CO_2 are evaluated in order to give a complete – but preliminary – overview on the effects of such energy retrofit. Being conscious that this approach may give only limited information on the real environmental impact of an investigated neighborhood and considering the uprising importance that is assuming the LCA towards a nearly/net zero energy buildings future, further analysis may be required aiming at attaining more detailed results from the environmental perspective. Therefore, it would be interesting in future works to focus on the development of an LCA approach to couple with the proposed technique, aiming at achieving more detailed results also from the environmental point of view.

6.3.3. Public grant policy

One of the main aims of this study consists in the optimization of the solar energy exploitation in order to reduce the PEC and the GC, assuring a good satisfaction level of the public perspective and of the private one. At this purpose, it is crucial that Governments adopt proper public grant policies, with the aim to promote energy efficiency and sustainability of the building sector. Italian Government has recently (*i.e.*, second half of 2020) adopted a massive public grant policy, which is investigated in this work. Aiming at outlining the importance of the public grant policies, the same analysis is conducted on the investigated neighborhood considering two cases:

a. no public grants;
b. Italian “Superbonus 110%” public grant policy [157] applied.

In this regard, in [157], EEMs are distinguished into two types:

- “Driving measures”: These EEMs consist in the insulation of the envelope for at least 25% of the gross envelope area or in the replacement of the centralized HVAC system with a more efficient one;
- “Driven measures”: These EEMs consist in the replacement of the existing windows, in the installation of a PV system, in the replacement of an autonomous HVAC system, in the implementation of building automation and control systems, in the insulation of an area of the envelope lower than 25% of the gross envelope area.

Driving measures are incentivized for 110% of the IC required for their realization, which means that the Government pays 10% more than the effective expense – within a maximum expense limit, depending on the EEM and on the number of residential units of the building. In addition, driving measures permit to obtain the same 110% public grant also to driven ones, but only if the latter are realized simultaneously to the former.

On the other hand, driven measures are incentivized less and the incentives depend on the measure, but if they are coupled with driving measures, they are incentivized for 110% too, as specified above.

All incentives are accorded in five years in terms of taxes reduction. Condition to accede to the "Superbonus" is the improvement of the building of at least two energy classes of the energy label or the achievement of the best class.

In table 6.9, the public grant percentages for each of the EEMs investigated in this study are reported in detail, as well as the relative expense limit: the amount overpassing this limit is not incentivized. Please, note that this public grant policy is valid only for residential units, while for commercial or office units only measures on the common parts of the buildings are allowed – the envelope is a common part as well as the centralized HVAC system. On the other hand, commercial and office units are allowed to use a different public grant policy, namely the "Conto Termico" [158]. However, this second program operates according to a very different way, thus in this work generic incentives are supposed to be applied to commercial units and to offices for what concerns the EEMs not affecting the common parts of the buildings.

Table 6.9. *Schema of the Italian public grant policy*

Italian Public grant Policy		
Energy Efficiency Measure	*Public grant Percentage**	*Investment Cost Limit*
Insulation of the external walls	110%	30 k€ for building unit**
Insulation of the roof	65%***	96 k€ for building unit
Replacement of the existing windows	50% (0% for commercial or office units)	54.5 k€ for building unit
Replacement of the centralized HVAC system	110%	20 k€ for building unit**
Replacement of an autonomous HVAC system	50% - 65%	30 k€ for building unit
Installation of PV panels	50% (0% for commercial or office units)	48 k€ for building unit (in total)
Installation of PV batteries	50% (0% for commercial or office units)	

** The indicated public grant percentages are for stand-alone measures.*

*** These investment cost limits are referred to the number of units of the investigated buildings. They vary according to the number of building units.*

**** The insulation of the roof may be a driving measure too, if the roof area is higher than 25% of the dispersant gross surface area of the building. In this case, the public grant percentage is equal to 110% and the investment cost limit is 30 k€ for building unit.*

Note that 30k€ per unit is the maximum investment cost limit comprehensive of all the EEMs applied to the opaque envelope, and so it takes into account also the insulation of the roof in presence of another driving measure. On the other hand, 96 k€ per unit is the maximum investment cost limit for stand-alone measures on the opaque envelope, without any driving measure.

6.3.4. Results and discussion

According to the methodology described in Section 6.2, two different analyses are performed:

- no public grant policy;
- Italian “Superbonus 110%” public grant policy.

For both the analyses, the same energy efficiency measures (EEMs) are investigated and the results are then compared. Firstly, EEMs are supposed to be applied on the envelope, and so eight scenarios are individuated: neighborhood as built (with no EEMs on the envelope) and seven retrofit scenarios. Consequently, an exhaustive search among several different EEMs on the primary generation systems – *i.e.*, heating, ventilating and air conditioning (HVAC) systems and photovoltaic (PV) systems – is performed. Finally, the decision-making process occurs and three suboptimal solutions are selected, in order to minimize the primary energy consumption (PEC) and the global cost (GC) on a 20 years period.

Neighborhood as built

The results in terms of PEC, GC and all other considered performance indicators for the neighborhood as built are the same as in [146, 152] and are indicated in table 6.10. The thermal energy demand for space heating (TEDh) varies between 17.9 kWh/m^{2}a for building 4 and 21.0 for building 1. The minimum values for buildings 3 (18.4 kWh/m^{2}a) and 4 can be explained by considering higher values of solar irradiation, due to the marginal shadowing effect produced by neighboring buildings, differently from buildings 1 and 2: so, free gains are achieved. As predictable, because of analogous reasons, buildings 3 and 4 present the highest values of thermal energy demand for space cooling (TEDc), which are respectively 29.2 kWh/m^{2}a and 28.5 kWh/m^{2}a, while, on the other hand, the TEDc for buildings 1 and 2 is respectively 26.2 kWh/m^{2}a and 28.3 kWh/m^{2}a. Moreover, for what concerns the PEC, the latter is included between 115.1 kWh/m^{2}a for buildings 3 and 4 and 119.4 kWh/m^{2}a for building 1.

Considering the financial aspect, interesting is to note that the running cost (RC) is almost the same for each building, varying from 12.2 €/m^{2}a for building 3 to 12.6 for building 1, which is characterized also by the highest value of PEC. To make it clearer, if one considers a building unit of around 100 m^2, the annual bills for energy services may range from about 1220 € to about 1260 €, which are common values for the city of Naples. In terms of GC, the highest value is for building 1 and it is 187.9 €/m^2, while the lowest value is for building 3 and it is 182.0 €/m^2. In conclusion, the equivalent emissions of greenhouse gases (CO_2-eq) is quite similar for each building and, in detail, it is included between 35.1 kg/m^{2}a for building 2 and 36.1 kg/m^{2}a for building 1.

Table 6.10. Neighborhood as built: objective functions and other performance indicators

	Neighborhood as built				
	Building 1	Building 2	Building 3	Building 4	**District**
TEDh [kWh/m^{2}a]	21.0	19.5	18.4	17.9	**19.4**
TEDc [kWh/m^{2}a]	26.2	28.3	29.2	28.5	**27.9**
PEC [kWh/m^{2}a]	119.4	116.6	115.1	115.1	**116.8**
RC [€/m^{2}a]	12.6	12.4	12.2	12.3	**12.4**
GC [€/m^2]	187.9	183.9	182.0	182.3	**184.4**
CO_2-eq [kg/m^{2}a]	36.1	35.4	35.1	35.2	**35.5**

At the neighborhood level, the results are quite the same, as predictable. Indeed, they are obtained by means of weighted sums from the individual results for each building. More in detail, the TEDh is equal to 19.4 kWh/m^{2}a, while the TEDc is 27.9 kWh/m^{2}a. The PEC is 116.8 kWh/m^{2}a. From the financial point of view, the RC is 12.4 €/m^{2}a, while the GC is 184.4 €/m^2. Finally, the CO_2-eq emissions are 35.5 kg/m^{2}a.

In figure 6.3, the monthly cumulative values of PEC for the neighborhood as built are depicted. The lowest values are assessed for intermediate temperature months, such as April and October. During these months, the HVAC systems are supposed to be turned off, according to Italian law for Naples and common practice concerning the activation of cooling, and so the energy consumption due to space conditioning is null. The situation is nearly the same for the month of May, even if by the half of May the HVAC systems are turned on to satisfy the cooling demand. The highest values of PEC are evaluated for the months of January and December, followed by July and August, during which the HVAC systems have to satisfy important space conditioning demands. Sensibly high values of PEC are attained also for the last months of the heating season – *i.e.*, February and March –, even if the thermal demands are lower compared to the previous months. It should be noted that, even if the cooling demand is higher than the heating one, as indicated in table 6.10 the PEC is higher during colder months. This happens because of the lower efficiency of the heating systems in the neighborhood as built compared to the cooling systems, which are characterized by a more efficient energy conversion process.

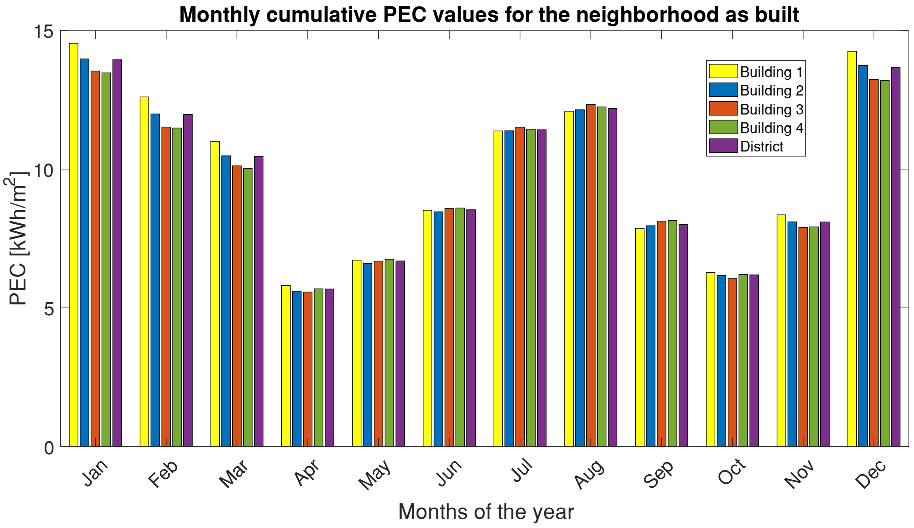

Figure 6.3. Monthly cumulative PEC values at neighborhood level (as built configuration). Values are the results of a weighted sum among the results for each building

No public grant policy

Once the neighborhood has been modeled, the optimization process of its energy retrofit is performed, aiming at minimizing the PEC and the GC. Seven different combinations of EEMs on the envelope are investigated and, for all of them as well as for the neighborhood as built, an exhaustive search among all the individuated EEMs for the primary energy systems – *i.e.*, HVAC systems and PV systems – is performed, as specified in the previous Section 6.2.3. For what concerns the PV systems, both the absence and the implementation of PV energy production sharing, by means of the creation of a local energy "community" (in this case, a small one), are investigated. Results at neighborhood level are shown in figure 6.4.

As predictable, the baseline neighborhood is characterized by the highest value of PEC. However, due to the absence of incentives, the GC of the neighborhood as built results to be lower compared to most of the investigated solutions. Attention to investment and global costs is investigated in many studies, for instance also by Ascione at al. [159] at the micro-district level in an Italian backcountry city, Kaklauskas *et al.* [160] with retrofit of buildings in the cold climate of Lithuania, Erhorn-Kluttig *et al.* [161] by taking into account many countries, specifically for what concerns the economic feasibility of nearly zero-energy buildings.

Among the non-dominated solutions collected in the Pareto front, the nZEB solution, the cost-optimal solution and the utopia solution are selected, according to methodology described in Section 6.2, and the relative combinations of EEMs are reported in detail in table 6.11. All the EEMs are intended to be applied simultaneously to all the buildings of the neighborhood.

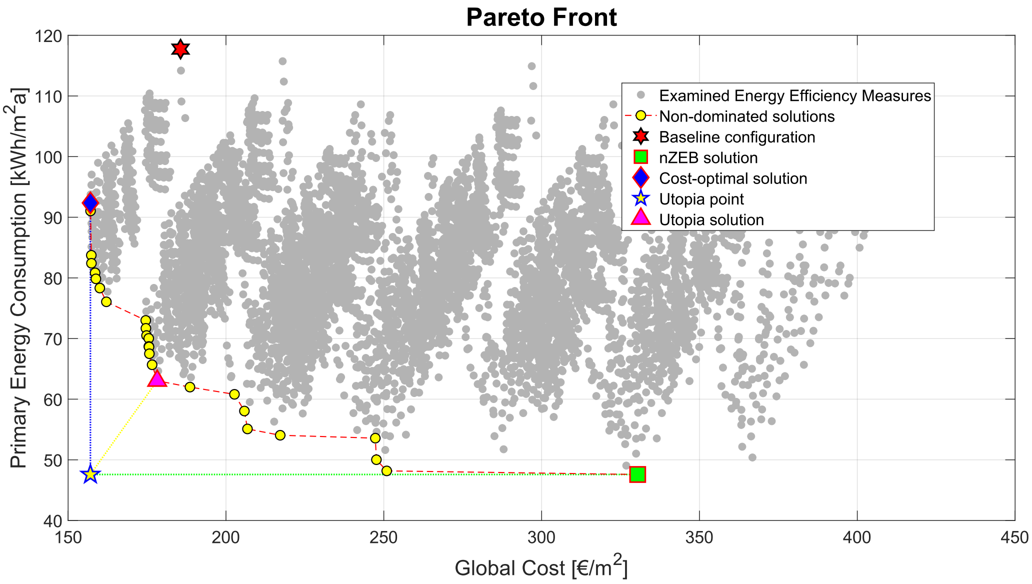

Figure 6.4. Investigated EEMs and Pareto Front in absence of public grants. Results are referred to the neighborhood level

Table 11. Combinations of EEMs for the selected suboptimal solutions in absence of any public grant policy

Suboptimal EEMs Combinations							
Suboptimal Solution	*Retrofit Scenario*	*PV Sharing*	*Type of PV Panels*	*Percentage of useful roof area for PV*	*Size of PV Batteries*	*Type of HVAC Generation Subsystem (Heating)*	*Type of HVAC Emitting Terminals (Heating)*
nZEB solution	*8*	*No*	*High-level monocrystalline PV panels*	*100%*	*6.5 kWh (single unit)*	*Reversible air-source electric heat pumps*	*Radiant underfloor heating*
Cost-optimal solution	*1 (as built)*	*Yes*	*Polycrystalline PV panels*	*100%*	*162 kWh (neighborhood)*	*Natural gas-fired water boilers (as built)*	*Baseboards (as built)*
Utopia Solution	*8*	*Yes*	*High-level monocrystalline PV panels*	*100%*	*216 kWh (neighborhood)*	*Natural gas-fired water boilers (as built)*	*Baseboards (as built)*

For what concerns the EEMs on the envelope, both the nZEB and the utopia solutions need the insulation of the roofs with a 0.08 m thick insulating layer and the replacement of the existing windows with double-glazed ones, with argon-filling, low-emitting coating and PVC frames. On the other hand, for the cost-optimal solution, no EEMs on the envelope are needed.

Concerning the EEMs on the primary energy systems, as for the nZEB solution, the PV sharing should not be implemented, even if high-level monocrystalline PV panels should cover the entire useful roof area of each building. In addition, PV batteries should be installed in every building unit of the neighborhood – with the exclusion of the common circulation areas – and should have a size equal to 6.5 kWh. The latter is the highest investigated size for the distributed energy storage configuration, which is the one adopted in absence of PV sharing. For what concerns the HVAC systems, reversible air-source electric heat pumps should be installed everywhere, replacing the existing natural gas-fired water boilers and the low-efficiency air-to-air heat pumps. Baseboards should be replaced with radiant underfloor heating systems. Being the most energy-efficient, it is reasonable that the implementation of the radiant floors result the intervention provided in this solution, even if it is not cost-efficient at all without any public grant.

For what concerns the cost-optimal solution, no EEMs are applied to HVAC systems, while the PV is maximized. In detail, PV sharing should be implemented and polycrystalline PV panels should be installed on 100% of the useful roof area of each building. In addition, PV energy production storages should have a size at neighborhood level equal to 162 kWh – note that when PV sharing is implemented, PV batteries have a centralized configuration and are in common for all the buildings of the neighborhood.

Finally, also the utopia solution does not require any EEMs on the HVAC systems. Regarding the PV systems, the creation of a local energy community that shares the PV production and storage is needed. In detail, high-level monocrystalline panels should cover once again the entire useful roof areas of each building, and the global size of PV batteries should be 216 kWh, which is the highest investigated size.

Notably, without any public grant, the EEMs that have the highest impact on the PEC and on the GC are the ones that provide the installation of extended PV systems. Detailed results of the aforementioned suboptimal solutions in terms of the objective functions and all the other performance indicators are presented in table 6.12 at neighborhood level. Results are provided at neighborhood level because at building level they are affected by the presence or the absence of the implementation of PV sharing, and so they could be incomparable. Indeed, the implementation of PV sharing requires several fundamental assumptions on how the expenses are distributed among the owners of the units situated in the buildings constituting the local energy consumption, assumptions that overcome the aims of this study. As specified, these latter are the minimization of the PEC and of the GC by optimizing the solar energy exploitation, and so not the implementation of the most efficient operational framework for the creation of a local energy community. However, as future development, it may be interesting the coupling between the methodology here adopted with different operational framework for the implementation of PV sharing.

Table 6.12. Objective functions and main performance indicators at neighborhood level for suboptimal solutions in absence of any public grant policy

	No Public Grant Policy		
	nZEB solution	Cost-optimal solution	Utopia solution
*dTEDh [kWh/m^{2}a]	17.2	0.0	17.0
dTEDc [kWh/m^{2}a]	-6.2	0.0	-6.2
dPEC [kWh/m^{2}a]	69.2	24.5	53.8
dRC [€/m^{2}a]	7.8	3.2	6.1
dGC [€/m^2]	-146.0	27.4	6.2
SPB [years]	> 20	6.4	13.9
DPB [years]	> 20	7.2	18.2
dCO$_2$-eq [kg/m^{2}a]	21.7	9.0	16.2

* "d" stands for "difference". It is the difference between the suboptimal solution and the neighborhood as built. Positive values indicate a reduction, while negative ones an increment.

For what concerns the nZEB solution, important effects are produced in terms of TEDh and TEDc. In detail, due to the presence of an insulation layer on the roofs, to the replacement of the single-pane windows with double glazed-ones and to the replacement of the emitting terminals for the HVAC systems, the TEDh is reduced by 17.2 kWh/m^{2}a. On the other hand, unfortunately, due to the same insulation layer and the same double-glazed windows, the TEDc is increased by 6.2 kWh/m^{2}a. This is the effect of the indoor overheating that can happen when a strong insulation is applied to the building envelope for improving the winter energy performance [162] and, to mitigate it, cool coatings [163], thermochromic paints [164], solar shadings and night ventilation [165], also hybrid [166] and/or by smart-adaptive windows [167], can be applied to improve a number of passive cooling phenomena, and thus the building coatings' albedo, reflection of solar radiation on windows, discharging of the heated mass during by convection and during the night [168]. Considering the effects of the lights, the electric facilities in general and of the HVAC generation subsystems – *i.e.*, reversible air-source electric heat pumps –, the PEC is assessed and its decrement is equal to 69.2 kWh/m^{2}a, which is the highest PEC reduction among the suboptimal solutions individuated. From a financial point of view, the RC is sensibly decreased and the reduction is equal to 7.8 €/m^{2}a. Unfortunately, due to the absence of any public grant policy, the GC is much higher than the neighborhood as built because of the important IC required. In detail, the GC is incremented by 146 €/m^2. In terms of SPB and DPB, both are longer than the assessment period, for the same reasons that produce the increment of the GC. Finally, in terms of environmental impact, the CO_2-eq is reduced by 21.7 kg/m^{2}a.

Concerning the cost-optimal solution, no effects are produced on the TEDh and TEDc, because EEMs concerning envelope or HVAC systems are not applied. Indeed, this solution provides only the EEMs involving the PV systems. In terms of PEC, a sensible reduction is obtained and this is equal to 24.5 kWh/m^{2}a. From the financial perspective, the reduction of the RC is equal to 3.2 €/m^{2}a, while the GC is reduced by 27.4 €/m^2. The SPB and the DPB are 6.4 and 7.2 years, respectively. In conclusion, the CO_2-eq emissions are reduced by 9.0 kg/ m^{2}a.

For what concerns the utopia solution, due to the insulation of the roofs and to the replacement of the windows, the TEDh is reduced by 17.0 kWh/m^{2}a, while, on the contrary, the TEDc rises by 6.2 kWh/m^{2}a. If the PEC is considered, the latter is decremented by 53.8 kWh/m^{2}a. Considering the financial point of view, the RC is reduced by 6.1 €/m^{2}a, while the GC has a reduction equal to 6.2 €/m^2. The slight and unexpected difference between the RC and the GC is explained by considering the important IC required to implement the EEMs involved in this solution and the absence of any public grant. The SPB and the DPB are quite long, even if shorter than the assessment period. In detail, they are 13.9 and 18.2 years, respectively. Finally, looking at the environmental impact, the CO_2-eq emissions are cut down by 16.2 kg/m^{2}a.

Globally, the nZEB and the utopia solutions produce nearly the same effects in terms of TEDh and TEDc, being characterized by the same interventions on the envelopes. Indeed, even if the emitting terminals are different, in presence of an insulated envelope, it is supposed that thermostatic valves for baseboards are installed, and so the effects of the presence of baseboards for utopia solution are partially compensated. On the other hand, for what concerns the cost-optimal solution, no variations occur in terms of TEDh and TEDc, not implementing any EEM on the envelope or on the HVAC systems. In terms of PEC, as predictable, the nZEB solution provides the highest reduction, which is equal to 69.2 kWh/m^{2}a, but a sensible reduction is obtained also for the utopia solution, where the PEC decreases by 53.8 kWh/m^{2}a. Finally, for the cost-optimal solution, the PEC reduction is much lower, and it is equal to 24.5 kWh/m^{2}a. From the financial perspective, the situation is completely different: even if the nZEB solution provides the highest reduction of the RC, this solution is characterized also by the highest GC because of the sensibly high IC required, especially for the implementation of the radiant underfloor emitting terminals, and the SPB and the DPB are much longer than the assessment period. Therefore, the nZEB solution for this case is not cost-effective at all. On the other hand, the cost-optimal solution, as predictable, produces the most important reduction in terms of GC, even if the RC reduction is the lowest compared to the two other suboptimal selected solutions. The reason is analogous to the one for the nZEB solution but opposite, which means that this is due to the lowest IC required to implement the proposed EEMs. The cost-optimal solution is obviously characterized also by the lowest values of SPB and DPB. For what concerns the utopia solution, it is the best tradeoff between energy efficiency and cost-optimality, guaranteeing both an important PEC reduction and a slight GC reduction, with acceptable SPB and DPB periods – acceptable because they are shorter than the assessment period. Finally, from the environmental perspective, the nZEB solution provides the highest reduction of CO_2-eq emissions, while the cost-optimal one yields the lowest reduction and the utopia one, once again, can be collocated in an intermediate position.

