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Assessment of buildings heating consumption and technical retrofit strategies at urban scale

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Abstract

Cities have a key role in achieving the 2030 EU environmental, energy, and climate targets, in particular the residential building sector, which is the major source of energy consumption in urban areas. The Italian building stock is composed of over 50% of buildings built between the '50s and '80s, which have obsolete thermal system technologies and inefficient envelopes. Urban energy planning should be used as a resource to highlight the major criticalities in existing buildings and to correctly identify the strategies to adopt. This thesis work analyzes residential buildings to evaluate actual heating energy consumption and their possible reduction due to different retrofit actions. Only open data from energy performance certificates and the Regional cadastre of thermal plants have been used as a source of thermo-physical, geometrical, and technical information. Since the city of Milan provides both as public data and easy downloadable, it has been chosen as case study. Energy performance certificates have been cleaned and missing information about thermal plants have been recovered through a simple statistical analysis of the cadastral data set. Bin method has been applied to evaluate building energy consumption, after and before retrofit strategies. Missing and not consistent information of energy performance certificates limits the development of a more refined method. The choice of different retrofit scenarios has been done according to the most diffused solutions, considering both passive and active ones. The application of different strategies has been driven by the analysis of the distribution of heating energy consumption of buildings, differentiated by some variables, like energy class or thermal system technologies. A spatial visualization has been realized using a Geographical Information System (GIS) to highlight urban areas with the highest consumption, at building and census tract levels. A map visualization, supported by technical analysis, simplifies the problem detection, to define correct solutions in terms of energy efficiency.

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List of Acronyms

EPC Energy Performance Certificate

BAU Business As Usual

GIS Geographical Information System

NEP National Energy Plan

NECP National Energy and Climate Plan

TFEU Treaty on the Functioning of the European Union

EU European Union

nZEB nearly Zero Energy Building

ZEB Zero Energy Building

RED Renewable Energy Directive

ZEB Zero Energy Building

REC Renewable Energy Community

CEC Citizens Energy Community

SME Small and Medium-sized Enterprise

EED Energy Efficiency Directive

GHG GreenHouse Gases

ETS Emission Trading Scheme

PEDh Primary Energy Demand for heating

UBEM Urban Building Energy Modeling

HVAC Heating, Ventilating and Air Conditioning

CLTD Cooling Loading Temperature Difference

SC Shading Coefficient

COP Coefficient Of Performance

SCOP Seasonal Coefficient Of Performance

KPI Key Performance Index

WGS84 World Geodetic System 1984

1 Introduction

In 2015, 193 countries of the world subscribed the *2030 Agenda for Sustainable Development*, a United Nations resolution adopted by the general assembly. The preamble says that *"This Agenda is a plan of action for people, planet and prosperity [...]. All countries and all stakeholders, acting in collaborative partnership, will implement this plan"* [1]. The document contains the definitions of 17 Sustainable Development Goals and 169 targets, which *"are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental"* [1]. The 7^{th} SDG aims to ensure access to affordable, clean, economic, sustainable, and reliable energy for all. It aims also to increase the share of renewable energy in the global mix of energy production and to double the overall rate of energy efficiency improvement. The 11^{th} SDG aims is about sustainable cities and communities, in order to transform cities and human settlements in inclusive, safe, lasting and sustainable places. More than half of the world's population lives in cities and this percentage should reach 70% to 2050. Cities are places in which are located around the 80% of the global economic activities, and they are responsible for 75% of the global greenhouse gases emissions [1]. The urban planning is a fundamental tool to achieve these SDGs, also from the energy management perspective. Urban planners can significantly contribute to transform urban areas in low-carbon and energy-efficient cities.

Indeed, the main purpose of this thesis work is to define a methodology to estimate buildings energy consumption at urban scale and to define post-retrofit scenarios to reduce both energy consumption and carbon emissions. Applying this methodology at urban scale means making it scalable for each building analyzed, using for each of them their own parameters related to the building envelope or to the thermal systems specifications. The buildings analyzed are 96000 and they are all residential. The methodology has been developed starting from open data. Open data are a great resource for the Public Administration, because they are easily accessible and available