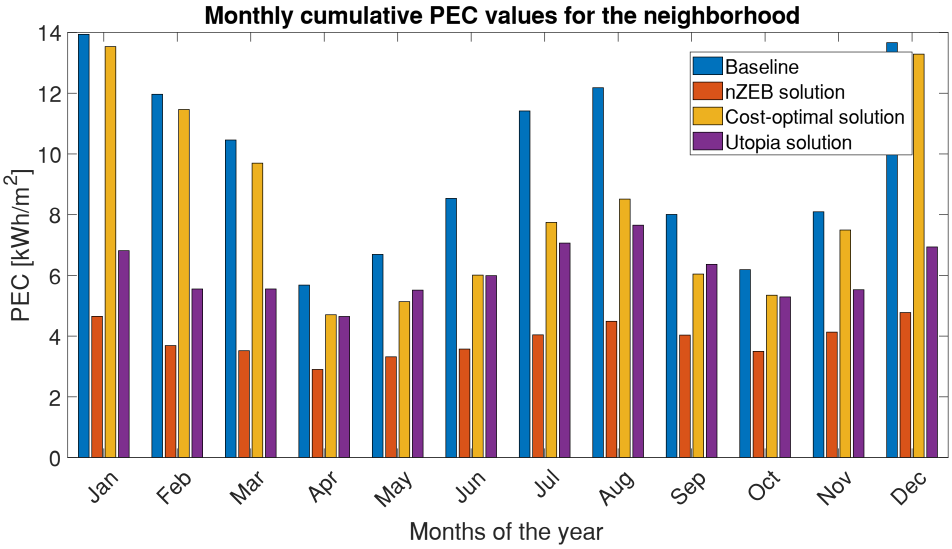

Figure 6.5. Comparison in terms of monthly cumulative PEC values for the neighborhood as built and the suboptimal solutions individuated in absence of public grant

In figure 6.5, a comparison is performed between the monthly cumulative values of PEC for the neighborhood as built and the three suboptimal solutions individuated. All suboptimal solutions show sensible reductions of PEC during every month of the year compared to the baseline situation. As predictable, the PEC values for the nZEB solution are the lowest, due to the combinations of the EEMs on both the envelope and the HVAC systems. For what concerns the cost-optimal solution, it presents slight reductions of PEC compared to the baseline configuration during colder months, while these reductions are particularly evident during the summer season, when the values of solar radiation are higher, and so the effects of the presence of PV systems are most tangible. Looking at the utopia solution, it provides quite stable low values of PEC during the whole year, due to the combination of both the EEMs on the envelope and the PV systems.

The implementation of PV systems on its own permits to achieve important results in terms of reduction of the PEC, especially during warmer months, and results even cost-effective without any public grant.

Italian “Superbonus 110%” public grant policy

The same analysis is performed also in presence of public grants. More in detail, the Italian “Superbonus 110%” policy described in Section 6.3.3 is applied, and figure 6.6 shows the optimization results at neighborhood level.

In presence of grant, the financial benefits are much more significant. In figure 6.6, it is possible to note a huge shift of the results of the investigated solutions towards cost-effectiveness, which is expressed by a general reduction of the GC values assessed. As a demonstration, in this case the neighborhood as built is in the top right part of figure 6.6, which means that its GC is higher compared to most of the examined EEMs’ combinations, while in figure 6.4 – *i.e.*, the homologous figure of the analysis without any public grant – it is in the top left part. In addition, another effect of the public grant policy applied consists in the reduced extension of the Pareto front, and solutions here collected are all characterized by lower values of GC compared to the GC value of the baseline neighborhood.

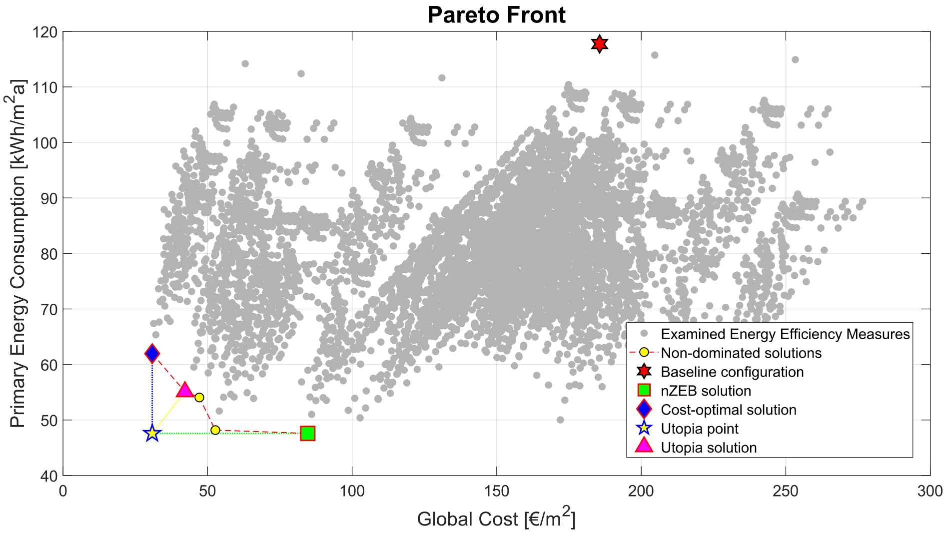

Figure 6.6. Investigated EEMs and Pareto Front in presence of public grant. Results are referred to the neighborhood level

As predictable, the nZEB solution does not vary, because it is the one that minimizes the most the PEC in the entire domain of the investigated solutions. However, the financial results for the nZEB solution are completely different in presence of public grant. All told, the suboptimal solutions individuated are detailed in table 6.13.

Concerning the EEMs on the envelope, both nZEB and utopia solutions provide insulation of the roofs with a 0.08 m thick layer, and the replacement of the existing windows. On the other hand, with reference to the cost-optimal solution, only the insulation of the roofs is necessary, with no more measures on the envelope.

For what concerns the EEMs on the primary systems, a distinction between the nZEB, the cost-optimal and the utopia solution occurs only in terms of measures concerning the HVAC systems. Indeed, the interventions affecting the PV systems are the same for all the three solutions. In detail, for all the suboptimal solutions individuated, PV sharing should not be implemented and high-level monocrystalline PV panels should entirely cover the useful area of the roof of each building. Moreover, 6.5 kWh PV batteries should be installed in all the apartments, commercial units and offices.

Concerning the EEMs on the HVAC systems, for both the nZEB solution and the cost-optimal one reversible air-source electric heat pumps should replace the existing heating and cooling generation systems. However, the main difference among these two solutions consists into the different HVAC emitting terminals for heating. In fact, baseboards should be replaced with radiant underfloor emitting terminals for the nZEB solution, while for the cost-optimal one with water-based fan-coils. Once again it is outlined how the radiant underfloor terminals are the most energy-efficient, but not the most cost-effective, even in presence of public grant. Finally, for the utopia solution, no EEMs should be implemented on the HVAC systems.

Table 6.13. Combinations of EEMs for the selected suboptimal solutions with public grant

Suboptimal EEMs Combinations							
Suboptimal Solution	*Retrofit Scenario*	*PV Sharing*	*Type of PV Panels*	*Percentage of useful roof area for PV*	*Size of PV Batteries*	*Type of HVAC Generation Subsystem (Heating)*	*Type of HVAC Emitting Terminals (Heating)*
nZEB solution	*8*	*No*	*High-level monocrystalline PV panels*	*100%*	*6.5 kWh (single unit)*	*Reversible air-source electric heat pumps*	*Radiant underfloor heating*
Cost-optimal solution	*3*	*No*	*High-level monocrystalline PV panels*	*100%*	*6.5 kWh (single unit)*	*Reversible air-source electric heat pumps*	*Water-based fan-coils*
Utopia Solution	*8*	*No*	*High-level monocrystalline PV panels*	*100%*	*6.5 kWh (single unit)*	*Natural gas-fired water boilers (as built)*	*Baseboards (as built)*

Globally, also in presence of public grant, the EEMs most affecting the PEC and the GC are the ones involving the PV systems: with reference to all three selected suboptimal solutions, the installation of high-level monocrystalline PV panels on the entire useful area of the roofs combined with the implementation of a distributed system of PV energy storages, each one with a capacity equal 6.5 kWh, results essential. It may be stated that, even in presence of public grant, all the other EEMs have only "marginal" effects compared to the ones involving the PV systems. Therefore, aiming at reducing the PEC and the GC, it is crucial to maximize the solar energy exploitation, as just seen. All told, detailed results of the suboptimal solutions in terms of the objective functions and all the other performance indicators are presented in table 6.14, at neighborhood level.

Table 6.14. Objective functions and main performance indicators at neighborhood level for suboptimal solutions in presence of the Italian "Superbonus 110%" public grant policy

	With Public Grant Policy		
	nZEB solution	Cost-optimal solution	Utopia solution
*dTEDh [kWh/m^{2}a]	17.2	2.5	17.0
dTEDc [kWh/m^{2}a]	-6.2	1.4	-6.2
dPEC [kWh/m^{2}a]	69.2	54.9	61.7
dRC [€/m^{2}a]	7.8	6.7	6.6
dGC [€/m^2]	99.8	153.6	142.3
SPB [years]	1.6	<1	<1
DPB [years]	1.6	<1	<1
dCO$_2$-eq [kg/m^{2}a]	21.7	19.4	19.1

* "d" stands for "difference". It is the difference between the suboptimal solution and the neighborhood as built. Positive values indicate a reduction, while negative ones an increment.

For the nZEB solution, the only difference in outcomes compared to the homologous solution of the analysis without public grant concerns the financial benefits, and so the other results are not discussed again. More in detail, in presence of public grant, the GC passes from an increment of 146.0 €/m^2 (without public grant) to a decrement of 99.8 €/m^2 (with public grant), compared to the GC of the neighborhood as built. In terms of payback periods, the SPB and the DPB are both 1.6 years, which means that, in presence of the considered public grant policy, the nZEB solution is also extremely cost-efficient. For what concerns the cost-optimal solution, differently from the homologous solution in case of no public grant, it produces a slight reduction of the TEDh and of the TEDc compared to the neighborhood as built. This is the result of the EEMs on both the envelope and the HVAC systems. In terms of PEC, the latter is decreased by 54.9 kWh/m^{2}a. From the financial perspective, important results are achieved. Indeed, the RC is reduced by 6.7 €/m^{2}a and the GC by 153.6 €/m^2. The second is the highest possible reduction for the GC among all the examined solutions. For this solution also the SPB and the DPB are particularly convenient, resulting lower than 1 year. Finally, the CO_2-eq emissions are cut down by 19.4 kg/m^{2}a.

Concerning the utopia solution, the EEMs applied to the envelope are the same as for the homologous solution in case of absence of public grant. In addition, as for the previous analysis, also in this case no EEMs involve the HVAC systems. Therefore, the TEDh and TEDc are the same as in the homologous solution without public grant. However, for all the other performance indicators and objective functions, relevant differences are present in comparison with the homologous solution. In fact, the EEMs concerning the implementation of PV systems are different. In this case, PV sharing is not implemented, and so a distributed PV energy storage is realized. The PEC is decremented by 61.7 kWh/m^{2}a, the RC by 6.6 €/m^{2}a and the GC by 142.3 €/m^2 compared to the neighborhood as built. The SPB and the DPB are lower than 1 year, as for the cost-optimal solution. Finally, the CO_2-eq emissions are reduced by 19.1 kg/m^{2}a. In conclusion, the changes in terms of PV systems coupled with the presence of public grant boost the energy and the financial savings compared to the utopia solution referred to the absence of public grant, and, in addition, sustainability is incremented too.

In general, it can be seen that the nZEB and the utopia solutions produce the same effects in terms of TEDh and TEDc compared to the homologous solutions in case of no public grant. On the other hand, for what concerns the cost-optimal solution, the involved EEMs in presence of public grant affect also the TEDh and the TEDc, differently from the homologous solution without any public grant. Considering the PEC, the nZEB solution provides the highest decrease, but relevant reductions are assessed also for the utopia solution and for the cost-optimal one. In general, PEC reductions for the selected suboptimal solutions are higher compared to the homologous solutions without public grant, and this is particularly evident for the cost-optimal solution.

From the financial point of view, all the three suboptimal solutions provide huge benefits. In detail, the nZEB solution produces the highest RC reduction compared to the neighborhood as built, but sensible decrements are attained also with the cost-optimal and the utopia solutions. For what concerns the GC, here it is sensibly cut down for all the solutions thanks to the public grant. More in detail, the highest GC decrement is assessed for the cost-optimal solution, followed by the utopia solution and by the nZEB one. About the latter, it is important to outline that this reduction is made possible only by the presence of the public grant, indeed the nZEB solution is the same for both the analysis – *i.e.*, without and with public grant –, but without public grant the financial benefits are null due to the high investment required. The high decrements of GC permit to have really short payback periods for all the suboptimal solutions, of the order of the year. In conclusion, from the financial perspective, all the suboptimal solutions result cost-effective.

Finally, from the environmental point of view, all the suboptimal solutions provide important reductions of CO_2-eq emissions. In particular, the nZEB solution permits the highest reduction.

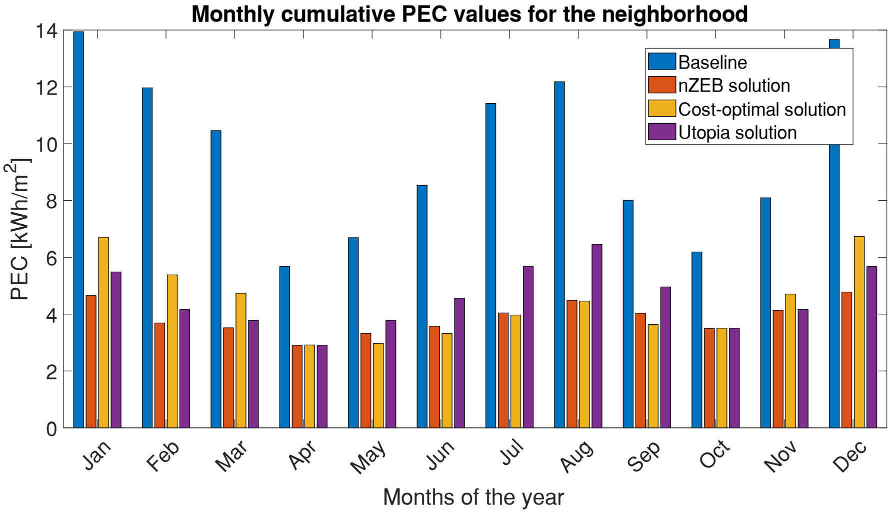

Figure 6.7. Comparison in terms of monthly cumulative PEC values for the neighborhood as built and the suboptimal solutions individuated in presence of public grant

In figure 6.7, a comparison is performed between the monthly cumulative values of PEC for the neighborhood as built and the three suboptimal solutions individuated in presence of public grant. All retrofit solutions present relevant reductions of PEC during every month of the year compared to the baseline situation. Once again, the PEC values for the nZEB solution are generally the lowest, with the exclusion of the hotter months. During these months, the cost-optimal solution is the one that presents the lowest values of PEC, because the replacement of the windows with ones that guarantee a lower air infiltration rate is partially counterproductive for the nZEB solution. Obviously, the aforementioned replacement becomes particularly energy effective during colder periods, in fact during the winter season the nZEB solution is characterized by the lowest values of PEC. The same observation is valid for the utopia solution as well, presenting the latter lower PEC values during the colder months and higher PEC values during the hotter months compared to the cost-optimal one. However, for the utopia solution, the absence of EEMs involving the HVAC systems is much more relevant on monthly PEC values. Finally, with reference to mid-temperature months such as April or October, all the suboptimal solutions provide the same monthly PEC values, which are affected only by the presence of PV systems – during these months the HVAC systems are supposed to be turned off. At this purpose, by observing the PEC reduction achieved during these months only by means of the implementation of proper PV systems – *i.e.*, intended as a whole collecting panel type, roof covering percentage, implementation or not of the PV sharing and the size of the PV batteries – it is possible to affirm that PV systems have a crucial role in reducing PEC even on them own. Thus, the optimization of the solar energy exploitation by means of the installation of proper PV systems is crucial aiming at reducing the impact of buildings on the environment, and so at promoting sustainability. All the other EEMs are important too, but their energy and environmental impact is lower compared to the one achieved by proper PV systems. In addition, other EEMs result hugely dependent from the public grant policies, while PV systems are cost-effective even without any public grant and this will be even more pronounced in next years, given the progressive decrease of costs of such technology. Therefore, PV systems would be convenient for the private perspective also in absence of public grant, because of their cost-efficiency. On the other hand, the public perspective, whose aim is to reduce the energy and the environmental impact of buildings, would pick a comprehensive combination of EEMs, considering also measures on both the envelope and the HVAC systems, in addition to the implementation of a proper PV system. The best tradeoff between energy efficiency and cost efficiency consists in applying EEMs only on the envelope and implementing the most adequate PV system, in presence or absence of public grant. Obviously, in presence of a public grant policy, EEMs on the HVAC should always be considered. Finally, aiming at coupling energy efficiency and cost efficiency, PV systems should always be installed, and their size should always be maximized. PV panels should be monocrystalline ones and should have high efficiency. For what concerns the PV sharing, it should be implemented only if public grant is absent. In fact, if PV systems are incentivized, it would be more energy-effective and cost-effective the installation of 6.5 kWh batteries in every home, commercial unit and office. This result is explained by considering that the actual Italian public grant policy does not provide any additional public grant for the implementation of local energy communities that share PV energy production. It would be interesting to verify if the same results concerning the financial inconvenience in presence of public grant are assessed by means of the coupling of the PV sharing with the rigorous model of a micro-grid, capable to maximize the financial gain from the allocation of the surplus of PV energy that is not self-consumed.

In conclusion, once again, the importance of the installation of PV systems is outlined. Indeed, with a proper PV system, both the public perspective and the private one can achieve a good satisfaction level, because both the energy and the financial performance are profoundly improved. Therefore, aiming at reducing the energy and environmental impact of the construction sector, Governments should adopt a public grant policy more focused on PV systems in spite of other EEMs. By exploiting a large-scale diffusion of high-efficiency PV systems, huge improvements in terms of sustainable impact of buildings could be achieved. In addition, an adequate public grant policy should be adopted, in order to promote the development of local energy communities. The latter is really energy and cost-effective only without considering the actual Italian public grant policy, which is more focused on other EEMs and, mainly, on the public grant of PV batteries instead of PV sharing, on whose potentialities should be invested more. Conversely, if public funding promotes different EEMs, it can happen that shared PV may have an inadequate attention, and this is a negative perspective.

Final remarks

The study faces the energy transition of small neighborhoods towards nearly Zero Energy Buildings (nZEBs) by optimizing the solar energy exploitation, with the aim to reduce the energy and the environmental impact of the building sector. A comprehensive analysis is performed, considering both the most common energy efficiency measures (EEMs) and innovative ones, with the scope to maximize the energy and the financial savings, and so to achieve a good satisfaction level for both the public perspective and the private one. In fact, the public hand aims at improving energy efficiency, while the latter aims at increasing the financial benefits, even if nowadays also the attention of private stakeholders towards sustainability is growing. The comprehensive analysis makes use of different software: CADMapper® and SketchUp® for modeling the geometry of the neighborhood; DesignBuilder® for realizing the first raw energy model; EnergyPlus to refine the energy model and to perform dynamic energy simulations; MATLAB® to post-process the results of the simulations. The comprehensive analysis is performed twice, considering both the absence of public grant and the presence of the Italian “Superbonus 110%” public grant policy.

As main result, the importance of the installation of PV systems is outlined, even in absence of public grant policy. Indeed, with a proper PV system, both the public perspective and the private one can achieve a good satisfaction level, because both the energy and the financial performance are profoundly improved.

However, the presented approach has two main limits, as most of the district energy modeling and retrofit approaches available in literature. Firstly, it does not consider the uncertainty in building energy demands due to the high stochasticity in occupant behavior. Secondly, it neglects the effects of global warming on building energy performance. For this purpose, in the next chapter it is proposed an approach that faces both the two aforementioned criticalities, considering the stochasticity in the human behavior and the effects of the global warming.

How to develop more accurate
district energy models and
to attain more robust results
for their energy retrofit planning?

CHAPTER 7. Effects of global warming on energy retrofit planning of neighborhoods under stochastic human behavior

7.1. Introduction

Most strategies/tools for the energy modeling and retrofit planning of the districts/neighborhood do not consider the stochasticity in the occupant behavior and neglect the effects of the global warming. Thus, results obtained by the common approaches may be unreliable and not applicable to reality or, if applicable, a significant discrepancy between the assessed performance indicators and the on-site measured ones can occur today and/or tomorrow (because of climate change) [19].

Therefore, this study aims at overcoming the two aforementioned critical issues. A novel approach is proposed to conduct proper analyses on the effects of ERMs on the main energy, financial and environmental performance indicators, when planning the energy retrofit of neighborhoods. It makes use of a dynamic energy simulator – *i.e.*, EnergyPlus – and a proper postprocessing engine – *i.e.*, MATLAB®. The year 2035 is considered as the reference year of the analysis because it is a mid-term time horizon, even if the proposed approach is still valid considering other time horizons. Different RCP scenarios are taken into account and compared to achieve robust results and insights about the effects of global warming on the retrofit solutions. The stochasticity in the human behavior is considered as well. As case study, an existing neighborhood in Naples (Italy) is investigated and an optimal combination of ERMs is proposed aiming at the minimization of primary energy consumption, running cost and CO2-eq emissions.

7.2. Methodology

7.2.1. Framework

The optimization of the energy retrofit measures (ERMs) to be applied to existing neighborhoods or districts is a highly difficult issue, which has to face crucial implications, such as energy, financial and environmental ones. Often, the main goals consist of reducing the primary energy consumption (PEC) and the polluting emissions with a view to the financial effects too. As seen, two opposite perspectives should always be considered:

- the public perspective, whose main goal is to reduce the environmental impact of the building stock, and so to lessen the PEC and to cut down the CO_2-eq emissions;
- the private perspective, whose main goal is to achieve the maximum financial profits, even if it is important to note that the attention of the collectivity towards sustainability is strongly increasing worldwide, thus sustainable solutions are often wished by this perspective too.

The proposed methodology may be used by both the aforementioned perspectives, ensuring a good tradeoff between them, since different performance indicators are addressed at the same time, satisfying both perspectives. The aim is proposing a comprehensive approach to investigate the mid-term effects of ERMs on the main energy, financial and environmental indicators when planning the energy retrofit of neighborhoods. Global warming and stochastic occupant behavior are taken into account to ensure reliable and realistic outcomes.

More in detail, the approach is organized in three consequent main phases (see figure 7.1):

1. realization of the energy model of the neighborhood;
2. assignment of stochastic schedules in order to better take into account the variability of the human behavior, and so to have results closer to reality;
3. individuation of the analysis conditions and scenarios, as well as of the performance indicators/ objective functions, and consequent planning of the ERMs to apply to the neighborhood.