[1] https://www.aics.gov.it/

for everyone. For this reason this thesis work uses as source of information only open data provided by the Public Administration. In Italy, the Metropolitan City of Milan was one of the first cities to provide open data available for citizens, and for that it has been chosen as case study of this thesis work. Data-sets used come from energy performance certificates and the regional registry of thermal systems of the Municipality. Since the real metered data are not available, but only parameters of buildings and thermal systems specifications have been used, the goal is to use a parametric model that allows making a good estimation of heating consumption, before and after some retrofit actions. This can be done applying the Bin Method, a steady-state method based on hourly temperature frequency, called bins. To perform the analysis and the comparison between different scenarios involved, some key performance indicators have been defined, both energy and environmental ones. They have been supported by the use of a quadrant chart. Starting from the analysis done with the quadrant chart, some retrofit strategies have been defined: passive, active, mix of passive and active and the integration of a photovoltaic plant in the mixed one. After the application of the retrofit strategies, six scenarios have been obtained, including also the BAU scenario. Two scenarios are defined for the passive strategies, one for the active one, one for the mixed and one for the mixed with the PV plant. The behaviour of the buildings in terms of carbon emissions and energy consumption has been observed, using as reference the quadrant chart defined for the BAU scenario. The results have been displayed also in urban map, developed with a GIS. The map visualization can be a support to take targeted decisions and to observe the distribution of energy consumption and its related carbon emissions in the territory.

The structure of this thesis document is subdivided in five chapters. Chapter 1 is composed by two section: the first illustrates the state of the art in the energy and environmental regulatory policies, both at European and National levels; the second illustrates a literature review about the topics covedered by this thesis work. In chapter 2 the methodology used to develop the thesis work is described, dividing it in four steps: the data preparation, the estimate of energy consumption with the bin method, the definition of retrofit scenarios and the spatial representation through urban maps. Chapter 3 describes how the methodology defined has been applied in the case study chosen for this thesis work. This chapter explains, by following the sequential order of the methodology, how the available data has been treated, how the buildings thermal systems have been modeled and how scenarios have been defined. Scenarios are six, one for the BAU case and five for retrofit strategies. Chapter 4 shows the results obtained from the case study for each scenario and a comparison between them. The last chapter 5 contains a discussion about the whole thesis work and a proposal for future developments. Appendix A contains the histograms representing the climatic bins data divided by month. Appendix B contains some figures about the carbon emissions savings for each scenario. Finally, the appendix C contains all the maps obtained from QGIS for energy consumption and carbon emissions, even these divided by scenarios.

1.1 State of the art

This sub-section describes firstly the state of the art of the policies defined at European and National levels to reach the energy transition. At European level the *Clean Energy Package*, while at National level the National Energy Strategy (NEP) and the National Energy and Climate Plan (NECP) will be described. Later, the state of the art of the main topics treated in this thesis work are described in the paragraph dedicated to the literature review.

1.1.1 European and National policies for the energy transition

The national energy planning needs to follow a coordinated approach with energy policy guidelines adopted within the European Union. The treaty on the functioning of the European Union (TFUE) introduces a specific legal basis for the energy sector, based on shared competences between the EU and its member countries. The energy policy of the European Union consists of four lines of action [2]:

- Security of supply, to ensure a reliable energy provision, where needed.

- Optimal operation of the energy market and its competitiveness, to ensure reasonable prices for energy users and companies.
- Promotion of energy savings and energy efficiencies, through the reduction of greenhouse gas emissions and the replacement of fossil fuels with a gradual integration of new and renewable energy production systems.
- Interconnection of energy grids.

Article 194 of TFUE [3] defines some energy policy sectors as areas of shared competence, but each member country is entitled to define the choice, the use, and the application of its energy sources. The most important policy regulation which defines a coordinated approach at European level, to reach 2030 goals, is the *Clean Energy Package*. It is composed by eight legislative acts, described in the following paragraph.

Clean energy package On November 30^{th} 2016, the European Commission published a new energy rulebook, called *Clean energy for all Europeans package*, composed of eight legislative acts shown in figure 1. It contains action measures related to energy efficiency, renewable energy sources, electricity market design initiatives, the security of electricity supply, and governance rules for energy Union; they will bring considerable benefits from economic, environmental, and consumer perspectives. It represents a key part of the energy transition for European member states and especially it is fundamental to overcome the difficulty of complete integration between European energy markets. The package of rules is seen as the continuation of the path relaunched from the Agreement of Paris of 2015.
On June 4^{th} 2019, the Council of Ministers of the European Union, has adopted the last legislative rules proposed by the *Clean energy package*. EU countries have one or two years to transpose the new directives into national law.
The EU energy directive 2018/844 about energy performances in buildings integrates the old EU directives 2010/31 [57] and 2012/27. The most relevant points concern the constraints on new buildings, which should all belong to the category nZEB, from December 31, 2020. The EU directive 2010/31 [57] gives a definition of an nZEB build-

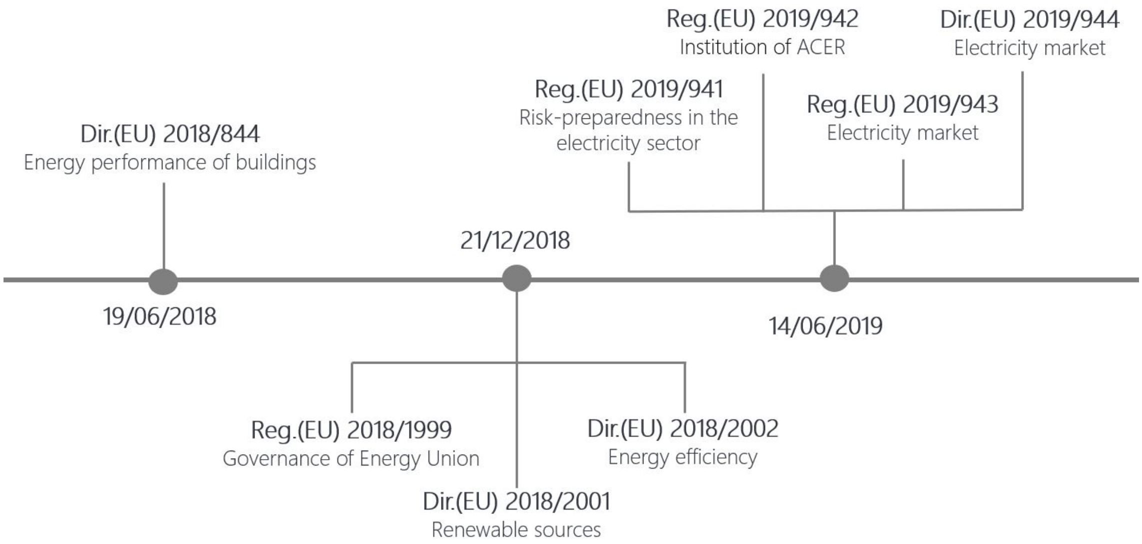

Figure 1: Clean energy package EU directives.

ing, which is a building with very high energy performances, with almost no heating demand covered only by energy produced by renewable sources. The definition of an nZEB building is very flexible, but the CEN (European Committee for Standardization) standard shall provide a common shared technical definition to calculate the low amount of energy required by nZEB, but keeping it flexible to consider the difference at the local, regional and national level. As explained by [11] the first definition proposed by CEN regards the satisfaction of four requirements: an nZEB must reflect the performance of the building by energy needs based on local conditions and its destination of use, the performance of the thermal systems by the energy use, the contribution by renewable sources and the compensation between exported and produced energy. There is a difference between the concept of an nZEB (nearly zero energy building) and a ZEB (zero energy building) [12]. The latter is a building that is autonomous and disconnected from the national distribution grid and it is defined as *off-grid*. The first is a building connected to the grid by which it exchanges energy continuously. In Italy it was promulgated the PANZEB (national action plan to increase nearly-zero energy buildings) [13], to give a precise definition of nZEBs, based on numerical indicators of energy consumption, and to encourage policies or financial measures for their development.

The EU regulation n.2018/1999 [5] regards the European governance about energy union, to reach the energy goals of the EU 2030 Agenda. This regulation defines five sectors: energy security, energy market, energy efficiency, decarbonization and research, innovation, and competitiveness [2].

According to goals of the EU 2030 Agenda, Article 3 of EU Directive 2018/2001 [14] fixes the amount of energy produced by renewable energy sources in the final gross consumption at 32% to 2030; the 14% of this percentage regards only the transport sector. For the transport sector, the energy sources must come from second-generation biofuels, replacing those belonging to the first-generation. This directive does not transpose directly the European targets to national targets, but each country defines its national goals to reach collectively the final binding target, without getting off the established percentage from January 1^{st} 2021 [4]. Each country must include energy policy choices as a part of their National Plans for Energy and Climate (NECPs), as established by Art. 3 of EU regulation 2018/1999 [5]. The EU directive 2018/2001, called also RED II, defines the role of citizens in energy production. Indeed, it defines the role of *prosumer* (art. 21), which can produce energy on-site and sell the excess of production. Through the definition of *prosumer* it is introduced the concept of *self-consumption*, which means to consume energy in the same site in which it is produced, also thanks to the use of storage systems, regardless of the subjects that have the role of producer and final user. ARERA suggests [6] to use the definition of *on-site production and consumption*, with respect to the *self-consumption*. Then, the directive RED II distinguishes between the *renewable self-consumers* and *collective renewable self-consumers*, which are both *prosumers*. The latter is a group of at least two self-consumers of renewable energy, which act collectively within a condominium. Self-consumers should be exempted by any tariff for the electric grid, if related to their self-consumed energy.