Figure 7.1. Schematic workflow of the proposed approach

7.2.2. Development of the energy model of the neighborhood

Performing the most accurate geometrical representation of the buildings of the neighborhood is the first step for the development of an accurate energy model. All told, CADMapper® is a Geographical Information System (GIS) application that handles 2D satellite maps and converts them into "*.dxf*" or "*.dwg*" files, which are structured CAD files. DesignBuilder® is a well-known graphical interface that allows a very versatile 3D geometrical modeling starting from the aforementioned CAD files. More in detail, in CADMapper® it is possible to individuate the geographical location of the neighborhood and consequently export the relative "*.dxf*" or "*.dwg*" file. Once done, the exported file is imported in DesignBuilder®, where it is easily transformed into a 3D geometrical model. Consequently, the definition of which buildings of the neighborhood have to be considered for the energy analysis – and which not – is performed. In detail, the first ones have to be energy modeled, while the second ones are modeled as simple 3d shapes in order to be considered only for their shadowing effects, avoiding a significant increment of the modeling effort and of the consequent computational time required. For what concerns the buildings that have to be energy modeled, the stratigraphies of every component of the building envelopes have to be defined. This is a crucial operation because it deeply affects the reliability of the results and it requires a huge amount of information – *i.e.*, number of layers, thicknesses, density, specific heat and conductivity of each layer –, thus, it should be conducted after a proper data collection. The latter could be performed even by using an abacus of the stratigraphies or by on-site inspections. Consequently, after the definition of the stratigraphies, the subdivision of the buildings into thermal zones occurs. Note that the methodology here applied for modeling the envelope of buildings is nearly the same as in [146] and in [152]. Being the aim of this study not to propose a novel methodology for the energy characterization of the envelopes of buildings, but to overcome the criticalities due to the stochasticity in the occupant behavior that may affect the energy demands and to the effects of the global warming on planning the energy retrofit of neighborhoods, the advantages of the adopted approach for the energy characterization of the envelopes have not been specified in detail in this manuscript. However, it is worthy to clarify an important point. The 3D vertical extrusion of 2D building geometry by considering types of buildings whose characteristics are predefined may be very inaccurate in certain situations, for two main reasons. Firstly, it may happen that in the same neighborhood some buildings have already been energy refurbished, while others not yet, and so the former may already have a highly insulated envelope, while the latter not, even if all the buildings have been built during the same years, and so theoretically they should present the same thermal characteristics for the envelope. Therefore, the use of buildings' archetypes in these situations may be very risky and may produce important losses in terms of accuracy of the results. Secondly, the 3D vertical extrusion of the 2D building geometry does not give the possibility to properly perform the thermal zoning of the investigated buildings. Indeed, by simply vertically extruding a 2D geometry it may happen that the whole building at the inside is considered as an empty volume, and so the horizontal partitions between each level may be neglected, or that, if considering the horizontal partitions between the levels, the vertical partitions between thermal zones may be neglected, with consequent losses in terms of accuracy of the results, because some thermal zones may be space conditioned and may have a certain destination of use, while others may be unconditioned and may have a different destination of use. All told, consisting the adopted methodology in a detailed energy modeling of each building constituting the neighborhood, it enables to attain higher levels of accuracy compared to simplified approaches, such as the ones that perform the 3D vertical extrusion and make use of archetype buildings techniques. For further information on the advantages adopted approach it is possible to refer to [146] and [152]. Once completed the energy modeling in DesignBuilder®, an "*.idf"* file is exported, which is the input file for the dynamic energy simulator EnergyPlus. Here, the level of detail of the energy model is enhanced by means of the definition of:

1. the usage profiles for each thermal zone;
2. the operation of the heating, ventilating and air conditioning (HVAC) systems.

These definitions could be performed in DesignBuilder® too, but EnergyPlus allows to implement this step in an easier and more accurate way. For this purpose, a stochastic approach is used to better consider the variability and the casualty of the human behavior, in order to obtain results that are closer to reality. Therefore, for what concerns the residential thermal zones, different usage profiles are defined and are assigned to thermal zones according to a normal (Gaussian) distribution. The same is partially done for the operation of the HVAC systems. This is better clarified in the subsequent Section 2.2. Once assigned the aforementioned usage profiles and operation schedules, ideal HVAC systems are defined in EnergyPlus to obtain the ideal thermal energy demand for space heating (TEDh) and the one for space cooling (TEDc). EnergyPlus is also used to assess the electricity consumption of the equipment (excluding the HVAC systems) and of the artificial lights. Note that the heating and the cooling generation systems as well as the relative subsystems – *i.e.*, the distribution networks, the emitting terminals and the regulation elements –, are not modeled in EnergyPlus in order to cut down the computational time required for the dynamic energy simulations. Therefore, these systems are modeled directly under MATLAB® environment.

In MATLAB® an in-house developed "coupling function" is used to enable the automatic interaction between MATLAB® and EnergyPlus. More in detail, MATLAB® is capable to automatically run EnergyPlus and consequently handle its output files – *i.e.*, "*.csv*" files – by postprocessing the results by:

- applying the desired HVAC systems, intended as combinations of generation, distribution, regulation and emission systems;
- applying possible renewable energy sources systems, *e.g.*, photovoltaic (PV) systems;
- assessing the objective functions and the main performance indicators. In detail, the considered objective functions are the PEC, the running cost (RC) and the CO_2-eq emissions, while other investigated performance indicators are the TEDh and the TEDc. Concerning these latter, note that the values contained in the *.csv* file are not well-organized, thus MATLAB® is fundamental to make them readable and usable for the investigation.

The technique of performing the postprocessing of the outcomes of the dynamic simulations in MATLAB® environment permits to deeply reduce the computational burden. In detail, the values of TEDh and TEDc are obtained starting from the *.csv* output file. Consequently, the electricity and fuel demands are evaluated on hourly basis thanks to encoded dynamic performance curves, for what concerns the HVAC generation systems, and to the efficiency values reported in the Italian technical standard UNI/TS 11300 [144], for what concerns the distribution, emission and regulation systems. The assessed values of electricity and fuel demand are converted in PEC, thanks to proper primary energy conversion factors, in RC, thanks to proper specific energy prices, and in CO_2-eq emissions, thanks to proper specific emissions factors.

7.2.3. A stochastic approach for scheduling the usage profiles in residential thermal zones

Aiming at achieving reliable results that are close to reality, it is crucial to individuate proper usage profiles for each thermal zone. Therefore, a stochastic approach is adopted. In detail, different usage profiles are defined and are discretely assigned to the residential thermal zones, according to a Gaussian distribution having variance equal to 2. Note that this operation is performed only for residential thermal zones, which are characterized by the highest levels of human behavior variability, and so a unique standardized usage profile is not close to reality and its use may deeply affect the reliability of the results. Obviously, a certain variability exists also for what concerns the usage profiles of other categories of thermal zones, but it is less noticeable compared to residential thermal zones. In future developments, it would be interesting to apply the same stochastic approach also to thermal zones that are not residential ones.

All told, by stochastically assigning different usage profiles to residential thermal zones, the simulated human behavior results closer to reality, especially compared to the case of one standardized usage profile assigned to all the thermal zones. Therefore, different occupation schedules are defined for the residential thermal zones and they are assigned discretely to the apartments, according to the aforementioned Gaussian distribution. In detail, the occupation schedules differ from each other by considering more or less extended holiday periods – *i.e.*, in both the summer season and the winter season – and more or less occupied hours during each day. Obviously, defining each usage profile does not consist only in defining different occupation schedules, but it is a more complicated issue because it requires to define:

- a specific lighting usage profile;
- a specific electric facility usage profile;
- a specific ventilation schedule;
- specific heating and cooling set-point schedules – even if the working hours are fixed and are the same for the whole buildings, considering centralized generation systems for each building;
- a specific shading system availability. In addition, for what concerns the shading systems, a proper solar set-point included between 150 W/m^2 and 400 W/m^2 is assigned to each apartment in order to better simulate the human sensibility and reaction to solar irradiation.

As told, the aim of using this stochastic approach is to attain results in terms of the objective functions and performance indicators that are the closest as possible to reality, considering, as possible, the variability of the human behavior. More in detail, the different usage profiles assigned to residential thermal zones have been determined based on the common local practice and on the authors’ expertise. For each usage profile a proper level of occupancy is scheduled. The assigned occupancy profile constitutes the main “core” of each usage profile, because all the other characteristics – in terms of schedules – are determined according to the occupancy. More in detail, nine different occupancy profiles have been determined, one for each usage profile, each one representing a typical residential user/family (see the Appendix). Occupancy profile “A” is characterized by the lowest time of permanence in the apartment from all the possible perspectives: number of hours per each day, number of days per each week, and number of weeks of vacation during the year. On the other hand, occupancy profile “I” is characterized by the highest time of permanence in the apartment from all the aforementioned perspectives: night and day permanence, weekdays and weekends permanence, no vacations. Obviously, the usage profiles whose occupancy corresponds to profile “A” or “I” are rare, and so they are the least common among all the thermal zones. All the other profiles are determined starting from profile “A” by progressively increasing the hours of permanence each day and the days of permanence each week, and by progressively reducing the number of weeks of vacation during the year, until profile “I” is reached. Once defined all the occupancy profiles, all the other schedules are determined by adopting a similar approach. For instance, for what concerns the lighting usage profiles, each one is defined considering the relative occupancy profiles, in order to avoid incongruencies – *e.g.*, lights turned on even if there is no one in the apartment for long periods, which is avoided by means of the developed usage profiles –, and the same is for the electric facility usage profiles and the ventilation schedules. Starting from the occupancy profiles, a higher mean value in terms of load factors is assigned by moving from profile “A” to profile “I”. In detail, this implies that, during the same availability hour of the considered facility – *i.e.*, lights, electric equipment, ventilation – higher load factors can be seen by passing from “A” to “I”. Slightly different is the approach for the definition of the heating and of the cooling setpoint schedules, because the HVAC systems may be operative even if the relative occupancy profiles establish that there is nobody in the apartments, as it often happens in real world. More in detail, by moving from usage profile “A” to usage profile “I”, the number of operation hours passes from seven to ten for what concerns the heating systems, while from two to twelve for what concerns the cooling ones. In addition, the distribution of the operation hours during each day and during each week or month varies according to the relative occupancy profiles, considering that the HVAC systems can be turned on few hours – usually one or two – before the next occupied hour in the apartments. In terms of setpoints, the same heating and cooling setpoints are assigned to all the schedules and, in detail, these are 20 °C and 26 °C, respectively. Finally, for what concerns the shading systems availabilities, each one is assigned considering the relative occupancy profile. This permits to achieve a high level of coherence for each usage profile, being the schedules related to the operation of lights, electric equipment, HVAC systems, ventilation and shading systems consistent with the occupancy profiles.

This approach has – as main implication – the possibility to better represent the stochasticity of the human behavior, and so to attain robust results for what concerns the contemporaneity of the energy loads, which is fundamental to be considered when the energy retrofit of a neighborhood is planned in order to avoid oversizing or undersizing issues related to the primary energy systems design, as well as for not overestimating the energy, financial and environmental benefits.

7.2.4. 2035: Representative Concentration Pathways for a mid-term time horizon analysis

Since the approach aims at a reliable mid-term time horizon analysis – *i.e.,* 2035 –, the implications of global warming need to be properly taken into account. For this purpose, the Representative Concentration Pathways (RCPs) scenarios – defined by the Intergovernmental Panel on Climate Change (IPPC) – are considered. They provide predictions of emissions and concentrations in the atmosphere of greenhouse gases. Each scenario is individuated by a specific value, which denotes the additional radiative forcing in 2100 compared to preindustrial conditions for that scenario. For instance, concerning "RCP 4.5", "4.5" means that the additional forcing will be 4.5 W/m^2 in 2100. Due to the uncertainty in the climate evolution, it results crucial to look at different climate projections, rather than just at a single projection, with the aim to attain a more rigorous prediction of the energy, financial and environmental performance of the neighborhood. Therefore, different RCPs have been considered in this study:

- RCP 4.5 50% warming: this is an intermediate warming case, with a moderately aggressive mitigation of GHG emissions. Note that the percentile is derived from a larger ensemble of projections on the climate and indicates the amount of projections that are colder. All told, for this RCP radiative emissions peak around 2040, then decline. The global temperature rises between 2 °C and 3 °C by 2100;
- RCP 8.5 50% warming: this is an upper-intermediate warming case, with no sensible mitigation of GHG emissions. Radiative emissions keep rising throughout 2100. The global temperature rises between 3 °C and 4 °C by 2100;
- RCP 8.5 95% warming: this is worst warming case, without any mitigation of GHG emissions. Radiative emissions keep rising throughout 2100. The global temperature rises between 4 °C and 5.5 °C by 2100.

Obviously, for each of the aforementioned cases, a proper weather file of the investigated location has been used considering the RCPs at the year 2035 in order to run EnergyPlus dynamic energy simulations. The chosen year of the analysis is 2035 because it is a mid-term time horizon, not subjected to the excessive uncertainty as 2050 or later, but not too close to present as 2025 or earlier. In addition, in 2035 the ERMs applied now should be still in use, having at least a 20-year lifespan.

For each of the three cases, six different scenarios have been examined – *i.e.*, one baseline scenario, where the neighborhood is as built, and five energy retrofit scenarios, where various combinations of ERMs are supposed to be applied simultaneously to all the buildings constituting the neighborhood –, in order to optimize the retrofit planning satisfying the needs of the stakeholders that are involved – *i.e.*, the public perspective and the private perspective. For this scope, individuating the objective functions is a crucial task. The chosen objectives are the reduction of the PEC, of the RC and of the CO_2-eq emissions. Note that the investment costs necessary have not taken into account for two main reasons: i) the latest Italian incentivation policy concerning the energy retrofit of buildings [157], which allows to completely energy retrofit certain buildings with very low or zero expenses for the owners; ii) the intention to primarily focus the analysis on the energy and environmental effects of the selected ERMs, and only secondarily on the financial implications. However, it would be interesting in future analysis to consider also the investment costs necessary to implement the different combinations of ERMs, especially in absence of financial support policies by the Governments.

"n" ERMs have been selected – according to the local construction practice – with the aim to investigate their effects on the objective functions, *i.e.*, PEC, RC and CO_2-eq emissions, as well as on TEDh and TEDc. A design variable is associated to each ERM, thus "n" variables are introduced. Some of them are parametrized in the EnergyPlus input file, while the others are encoded directly in MATLAB®. By means of an in-house developed MATLAB® function [89, 147], for each scenario a new energy model of the neighborhood is automatically created, and its dynamic energy simulation is run in EnergyPlus. Consequently, MATLAB® handles the output *.csv* file and postprocesses the results evaluating the objective functions and other performance indicators, referring to the examined scenario. The process is performed for all the six scenarios of each of the three RCPs – *i.e.*, RCP 4.5 50% warming, RCP 8.5 50% warming and RCP 8.5 95% warming.

7.3. Presentation of the case study

7.3.1. Baseline configuration of the neighborhood ("as built configuration")

An existing neighborhood ubicated in a highly-populated quartier of Naples (South Italy, Mediterranean climate) has been considered as case study. The neighborhood is representative of the building stock of the 70s in reinforced concrete of the Southern Italy. Five buildings are part of the neighborhood. More in detail, four buildings are mostly residential ones, while the fifth is an educational building. Residential buildings have from five to nine levels, and each story has a net height of 3.1 m. On the other hand, the school has three stories, and each one is characterized by a net height of 3.9 m. For what concerns the gross floor area, this varies from 3662 m^2 to 6284 m^2 per building. The glazing area is included between 552 m^2 and 1152 m^2 depending on the building. Shading systems are installed upon every window. In detail, blind shades with medium values of reflectance and visible transmittance are used. In addition, important shadowing effect are due to the closest buildings, which are geometrically modeled, with the aim to take into account the aforementioned shadowing phenomena, as shown in figure 7.2.

Concerning the use destinations in detail, shops occupy the entire first level – *i.e.*, the ground floor – of each residential building, while offices occupy their entire second level, with the exception of few common circulation areas. On the other side, the educational building has classrooms, toilets and circulation areas at every level, with an additional office area at the second story above the ground. Gym has not been considered because it consists of a wide outdoor area. In total, 255 thermal zones are present, 185 of which are space conditioned. The remaining zones that are unconditioned are the common circulation areas of the residential buildings. The individuated distribution of the thermal zones is as follows (see figure 7.2):

- building 1: 25 apartments, 21 common circulation areas, 7 offices, 11 shops;
- building 2: 25 apartments, 16 common circulation areas, 4 offices, 12 shops;
- building 3: 18 apartments, 15 common circulation areas, 6 offices, 9 shops;
- building 4: 24 apartments, 18 common circulation areas, 6 offices, 10 shops;
- educational building: 17 classrooms, 3 corridors, 1 office, 7 toilets; it is important to remind that the individuated classrooms are not the real classrooms, as for all other thermal zones, but macro classrooms, which can include even more classrooms having the same boundary conditions.

According to the Italian constructive practice of the 70s, each building of the neighborhood has the same envelope. Concerning the opaque envelope, tables 7.1 to 7.3 report in detail the stratigraphies of the external walls, the ground floor and the roof, from the internal to the external layer. The ground floor is already well-insulated. All the U-values are reported in table 7.4.

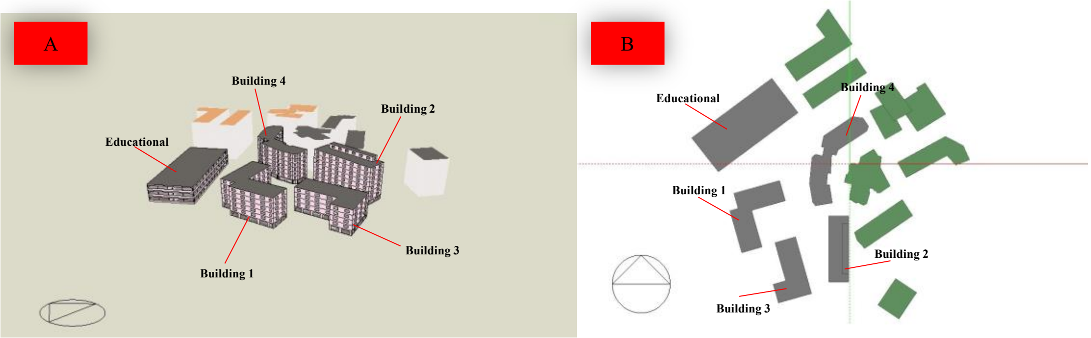

Figure 7.2. A: Neighborhood 3D rendering. B: Aerial view. Green buildings are the shadowing buildings

Table 7.1. Stratigraphy of the external walls

Layer n°	Material	Thickness [m]	Conductivity [W/m K]	Density [kg/m^3]	Specific heat [J/kg K]
1	Plaster	0.02	1.40	2000	670
2	Lapillus block	0.08	0.38	1000	880
3	Air gap	0.12	-	-	-
4	Hollow bricks	0.12	0.90	800	1000
5	Plaster	0.03	1.40	2000	670

Table 7.2. Stratigraphy of the ground floor

Layer n°	Material	Thickness [m]	Conductivity [W/m K]	Density [kg/m^3]	Specific heat [J/kg K]
1	Wood floor	0.03	0.14	650	1200
2	Screed	0.07	0.90	1800	1000
3	Concrete	0.10	1.13	2000	1000
4	Urea-formaldehyde	0.13	0.04	10	1400

Table 7.3. Stratigraphy of the roof

Layer n°	Material	Thickness [m]	Conductivity [W/m K]	Density [kg/m^3]	Specific heat [J/kg K]
1	Plaster	0.02	1.40	2000	670
2	Hollow-core Concrete	0.20	0.51	800	1000
3	Reinforced Concrete	0.06	2.50	2400	1000
4	Concrete	0.15	1.13	2000	1000
5	Asphalt	0.01	0.70	2100	1000

Concerning the transparent envelope, each building has single pane windows, but there are different types of frames. In detail, all the thermal zones are equipped with wooden frames, with the exception of the shops, which are equipped with aluminum frames with thermal break. The glazing area, too, varies as a function of the use destination, *i.e.*, for the educational building it is around 50% of the respective gross wall area, for shops it is nearly 60%, and, finally, for the remaining thermal zones in the residential buildings it is around 20%. The windows U-values are shown in table 7.4. In detail, the thermal transmittance U is equal to 5.89 W/m^{2}K for all the thermal zones, with the exception of the shops, where it is equal to 5.44 W/m^{2}K. Concerning the solar heat gain coefficient (SGHC), it is 0.86 for all the thermal zones, safe for the shops, where it is equal to 0.44.

Concerning the HVAC systems, each building is equipped with a natural gas fired water boiler that provides hot water at 80 °C to baseboards. The water boilers are all characterized by a nominal efficiency (η) at the lower heating value (LHV) equal to 0.80. On the other hand, air-cooled chillers with a nominal coefficient of performance (COP) of 2.5 feed fan-coils. The terminals of the HVAC systems are installed in all the thermal zones, with the exception of the common circulation areas in the residential buildings. For the heating system, also the effects in terms of efficiencies of distribution pipes, regulation systems and emitting systems have been taken into account.

Table 7.4. Main characteristics of the neighborhood

Main Boundary Conditions of Energy Simulations			
Climatic data	IWEC → EPW	Number of thermal zones	255 (conditioned 185)
Occupancy	*Depending on the thermal zone*		
Dimensions and Geometry			
Building 1			
Gross Floor Area	6417 m^2	Gross Roof Area	917 m^2
Gross Wall Area	4083 m^2	Height	22.4 m (7 floors)
Total Gross Volume	20534 m^3	Window Opening Area	986 m^2
Surface to Volume Ratio	0.33 m^{-1}	Gross Window-Wall Ratio	24.2%
Building 2			
Gross Floor Area	5211 m^2	Gross Roof Area	632 m^2
Gross Wall Area	3316 m^2	Height	28.8 m (9 floors)
Total Gross Volume	16676 m^3	Window Opening Area	772 m^2
Surface to Volume Ratio	0.31 m^{-1}	Gross Window-Wall Ratio	23.3%
Building 3			
Gross Floor Area	3662 m^2	Gross Roof Area	732 m^2
Gross Wall Area	2082 m^2	Height	16.0 m (5 floors)
Total Gross Volume	11719 m^3	Window Opening Area	552 m^2
Surface to Volume Ratio	0.34 m^{-1}	Gross Window-Wall Ratio	26.5%
Building 4			
Gross Floor Area	5373 m^2	Gross Roof Area	896 m^2
Gross Wall Area	3086 m^2	Height	19.2 m (6 floors)
Total Gross Volume	17200 m^3	Window Opening Area	780 m^2
Surface to Volume Ratio	0.33 m^{-1}	Gross Window-Wall Ratio	25.3%
Educational Building			
Gross Floor Area	6284 m^2	Gross Roof Area	2094 m^2
Gross Wall Area	2392 m^2	Height	12.0 m (3 floors)
Total Gross Volume	25134 m^3	Window Opening Area	1152 m^2
Surface to Volume Ratio	0.31 m^{-1}	Gross Window-Wall Ratio	48.2%
Whole district			
Gross Floor Area	26947 m^2	Gross Roof Area	5271 m^2
Gross Wall Area	14959 m^2	Window Opening Area	4242 m^2
Total Gross Volume	91264 m^3		
Building Envelope			
U ground	0.37 W/m^{2}K	U roofs	1.09 W/m^{2}K
U walls	1.01 W/m^{2}K	U windows-shop	5.44 W/m^{2}K
Infiltration rate	0.70 ACH	U windows-all other	5.89 W/m^{2}K
Shading systems	Medium reflect – Medium trans blind		
HVAC Systems			
Heating generation systems	Natural gas-fired water boilers	Cooling generation systems	Air-cooled electric chillers
η generation (heating)	0.80	COP (cooling)	2.50

7.3.2. Stochastic usage schedules

The first step is to individuate proper usage schedules for the residential apartments in order to guarantee a higher accuracy of the results. Accordingly, by stochastically assigning different usage schedules to apartments, the simulated human behavior results closer to reality, especially compared to when only one standard occupancy profile is assigned to all thermal zones. Therefore, a stochastic approach has been adopted, and nine different residential occupancy profiles have been defined. As specified in Section 7.2.3, they have been assigned discretely to apartments according to a normal distribution having standard deviation equal to 2 (there are 9 available options, *i.e.*, schedules). The occupancy profiles have been assigned to apartments as indicated in table 7.5. See the Appendix for details on the schedules “A” – “I”. The intensity of the occupancy rises passing from profile “A” to profile “I”. In addition, being these profiles assigned according to a normal distribution, extreme profiles are less common than the ones corresponding to the middle of the interval “A” – “I”.