The directive defines also the *renewable energy communities* (REC) (art. 22), while the *citizens' energy communities* (CEC) are defined in the EU directive 2019/944 about electricity market [7]. They are defined as:

- Renewable energy community It is a legal entity which is autonomous, it allows open and voluntary participation, it is controlled by shareholders located near the community, and it produces energy from renewable sources. Members should be SMEs, local authorities, or common people. Its main purpose is to provide benefits for the community from the environmental, social, and economic perspectives, without pursuing financial profits [8]. The REC definition does not include distribution activity.

- Citizens' energy community It is a legal entity which allows open and voluntary participation, it is controlled by shareholders like local authorities, common people, and small enterprises. Members could be any category of entities. Its main purpose is to provide benefits for the community from the environmental, social, and economic perspectives, without pursuing financial profits. The CEC is independent of the production from renewable sources and it can be interested in electricity generation, distribution, supply and consumption, and other related services.

According to [6], the *self-consumer* can manage energy storage, whose energy cannot have dual pricing for grid costs. It may receive remuneration for the energy fed into the grid, for example through incentive policies, because this energy has a high value for social and environmental aspects.
The EU 2030 Agenda defines two more final targets related to greenhouse gas emissions and energy efficiency. According to the Paris agreement of 2016, the EU regulation 2018/842 [9] limits the greenhouse gas emissions for each member state. At the European level, the 2030 binding target is to reduce the emissions of about -40% to the 1990 levels.
Directives about energy efficiency introduce new guidelines at the European level by extending consumer rights in the sector of measurements and billing for heating, cooling and hot water production. The EU Directive 2018/2002 [15] (EED energy efficiency directive) establishes a headline for energy efficiency target of at least 32.5% with respect to the 2007 scenario and if compared to projections of the expected final energy use

of 2030. This reduction corresponds to final energy consumption of 956 Mtoe and/or primary energy consumption of 1273 Mtoe (art. 3(2)). Each member state can adopt a mandatory scheme to follow, like Italian energy efficiency certificates. It is possible to account for the energy savings in transformation, distribution, and transmission sectors as mandatory measures of energy efficiency, as well as the 30% of the energy produced in a building by renewable sources. The EED directive says that by October 31, 2022, the European Commission must evaluate if the European Union has reached 2020 targets about energy efficiency. In 2023 the European Commission must evaluate another time the limits reached on that date, and it can set stricter limits to 2030. At the national level, each country should define its contribution to reach 2030 goals. The directive includes also guidelines to measure natural gas or electricity and for their metering.

The last fundamental directive included in the *clean energy package* is that related to the electricity market, already mentioned for the definition of CECs. The general purpose of this directive is to increase the level of competition inside the European market, giving more leeway to consumers. It expects an increase in supply offers and in their efficiency, the reduction of costs for final users, the elimination of barriers to the entry in the European market, and other technical aspects.

Italian energy strategies: NES and NECP Italy follows the path suggested by the European Union to reach the targets beyond 2020, with the adoption of a national energy strategy (NES), issued on November 10^{th} 2017 through an Interministerial Decree [16]. It was published to define a starting point for drawing up the national plan for energy and climate (NEPC). In 2015 Italy reached European goals in advance; it achieved the 17.5% of the penetration of renewable energy, with the introduction of many technological advances, to combine the reduction of energy prices and sustainability. The quantitative targets imposed by the national energy strategy (NES) are [17]:

- energy efficiency: reduction of final energy consumption from 118 to 108 Mtep, with an energy savings of 10 Mtep in 2030;

- RES: 28% of total consumption by renewable sources, divided by sectors with 55% of electricity consumption, 30% of thermal consumption, 21% of the transport sector;
- reduction of the gap between the Italian gas price and the North Europe gas price, and the reduction with respect to the EU electricity prices;
- end of electricity production from coal with infrastructure measures;
- oil downstream to increase the number of biorefineries and sustainable biofuels;
- reduction of greenhouse gas emissions to 39% in 2030 and to 63% in 2050;
- duplication of investments in clean energy research and development;
- promotion of sustainable mobility and services for shared mobility;
- new investments to increase flexibility and resilience, diversification of gas supply sources, and more efficient management of demand peaks and flows;
- reduction of energy dependence on foreign countries to 64%.

The document explains that initiatives in the residential sector are a priority for the national energy strategy. It is a sector with large consumption and emissions, but energy efficiency actions are hindered by two main limits. The first is the lack of consumer awareness about potential benefits derived by the adoption of energy saving measures, and the second is the initial investment cost, due to a lack of economic incentives. To promote the energy saving measures in the residential sector, it has been proposed an optimization of the tax deduction system for building recovery, combined with financial instruments. The energy efficiency national fund must privilege standardized actions that guarantee energy savings, based on parameters as energy class, climate zone, and retrofit action. These measures can be applied also by aggregating similar or nearby buildings. Home automation technologies, grid digitization, and smart metering have an important role in national energy strategy.

Regulations about heating and cooling plants must be more stringent to replace combustion thermal systems, characterized by high emissions and low efficiencies. The last proposals for the residential sector include a strengthening of minimum standard in the buildings construction sector and a rules integration between the energy efficiency sector and renewable energy sources applied in buildings.

To achieve the 2030 EU targets, each European member country must establish a 10-year (from 2021 to 2030) integrated national energy and climate plan (NECPs). As previously explained, this plan is composed by five intervention guidelines, to define a new energy policy according to European rulings. The development and the implementation of these plans must be done through an iterative process between member states and the European Commission. Member states had to communicate their national plans by January 31, 2019, then by January 31, 2029, and later every ten years. The national plan, according to Articles 3 and 5 on Annex I of EU regulation 2018/1999, must contain a description of the national goals and contributions to reach the European targets, the path to follow to reach the energy efficiency, the introduction of renewable sources, the reduction of greenhouse gas emissions, and the electricity interconnections, a description of policies and potential investments, regulatory impediments, and an evaluation of potential impacts of these actions. In Italy, on January 21, 2020, the Ministry of economic development sent to European commission the final NECP document. Figure 2 shows the main Italian goals, which includes a 30% of final energy consumption produced by RES, a 22% of final energy consumption in the transports sector (UE imposes 14%), a reduction of primary energy consumption of about 43% (UE imposes 32.5%), a reduction of greenhouse gas emissions of about 33% (UE imposes 30%). Figure 3, done by ISPRA [2], shows the trend of GHG emissions of non-ETS sectors, if all policy measures defined in the Italian NECP will be applied. The EU ETS (European Union Emission Trading Scheme) was the first trading scheme in the world for GHG emissions, published in 2005. The ESD and ESR goals represent respectively sectors covered by the Emission Trading Scheme, and those

[2] isprambiente.gov.it

	Obiettivi 2020 UE	Obiettivi 2020 ITALIA	Obiettivi 2030 UE	Obiettivi 2030 ITALIA (PNIEC)
Energie rinnovabili (FER)				
Quota di energia da FER nei Consumi Finali Lordi di energia	20%	17%	32%	30%
Quota di energia da FER nei Consumi Finali Lordi di energia nei trasporti	10%	10%	14%	22%
Quota di energia da FER nei Consumi Finali Lordi per riscaldamento e raffrescamento			+1,3% annuo (indicativo)	+1,3% annuo (indicativo)
Efficienza energetica				
Riduzione dei consumi di energia primaria rispetto allo scenario PRIMES 2007	-20%	-24%	-32,5% (indicativo)	-43% (indicativo)
Risparmi consumi finali tramite regimi obbligatori efficienza energetica	-1,5% annuo (senza trasp.)	-1,5% annuo (senza trasp.)	-0,8% annuo (con trasporti)	-0,8% annuo (con trasporti)
Emissioni gas serra				
Riduzione dei GHG vs 2005 per tutti gli impianti vincolati dalla normativa ETS	-21%		-43%	
Riduzione dei GHG vs 2005 per tutti i settori non ETS	-10%	-13%	-30%	-33%
Riduzione complessiva dei gas a effetto serra rispetto ai livelli del 1990	-20%		-40%	
Interconnettività elettrica				
Livello di interconnettività elettrica	10%	8%	15%	10%[1]
Capacità di interconnessione elettrica (MW)		9.285		14.375

Figure 2: Italian NEPC goals.