Table 5. Assignment of occupancy profiles to residential buildings. Numbers in columns denote the amounts of apartments

Occupancy Profiles									
	Occ. A	*Occ. B*	*Occ. C*	*Occ. D*	*Occ. E*	*Occ. F*	*Occ. G*	*Occ. H*	*Occ. I*
Building 1	1	2	3	4	6	5	3	1	0
Building 2	1	2	3	4	6	4	3	1	1
Building 3	1	1	2	3	4	3	3	2	0
Building 4	0	1	3	5	5	4	2	2	1
Neighborhood	3	6	11	16	21	16	11	6	2

Starting from the aforementioned occupancy profiles, different usage schedules for lighting, electric facility, ventilation, heating set-point, cooling set-point and shading system availability have been defined and assigned to apartments, coherently with the occupancy profiles. This implies that lighting and ventilation values are null during hours when occupancy values are null, and the same happens for what concerns the shading system availability. Differently, the hourly values referred to electric facility usage are never null, due to the presence of standby currents and of alarm systems, as in reality. Obviously, during hours when occupancy is null, the electric usage values are sensibly lower compared to when occupancy is not null. Finally, concerning the heating and the cooling set-point, it has been supposed that the HVAC systems have to guarantee the set-point temperatures – *i.e.*, 20 °C and 26 °C, respectively – also during hours when occupancy is null, in order to deploy the thermal inertia phenomenon, ensuring a higher thermal comfort during the hours when occupancy is not null.

7.3.3. Energy Retrofit Measures

Once performed the usage profiles assignment, the next step consists in identifying the energy retrofit measures (ERMs) to investigate. For each of the three cases under investigation – *i.e.*, Representative Concentration Pathway (RCP) 4.5 50% warming, RCP 8.5 50% warming and RCP 8.5 95% warming –, six scenarios have been examined – *i.e.*, one baseline scenario, where the neighborhood is as built, and five energy retrofit scenarios. The main aim is to conduct an analysis with the scope to individuate the retrofit scenario that results the best tradeoff in terms of reductions of primary energy consumption (PEC), running cost (RC) and CO_2-eq emissions, taking into account the difficulty to implement the ERMs too. The following ERMs have been taken into account:

1. installation of photovoltaic (PV) panels on the roofs. No energy storages are considered in coupling with the PV systems, because in Italy there is the possibility to deal with the electricity surplus produced by PV panels by feeding such energy into the grid, *i.e.*, the net-metering option, which is a common configuration for Italian residential buildings. In detail, the surplus electricity is sold to the GSE – *i.e.*, the national electricity authority;
2. creation of a local energy community by implementing photovoltaic energy sharing. Note that, as specified in the previous chapter, being different the aim of this study, the attention of the authors has not been focused on the development of an optimized framework for the creation of a local energy community, but the hourly balance between the electricity produced by all the installed PV systems and the electricity need at the neighborhood level has been evaluated. This approach, once again, permits to achieve a general overview on the possible effects of the implementation of a local energy community on the considered energy, financial and environmental indicators. Indeed, by considering the aforementioned hourly balances, each building shares its production and its energy needs with all the other buildings of the neighborhood, and thus the buildings can be considered as one only entity, creating a local energy community;
3. replacement of the HVAC systems. High-efficiency reversible air-source electric heat pumps are installed in each building. Obviously, in coupling with the installation of the heat pumps there is the dismission of the baseboards, thus fan-coils are used as emitting terminals during both the heating and the cooling season;
4. actions on the envelopes, opaque and transparent. For what concerns the formers, insulation layers on the external walls and on the roofs are posed – the insulation

layers are as thick as necessary to comply with the law limit [125]. Concerning the windows, single pane ones are replaced with double-glazed windows with argon-filling and low-emitting coatings. Also the frames are replaced with less conductive PVC frames. Note that the replacement of the windows implies a reduction of the air infiltration rate, which passes from 0.7 air changes per hour (ACH) to 0.3 ACH.

The considered ERMs have been selected based on the local most common practice and respect the energy requirements established by the Italian law [125].

Note that the PV panels are modeled under MATLAB® environment in order to drastically reduce the computational burden. Such a reduction of the simulation times is fundamental to make feasible the investigation of several scenarios, as done in this study. However, the thermal interaction between PV panels and roof surfaces is neglected. In this regard, the shadowing produced by PV panels can imply both a positive and a negative effect. More in detail, the shadowing produced by panels can have a positive effect during the summer season, allowing to reduce the thermal energy demand for cooling (TEDc), but, conversely, the same shadowing can produce an increment of the thermal energy demand for space heating (TEDh) during the winter period. In addition, it should be noticed that PV panels reach higher temperatures during the maximum irradiation hours, which influence the temperature of the roof surfaces, and therefore both the aforementioned positive and negative effects can be counterbalanced – *i.e.*, high temperatures of PV panels can produce a reduction of the TEDh and an increment of the TEDc.

Table 7.6. Characterization of the investigated ERMs

Envelope	
Energy Retrofit Measure	*Characterization*
Additional insulation layer on the external walls	Thickness of 0.07 m, conductivity of 0.030 W/mK
Additional insulation layer on the roofs	Thickness of 0.08 m, conductivity of 0.030 W/mK
Replacement of windows	Double-glazed windows with argon-filling, low-emitting coatings and PVC frames. U=1.49 W/m^{2}K, SHGC=0.56
HVAC Systems + Photovoltaics (PV)	
Energy Retrofit Measure	*Characterization*
Replacement of the heating and of the cooling generation systems	Reversible air-source electric heat pumps. COPh=4.5, COPc=4.0
Installation of PV panels	Monocrystalline PV panels, facing South and inclined at 30° to the horizontal level
Implementation of PV sharing	Creation of a local energy community that shares the energy produced by PV systems

For each of the cases under investigation, six scenarios have been examined, which differ each from other by an increasing level of energy retrofit. The aforementioned ERMs have been combined according to table 7.7. The Scenario 1 corresponds to the baseline configuration of the neighborhood (as built). Note that the ERMs are supposed to be implemented simultaneously for all the buildings of the neighborhood. In future studies there may be the opportunity to differentiate the retrofit measures among the buildings of the neighborhood.

Table 7.7. Scheme of the investigated scenario

Investigated Scenarios						
ERMs	*Scen 1*	*Scen 2*	*Scen 3*	*Scen 4*	*Scen 5*	*Scen 6*
Installation of PV panels		x	x	x	x	x
Implementation of PV sharing			x	x		x
Replacement of the HVAC systems				x	x	x
Additional insulation layer on the external walls					x	x
Additional insultation layer on the roofs					x	x
Replacement of windows					x	x

In the presented case study, the PEC, the RC and the CO_2-eq emissions have been evaluated as in equations 7.1, 7.2 and 7.3. In addition, in order to have additional information concerning the implications of the energy retrofit, also the thermal energy demand for space heating (TEDh) and for space cooling (TEDc) have been assessed. Table 7.8 reports the main factors for the assessment of PEC, RC and CO_2-eq.

Table 7.8. Main factors for the assessment of the performance indicators

Energy Prices, Conversion Factors and Emission Factors			
Gas price	0.90 €/Sm^3	Electricity price	0.23 €/kWh
		Electricity selling price	0.07 €/kWh
Gas-to-primary energy conversion factor	1.05	Electricity-to-primary energy conversion factor	1.95
Gas CO_2 emission factor	0.237 kg CO_2/kWh	Electricity CO_2 emission factor	0.708 kg CO_2/kWh

The PEC has been evaluated as follows:

$$\mathrm{PEC} = \mathrm{E_{el}} \cdot \mathrm{fp_{el}} + \mathrm{E_{gas}} \cdot \mathrm{fp_{gas}} \tag{7.1}$$

where:

- E_{el} is the electricity consumed per year, purchased from the grid;
- fp_{el} is the electrical-to-primary energy conversion factor;
- E_{gas} is the energy consumption related to gas. It is assessed by dividing the gas consumption by the lower heating value (LHV);
- fp_{gas} is the gas-to-primary energy conversion factor.

The RC due to energy uses has been evaluated as it follows:

$$\mathrm{RC} = \mathrm{E_{el}} \cdot \mathrm{C_{el}} - \mathrm{G_{el}} \cdot \mathrm{S_{el}} + \mathrm{Vol_{gas}} \cdot \mathrm{C_{gas}} \tag{7.2}$$

where:

- C_{el} is the price of the electricity when it is purchased from the grid;
- G_{el} is the surplus of electricity produced by PV systems that is not self-consumed, and so it is fed into the grid;
- S_{el} is the selling price of the electricity;
- Vol_{gas} is the volume of gas consumed;
- C_{gas} is the price of the gas.

Finally, the CO_2-eq emissions have been assessed according to equation 7.3:

$$\mathrm{CO_2\text{-}eq} = \mathrm{E_{el}} \cdot \mathrm{fc_{el}} + \mathrm{E_{gas}} \cdot \mathrm{fc_{gas}} \tag{7.3}$$

where:

- $\mathrm{fc_{el}}$ is the CO_2-eq emission factor for the electricity;
- $\mathrm{fc_{gas}}$ is the CO_2-eq emission factor for the gas.

7.3.4. Results and discussion

According to the methodology described in Section 7.2, three different cases have been examined:

- RCP 4.5 50% warming;
- RCP 8.5 50% warming;
- RCP 8.5 95% warming.

For each of the aforementioned cases, six different scenarios have been investigated, *i.e.*, one where the neighborhood is as built and five where the neighborhood is retrofitted.

Stochastic approach: model validation

Before considering the aforementioned RCPs, a comparison has been performed between results obtained by means of the stochastic schedules assignment described in the previous Sections and the ones obtained by using – for all the residential thermal zones – standardized ASHRAE schedules for what concerns the occupancy, the lighting usage, the electric facility usage, the ventilation as well as the heating and the cooling set-points.

Note that the heating set-point schedules have been modified by reducing the operation hours of the HVAC systems in order to respect the Italian law limits. The aim is to outline the importance of adopting a stochastic approach. For this purpose, the EnergyPlus typical weather data file available for Naples has been used. Results at the neighborhood scale are displayed in table 7.9.

Table 7.9. Scenario 1: Results comparison between standardized schedules and stochastic ones

SCENARIO 1	**Standardized schedules**	**Stochastic schedules**	***Discrepancy***
TEDh [kWh/m^{2}a]	13.5	20.0	*-48.1%*
TEDc [kWh/m^{2}a]	31.5	31.0	*1.6%*
PEC [kWh/m^{2}a]	142.8	121.5	*14.9%*
RC [€/m^{2}a]	15.7	12.9	*17.8%*
CO_2-eq [kg/m^{2}a]	46.0	36.8	*20.0%*

The TEDh assessed by using standardized schedules is equal to 13.5 kWh/m^{2}a, while the one attained by adopting stochastic schedules is 20.0 kWh/m^{2}a, as seen. The discrepancy is equal to -48.1%, which is mainly due to the differences in the endogenous heat gains. The underestimation achieved by using the standardized schedules may imply the under-sizing of the heating systems during design or retrofit planning, with its obvious negative consequences on occupants’ thermal comfort.

For what concerns the TEDc, the value assessed by adopting standardized schedules is equal to 31.5 kWh/m^{2}a, while the one evaluated by means of the stochastic approach is 31.0 kWh/m^{2}a. The discrepancy is low, equal to 1.6%, and this could be explained by considering that the cooling set-point schedules in both approaches do not present important differences, and the same occurs for the ventilation schedules.

Taking into account the energy consumption of HVAC systems as well as of electric equipment and artificial lights, the PEC is assessed. It is equal to 142.8 kWh/m^{2}a for the standardized schedules approach, while it is 121.5 kWh/m^{2}a for the stochastic one. This implies a discrepancy equal to 14.9%, and thus there is an overestimation of neighborhood’s energy impact, which may produce an overestimation of the energy benefits during design or retrofit planning, with a consequent erroneous choice of the ERMs to be applied.

In terms of RC, by using the standardized schedules it is equal to 15.7 €/m^{2}a, while with the stochastic ones it is equal to 12.9 €/m^{2}a, which means a discrepancy equal to 17.8%. As occurs for the PEC, the adoption of a standardized approach may produce an overestimation of the RC, and thus a consequent overestimation of the financial benefits that may be achieved applying the ERMs.

Finally, for what concerns the CO_2-eq emissions, they vary from 46.0 kg/m^{2}a for the standardized approach to 36.8 kg/m^{2}a for the stochastic one. The discrepancy is equal to 20.0%, which may induce erroneous estimation and choices during design or retrofit planning from an environmental viewpoint too.

As seen, the adoption of the stochastic approach is crucial because it deeply affects the considered objective functions and performance indicators. Using standardized schedules may induce an overestimation of the energy, financial and environmental benefits of certain ERMs, and thus erroneous choices may be performed.

For validation purposes, results in terms of the RC have been compared to the statistical data of the Italian ISTAT [169]. Indeed, due to users' privacy issues, there is a lack of data concerning the energy consumption of the "real" neighborhood, thus the reliability of the model can be verified only by considering the available statistical data – note that the ISTAT data refer to the year 2013. The annual running cost for energy uses for an apartment of 100 m^2 in Campania is equal to 1350 €, *i.e.*, 13.5 €/m^{2}a. As shown in table 7.10, the latter is really close to the values assessed for the residential buildings by the developed energy model that makes use of stochastic schedules, while an important discrepancy has been assessed by considering the standardized schedules. Therefore, the model may be considered validated, and once again it is remarked the importance of adopting a stochastic approach for better describing the variability of the human behavior.

Table 7.10. Details on the RC for each building of the neighborhood as built (Scenario 1)

RC [€/m^{2}a] for Scenario 1	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	**Neighborhood**
Standardized Schedules	17.3	17.6	16.6	17.3	11.1	15.7
Stochastic Schedules	13.5	13.3	13.4	13.5	11.3	12.9

<u>RCP 4.5 50% warming</u>

Scenario 1: The first examined scenario consists of studying the energy and environmental performance of the neighborhood as built, without any ERM. The examined performance indicators are reported in table 7.11.

The TEDh varies from 6.0 kWh/m^{2}a for the educational building to 14.6 kWh/m^{2}a for building 1. The higher values for buildings 1 and 2 (13.0 kWh/m^{2}a) are due to the lower solar direct radiation because of neighboring buildings. On the other side, the educational building has the lowest TEDh – *i.e.,* 6.0 kWh/m^{2}a –, because of the highest internal gains (for the use destination) and solar direct radiation, not suffering from shadowing effect due to neighboring buildings and having at the same time the widest rooftop. For the same reasons, buildings 1 and 2 have the lowest TEDc values – *i.e.,* 39.9 kWh/m^{2}a and 41.2 kWh/m^{2}a, respectively –, while the educational building has the highest value – *i.e.,* 65.7 kWh/m^{2}a. The PEC varies from 109.2 kWh/m^{2}a for the educational building to 125.9 kWh/m^{2}a for the building 4. The educational building is characterized by the lowest value because of the reduced energy consumption due to electric facilities as well as for the lower use of the building. From the financial point of view, the RC is quite similar for all the residential buildings – *i.e.,* it is included between 13.4 €/m^{2}a for building 2 and 13.7 €/m^{2}a for buildings 3 and 4 –, while it is slightly lower for the educational building – *i.e.,* 12.0 €/m^{2}a –, which is characterized also by the lowest PEC, as seen. Finally, the CO_2-eq emissions are included between 35.3 kg/m^{2}a for the educational building and 40.1 kg/m^{2}a for building 4.

Table 7.11. RCP 4.5 50% warming: Performance indicators of the neighborhood as built (Scenario 1)

SCENARIO 1	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	14.6	13.0	12.8	12.3	6.0	11.4
TEDc [kWh/m^{2}a]	39.9	41.2	43.8	41.7	65.7	47.6
PEC [kWh/m^{2}a]	125.1	123.2	125.5	125.9	109.2	120.9
RC [€/m^{2}a]	13.5	13.4	13.7	13.7	12.0	13.2
CO_2-eq [kg/m^{2}a]	39.3	39.0	39.8	40.1	35.3	38.4

With reference to the neighborhood as a single entity, the TEDh and the TEDc are 11.4 kWh/m^{2}a and 47.6 kWh/m^{2}a, respectively, while the PEC is equal to 120.9 kWh/m^{2}a. The RC is equal to 13.2 €/m^{2}a and the CO_2-eq emissions value is 38.4 kg/m^{2}a. These values are the results of a weighted sum based on the conditioned area of each building constituting the neighborhood.

Scenario 2: The second examined scenario consists of studying the energy and the environmental performance of the neighborhood considering the installation of monocrystalline PV panels on 90% of the useful roof areas (10% is left free to ensure roof accessibility). The examined performance indicators are reported in table 7.12.

As predictable, the TEDh and the TEDc do not vary from the previous scenario, not having applied any ERM on the HVAC systems or on the envelopes. For what concerns the PEC, it is deeply influenced by the presence of PV systems and it varies from 70.9 kWh/m^{2}a for the educational building to 111.8 kWh/m^{2}a for the building 2. Once again, the educational building is characterized by the lowest value of PEC. This result is accentuated because such building has the widest rooftop area, and so its PV electricity production is the highest. From the financial point of view, the RC has important benefits by means of the presence of the PV systems. As predictable, the RC is lower where the boundary conditions and the geometry are favorable to the solar radiation deployment, and so it is included between 6.4 €/m^{2}a for the educational building – where the PEC too is the lowest – and 12.0 €/m^{2}a for buildings 2 – where the PEC too is the highest. Finally, concerning the CO_2-eq emissions, once again the educational building has the lowest value – *i.e.*, 21.4 kg/m^{2}a –, while building 2 has the highest one – *i.e.*, 34.8 kg/m^{2}a.

With reference to the whole neighborhood as an entity, the PEC is equal to 93.5 kWh/m^{2}a, the RC is equal to 9.4 €/m^{2}a and the CO_2-eq emissions value is 28.5 kg/m^{2}a.

Table 7.12. RCP 4.5 50% warming: Performance indicators of the neighborhood with PV panels (Scenario 2)

SCENARIO 2	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	14.6	13.0	12.8	12.3	6.0	11.4
TEDc [kWh/m^{2}a]	39.9	41.2	43.8	41.7	65.7	47.6
PEC [kWh/m^{2}a]	100.7	111.8	92.9	97.0	70.9	93.5
RC [€/m^{2}a]	10.3	12.0	9.3	9.9	6.4	9.4
CO_2-eq [kg/m^{2}a]	30.4	34.8	28.0	29.6	21.4	28.5

Scenario 3: The third examined scenario consists of studying the energy and the environmental performance of the neighborhood considering the installation of monocrystalline PV panels on 90% of the useful roof areas, as in the previous scenario, coupled with the creation of a local energy community that shares the PV production. In this case, the examined performance indicators are assessed only considering the whole neighborhood as an entity. They are reported in Table 7.13.

Table 7.13. RCP 4.5 50% warming: Performance indicators of the neighborhood with PV panels and PV sharing (Scenario 3)

SCENARIO 3	***Neighborhood***
TEDh [kWh/m^{2}a]	11.4
TEDc [kWh/m^{2}a]	47.6
PEC [kWh/m^{2}a]	91.5
RC [€/m^{2}a]	9.3
CO_2-eq [kg/m^{2}a]	27.7

Also in this case, the TEDh and the TEDc do not vary from the two previous scenarios, not having considered the application of ERMs on the HVAC systems or on the envelopes. For what concerns the PEC, it is equal to 91.5 kWh/m^{2}a, thus it is slightly lower compared to the previous scenario, and the same is for the RC – *i.e.*, 9.3 €/m^{2}a – and the CO$_2$-eq emissions – *i.e.*, 27.7 kg/m^{2}a.

Scenario 4: The fourth examined scenario consists of coupling the installation of monocrystalline PV panels on 90% of the useful roof areas with the PV sharing, as in the previous scenario 3, and the replacement of the existing HVAC systems for both the space heating and the space cooling with more efficient reversible air-source electric heat pumps. As previously done, due to the implementation of the PV sharing, the examined performance indicators are assessed only considering the whole neighborhood as one entity. They are reported in table 7.14.

Table 7.14. RCP 4.5 50% warming: Performance indicators of the neighborhood with PV panels, PV sharing and more efficient reversible air-source electric heat pumps (Scenario 4)

SCENARIO 4	***Neighborhood***
TEDh [kWh/m^{2}a]	11.1
TEDc [kWh/m^{2}a]	47.6
PEC [kWh/m^{2}a]	74.7
RC [€/m^{2}a]	7.0
CO$_2$-eq [kg/m^{2}a]	21.6

Differently from the previous scenarios, the TEDh varies due to the replacement of the HVAC systems and it is equal to 11.1 kWh/m^{2}a. This is explained by considering an increment of the efficiencies of the distribution, regulation and emitting systems. On the other hand, the TEDc does not vary, because the aforementioned systems are the same of the previous scenario – *i.e.*, concerning the TEDc, only the generation systems are replaced. Due to the replacement of the HVAC systems, important improvements for all the other performance indicators are obtained. More in detail, at the neighborhood level, the PEC results to be 74.7 kWh/m^{2}a, the RC is 7.0 €/m^{2}a and the CO$_2$-eq emissions are 21.6 kg/m^{2}a, and so all three are much lower compared to all the previous scenarios.

Scenario 5: The fifth examined scenario consists of coupling the installation of PV systems with the replacement of the existing HVAC systems with more efficient reversible air-source electric heat pumps and other ERMs affecting the envelopes of buildings. More in detail, the latter are the posing of insulation layers on the external walls (0.07 m thick) and on the roofs (0.08 m thick) and the replacement of the single pane windows with double-glazed ones with argon-filling, low-emitting coatings and PVC frames. The examined performance indicators are indicated in table 7.15.

Table 7.15. RCP 4.5 50% warming: Performance indicators of the neighborhood with PV panels, more efficient reversible air-source electric heat pumps and ERMs on the envelopes (Scenario 5)

SCENARIO 5	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	1.6	1.3	1.2	1.1	0.3	1.0
TEDc [kWh/m^{2}a]	34.6	36.7	38.9	37.6	59.9	42.6
PEC [kWh/m^{2}a]	68.2	80.3	62.8	67.5	44.0	63.5
RC [€/m^{2}a]	6.9	8.7	6.1	6.8	3.4	6.2
CO_2-eq [kg/m^{2}a]	21.2	25.6	19.3	21.1	12.7	19.6

In this case both the TEDh and the TEDc vary due to the ERMs on the envelopes. For what concerns the TEDh, it is deeply reduced by the presence of the adopted ERMs, in fact it is included between 0.3 kWh/m^{2}a for the educational building and 1.6 kWh/m^{2}a for building 1, and so, generally speaking, it is almost zero. Also the TEDc results reduced by the considered ERMs, even if in a less sensible way. In detail, the TEDc vary from 34.6 kWh/m^{2}a for building 1 to 59.9 kWh/m^{2}a for the educational building. Considering also the effects of the primary energy systems as well as the energy consumption due to electric equipment and to lights, the PEC is assessed and varies from 44.0 kWh/m^{2}a for the educational building to 80.3 kWh/m^{2}a for the building 2. From the financial point of view, the RC is quite similar for buildings 1, 3 and 4 – *i.e.,* 6.9 €/m^{2}a, 6.1 €/m^{2}a and 6.8 €/m^{2}a, respectively –, while it is slightly higher for building 2 – *i.e.,* 8.7 €/m^{2}a – and sensibly lower for the educational building – *i.e.,* 3.4 €/m^{2}a –, which is characterized also by the lowest PEC, as seen. In conclusion, concerning the CO_2-eq emissions, they are included between 12.7 kg/m^{2}a for the educational building and 25.6 kg/m^{2}a for building 2.