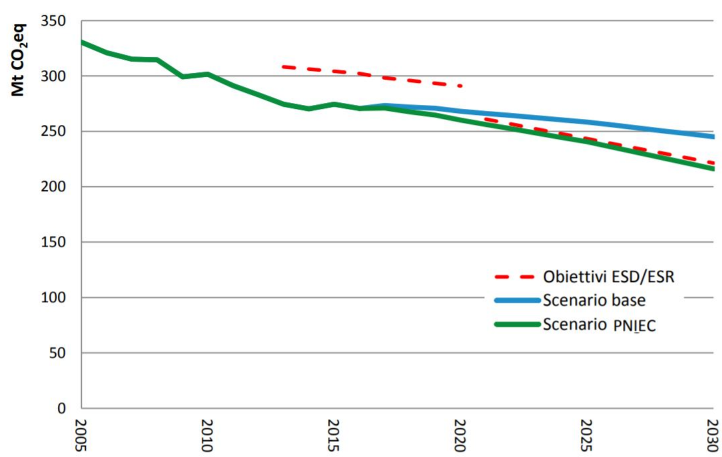

Figure 3: Historical trends of emissions in non-ETS sectors by ISPRA.

covered by the Effort Sharing Decision [18]. They also represent the base scenario and the expected scenario by the Italian NECP. Considering the trend divided by sectors, the larger contribution is represented by transport and civil sectors, which correspond to the residential and the tertiary sector. In the residential sector, the reduction in GHG emissions according to the Italian NECP, will be equal to 35 $MtCO_{2,eq}$ [19] and it reflects the expected acceleration of the renovation of existing buildings, in terms of the introduction of high-performances technologies and buildings envelopes substitutions. Italy will use mandatory scheme imposed by the energy efficiency certificates, called also *white certificates*, and other measures, to increase the saving of final energy, in the period 2021-2030, according to the article 7 of the Energy Efficiency Directive (EED). The proposal is to promote a better differentiation of tools by sector of interest, to make the measures more efficient. The tools used to increase energy efficiency are the same as the EED:

- energy performance certificates;
- tax deductions for energy efficiencies measures and for the recovery of existing buildings;
- thermal account;
- National Fund for Energy Efficiency;
- Enterprise Plan 4.0;
- Program for the energetic requalification of the buildings of the Public Administration;
- Program for energy efficiency measures promoted by 2021-2027 policies;
- national energy efficiency information and training plan;
- set of measures for sustainable mobility.

It was estimated that to 2030, it will be an annual energy savings of 5.7 Mtoe, due to buildings renovation, of which 3.3 Mtoe from the residential sector and 2.4 Mtoe from the tertiary sector (public and private).