Considering the values of all the aforementioned indicators at the neighborhood level , the TEDh and the TEDc are 1.0 kWh/m^{2}a and 42.6 kWh/m^{2}a, respectively, while the PEC is equal to 63.5 kWh/m^{2}a. The RC is equal to 6.2 €/m^{2}a and the CO_2-eq emissions are equal to 19.6 kg/m^{2}a.

Scenario 6: The sixth and last scenario investigated consists of coupling the ERMs adopted in the previous scenario – *i.e.,* installation of PV systems, replacement of HVAC systems, insulation of the external walls and of the roofs, replacement of the windows – together with the implementation of the PV sharing. As in some other previous scenarios, the examined performance indicators are assessed only considering the whole neighborhood as an entity. They are reported in table 7.16.

Table 7.16. RCP 4.5 50% warming: Performance indicators of the neighborhood with PV panels, PV sharing, more efficient HVAC systems and ERMs on the envelopes (Scenario 6)

SCENARIO 6	***Neighborhood***
TEDh [kWh/m^{2}a]	1.0
TEDc [kWh/m^{2}a]	42.6
PEC [kWh/m^{2}a]	61.8
RC [€/m^{2}a]	6.1
CO_2-eq [kg/m^{2}a]	19.0

As predictable, the TEDh and the TEDc are not different from the values of the previous scenario. For what concerns the PEC, the RC and the CO_2-eq emissions, they are all slightly reduced compared to scenario 5 and are respectively equal to 61.8 kWh/m^{2}a, to 6.1 €/m^{2}a and to 19.0 kg/m^{2}a.

Comparison: A comparison between the values assessed for the selected performance indicators in each scenario has been performed. More in detail, the comparison is realized between the neighborhood as built (Scenario 1) and all the other scenarios, where ERMs are applied to buildings. The comparison has been performed at the neighborhood level and the results are indicated in table 7.17, where positive values of Δ indicate a favorable effect – *i.e.*, a reduction of the considered performance indicator.

Table 7.17. RCP 4.5 50% warming: Comparison of the performance indicators at the neighborhood level between the neighborhood as built (Scenario 1) and all the other scenarios

Neighborhood level	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Reference: Scenario 1***
ΔTEDh [kWh/m^{2}a]	0	0	0.3	10.4	10.4	11.4
ΔTEDc [kWh/m^{2}a]	0	0	0	5	5	47.6
ΔPEC [kWh/m^{2}a]	27.4	29.4	46.2	57.4	59.1	120.9
ΔRC [€/m^{2}a]	3.8	3.9	6.2	7	7.1	13.2
ΔCO_2-eq [kg/m^{2}a]	9.9	10.7	16.8	18.8	19.4	38.4

** Note that the values under the column "Scenario 1" are the reference values.*

For the other scenario, positive values denote a reduction (saving).

As predictable, reductions in terms of TEDh and TEDc are obtained only for scenarios that are characterized by the presence of ERMs involving the HVAC systems or the envelopes. In detail, when ERMs are applied to HVAC systems only, at the neighborhood level the TEDh is reduced by 0.3 kWh/ m^{2}a, while the TEDc does not vary. When ERMs are applied to both the HVAC systems and envelopes, the TEDh is reduced by 10.4 kWh/m^{2}a, while the TEDc by 5.0 kWh/m^{2}a. When the primary energy systems are considered as well as the energy consumption due to lights and electric facilities, the PEC is assessed. In terms of PEC, as predictable, the highest reductions are guaranteed when more ERMs are applied, which means for Scenarios 5 and 6 – *i.e.*, the PEC reductions are 57.4 kWh/m^{2}a and 59.1 kWh/m^{2}a, respectively –, even if by only installing PV panels as in Scenario 2 sensible reductions are obtained too – *i.e.*, the PEC is reduced by 27.4 kWh/m^{2}a. It is interesting to note that the implementation of the PV sharing in coupling with the PV panels has only a marginal effect on the PEC reduction, even if some results are obtained. This "marginality" of the PV sharing is much more evident when referring to RC reduction. In this case, when PV sharing is not implemented, such as in Scenarios 2 or 5, the RC reduction is equal to 3.8 €/m^{2}a or to 7.0 €/m^{2}a, respectively, while when it is implemented, such as in Scenarios 3 or 6, the RC reduction is equal to 3.9 €/m^{2}a or to 7.1 €/m^{2}a. Finally, for what concerns the environmental impact of the ERMs, the reduction of CO_2-eq emissions is included between 9.9 kg/m^{2}a for Scenario 2 and 19.4 kg/m^{2}a for Scenario 6. As predictable, also for what concerns the CO_2-eq emissions, higher reductions are obtained by applying more ERMs.

All told, for the RCP 4.5 50% warming case, all the retrofit scenarios produce important benefits in terms of energy, financial and environmental indicators compared to the neighborhood as built. As predictable, Scenario 6 is the one where all the performance indicators are minimized, and so both the public perspective and the private perspective are satisfied. In detail, it provides the installation of PV panels on 90% of the useful roofs areas, the implementation of PV sharing the replacement of HVAC systems with more efficient reversible air-source electric heat pumps, the insulation of the external walls and of the roofs and the replacement of the single pane windows with double-glazed ones with argon-filling, low-emitting coatings and PVC frames. However, really interesting is also the solution examined in Scenario 4, the same ERMs are considered, with the exception of the interventions on the envelopes – *i.e.*, no insulation of the external walls and of the roofs, no replacement of the windows. This solution may be the most interesting one because it results the best tradeoff between energy, economic and environmental savings and difficulty to be implemented, in fact Scenarios 5 and 6 provide higher reductions of the aforementioned performance indicators, but they are much more complex to be implemented, involving ERMs to be applied on the envelopes. Thus, they generally encounter less tenants' availability/will to their realization requiring also higher investment costs.

RCP 8.5 50% warming

Scenario 1: As for the previous case, the first examined scenario consists of studying the energy and the environmental performance of the neighborhood as built, without ERMs. The examined performance indicators are reported in table 7.18.

Table 7.18. RCP 8.5 50% warming: Performance indicators of neighborhood as built (Scenario 1)

SCENARIO 1	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	14.4	12.8	12.6	12.1	5.9	11.2
TEDc [kWh/m^{2}a]	40.4	41.8	44.4	42.3	66.3	48.1
PEC [kWh/m^{2}a]	125.2	123.3	125.6	126.1	109.5	121.1
RC [€/m^{2}a]	13.6	13.4	13.7	13.8	12.1	13.2
CO_2-eq [kg/m^{2}a]	39.4	39.0	39.9	40.2	35.4	38.5

Globally, the situation is really similar to the previous case, only few indicators vary. In detail, the TEDh is included between 5.9 kWh/m^{2}a for the educational building and 14.4 for building 1. As seen, the higher values for buildings 1 and 2 (12.8 kWh/m^{2}a) are justified considering the shadowing effect due to neighboring buildings. Also in this case, the educational building has the lowest TEDh – *i.e.,* 6.0 kWh/m^{2}a – and the highest TEDc – *i.e.,* 66.3 kWh/m^{2}a–, while buildings 1 and 2 are characterized by the lowest values of TEDc – *i.e.,* 40.4 kWh/m^{2}a and 41.8 kWh/m^{2}a, respectively. Considering the effects of the HVAC systems as well as the energy consumption due to electric facilities and to lights, the PEC is evaluated. The latter is included between 109.5 kWh/m^{2}a for the educational building and 126.1 kWh/m^{2}a for the building 4, as in the homologous scenario of the previous case, and the same is for the RC, with the exception of slight variations. In detail, the RC is quite similar for all the residential buildings – *i.e.,* it varies from 13.4 €/m^{2}a for building 2 to 13.8 €/m^{2}a for buildings 3 and 4 –, while it is lower for the educational building – *i.e.,* 12.0 €/m^{2}a. In conclusion, the CO_2-eq emissions vary from 35.4 kg/m^{2}a for the educational building and 40.2 kg/m^{2}a for building 4.

Considering the whole neighborhood as one entity, the TEDh and the TEDc are 11.2 kWh/m^{2}a and 48.1 kWh/m^{2}a, respectively, while the PEC is equal to 121.1 kWh/m^{2}a. The RC is equal to 13.2 €/m^{2}a and the CO_2-eq emissions value is 38.5 kg/m^{2}a, and so these values are really close the ones assessed in the previous case.

Scenario 2: The second examined scenario consists of investigating the same neighborhood but considering the installation of monocrystalline PV panels on 90% of the useful roof areas. The examined performance indicators are reported in table 7.19.

Once again, the TEDh and the TEDc are the same of the previous scenario, not having applied any ERM on the HVAC systems or the envelopes. Concerning the other indicators – *i.e.,* PEC, RC and CO_2-eq emissions –, not relevant variations from the homologous scenario of the previous case – *i.e.,* RCP 4.5 50% warming – can be appreciated.

Table 7.19. RCP 8.5 50% warming: Performance indicators of the neighborhood with PV panels (Scenario 2)

SCENARIO 2	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^2a]	14.4	12.8	12.6	12.1	5.9	11.2
TEDc [kWh/m^2a]	40.4	41.8	44.4	42.3	66.3	48.1
PEC [kWh/m^2a]	100.7	111.9	93.0	97.2	71.3	93.6
RC [€/m^2a]	10.3	12.0	9.3	10.0	6.4	9.4
CO_2-eq [kg/m^2a]	30.5	34.9	28.1	29.7	21.5	28.6

In detail, for what concerns the PEC, it is included between 71.3 kWh/m^2a for the educational building and 111.9 kWh/m^2a for building 2. Once again, the educational building is characterized by the lowest value of PEC. From the financial perspective, the PV systems guarantee important benefits to the RC. As in previous situations, the RC is lower where the boundary conditions and the geometry of buildings favor the solar radiation deployment. More in detail, the RC varies from 6.4 €/m^2a for the educational building to 12.0 €/m^2a for buildings 2. In conclusion, for what concerns the CO_2-eq emissions, the educational building is characterized by the lowest value – *i.e.,* 21.5 kg/m^2a –, while building 2 by the highest one – *i.e.,* 34.9 kg/m^2a.

Considering the whole neighborhood as one entity, the PEC, the RC and the CO_2-eq emissions are respectively 93.6 kWh/m^2a, 9.4 €/m^2a and 28.6 kg/m^2a.

Scenario 3: The third examined scenario consists once again into studying the energy and the environmental performance of the neighborhood considering the installation of monocrystalline PV panels on 90% of the useful roof areas, as in the previous scenario, with the implementation of the PV sharing. The resulting Performance indicators referred to the neighborhood level are reported in table 7.20.

The TEDh and the TEDc do not vary from the two previous scenarios. Concerning the PEC, it is equal to 91.6 kWh/m^2a, and so it is lower compared to the previous scenario, and the same is for the RC – *i.e.,* 9.3 €/m^2a – and the CO_2-eq emissions – *i.e.,* 27.8 kg/m^2a.

Table 7.20. RCP 8.5 50% warming: Performance indicators of the neighborhood with PV panels and PV sharing (Scenario 3)

SCENARIO 3	***Neighborhood***
TEDh [kWh/m^{2}a]	11.2
TEDc [kWh/m^{2}a]	48.1
PEC [kWh/m^{2}a]	91.6
RC [€/m^{2}a]	9.3
CO_2-eq [kg/m^{2}a]	27.8

Scenario 4: As in the homologous scenario of the previous case, the fourth scenario consists of coupling the installation of PV panels with the PV sharing and the replacement of the existing HVAC systems with more efficient reversible air-source electric heat pumps, which satisfy both the heating and the cooling demands. Results are indicated in table 7.21.

Table 7.21. RCP 8.5 50% warming: Performance indicators of the neighborhood with PV panels, PV sharing and more efficient reversible air-source electric heat pumps (Scenario 4)

SCENARIO 4	***Neighborhood***
TEDh [kWh/m^{2}a]	10.9
TEDc [kWh/m^{2}a]	48.1
PEC [kWh/m^{2}a]	74.8
RC [€/m^{2}a]	7.0
CO_2-eq [kg/m^{2}a]	21.7

In this scenario, the TEDh is slightly reduced – *i.e.*, it is 10.9 kWh/m^{2}a –, while the TEDc does not vary from the previous scenarios. For what concerns all the other performance indicators, sensible improvements are obtained compared to previously discussed scenarios, due to the replacement of the HVAC systems. In detail, at the neighborhood level, the PEC is equal to 74.8 kWh/m^{2}a, the RC is 7.0 €/m^{2}a and the CO_2-eq emissions are 21.7 kg/m^{2}a.

Scenario 5: The fifth examined scenario consists of coupling the installation of PV systems and the replacement of the existing HVAC systems with ERMs on the envelopes – *i.e.,* insulation layers on the external walls (0.07 m thick) and on the roofs (0.08 m thick), replacement of single pane windows with double-glazed ones with argon-filling, low-emitting coatings and PVC frames. Results are reported in table 7.22.

Due to ERMs on the HVAC systems and on the envelopes, the TEDh, is deeply reduced and it varies between 0.3 kWh/m^{2}a for the educational building and 1.6 kWh/m^{2}a for building 1. Concerning the TEDc, it is influenced by the considered ERMs too. More precisely, the TEDc values are included between 35.0 kWh/m^{2}a for building 1 and 60.3 for the educational building. Taking into account the effects of the primary energy systems as well as the energy consumption due to electric facilities and to lights, the PEC is evaluated and it is included between 44.2 kWh/m^{2}a for the educational building and 80.4 kWh/m^{2}a for the building 2. Considering the financial perspective, the RC is similar for buildings 1, 3 and 4 – *i.e.*, 7.0 €/m^{2}a, 6.1 €/m^{2}a and 6.8 €/m^{2}a, respectively – , while it is sensibly lower for the educational building – *i.e.*, 3.4 €/m^{2}a – and slightly higher for building 2 – *i.e.*, 8.7 €/m^{2}a. For what concerns the environmental impact, the CO_2-eq emissions vary from 12.8 kg/m^{2}a for the educational building and 25.7 kg/m^{2}a for building 2.

Table 7.22. RCP 8.5 50% warming: Performance indicators of the neighborhood with PV panels, more efficient reversible air-source electric heat pumps and ERMs on the envelopes (Scenario 5)

SCENARIO 5	Building 1	Building 2	Building 3	Building 4	Educational Building	*Neighborhood*
TEDh [kWh/m^{2}a]	1.6	1.3	1.2	1.1	0.3	1.0
TEDc [kWh/m^{2}a]	35.0	37.0	39.3	37.9	60.3	42.9
PEC [kWh/m^{2}a]	68.4	80.4	62.9	67.7	44.2	63.6
RC [€/m^{2}a]	7.0	8.7	6.1	6.8	3.4	6.3
CO_2-eq [kg/m^{2}a]	21.2	25.7	19.4	21.1	12.8	19.7

At neighborhood level, the situation is almost the same. In detail, the TEDh and the TEDc are 1.0 kWh/m^{2}a and 42.9 kWh/m^{2}a, respectively, the PEC is 63.6 kWh/m^{2}a, the RC is 6.3 €/m^{2}a and the CO_2-eq emissions are equal to 19.7 kg/m^{2}a.

Scenario 6: The sixth and last scenario investigated consists of coupling all the previously seen ERMs – *i.e.*, installation of PV systems, implementation of PV sharing, replacement of HVAC systems, insulation of the external walls and of the roofs, replacement of the windows. The examined performance indicators are indicated in table 7.23.

Table 7.23. RCP 8.5 50% warming: Performance indicators of the neighborhood with PV panels, PV sharing, more efficient HVAC systems and ERMs on the envelopes (Scenario 6)

SCENARIO 3	*Neighborhood*
TEDh [kWh/m^{2}a]	1.0
TEDc [kWh/m^{2}a]	42.9
PEC [kWh/m^{2}a]	61.9
RC [€/m^{2}a]	6.1
CO_2-eq [kg/m^{2}a]	19.0

Firstly, the TEDh and the TEDc have the same values of the previous scenario, as predictable. Concerning the PEC, the RC and the CO_2-eq emissions, they are all inferior compared to scenario 5 and are respectively equal to 61.9 kWh/m^{2}a, to 6.1 €/m^{2}a and to 19.0 kg/m^{2}a.

Comparison: As for the previous case, a comparison between the performance indicators assessed in each scenario has been realized. Once again, the comparison consists of comparing the values of the performance indicators evaluated for the neighborhood as built (Scenario 1) with the ones obtained for all the other scenarios, where ERMs are applied to buildings. The comparison has been performed at the neighborhood level and the results are reported in table 7.24. Note that positive Δ values denote a reduction of the considered performance indicator.

Table 7.24. RCP 8.5 50% warming: Comparison of the main performance indicators at the neighborhood level between the neighborhood as built (Scenario 1) and all the other scenarios

Neighborhood level	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Reference: Scenario 1*
ΔTEDh [kWh/m^{2}a]	0	0	0.3	10.2	10.2	11.2
ΔTEDc [kWh/m^{2}a]	0	0	0	5.2	5.2	48.1
ΔPEC [kWh/m^{2}a]	27.5	29.5	46.3	57.5	59.2	121.1
ΔRC [€/m^{2}a]	3.8	3.9	6.2	6.9	7.1	13.2
ΔCO_2-eq [kg/m^{2}a]	9.9	10.7	16.8	18.8	19.5	38.5

** Note that the values under the column "Scenario 1" are the reference values.*
For the other scenario, positive values denote a reduction (saving).

Reductions in terms of TEDh and TEDc are obtained only for scenarios that involve ERMs affecting the HVAC systems or the envelopes. More in detail, if ERMs are applied to only to HVAC systems, the TEDh is reduced by 0.3 kWh/m^{2}a, while the TEDc does not vary. When ERMs applied to envelopes too, the TEDh is reduced by 10.2 kWh/m^{2}a, while the TEDc by 5.2 kWh/m^{2}a. Considering the primary energy systems as well as the energy consumption due to lights and electric facilities, the PEC is evaluated. As predictable, the highest reductions of PEC are obtained when more ERMs are taken into account, which means for Scenarios 5 and 6 – *i.e.*, the PEC is reduced by 57.5 kWh/m^{2}a and 59.2 kWh/m^{2}a, respectively –, even if by only implementing PV systems as in Scenario 2 sensible reductions are obtained too – *i.e.*, the PEC reduction is equal to 27.5 kWh/m^{2}a. Once again, it is confirmed that the implementation of the PV sharing in coupling with the PV panels guarantees only marginal reductions in terms of PEC, RC and CO_2-eq emissions, even if for the former (PEC) some sensible improvements are obtained, while for the latter (RC and CO_2-eq emissions) the marginality is much more evident. When referring to RC, if PV sharing is not implemented, such as in Scenarios 2 or 5, the reduction is equal to 3.8 €/m^{2}a or to 7.0 €/m^{2}a, respectively, while when it is implemented, such as in Scenarios 3 and 6, the RC reduction is equal to 3.9 €/m^{2}a or to 7.1 €/m^{2}a. The situation is quite similar when CO_2-eq emissions are considered. More in general, the CO_2-eq emissions reduction is included between 9.9 kg/m^{2}a for Scenario 2 and 19.5 kg/m^{2}a for Scenario 6. As previously seen, also for what concerns the CO_2-eq emissions, more sensible reductions are obtained more ERMs are applied.

Generally speaking, also for the RCP 8.5 50% warming case, all the retrofit scenarios produce important improvements in terms of energy, financial and environmental performance indicators compared to the neighborhood as built. As seen, more ERMs imply higher reductions for the aforementioned indicators, and so, once again, the solution provided in Scenario 6 results to be the one that minimizes the most all the performance indicators, satisfying both the public and the private perspectives. It consists of ERMs on the envelopes – *i.e.,* insulation of the external walls and of the roofs, replacement of the single pane windows with double-glazed ones with argon-filling, low-emitting coatings and PVC frames – and on the primary energy systems – *i.e.*, installation of PV panels on 90% of the useful roofs areas, implementation of PV sharing and replacement of the existing HVAC systems with more efficient reversible air-source electric heat pumps. However, also in this case, the best tradeoff between energy, economic and environmental savings and difficulty to implement may be the solution examined in the Scenario 4, where the measures on the primary energy systems are the same as in Scenario 6, but the envelopes are not retrofitted. In fact, Scenarios 5 and 6 provide higher reductions/savings of the performance indicators, but they are more difficult to implement.

RCP 8.5 95% warming

Scenario 1: As previously said, the first scenario consists of studying the energy and the environmental performance of the neighborhood as built, without any ERM. The examined performance indicators are reported in table 7.25.

Table 7.25. RCP 8.5 95% warming: Performance indicators of the neighborhood as built (Scenario 1)

SCENARIO 1	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	12.2	10.8	10.7	10.3	5.0	9.5
TEDc [kWh/m^{2}a]	43.6	44.8	47.6	45.4	69.5	51.3
PEC [kWh/m^{2}a]	124.8	123.2	125.7	126.1	111.1	121.4
RC [€/m^{2}a]	13.6	13.5	13.8	13.8	12.3	13.3
CO_2-eq [kg/m^{2}a]	39.7	39.4	40.3	40.6	36.2	39.0

In this case, the situation is quite different compared to the two previous cases, due to higher external temperatures. Generally speaking, in this case the TEDh is lower compared to RCP 4.5 50% warming and to RCP 8.5 50% warming, while the TEDc is higher. In detail, the TEDh is included between 5.0 kWh/m^{2}a for the educational building and 12.2 for building 1. The higher value for building 1 is due to neighboring buildings, which produce an important shadowing effect. The educational building is characterized again by the lowest TEDh – *i.e.*, 5.0 kWh/m^{2}a – and the highest TEDc – *i.e.*, 69.5 kWh/m^{2}a –, while building 1 has the lowest TEDc – *i.e.*, 43.6 kWh/m^{2}a. However, all TEDc values are much higher than in the two previous cases. For what concerns the PEC, it varies between 111.1 kWh/m^{2}a for the educational building and 126.1 kWh/m^{2}a for building 4. From a financial perspective, the RC is quite similar for all the residential buildings – *i.e.*, it varies from 13.5 €/m^{2}a for building 2 to 13.8 €/m^{2}a for buildings 3 and 4 –, while it is lower for the educational building – *i.e.*, 12.3 €/m^{2}a. Finally, from an environmental point of view, the CO_2-eq emissions are included between 36.2 kg/m^{2}a for the educational building and 40.6 kg/m^{2}a for building 4.