1.1.2 Literature review

This sub-section will introduce the main topics treated by this thesis work, showing a summary about approaches and results explained in the most relevant scientific papers collected. The main topics analyzed focus on the use of open-data and EPCs in energy sector, the methods mostly used to estimate energy consumption and the most known approaches to make these estimates at urban level. The last part of this paragraph is dedicated to the analysis of papers which try to represent the results obtained at urban level with the use of energy maps in GIS. First of all, the relevance of using open data as source of information and their application in energy sector has been highlighted by some studies. Pfenninger et al.[21] explain why models and data should be open, and they summarize this concept in four main reasons: improved quality of science, more effective cooperation across the boundaries of science-policy, larger productivity through the sharing of burden, large relevance to societal debates. They explains also why data are mostly not open: for ethical and security reasons, because the process to track and collect data is time-consuming and it implies large investments, but especially cause to institutional inertia. They says that also what needs to be done in order to enlarge the possibility to use open data by the energy research community: reduce duplication of works developing common standards and data-sets, increase the generalization, scalability, and the transparency of works, engage multiple stakeholders have more incentives. Bazilian et al.[20] gives a refined overview of the application of open data, especially in energy sector. They explain that open and publically accessible data and software can be used to develop robust analysis in energy sector because they can be a support for the modelling process and for public engagement in energy issues. They analyze some research works to prove that open energy data may help to develop better-informed energy decisions. An example of public and accessible data should be done by the energy performance certificates data-sets, but not all regions or countries make them available. The EPCs are also the data-sets used in this thesis work, then their application as open and not-open data has been studied. There are many scientific papers which analyze the main applications of EPCs to extract information of building performances. Pasichnyia et al.[22] review the existing application of EPC data, analyzing 79 papers, showing that EPC data can be improved through adding the EPC characteristics. They propose a method to define the quality of EPCs using data analytic. They highlight that EPCs can be used by local or national authorities to improve energy planning or to define decision-making processes. They highlight also that EPCs can be a useful tool for citizens or owners of the buildings because both of them can understand in a right way which are their expenses related to energy, and they can critically analyze possible interventions to reduce them. Also, utility companies can use EPCs to offer their services, products, counseling, and possible retrofits. They conclude the work saying that enlarge the application of EPCs data is fundamental to place stronger requirements on the quality and content of information. The same conclusions have been outlined by Madrazo et al.[23], but they directly developed a project to make the actions to improve energy performances easier for planners and owners. They collect data from different sources (EPCs, land registry, cadastral registry of thermal systems), and some errors and inconsistencies arose. They says that solutions to avoid these errors should be found at the data source level. While Gelegenis et al.[24] try to understand if EPCs can be used for energy saving purposes. They analyse the market trends obtained by EPCs in Greece, to understand how the EPC can be a profitable tool to helps in improving buildings' energy performances. The results of the study show that EPC is transformed into a trivial administrative procedure, which needs control in the implementation procedure and good training for energy inspectors. The main problems are related to the fact that proposed measures in EPCs have high costs, that they are often completely absent, or that they are not applied by the owners of buildings. Some papers try to apply the information given by the EPCs for energy planning purposes, and they are described here. Lopez-Gonzalez [25] use EPCs to evaluate the primary energy consumption in the residential sector in a city, calculating both the specific consumption and the correspondent carbon emissions. These parameters have been studied based on building type, climate zone, and building regulations. For each climate zone, year of construction, and type of buildings, they analyze the statistical parameters both for consumption and CO_2 emissions. It is demonstrated in this study, that the results can be joined with the land registry to make some in-depth analysis and to define saving measures. Streicher et al.[26] analyze statistically buildings energy certificates to estimate a thermal performance level for some building archetypes, with their heating systems and building envelope elements. In this paper, with respect to the previous one, it is introduced the concept of archetype of a building. Attanasio et al.[27] propose a methodology to estimate the primary energy demand for space heating of a building with an automated system, and to find the relationship between the PED_h and the main building features described in energy performance certificates. They use a two-layer approach, analyzing 90000 EPCs in Piedmont region, and creating a flexible configuration for different applications. The EPCs can be easily used if they are treated aggregating them on the basis of thermo-physical parameters, as done by Fabbri [28]. He studies the EPCs database of the Emilia-Romagna region, in order to measure a territory and to elaborate some saving measures. He also compared bottom-up and top-down methods, to define policy scenarios. He observe that the relationship between the energy consumption and the building geometry is not linear and they define some index to compare the results obtained applying the bottom-up and the top-down methods. As in the previous study by Streicher et al.[26], the path chosen was to aggregate data or define archetypes, in order to include a larger sample of buildings, independently if they are residential or not. The studies done by Pasichnyi et al.[29] and by Wallin et al.[30] are focused only on residential buildings, which are subdivided according to their typology (multi-family buildings or apartments). The difference with respect to the previous studies is that the energy consumption information has been taken from heat energy use metering data, while EPCs have been used just for geometrical features. They apply a hybrid approach, integrating both physical and statistical ones. Three building archetypes have been developed for the case of retrofitting packages: multi-residential buildings (1946-1975), offices, and multi-residential buildings (>1996); while, in the case of electric heating, six archetypes have been analysed. Archetyping approaches have been received attention, especially in UBEMs applications (Urban Energy Building Modeling). UBEM is a hybrid approach that received a lot of interest in recent years because is an efficient hybrid model, which combined bottom-up or engineering approaches with top-down or statistical ones, as done by Nageler et al.[31]. The top-down approach does not distinguish energy consumption by individual end-uses. It has been elaborated to determine long-term changes or transitions into the residential sector. These models are distinguished between technological and econometric ones. Technological models link the characteristics of the whole building sample to energy consumption, while econometric ones analyze the building stock using prices and incomes. The bottom-up models consider individual variables, differentiating for end-uses, type of building, or other variables. The sample analyzed is a lower level with respect to the entire sector, and the groups identified are used to represent the entire region or nation [32]. The last work mentioned bases its calculations on the data metered by the energy supplier, which provides at least hourly energy values. If the supplier does not provide the metered energy consumption, some methods to calculate it have been elaborated. Some of them are based on climate data, like bin methods or hourly methods. The bin method is a steady-state method introduced for the first time by Thamilseran and Haberl [40], with the goal to take also into account non-linear temperature dependencies of building's energy use. Wang et al.[33] and Elhelw et al.[34] apply a modified bin method to define and optimize some retrofitting solutions. The method has been applied to a single building, which is an office, and not on at large scale as in previous scientific papers. It highlights that the modified bin method is a convenient and simple simulation method to analyze retrofit schemes for the existing buildings because it required low computational time and it is easy to formulate. Naldi et al.[35] compare the application of the bin method and the hourly simulation for the seasonal performance of an air-source heat pump. The numerical results show that the bin method gives results in good agreement with the dynamic hourly simulation, but the results in terms of SCOP are quite different. The bin method is a good approach especially when it is applied at large scale, and for this reason it is chosen for this thesis work. The application of the bin method at a large scale is described by Han et al.[43]. They calculate the building energy consumption of the city Chongqing, through the definition of a multi-objective model, evaluating also carbon emissions and the initial-cost. They define some weight factors, in order to determine the priority levels of the sub-objectives. They identify five types of buildings to apply the multi-objective model, performing a sensitivity analysis to understand which parameters larger influence the energy consumption reduction. Energy consumption at urban scale can be estimated, not only with the application of a steady-state or dynamic methods, but also through the definition of a linear regression model and with the support of a GIS system, as done by Torabi et al.[36]. They define a geospatial bottom-up statistical model, which estimate the energy consumption of a large number of building in the residential sector. The spatial representation is done to gives a tool for urban planners or decision-makers to define the path to follow to reach energy efficiency and to introduce renewable energy technologies. Other papers use a spatial representation as a support for energy-planning. Cerquitelli et al.[37] developed a new data-visualization framework called INDICE (INformative DynamiC dashboard Engine) in order to explore a large number of EPCs. They create energy maps useful to define the energy performance and consumption of buildings located in different zones. There are many types of maps elaborated, at census tract level and district one, like cluster-marker maps, choropleth and scatter maps. Caputo et al.[38] used a Geographic Information System city buildings database to develop a methodology to characterize the energy performance of buildings already built in a city. After the data collection and the characterization of the building stock, building archetypes have been built to determine energy consumption and possible retrofit strategies. Since it has been applied to the city of Milan, the results from the simulations have been compared to the data available from the Regional web portal about EPCs. In this case, EPCs are used to make a comparison between the simulated results and the expected ones.