Globally, at the neighborhood level, the TEDh and the TEDc are 9.5 kWh/m^{2}a and 51.3 kWh/m^{2}a, respectively, while the PEC is equal to 121.4 kWh/m^{2}a. In conclusion, the RC is 13.3 €/m^{2}a and the CO_2-eq emissions value is equal to 39.0 kg/m^{2}a.

Scenario 2: The second scenario consists of installing monocrystalline PV panels on 90% of the useful roof areas of the neighborhood buildings. Results are indicated in table 7.26.

Table 7.26. RCP 8.5 95% warming: Performance indicators of the neighborhood with PV panels (Scenario 2)

SCENARIO 2	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	12.2	10.8	10.7	10.3	5.0	9.5
TEDc [kWh/m^{2}a]	43.6	44.8	47.6	45.4	69.5	51.3
PEC [kWh/m^{2}a]	100.1	111.8	92.8	96.9	72.6	93.7
RC [€/m^{2}a]	10.4	12.1	9.4	10.0	6.6	9.5
CO_2-eq [kg/m^{2}a]	30.7	35.2	28.4	30.0	22.2	28.9

No ERMs are applied on the HVAC systems neither on the envelopes, thus the TEDh and the TEDc are the same of the previous scenario (neighborhood as built). Concerning the PEC, it varies from 72.6 kWh/m^{2}a for the educational building to 111.8 kWh/m^{2}a for building 2. Once again, the educational building is characterized by the lowest value of PEC. From the financial perspective, the implementation of PV systems guarantees important improvements in terms of RC, therefore the RC is lower where the boundary conditions and the geometry of buildings are favorable to the direct solar radiation deployment. More in detail, the RC is included between 6.6 €/m^{2}a for the educational building and 12.1 €/m^{2}a for buildings 2. Finally, from the environmental perspective, the educational building is characterized by the lowest value of CO_2-eq emissions – *i.e.,* 22.2 kg/m^{2}a –, while building 2 by the highest one – *i.e.,* 35.2 kg/m^{2}a.

At neighborhood level, the PEC, the RC and the CO_2-eq emissions are equal to 93.7 kWh/m^{2}a, to 9.5 €/m^{2}a and to 28.9 kg/m^{2}a, respectively.

Scenario 3: The third scenario consists of coupling the installation of monocrystalline PV panels, as in the previous scenario, with the implementation of the PV sharing. The main performance indicators referred to the neighborhood level are indicated in table 7.27.

Table 7.27. RCP 8.5 95% warming: Performance indicators of the neighborhood with PV panels and PV sharing (Scenario 3)

SCENARIO 3	***Neighborhood***
TEDh [kWh/m^{2}a]	9.5
TEDc [kWh/m^{2}a]	51.3
PEC [kWh/m^{2}a]	91.7
RC [€/m^{2}a]	9.4
CO_2-eq [kg/m^{2}a]	28.2

No variations happen to the TEDh and the TEDc, due to the absence of ERMs involving the envelopes. The PEC is equal to 91.7 kWh/m^{2}a, thus it is lower compared to the previous scenario, and the same is for the RC – *i.e.,* 9.4 €/m^{2}a – and the CO_2-eq emissions – *i.e.,* 28.2 kg/m^{2}a.

Scenario 4: As in the homologous scenario of the other two cases, the fourth scenario consists of coupling the installation of PV panels with the PV sharing and the replacement of the existing HVAC systems with more efficient reversible heat pumps for both space heating and space cooling. Results in terms of the addressed performance indicators are reported in table 7.28.

In this scenario, the TEDh is slightly reduced compared to the previous scenarios, while the TEDc is the same. However, concerning all the other indicators, important improvements are guaranteed by the presence of the heat pumps. More in detail, the PEC is 74.5 kWh/m^{2}a, the RC is 7.1 €/m^{2}a and the CO_2-eq emissions are 21.9 kg/m^{2}a.

Table 7.28. RCP 8.5 95% warming: Performance indicators of the neighborhood with PV panels, PV sharing and more efficient reversible air-source electric heat pumps (Scenario 4)

SCENARIO 4	***Neighborhood***
TEDh [kWh/m^{2}a]	9.2
TEDc [kWh/m^{2}a]	51.3
PEC [kWh/m^{2}a]	74.5
RC [€/m^{2}a]	7.1
CO_2-eq [kg/m^{2}a]	21.9

Scenario 5: The fifth scenario consists of coupling the installation of PV systems and the replacement of the existing HVAC systems with ERMs on the envelopes– *i.e.,* insulation layers on the external walls (0.07 m thick) and on the roofs (0.08 m thick), replacement of single pane windows with double-glazed ones with argon-filling, low-emitting coatings and PVC frames. Results are reported in table 7.29.

Table 7.29. RCP 8.5 95% warming: Performance indicators of the neighborhood with PV panels, more efficient reversible air-source electric heat pumps and ERMs on the envelopes (Scenario 5)

SCENARIO 5	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Educational Building**	***Neighborhood***
TEDh [kWh/m^{2}a]	1.3	1.0	0.9	0.8	0.2	0.8
TEDc [kWh/m^{2}a]	36.9	38.9	41.2	39.8	62.1	44.8
PEC [kWh/m^{2}a]	68.7	81.1	63.3	68.1	45.0	64.2
RC [€/m^{2}a]	7.0	8.8	6.2	6.9	3.5	6.3
CO_2-eq [kg/m^{2}a]	21.4	26.0	19.6	21.4	13.1	19.9

Because of the ERMs on the HVAC systems and on the envelopes, the TEDh, is sensibly reduced and it is included between 0.2 kWh/m^{2}a for the educational building and 1.3 kWh/m^{2}a for building 1. For what concerns the TEDc, it varies from 36.9 kWh/m^{2}a for building 1 to 62.1 for the educational building. In terms of PEC, important reductions are obtained as well. More in detail, it is included between 45.0 kWh/m^{2}a for the educational building and 81.1 kWh/m^{2}a for building 2. From a financial point of view, the RC is similar for buildings 1, 3 and 4 – *i.e.,* 7.0 €/m^{2}a, 6.2 €/m^{2}a and 6.9 €/m^{2}a, respectively. The situation is slightly different for building 2 and for the educational building, where the RC is sensibly higher – *i.e.,* 8.8 €/m^{2}a – or lower – *i.e.,* 3.5 €/m^{2}a –, respectively. Finally, from an environmental perspective, the CO_2-eq emissions are included between 13.1 kg/m^{2}a for the educational building and 26.0 kg/m^{2}a for building 2.

At neighborhood level, the TEDh and the TEDc are 0.8 kWh/m^{2}a and 42.9 kWh/m^{2}a, respectively. The PEC is 64.2 kWh/m^{2}a, the RC is 6.3 €/m^{2}a and the CO_2-eq emissions are equal to 19.9 kg/m^{2}a.

Scenario 6: The sixth and last scenario consists of coupling all the previously seen ERMs – *i.e.,* installation of PV systems, implementation of PV sharing, replacement of HVAC systems, insulation of the external walls and of the roofs, replacement of the windows. Results are reported in table 7.30.

The TEDh and the TEDc are not different from the previous scenario, as predictable. Concerning the PEC, the RC and the CO_2-eq emissions, they are all inferior compared to scenario 5 and are respectively equal to 62.5 kWh/m^{2}a, to 6.2 €/m^{2}a and to 19.3 kg/m^{2}a.

Table 7.30. RCP 8.5 95% warming: Performance indicators of the neighborhood with PV panels, PV sharing, more efficient HVAC systems and ERMs on the envelopes (Scenario 6)

SCENARIO 3	***Neighborhood***
TEDh [kWh/m^{2}a]	0.8
TEDc [kWh/m^{2}a]	44.8
PEC [kWh/m^{2}a]	62.5
RC [€/m^{2}a]	6.2
CO_2-eq [kg/m^{2}a]	19.3

Comparison: Similarly to the two previous cases, a comparison has been performed between the values of the performance indicators assessed for the neighborhood as built (Scenario 1) with the ones obtained for all the other scenarios, where ERMs are applied to buildings. Results are indicated in table 7.31. As said, note that positive Δ values denote a positive effect – *i.e.,* a reduction of the considered performance indicator.

Table 7.31. RCP 8.5 95% warming: Comparison of the main performance indicators at the neighborhood level between the neighborhood as built (Scenario 1) and all the other scenarios

Neighborhood level	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Reference: Scenario 1***
ΔTEDh [kWh/m^{2}a]	0	0	0.3	8.7	8.7	9.5
ΔTEDc [kWh/m^{2}a]	0	0	0	6.5	6.5	51.3
ΔPEC [kWh/m^{2}a]	27.7	29.7	46.9	57.2	58.9	121.4
ΔRC [€/m^{2}a]	3.8	3.9	6.2	7	7.1	13.3
ΔCO_2-eq [kg/m^{2}a]	10.1	10.8	17.1	19.1	19.7	39

** Note that the values under the column "Scenario 1" are the reference values.*
For the other scenario, positive values denote a reduction (saving).

Reductions in terms of TEDh and TEDc are seen only for scenarios where ERMs affect the HVAC systems or the envelopes – *i.e.,* Scenarios 4, 5 and 6 –, as predictable. In Scenario 4, the TEDh is reduced by 0.3 kWh/m^{2}a, while the TEDc does not vary from the baseline situation. For what concerns Scenarios 5 and 6, sensible decrements for both the TEDh and the TEDc are attained. In detail the TEDh is reduced by 8.7 kWh/m^{2}a, while the TEDc by 6.5 kWh/m^{2}a. In terms of PEC, the situation is really different by passing from one scenario to another. In detail, the highest reduction of PEC is obtained in Scenario 6, where all the ERMs are taken into account, and it is equal to 58.9 kWh/m^{2}a. In Scenario 5, where the same ERMs are considered with the exception of the PV sharing, the PEC reduction is still sensible compared to the neighborhood as built and it is 57.2 kWh/m^{2}a. However, important reductions are obtained even if ERMs are not applied to envelopes, such as in the remaining Scenarios 2, 3 and 4. In these cases, the PEC reduction is equal to 27.7 kWh/m^{2}a, to 29.7 kWh/m^{2}a and to 46.9 kWh/m^{2}a, respectively. The PV sharing guarantees some sensible improvements in terms of PEC, while the improvements are more marginal referring to RC and to CO_2-eq emissions. Concerning the RC, if PV sharing is not implemented, such as in Scenarios 2 and 5, the reduction is equal to 3.8 €/m^{2}a or to 7.0 €/m^{2}a, respectively, while, on the other hand, if it is implemented, such as in Scenarios 3 and 6, the RC reduction is equal to 3.9 €/m^{2}a or to 7.1 €/m^{2}a. The situation is quite similar when referring to CO_2-eq emissions. In general, the CO_2-eq emissions reduction is varies between 10.1 kg/m^{2}a for Scenario 2 and 19.7 kg/m^{2}a for Scenario 6. As said, CO_2-eq emissions are reduced more in deep if all the ERMs are applied, as predictable.

In conclusion, also for this last case – *i.e.,* RCP 8.5 95% warming –, all the considered retrofit scenarios have sensible implications in terms of energy, financial and environmental performance indicators compared to the neighborhood as built, without any ERM. As predictable, if more ERMs are combined, higher reductions for the aforementioned indicators are obtained, and so the solution provided in Scenario 6 results to be the one that minimizes the most the PEC, the RC and the CO_2-eq emissions, satisfying the most both the public perspective and the private perspective. However, once again, the best tradeoff between energy, economic and environmental savings and difficulty to implement may be the ERMs investigated in Scenario 4, where the envelopes are not retrofitted. In fact, in Scenarios 5 and 6, ERMs involve also the envelopes, and so they may be much more difficult to implement.

Comparison

Firstly, a brief comparison has been performed for the neighborhood "as built" – *i.e.,* the so-called "Scenario 1" – between the typical weather data and the different RCPs ones. The hourly results of the outdoor temperature and of the cooling demand have been shown with reference to the month of August, which has been considered as representative of the summer period. On the other hand, the hourly results of the heating demand for the same Scenario 1 have been displayed for the month of December, which has been assumed as reference month for the winter season. Note that the results in terms of heating and cooling demands have been depicted taking into account the stochastic approach, having previously validated its robustness in Section 4.1. Concerning the PV production, due to the higher uncertainty of the predictions on the solar radiation variations compared to the ones on the outdoor air temperatures, no differences have been assumed by passing from the typical weather data file available for Naples to the "RCP 8.5 95% warming" one for safety reasons, in order not to overestimate the energy and financial benefits produced by the implementation of PV systems.

For what concerns the outdoor air temperature, it is evident the increment of temperature by passing from the typical weather data file to the RCPs ones (see figure 7.3). This is particularly clear during the night hours, where a difference of around 6 °C with peaks of 8 °C is seen. During daylight hours, the aforementioned difference is lower and is equal to around 4 °C, with peaks of 6 °C. A slight difference between the homologue temperature values for the various RCPs is present too, even if it is much less evident compared to the difference with the typical weather data file. Indeed, the temperature difference between RCP 4.5 50% warming – *i.e.*, the least severe case – and RCP 8.5 95% warming – *i.e.*, the most severe case – is equal to around 1 °C.

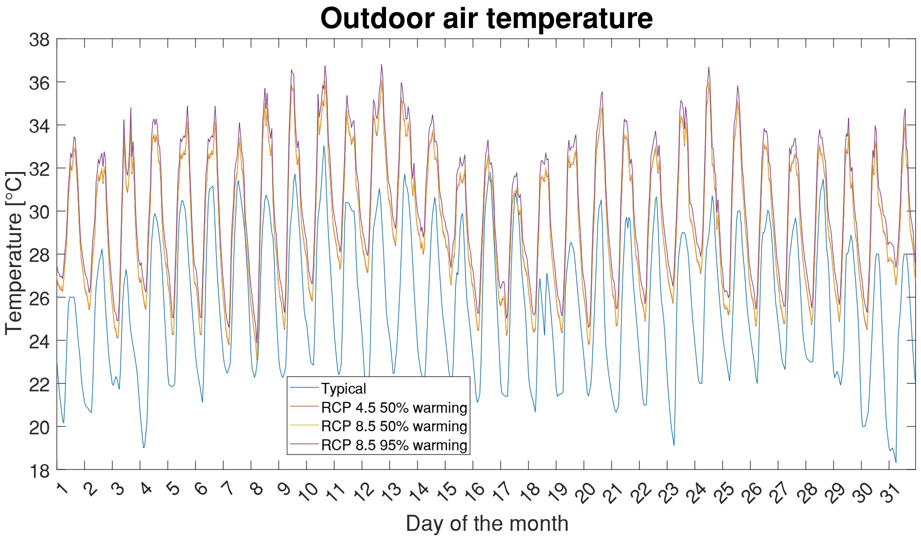

Figure 7.3. Outdoor air temperature trends during the month of August for the different weather data files considered

For what concerns the TED for heating at the neighborhood level, it is possible to notice that during the whole month of December the energy demand for the typical weather data file is much higher than the one relative to the RCPs weather data files (see figure 7.4).

In detail, the difference in terms of TEDh between the typical weather data file and the RCPs ones is equal to around 200-400 kWh during most hours of the months, even if a difference peak of around 1000 kWh is seen on the 27th of December. For what concerns the differences between the various RCPs weather files, these are lower compared with the ones between the typical weather data file and the RCPs ones, being of the magnitude of 50-100 kWh during the whole month.

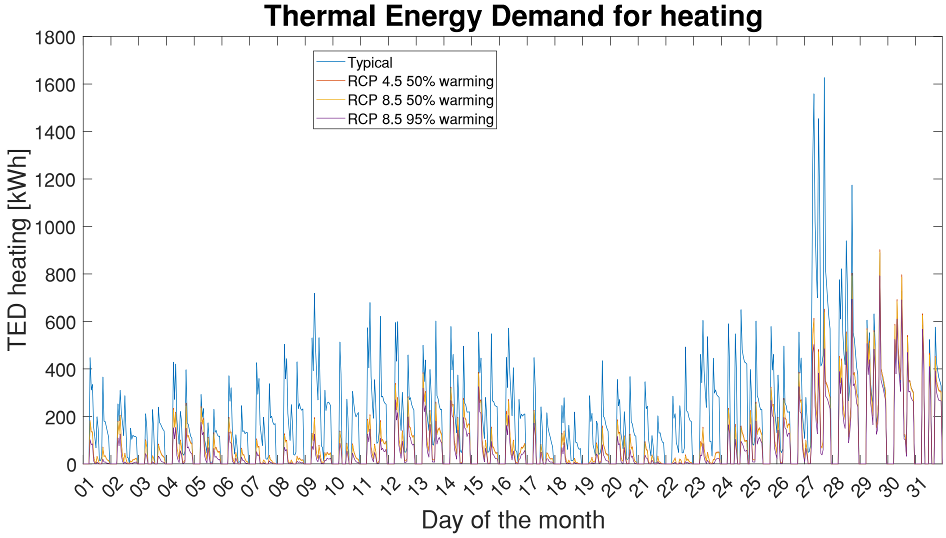

Figure 7.4. Heating energy demand trends during the month of December for the different weather data files considered

For what concerns the TED for cooling at the neighborhood level, as predictable, the values assessed are higher for the RCPs weather files compared to the ones obtained by considering the typical one (see figure 7.5). In detail, during the whole month, the mean difference on an hourly basis between the TEDc evaluated with the RCP 8.5 95% warming and the one assessed with the typical weather file is equal to around 150 kWh, while the highest peak difference is equal to around 1200 kWh – it happens on the 31st of August. Focusing on the values obtained only by considering the RCPs weather files, the mean difference between the most severe one – *i.e.*, RCP 8.5 95% warming – and the least severe one – *i.e.*, RCP 4.5 50% warming – is equal to 30 kWh, while the difference peak is equal to around 200 kWh and occurs on the 23rd of August.

All told, relevant differences have been assessed in terms of energy demand for heating and energy demand for cooling by varying the weather data file, and so by taking into account also the various RCPs. Therefore, once again it is outlined the importance of taking into account also the global warming effects when investigating energy retrofit solutions for the building sector.

A further comparison has been performed among all the Scenarios of all the three cases – *i.e.*, RCP 4.5 50% warming, RCP 8.5 50% warming and RCP 8.5 95% warming. Results at the neighborhood level are displayed in the following figures 7.6 and 7.7.

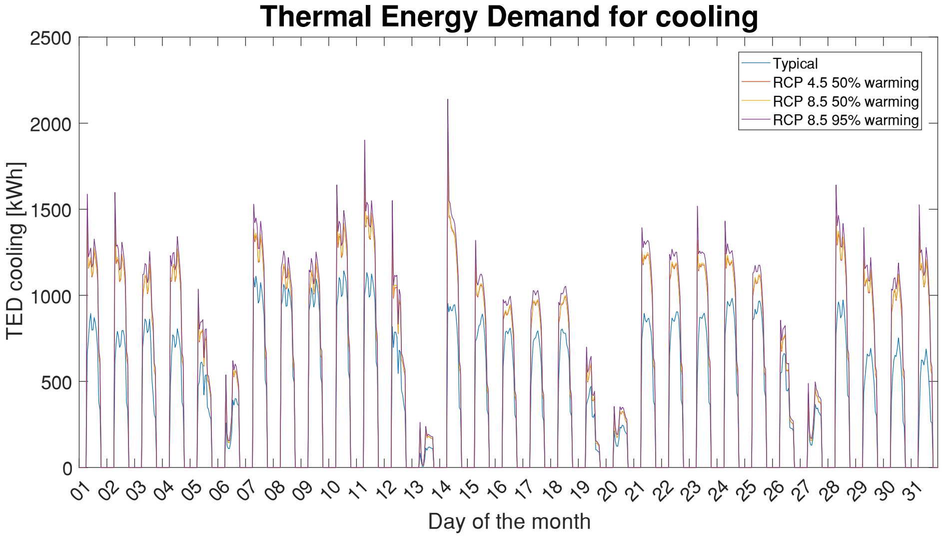

Figure 7.5. Cooling energy demand trends during the month of August for the different weather data files considered

Considering the neighborhood as built, the TEDh slightly decreases by passing from the least severe case (RCP 4.5 50% warming) to the most critical one (RCP 8.5 95% warming), while, on the other hand, the TEDc increases, as predictable. This difference in terms of TEDh and TEDc variation is much more evident by passing from RCP 8.5 50% warming to RCP 8.5 95% warming compared to when passing from RCP 4.5 50% warming to RCP 8.5 50% warming. This may be explained considering that the differences in terms of external temperatures are much more pronounced for the former couple compared to the ones for the latter one. Considering also the TEDh and the TEDc assessed by means of the typical weather data file, it is possible to observe the effects of the global warming on the energy performance of the neighborhood. Indeed, the TEDh passes from 20 kWh/m^{2}a (at neighborhood level) for the typical weather data file to 9.5 kWh/m^{2}a for RCP 8.5 95% warming, while the TEDc passes from 31.0 kWh/m^{2}a for the typical weather data file to 51.3 kWh/m^{2}a for RCP 8.5 95% warming. These sensible discrepancies show the importance of taking into account the effects of the global warming when evaluating the energy performance of a neighborhood, aiming at attaining robust results, especially if during the retrofit planning it is investigated the replacement of the HVAC systems, and so it is required to properly sizing them. Indeed, without considering the effects of global warming, the HVAC systems cannot be properly designed with predictable consequences not only on the thermal comfort of the occupants, but also on their health.

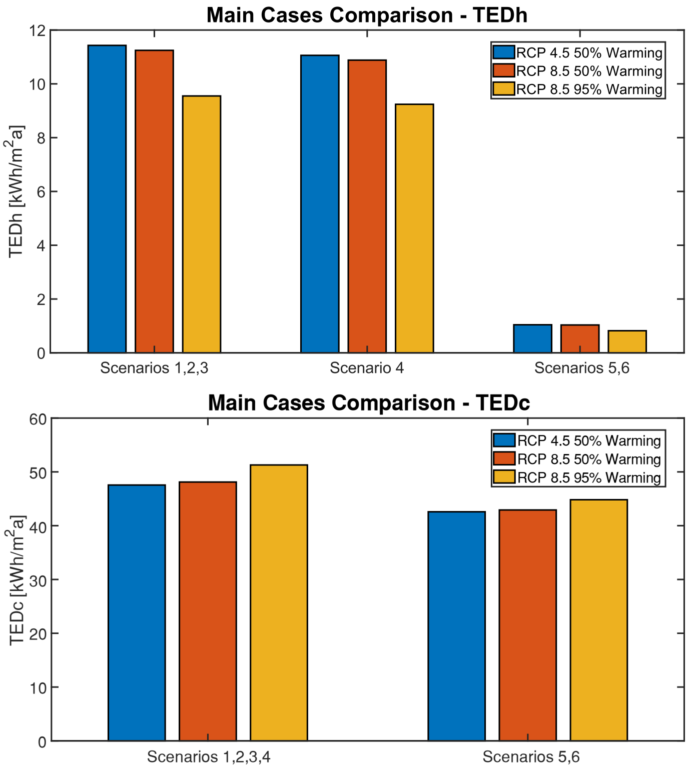

Figure 7.6. Effects of the ERMs on the HVAC systems or on the envelopes in terms of TEDh and TEDc for all the three cases considered. Sensible variations are particularly evident when passing from RCP 4.5 50 warming to RCP 8.5 95% warming

When ERMs involve the envelopes too, the aforementioned differences between the three cases investigated become less evident for both the TEDh and the TEDc, even if they are still present. The application of ERMs to the envelopes produces a crucial reduction of the TEDh for all the cases, allowing to nearly make it zero. The effects implied by the same measures are less pronounced when referring to TEDc, even if some improvements are obtained for this indicator too.

When referring to the other indicators – *i.e.*, the PEC, the RC and the CO2-eq emissions –, the differences in homologous scenarios among the three cases are generally less notable, especially for what concerns the cases RCP 4.5 50% and the RCP 8.5 50%, which are characterized by almost the same values of each indicator – note that a small difference is present, but it is nearly unnoticeable. This can be linked to the time horizon considered in the evaluation. At the year 2035, all the RCPs taken into account are characterized only by slight differences in terms of solar radiation and outdoor temperature – as predictable, the differences are more evident only by comparing the RCPs 4.5 50% warming and 8.5 50% warming with the RCP 8.5 95% warming. Therefore, in future works it would be worthy to analyze the effects of the same ERMs considering a farer time horizon, such as the years 2050 or 2060, even if farer years are characterized by high-rising uncertainty, compared to the reference year 2035 considered in this study.

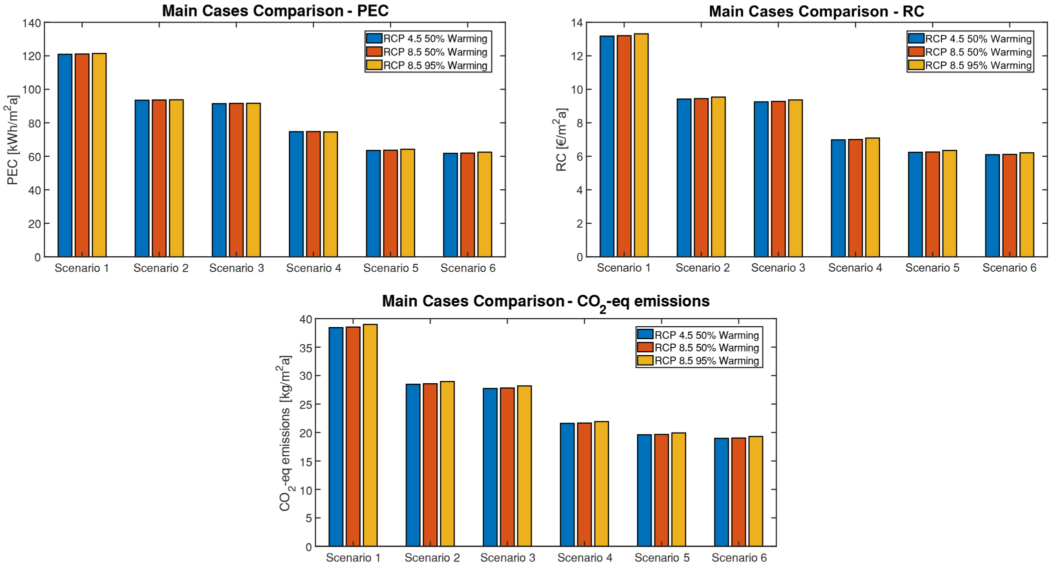

Figure 7.7. Effects of the ERMs on the envelopes in terms of PEC, RC and CO_2-eq emissions for all the three cases considered

Notably, the fact that climate change has apparently less influence on some indicators than expected is particularly evident for the PEC. More in general, by passing from the first scenario to the sixth, the PEC has a deep reduction by means of the considered ERMs. The decrement of the PEC is more sensible when more ERMs are applied, as predictable. This decrement is particularly considerable when passing from the neighborhood as built to Scenarios 2 or 3, or from the latter to Scenario 4. The difference between Scenarios 4, 5 and 6 is present, even if it is less remarkable. In addition, as said, the difference in terms of PEC between with and without implementing the PV sharing is almost zero. The situation is quite the same also for what concerns the RC and CO_2-eq emissions, as predictable, even if the discrepancy for each scenario between RCP 8.5 50% warming and RCP 8.5 95% warming is a bit more evident than for the PEC.

Once again, a comparison has been performed considering also the PEC, the RC and the CO_2-eq emissions for the neighborhood as built assessed by means of the typical weather data file. For what concerns the PEC, it is even higher than the one assessed in the RCP 8.5 95% warming case – *i.e.*, 121.5 kWh/m^{2}a (at the neighborhood level) for the typical weather data file, 121.4 kWh/m^{2}a for the RCP 8.5 95% warming case. In terms of RC, the latter is lower compared to all the other RC values of the homologous scenarios. Finally, the CO_2-eq emissions are the lowest too.

Notably, assuming a mid-term time horizon, the global warming has apparently a significant influence only on the TEDh and the TEDc, which deeply affect the sizing of the HVAC systems, while its influence on the PEC, on the RC and on the CO_2-eq emissions is apparently neglectable. However, this may be explained by considering that the TEDh decrement implies a reduction of the operation of the heating generation system, which is basically characterized by a lower energy efficiency, for its intrinsic nature, compared to the cooling generation system, with consequent reduction of its negative contributions in the assessment of the PEC, of the RC and of the CO_2-eq emissions. On the other hand, the significant increment of the TEDc implies a higher operativity of the cooling generation system. Unfortunately, the increment of the outdoor temperatures produces also a decrement of the operative COP of such cooling systems. Globally, these contrasting effects as concerns heating and cooling demands are counterbalanced (with reference to the examined time horizon), thereby not causing significant changes in PEC, RC and CO_2-eq emissions. However, the great variations in terms of TEDh and TEDc caused by the global warming are the demonstration of how important is to take into account climate change when planning the energy retrofit of a neighborhood or a district.

All told, the outcomes have shown that among all the investigated scenarios, the ones that provide ERMs on the envelopes too – *i.e.*, Scenarios 5 and 6 – are the most efficient from both the energy and the environmental perspective, and results even cost-effective, producing an important reduction of RC too. The solution provided in Scenario 6 is the one that both the public perspective and the private perspective would choose, because it allows to minimize the PEC, the RC and the CO_2-eq emissions. However, if the difficulties in physically implementing these kinds of ERMs are taken into account, the best tradeoff solution between energy, financial and environmental savings and difficulty of implementation may be the ERMs proposed in Scenario 4 – *i.e.*, installation of monocrystalline PV panels on 90% of useful roof areas, implementation of PV sharing and replacement of existing HVAC systems with more efficient reversible air-source electric heat pumps for both space heating and space cooling. The ERMs considered in Scenario 4, in fact, allow to deeply reduce the PEC, the RC and the CO_2-eq emissions compared to the neighborhood as built (Scenario 1) in all the cases, without having to face severe construction difficulties as for the ERMs involving the envelopes.

Therefore, scenario 4 can represent the most adequate trade-off between energy, financial and environmental savings and difficulty to implement.

In conclusion, the proposed analysis approach enables to achieve worthy outcomes for what concerns the energy retrofit planning of neighborhoods of buildings, with feasible computational burden and times – *i.e.,* each simulation run lasts about 12 minutes by using a processor Intel® Core^{TM} i7-8750H at 2.20 GHz. Therefore, precious indications have been achieved with the aim to renovate the Italian building stock, taking into account crucial issues such as global warming.

Final remarks

The study presented in this chapter provides a comprehensive approach to investigate the effects of common energy retrofit measures (ERMs) on energy, financial and environmental performance indicators when planning the energy retrofit of districts or neighborhoods. The main novelties introduced to the current body of knowledge consist of: 1) considering the stochasticity of the occupant behavior that deeply affects the energy demand by differentiating the usage profiles and assigning them to residential thermal zones according to a normal distribution; 2) considering the effects of global warming on the ERMs by taking into account different Representative Concentration Pathways (RCPs). More in detail, the approach is based on EnergyPlus, as dynamic energy simulator, and MATLAB®, as postprocessing engine.

The provided approach enables to attain reliable results in planning the energy retrofit of districts or neighborhoods. Therefore, it can be an important tool capable to simultaneously satisfy all the actors involved in the decision making process, such as the public perspective, whose main goal is to reduce the energy and the environmental impact of the existing building stock, and the private perspective, whose main goal is to maximize the financial profits from the building retrofit, even if in general the attention of the collectivity towards sustainability is strongly increasing worldwide, thus sustainable solutions are wished by this perspective too.

This is how the multi-objective optimization of the energy retrofit of single buildings or neighborhoods/districts should be conducted, aiming at massively reducing human impact on the environment.

Appendix – Stochastic residential occupancy profiles

Table A1. Residential occupancy profile "A"

OCCUPANCY PROFILE - A																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 1/6	All Days																								
1/7 – 6/30	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00														1.00	1.00	1.00	1.00
	Weekends																								
7/1 – 8/31	All Days																								
9/1 – 12/23	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00														1.00	1.00	1.00	1.00
	Weekends																								
12/24 – 1/31	All Days																								

Table A2. Residential occupancy profile "B"

OCCUPANCY PROFILE - B																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 1/3	All Days																								
1/4 – 6/30	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50											1.00	1.00	1.00	1.00	1.00	1.00
	Weekends																								
7/1 – 8/31	All Days																								
9/1 – 12/27	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50											1.00	1.00	1.00	1.00	1.00	1.00
	Weekends																								
12/28 – 1/31	All Days																								

Table A3. *Residential occupancy profile "C"*

OCCUPANCY PROFILE - C																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 7/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.20	0.20						0.40	0.40	0.40	0.50	0.50	0.50	1.00	1.00	1.00
	Saturdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00						0.50	0.50	0.50	0.50	0.50	0.50					1.00
	Sundays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00											1.00	1.00	1.00	1.00	1.00
8/1 – 8/31	All Days																								
9/1 – 12/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.40	0.20	0.20						0.40	0.40	0.40	0.50	0.50	0.50	1.00	1.00	1.00
	Saturdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00						0.50	0.50	0.50	0.50	0.50	0.50					1.00
	Sundays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00											1.00	1.00	1.00	1.00	1.00

Table A4. *Residential occupancy profile "D"*

OCCUPANCY PROFILE - D																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 8/12	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.30	0.30	0.20	0.20				0.40	0.40	0.40	0.50	0.50	0.50	1.00	1.00	1.00
	Saturdays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.70	0.70	0.70	0.70	0.70	0.20	0.20	0.20	0.20	1.00
	Sundays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00								0.70	0.70	0.80	1.00	1.00	1.00	1.00	1.00
8/13 – 8/26	All Days																								
8/27 – 12/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.30	0.30	0.20	0.20				0.40	0.40	0.40	0.50	0.50	0.50	1.00	1.00	1.00
	Saturdays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.70	0.70	0.70	0.70	0.70	0.20	0.20	0.20	0.20	1.00
	Sundays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00								0.70	0.70	0.80	1.00	1.00	1.00	1.00	1.00

Table A5. *Residential occupancy profile "E"*

Occupancy Profile - E																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 8/12	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.30	0.30	0.20	0.20	0.30	0.30	0.40	0.50	0.50	0.50	0.80	0.80	1.00	1.00	1.00	1.00
	Saturdays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.50	0.50	0.50	0.50	0.80
	Sundays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.80	0.80	1.00	1.00	1.00	1.00	1.00
8/13 – 8/19	All Days																								
8/20 – 12/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.30	0.30	0.20	0.20	0.30	0.30	0.40	0.50	0.50	0.50	0.80	0.80	1.00	1.00	1.00	1.00
	Saturdays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.50	0.50	0.50	0.50	0.80
	Sundays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	1.00	1.00	1.00	1.00	1.00	0.80	0.80	1.00	1.00	1.00	1.00	1.00

Table A6. *Residential occupancy profile "F"*

Occupancy Profile - F																									
PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 8/12	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.20	0.20	0.20	0.20	0.50	0.50	0.50	0.80	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00
	Weekends	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00								0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00
8/13 – 8/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.50	0.50	0.50	0.50	0.50	0.80	0.80	1.00	1.00	1.00	1.00	0.80	0.80	0.80	1.00	1.00
	Weekends																								
9/1 – 12/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.20	0.20	0.20	0.20	0.50	0.50	0.50	0.80	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00
	Weekends	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00								0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00

Table A7. *Residential occupancy profile “G”*

OCCUPANCY PROFILE - G

PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 12/31	Weekdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.20	0.20	0.20	0.20	0.20	0.20	0.50	0.50	1.00	1.00	1.00	1.00
	Weekends	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00							1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table A8. *Residential occupancy profile “H”*

OCCUPANCY PROFILE - H

PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 12/31	Weekdays Saturdays	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Sundays	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table A9. *Residential occupancy profile “I”*

OCCUPANCY PROFILE - I

PERIOD	*DAY*	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-24**
1/1 – 12/31	All Days	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.70	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

CHAPTER 8. Conclusions

Cities are responsible for about 65% of the world energy consumption and buildings bear a crucial responsibility, accounting for around 40% of energy consumption and for around 36% of CO2-eq emissions at the European Union (EU) level, as seen. Therefore, it is widely recognized that there is a crucial need of improving the energy efficiency of the building sector, aiming at coping the huge human impact on the environment. For this purpose, several strategies have been studied in literature with the aim to fight the issues related to the polluting impact of buildings. Some strategies mainly focus on stand-alone buildings, while others are particularly suitable for districts. Considering this background, in this study five different approaches and applications have been proposed, with the aim to enhance the current body of knowledge, and thus to solve the existing knowledge gaps. All these five approaches are based on the same general methodological approach, which has been particularized and adapted to the investigated situations, with the aim to fulfill the knowledge gaps outlined in Chapter 2 and, more in general, to give more powerful instruments to face most of the possible energy, financial and environmental issues due to buildings. Generally speaking, this "primitive" approach consists in coupling an easy-to-use geometrical modeling software with a reliable dynamic energy simulator and a powerful post-processing engine. As seen, the geometrical model is mainly realized by means of the well-known graphical interface DesignBuilder®, while the energy model is refined by the free tool Energy Plus, where also the dynamic energy behavior of the building/neighborhood is simulated. Finally, the adoption of MATLAB® as post-processing engine allows to automatically run energy simulations – thanks to an in-house developed coupling function between Energy Plus and MATLAB® itself –, each one considering a specific combination of energy efficiency measures, and, moreover, to assess the objective functions. In conclusion, two or more “optimal” solutions among all the investigated combinations may be picked by the designer, according to the needs of the involved stakeholders. This is the general methodological approach from which all the techniques discussed in this thesis are derived.

All told, in the following lines, the purposes and the main outcomes obtained from the independent application of the proposed approaches are described. Finally, some general results of this study are outlined.

8.1. Independent application of the proposed approaches

The first study provides a comprehensive approach to optimize the energy design of the building envelope with the aim to simultaneously increase the energy performance, the economic benefits and the thermal comfort, allowing to satisfy both the public perspective and the private one. By means of the coupling of the optimization "engine" MATLAB® with the dynamic energy simulator EnergyPlus, a genetic algorithm performs an optimization process that minimizes three different objective functions: primary energy consumption, global cost and discomfort hours. MATLAB® automatically runs EnergyPlus simulations and manages the outputs of energy simulations. The performed optimization process considers energy measures for the envelope by assuming as energy systems the more efficient and common ones available on the market, according to local best-practice. Finally, two optimal solutions are individuated: the nZEB one – which is the solution on the Pareto front that minimizes the primary energy consumption – and the cost-optimal one – which is the solution on the Pareto front that minimizes the global cost.

As a case study, the proposed approach is applied for the energy design of a new building, typical of the Italian residential stock. The same geometrical model is supposed to be located in 4 different Italian cities, each one representing a climatic zone: Palermo (climatic zone B), Naples (C), Florence (D), Milan (E). Globally, the optimal results provide the following main conclusions:

- the set-point temperatures for space conditioning have a strong influence on the considered objective functions, independently on the climatic zone. The set point values of the HVAC system for space heating and cooling are the same for all climatic zones, *i.e.*, 19 °C and 27 °C, respectively – except for the cost-optimal solution for Palermo, where the cooling set-point is 25 °C in order to guarantee satisfying thermal comfort levels for the occupants;
- the solar absorbance of the external surfaces of roof and vertical walls tend to increase from warmer to colder climatic zones;
- when implemented, the thermal insulation layer is external because this allows to achieve higher values of envelope temperatures; an external polyurethane layer 0.10 m or 0.12 m thick should be implemented for both vertical walls and roof – except for few cases – while the floor insulation is generally not considered as optimal solution;

- the optimal U-values of vertical walls and roof are around 0.20 W/m^{2}K, while higher optimal values are achieved for the floor;
- more massive external vertical walls should be preferred in colder climates because of their thermal inertia. However, in warmer climatic zones roofs should be more massive to better exploit their thermal inertia during the cooling season, being critically invested by the solar irradiation. In this regard, the nZEB solutions provide that roof block density should pass from 1800 kg/m^3 for Palermo to 1000 kg/m^3 for Milan, and similar results are achieved for the cost-optimal solutions too;
- as concerns the windows, moving from warmer to colder climatic zones, windows with higher SHGC values should be installed. Finally, triple-glazed with argon-filling and low-e coating windows are recommended not only in colder climates but also in average ones such as Naples, given the use destination (residential) that does not provide high internal heat loads (which could provide high space cooling demand in presence of high-insulated building envelopes);
- the optimal orientation for all the climatic zones is with the major side exposed to the East-West for energy and comfort reasons.

Furthermore, in comparison with reference designs complying with Italian regulations and construction practices, all solutions ensure significant energy savings and most of them imply high net present values with payback times equal to zero or lower than 10 years. Notably, the proposed cost-optimal solutions are much more cost-effective, as predictable, and at the same time they are almost as energy-efficient as the nZEB ones especially for colder climates, and therefore also the public stakeholders – and not only the private ones – could opt for this type of solutions in several situations.

Finally, the achieved outcomes can provide precious indications to both public and private stakeholders for rebuilding part of the Italian/European residential stock – depending on the climatic location – with a view to energy-efficiency and cost-optimality.

Unfortunately, the presented methodology is suitable only for new buildings, involving in the optimization process many design variables that may be varied exclusively during the early-stage of the energy design of a new construction. This is the main limit of this study. Therefore, a further approach has been presented in this study for the optimization of the energy retrofit of existing buildings.

The second approach proposes an optimization methodology for building energy design/retrofit based on two main objective functions, – *i.e.*, the reduction of global cost and greenhouse gas emissions –, aiming at conjugating the two involved decision-makers: the private one (minimization of financial expenditure) and the public one (minimization of pollution and environmental impacts of buildings).

As in the previous approach, the optimization process is structured in two consequent stages, the first one consists in the implementation of a genetic algorithm by means of the coupling of MATLAB® and EnergyPlus, whilst during the second stage a smart exhaustive sampling is conducted entirely in MATLAB®, thereby ensuring feasible computational times even if around 30000 retrofit scenarios are investigated. As a case study, a typical office reference building representative of the Italian building stock since 1971 is investigated. The cost-optimal solution provided by the application of the proposed methodology to this case study permits to strongly reduce the GHG emissions, which change from 78.8 kg/m^{2}a to 53.5 kg/m^{2}a, as well as the global cost, which decreases of around 119 €/m^2 (assuming a discount rate equal to 3%).

The importance of the application of the proposed optimization methodology is that the reduction of the CO_2-eq emissions can enable the different countries to respect the limits imposed by the international agreements on polluting emissions for fighting climate change, while the minimization of the global cost makes the adoption of proper energy efficiency measures more appealing to building owners, letting them play also an important role for the community.

Finally, the applied methodology enables to reach more than satisfying results not only in fighting the climate change under a macroscopic approach, but also in contrasting the urban overheating by adopting a local-limited approach.

Unfortunately, as most of the techniques available in literature for facing the energy and environmental impact of buildings, both the described approaches focus only on stand-alone buildings, and this is their main limit. Indeed, the simultaneous investigation of more than one building may be more appropriate, in order to achieve higher levels of integration between the different tasks to be conducted when planning the energy management of cities [104]. Therefore, it has been presented a novel integrated approach, which investigates the optimization of the energy retrofit of districts/neighborhoods of buildings.

The aim of this third study is to provide a novel comprehensive approach to face the complicated issues related to the reliable energy modeling of districts/neighborhoods and to guide professionals during the retrofit planning. The approach is based on a bottom-up technique that makes use of a Geographic Information System (GIS) tool to realize accurate geometrical models. Once again, EnergyPlus is used as dynamic energy simulator, while MATLAB® is the external post-processing engine, which makes the approach versatile and easy to be used. As case study, part of an existing neighborhood located in Naples (Italy) and representative of the Southern Italy building stock is energy modeled, and its retrofit is optimized by investigating ten packages of energy measures, distinguished in three retrofit levels according to the Italian Law. For each of them, both the absence and the presence of monocrystalline photovoltaic (PV) panels installed on 90% of the useful roof areas are considered. All packages are investigated simultaneously applied to all four buildings of the district. Finally, two optimal solutions are achieved, the "nZEB one" minimizing primary energy consumption, and the "cost-optimal one" minimizing global costs.

Globally, the results show that the PV systems strongly improve energy and financial performance, and so, when possible, they have to be always installed. Aiming at minimizing the energy consumption – public perspective – the most effective retrofit measures are the installation of PV systems, heat pumps, new windows with low U-value as well as the thermal insulation of the building envelope. On the other hand, some of these measures are not cost-effective, and in the present study this is the case of windows' replacement. Of course, this depends on climate, winter coldness, solar radiation and building peculiarities in terms of technology and use. Therefore, elsewhere, such intervention would have different performance. Concerning the presented case study, aiming at minimizing the energy consumption – private perspective – the most effective measures are only of PV systems, the heat pumps and roof insulation. Therefore, the other nZEB measures need more substantial public incentives to ensure acceptable financial performance.

In summary, the proposed approach allows to achieve reliable and detailed results at different scale levels – *e.g.*, single apartment, single building, whole district – without requiring excessive computational burden thanks to the automatic interaction established between MATLAB® and EnergyPlus. Therefore, it can be a precious tool for different stakeholders, from the single citizen for achieving financial benefits from building retrofit to public institutions for addressing and optimizing the energy policies aiming at reducing the energy and environmental footprint of the exciting building stock.

Despite having outlined the importance of the installation of PV systems in order to reduce the energy, financial and environmental impact of districts or neighborhoods of buildings, among the energy efficiency measures investigated in this study it is not taken into account the implementation of a local energy community that shares the energy produced by means of PV solar systems. Indeed, the lack of investigations on PV sharing in coupling with other energy efficiency measures is one of the limits of the current state of the art, especially considering that EU Member States are promoting the creation of local energy communities. Another limit, as most of the studies available in literature, it is that the incentivation policies adopted by each of the Member States of the EU in order to boost the energy refurbishment of their building stocks are not properly considered. Aiming at coping the two aforementioned issues, it has been presented another integrated approach, which is an enhanced version of the methodology described in this study.

The fourth presented study faces the energy transition of small neighborhoods towards nearly Zero Energy Buildings (nZEBs) by optimizing the solar energy exploitation, with the aim to reduce the energy and the environmental impact of the building sector. A comprehensive analysis is performed, considering both the most common energy efficiency measures (EEMs) and innovative ones, with the scope to maximize the energy and the financial savings, and so to achieve a good satisfaction level for both the public perspective and the private one. In fact, the public hand aims at improving energy efficiency, while the latter aims at increasing the financial benefits, even if nowadays also the attention of private stakeholders towards sustainability is growing. The main novelties introduced to the current state of art are: 1) considering both energy and financial performance indicators for the energy retrofit of a neighborhood; 2) investigating the energy retrofit of a neighborhood by examining in a comprehensive manner a wide range of energy efficiency measures, affecting the envelope, the Heating, Ventilation and Air Conditioning (HVAC) systems and PV systems at the same time; 3) considering the effects of innovative solutions such as the implementation of PV sharing in coupling with other EEMs; 4) taking into account the effects of the massive public grant policy introduced in Italy for promoting energy efficiency of buildings, namely the “Superbonus 110%”.

The comprehensive analysis makes use of different software: CADMapper® and SketchUp® for modeling the geometry of the neighborhood; DesignBuilder® for realizing the first raw energy model; EnergyPlus to refine the energy model and to perform dynamic energy simulations; MATLAB® to post-process the results of the simulations. More in detail, once the geometrical model is obtained, the thermal energy demands for heating (TEDh) and for cooling (TEDc) of each building of the neighborhood are evaluated by means of EnergyPlus. Consequently, they are converted into primary energy consumption (PEC) values by in-house developed MATLAB® codes, considering proper efficiency curves for the desired HVAC systems. Finally, always in MATLAB®, the effects of PV systems and of the public grant policy are considered, and the objective functions to minimize – *i.e.*, the PEC and the global cost – are assessed.

As case study, it is investigated an existing neighborhood located in Naples (Southern Italy) that is representative of the Southern Italy building stock of the 70s. The aim is to individuate the combination of EEMs that minimizes both the PEC and the global cost, guaranteeing a good satisfaction level for both the public perspective and the private one. The comprehensive analysis is performed twice, considering both the absence of public grant and the presence of the Italian "Superbonus 110%" public grant policy. Some general assumptions can be made by observing the results of the two carried out investigations:

- the combination of EEMs that results to be the most convenient from the public perspective consists in: 1) replacing single-pane windows with double-glazed ones and insulating the roofs, as measures on the envelope; 2) replacing natural gas-fired water boilers and low-efficiency air-to-air heat pumps with more efficient reversible air-source electric heat pumps, feeding water at radiant underfloor emitting terminals, as measures on the HVAC systems; 3) installing high-level monocrystalline PV panels on 100% of useful area of roofs together with 6.5 kWh PV batteries in each apartment, commercial unit and office of the buildings, as measures on the PV systems. Note that the PV sharing should not be implemented in this case. In addition, this combination is not cost-effective at all without any public grant, due to the high required investment cost required. Therefore, it would not be preferred by private owners without being the latter incentivized;
- the combination of EEMs that would be chosen by private perspective varies according to the presence or not of public grant. Without public grant, it consists only in installing polycrystalline PV panels on 100% of useful area of roofs and in implementing PV sharing with centralized PV batteries having globally 162 kWh of capacity. On the contrary, if public grant is considered, this combination implements the following EEMs: 1) insulation of the roofs; 2) replacement of the natural gas-fired water boilers and low-efficiency air-to-air heat pumps with more

efficient reversible air-source electric heat pumps, in coupling with fan-coils; 3) installation of high-level monocrystalline PV panels on 100% of useful area of roofs together with 6.5 kWh PV batteries in every apartment, commercial unit and office of the buildings;

- the combination of EEMs that may result the best-tradeoff between energy-efficiency and cost-efficiency consists in: 1) replacing windows with double-glazed ones and insulating the roofs; 2) applying no EEMs on the HVAC systems; 3a) installing high-level monocrystalline PV panels on 100% of the useful roof areas of buildings together with the implementation of PV sharing with centralized PV batteries having globally 216 kWh of capacity, in absence of public grant; 3b) the same as 3a) but without implementing the PV sharing, and so with distributed PV batteries of 6.5 kWh of capacity in every apartment, commercial unit and office of the buildings in spite of the centralized storage system;
- the optimization of the solar energy exploitation by means of proper PV systems is crucial, aiming at reducing the impact of buildings on the environment. All the other EEMs permits only to achieve lower energy and environmental benefits compared to PV systems. Moreover, other EEMs are deeply dependent from the public grant policies, while PV systems are cost-effective even without any public grant. Therefore, when possible, PV systems should always be installed, and their size should always be maximized;
- the actual Italian public grant policy does not really promote the implementation of local energy communities, and so PV sharing with centralized PV energy storage systems result less cost-effective in comparison with not implementing it and installing distributed PV batteries in every building unit. As seen, with PV sharing are achieved important financial savings only when no public grant is considered at all, which means that basically it is an interesting solution from the financial point of view, but unfortunately the actual public grant policy is a strong stimulus for other EEMs, which are more conventional;
- Governments should adopt a public grant policy more focused on PV systems, despite other EEMs. In fact, by promoting the large-scale diffusion of high-efficiency PV systems, huge results in terms of reducing the energy, financial and environmental impact of buildings may be attained. In addition, an adequate public grant policy should be adopted, in order to promote the development of local energy communities.

In conclusion, once again, the importance of the installation of PV systems is outlined. Indeed, with a proper PV system, both the public perspective and the private one can achieve a good satisfaction level, because both the energy and the financial performance are profoundly improved.

Unfortunately, the presented approach has two limits: 1) it does not take into account the uncertainty in building energy demands due to the stochasticity in occupant behavior; 2) it does not consider the effects of global warming on building energy performance. In this regard, climate change cannot be neglected "a priori" when a reliable analysis of building energy performance is sought, because the increase of average temperature worldwide can produce a significant variation of energy demands for space heating and cooling. Therefore, it is crucial to consider the effects of global warming when the energy design or retrofit of a neighborhood is planned. For this purpose, it has been proposed a further approach that copes both the two aforementioned criticalities, considering the stochasticity in the human behavior and the effects of the global warming.

The last presented study provides a comprehensive approach to investigate the effects of common energy retrofit measures (ERMs) on energy, financial and environmental performance indicators when planning the energy retrofit of districts or neighborhoods. The main novelties introduced to the current body of knowledge consist of: 1) considering the stochasticity of the occupant behavior that deeply affects the energy demand by differentiating the usage profiles and assigning them to residential thermal zones according to a normal distribution; 2) considering the effects of global warming on the ERMs by taking into account different Representative Concentration Pathways (RCPs). More in detail, the approach is based on EnergyPlus, as dynamic energy simulator, and MATLAB®, as postprocessing engine. The analysis is conducted referring to 2035 because it is a mid-term time horizon, not subjected to the excessive uncertainty as 2050 or later, but not too close to today, being the aim of the approach to study future implications of ERMs, even if further time horizons may be considered.

An existing neighborhood ubicated in Naples (South Italy) and representative of the Southern Italy building stock has been investigated as case study, with the scope of determining the ERMs combination that minimizes the PEC, the running cost (RC) and the CO_2-eq emissions, attaining a good satisfaction level for both the stakeholders involved – *i.e.*, the public perspective and the private one. Three different RCPs have been considered: RCP 4.5 50% warming (intermediate warming case), RCP 8.5 50% warming (upper-intermediate warming case) and RCP 8.5 95% warming (worst warming case). For each of the RCPs, six different scenarios have been investigated – *i.e.*, neighborhood as built and five retrofit combinations.

Firstly, a comparison has been performed for the neighborhood as built scenario between the use of standardized ASHRAE schedules and the adoption of stochastic ones. Results show significant differences in terms of the objective functions and the other performance indicators, with discrepancies varying from -48.1% for the thermal energy demand for space heating (TEDh) – *i.e.*, with standard schedules the assessed value is lower – to 20.0% for the total CO_2-eq emissions – *i.e.*, with standard schedules the value is higher. If the standardized approach is used, the aforementioned discrepancies may produce an overestimation of the energy, financial and environmental benefits of the investigated ERMs, and thus the stakeholders might be induced in erroneous choices when planning the energy retrofit of the neighborhood.

For what concerns the RCPs, results show that for all the RCPs not sensible variations in terms of the main performance indicators are assessed in the homologous scenarios, with the exception of the thermal energy demand for space heating (TEDh) and for space cooling (TEDc). These two indicators are deeply influenced by the RCPs, and so it is demonstrated how the global warming affects the reliability of the results, especially when assessing the space conditioning loads/demands. On the other hand, the climate change has apparently slighter effects on energy, financial and environmental indicators than expected, but this is the result of a balance between its positive implications on the TEDh, and so on the heating system, and negative implications on the TEDc, and so on the cooling system. Such significant effects on TEDh and TEDc are the clear demonstration of how important is to consider the climate change when planning the energy retrofit of a neighborhood or district. In any case, it would be interesting to consider, in future works, the effects of the same ERMs but assuming a farer reference year, *e.g.*, 2050 or 2060.

For all the RCPs, the scenario that minimizes PEC, RC and CO_2-eq emissions is the one that features the installation of monocrystalline PV panels on 90% of useful roof areas, the implementation of a local energy community that shares the PV production, the replacement of the HVAC systems, as well as the insulation of external walls and roofs, and the replacement of single pane windows with double-glazed ones, with argon-filling, low-e coatings and PVC frames. At the district level, this ERMs' combination implies a reduction of the PEC that varies from 58.9 kWh/m^{2}a (RCP 8.5 95% warming) to 59.1 kWh/m^{2}a (RCP 4.5 50% warming), a reduction of the RC that is equal to around 7.1 €/m^{2}a (for all RCPs) and a reduction of the CO_2-eq emissions that is included between 19.4

kg/m^{2}a (RCP 4.5 50) and 19.7 kg/m^{2}a (RCP 8.5 95%). This retrofit package is the one that both public perspective and private actors would choose. However, results show also that another interesting solution is the one that involves the same ERMs, with the exception of the retrofit measures affecting the envelopes. Indeed, such a solution would guarantee high reductions of PEC, RC and CO_2-eq emissions – *i.e.*, PEC reduction around 46 - 47 kWh/m^{2}a, RC reduction around 6.2 €/m^{2}a and CO_2-eq emissions reduction around 17 kg/m^{2}a –, without having to face the difficulties due to the refurbishment of the envelopes. Therefore, it would be an interesting tradeoff between energy, financial, environmental benefits and difficulty/complexity as concerns the implementation.

In summary, the provided approach enables to attain reliable results in planning the energy retrofit of districts or neighborhoods. Therefore, it can be an important tool capable to simultaneously satisfy different perspectives, such as the public perspective, whose main goal is to reduce the energy and the environmental impact of the existing building stock, and the private perspective, whose main goal is to maximize the financial profits from the building retrofit, even if in general the attention of the collectivity towards sustainability is strongly increasing worldwide, thus sustainable solutions are wished by this perspective too.

8.2. General outcomes

All the presented approaches are powerful instruments to cope the energy, financial and environmental issues that occur when the energy design or retrofit of stand-alone buildings or districts of buildings of any size or category is conducted. Indeed, every approach is the most suitable to solve the energy efficiency solutions search problem of a specified type of building. Using a stand-alone entity point of view, a methodology has been presented for the energy design of new buildings, while another one can be applied for planning the energy retrofit of existing buildings. On the other hand, considering an upper-scale perspective, which allows to attain higher levels of energy efficiency involving more buildings, and so aiming at promoting the energy efficiency of districts or neighborhoods of buildings, three approaches have been presented, each one with its own peculiarities. Indeed, one approach can be applied to investigate neighborhoods/districts implementing energy efficiency measures at any scale level, from the single apartment to the whole stock, and so it is like the "linking approach" between the stand-alone approaches and the district approaches, permitting to deeply cut down the computational burden, allowing to simultaneously investigate the effects of a particular combination of energy efficiency measures at all the possible scale levels. Another approach is particularly suitable for the investigation of the energy, financial and environmental implications due to the solar energy exploitation and to the implementation of massive public grant policies. Finally, the last presented approach allows to attain the most reliable results, considering both the high stochasticity in the human behavior and the effects of global warming on the energy retrofit measures. Note that a stochastic approach may be potentially adopted also for simulating the energy, financial and environmental performance of new buildings, where data on the behaviors of the potential occupants are null. This could be justified by considering the promising results obtained in Chapter 7, where it has been demonstrated that the adoption of a stochastic approach instead of standardized schedules for describing the human behavior leads to important reductions in terms of discrepancies between simulation results and measured data. Therefore, in eventual future studies, it is opinion of the author that the use of the stochastic also for new buildings may potentially have interesting implications in terms of energy, financial and environmental indicators. All told, all the aforementioned approaches are particularized versions of the same “primitive” technique, which has been modified and adapted to multiple situations, in order to allow the designer to always know and implement the best combination of energy efficiency measures for each building or neighborhood. In this way, a double benefit can be always reached: a benefit for the buildings’ owners/occupants, who obtain the maximum economic saving, and a benefit for the community/environment, because a wide diffusion of cost-optimal energy retrofits would determine a huge reduction of energy consumption and polluting emissions of the building sector. Note that the proposed “primitive” approach from which all the five techniques presented in this thesis have been derived has been used also in other studies available in literature. Therefore, it has been assumed as already validated, and so no further investigations have been conducted by the author to demonstrate its robustness. However, for validation purposes, some observations on the RC assessed by means of the presented approaches are here conducted. Unfortunately, due to users’ privacy issues, there is a lack of data concerning the detailed energy consumption of the investigated buildings, thus the reliability of the developed model can be verified only by considering the available statistical data. All told, considering the approach discussed in Chapter 5, in the baseline configuration of the neighborhood the RC is quite similar for all the buildings and is included between 12.2 €/m^2 and 12.6 €/m^2. It means that, considering a flat of 100 m^2, the annual bills can be in the range 1223 – 1263 €/a, and these costs are a kind of validation, being quite common in this location. Moreover, referring to the approach presented in Chapter 7, a further comparison is possible. Considering the statistical data of the Italian ISTAT – note that the ISTAT data refer to the year 2013 –, after an elaboration it is obtained that the annual running cost for energy uses for a family in Campania is equal to around 1350 €, *i.e.*, 13.5 €/m^{2}a considering a 100 m^2 apartment. This share is really close to the values assessed for the residential buildings (in the baseline configuration) by the developed energy model. Indeed, the evaluated RC is included in the range 13.3 €/m^2 – 13.5 €/m^2. Obviously, generally speaking, some discrepancies may occur because of different boundary conditions, among which the comparison of cities and regions (*e.g.*, Napoli is much warmer than the average climates of Campania, being on the coastline of region with also cold mountain areas), the sum of different energy sources (natural gas, LPG, wood and others), the average repartition of costs for space heating, domestic hot water and kitchen uses, the size of the typical apartment, but globally all the results are quite reliable. Moreover, the best meter of such validation is the reading of common energy bills, and the outcomes of the proposed approaches are consistent with common bills.

For what concerns the results achieved by the proposed approaches, some general assumptions can be made, in order to give also precious indications on how the energy efficiency measures should be combined to result more convenient from the energy, financial and environmental perspectives, and so to satisfy all the involved stakeholders. Firstly, if considering only measures on the envelopes, the insulation of the walls has the highest effects in terms of reducing the energy impact of buildings, but it is also a really expensive measure, as well as invasive if referring to the retrofit of existing buildings, especially in presence of high buildings with balconies, because people living here should not use their balconies for the entire duration of the works. On the other hand, the insulation of the roofs has slightly lower effects in reducing the energy impact, but it is much less expensive. Therefore, the insulation of the roofs could be considered as the best trade-off between the energy and the financial perspectives. Moreover, it is not cause of relevant inconveniences for the occupants when retrofitting the building where they live. For what concerns the insulation of the floors – when these are in direct contact with the terrain –, this kind of intervention result not convenient from both the energy and the financial point of views, and so it could be omitted. All told, the optimal U-values for vertical walls and roofs that should be reached are around 0.20 W/m^{2}K in both cold and warm Italian climates, obviously for different reasons from ones to the others – *i.e.*, reducing the heating demand for cold climates, reducing the cooling demand for warm climates, while higher optimal values can be easily considered for the floors without having any serious negative implication. Concerning the replacement of the existing windows, this measure on its own is not convenient at all for medium temperature climates, not having relevant effects on the energy performance of buildings compared to the aforementioned measures on the walls and on the roofs, and moreover resulting really expensive. Obviously, as already said, this depends on climate, winter coldness, solar radiation and building peculiarities in terms of technology and use, and so, elsewhere, such intervention could have different performance. However, when the replacement of the windows is considered in coupling with the insulation of the roofs, the situation changes, and also passing from a single pane window to double or triple pane windows results convenient from both the energy and the financial perspectives, with or without any public grant.

On the other hand, considering the measures on the HVAC systems, the replacement of existing generators with more efficient reversible air-source electric heat pumps is the best intervention on the HVAC systems from all the perspectives – *i.e.*, energy, financial and environmental –, allowing to attain the highest reductions in terms of energy consumption and CO_2-eq emissions, as well as the highest financial profitability. This is true in both the presence and the absence of public grant. Note that, having the set-point temperatures for space conditioning a strong influence on the performance of buildings, independently on the climatic zone, also them should be optimized. In detail, the heating set-point should be lowered to 19 °C instead of 20 °C, as usually set in Italy, while the cooling set-point should be risen to 27 °C instead of 26 °C.

Finally, for what concerns the implementation of renewable energy systems, results show that it should always be maximized the size of the PV systems, covering as most as possible the available areas on the roofs, independently on the climatic zone. This should be done in both the presence and the absence of public grant. Of course, when incentivized, monocrystalline panels should be preferred to polycrystalline ones, being the former characterized by higher levels of producibility compared to the latter. However, polycrystalline panels are less expensive, and so it results that without incentivation they are the best trade-off between reducing the energy impact of buildings and maximizing the financial gains. Regarding the use of PV storage systems, they result crucial from the financial perspective, having only limited implications in terms of energy efficiency of buildings. Obviously, the use of batteries has serious effects in reducing the losses when looking at the entire grid, because they boost the self-consumption of the produced electricity, and so they cut down the aliquot fed into the grid. However, limiting the discussion to the energy performance of buildings, their energy implications are not so relevant compared to the ones due to the installation of PV panels on their own. Despite this, to maximize both the energy and the financial savings deriving from the installation of PV systems, the optimal situation would consist in implementing a general PV system for each building and batteries in every apartment. Indeed, PV sharing results convenient only if incentivized, but the actual Italian policy does not really promote the creation of local energy communities, and so PV sharing is less cost-effective compared to the aforementioned configuration. With PV sharing are attained important financial gains only when no public grant is considered. This means that it is an interesting solution from the financial perspective, but unfortunately the actual incentivation policy tends to boost other energy efficiency measures. It is opinion of the author that Governments should adopt a public grant policy more focused on PV systems, despite other efficiency measures. Indeed, all the other measures permit only to achieve lower energy and environmental benefits compared to PV systems. Moreover, the other energy efficiency measures are deeply dependent from the public grant policies, while PV systems are cost-effective even without any public grant.

In conclusion, results show that the combination of energy efficiency measures that minimizes the most the energy and the environmental impact of the building sector is a combination of interventions on both the envelopes and the primary systems. In detail, it consists in insulating the external walls and the roofs, replacing the existing windows with ones characterized by low values of thermal transmittance, installing reversible heat pump for providing hot and cold water to the emitting terminals, implementing PV systems with proper PV storages. However, the best trade-off solution between reducing energy impact of buildings and maximizing the financial gaining, and so the best solution that allows to satisfy both the public and the private perspectives consists in combining the same aforementioned measures on the primary systems, without considering interventions on the envelopes. In detail, this means that reversible air-source electric heat pumps for heating and cooling should be installed together with PV systems and PV energy storages.

All told, as seen, by means of the proposed approaches, reliable results are attained in really short time, deeply cutting down the computational effort without having implications in terms of accuracy. This may appear banal, but only in appearance, because it is probably the most powerful element of innovation introduced by this study, enabling to concretely cope the energy, environmental and financial issues related to the building sector. Indeed, differently from many studies available in literature, where amazing results are attained, but they are only theoretical results that are not applicable to real world, due to many reasons – *i.e.*, financial problems, unreliability of the results because of oversimplification of the investigated problem, immaturity of the investigated technologies for a large-scale application –, the solutions proposed by the presented approaches are concrete and ready to use. Therefore, the “time-to-application” – intended as the time between the conclusion of an investigation and the application of its results to real world buildings – may be really short, and so results may be concretely tangible in real world. Note that, even if the main aim of this thesis is to provide different integrated methodological approaches to cope with the energy and environmental impact of the building sector in most of the possible situations, the decision of focusing the investigations of the presented approaches mainly on traditional energy efficiency measures, with the exception of the sharing energy communities, is not casual. Indeed, the combinations of well-known energy measures are the only that permit to attain tangible results in today world and, moreover, being already large-scale diffused, these results can have serious implications in solving the energy and environmental issues related to buildings all over the planet. It is undoubtful that more innovative measures could lead to better results in terms of energy, financial and environmental savings, and it would be really interesting to investigate their implications in future studies, but their main limit, unfortunately, is that their time-to-application would be much longer, risking not to have tangible results in today world. This is a risk that is not possible to be taken, because the situation is critical and there is no more time. Energy efficiency is not only finding cutting-edge solutions for reducing the impact of building, energy efficiency is also, or mainly, finding solutions that may be applicable in short time, solving the crucial issues affecting the Earth.

This is energy efficiency. This is the only possible starting of the undelayable green revolution for the world where we live in.

Nomenclature

C	specific price	*[€/kWh] or[€/Sm^3]*
c_e	élite count	---
CO_2-eq	CO_2 equivalent emissions	*[kg/m^{2}a]*
COP	coefficient of performance	*[-]*
d	discount factor	*[-]*
DPB	discounted payback	*[years]*
E	energy	*[kWh/m^{2}a]*
F	vector of the objective functions	*[kWh]*
f_c	Crossover fraction	---
fc	CO_2-eq emission factor	*[kgCO$_2$-eq /kWh]*
f_m	Mutation probability	---
fp	primary energy conversion factor	*[-]*
G	electricity sold to the grid	*[kWh/m^{2}a]*
g_{max}	maximum number of generations	
GC	global cost	*[€/m^2]*
IC	investment cost	*[€/m^2]*
IN	incentives	*[€/m^2]*
n	number of decision variables	---
PEC	primary energy consumption	*[kWh/m^2]*
RC	running cost	*[€/m^{2}a]*
S	selling price	*[€/kWh]*
s	population size	---
SHGC	solar heat gain coefficient	*[-]*
SPB	simple payback	*[years]*
TED	thermal energy demand	*[kWh/m^{2}a]*
tol	tolerance in the average change of the Pareto front	---
U	thermal transmittance	[W/m^{2}K]
Vol	volume	[Sm^3]
x	vector of the decision variables	
Greek symbols		
η	nominal efficiency of a gas boiler related to the low calorific value	---
τ	number of the assessment year	---
Subscripts		
c or cool	referred to cooling	
e or el	referred to electricity	
g or gas	referred to gas	
h or heat	referred to heating	
roof	referred to the roof	
tot	referred to the sum of the energy needs for space cooling and heating	

wall	referred to the external vertical walls
windows	referred to the windows (frame + glasses)

Acronyms

BEO	Building energy optimization
EEM	Energy efficiency measure
EMD	Energy modeling of the district/neighborhood
EPBD	Energy performance of buildings directive
ERM	Energy retrofit measure
ERPD	Energy retrofit planning of the district/neighborhood
EU	European Union
GA	Genetic algorithm
GHG	Greenhouse gas
GIS	Geographic information system
HVAC	Heating, ventilating and air conditioning
LHV	Lower heating value
nZEB	Nearly zero-energy building
PV	Photovoltaic
RCP	Representative concentration pathway

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