2 Methodology

The main steps followed in the current methodology explained here, are summarized in figure 4. The first step involves the data preparation to obtain a complete data-set to be used. The current methodology uses only open data which can be easily downloaded and it is developed through the use of an open-source programming language and an open-source software. Energy Performance Certificates (EPCs) and the Regional cadastre of thermal systems (CURIT) have been used as data sources, to provide additional information about building thermal plants.

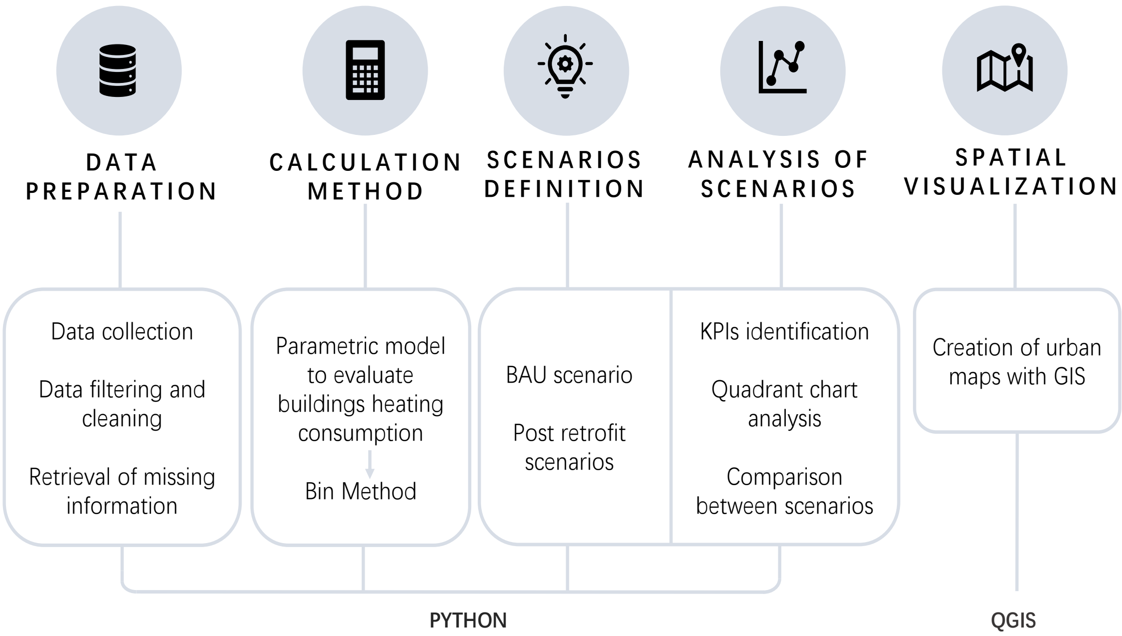

Figure 4: Steps of methodology.

The second step regards the definition of the calculation method through the develop of a parametric model to estimate buildings heating consumption, through the application of the Bin Method. The Bin Method has been applied to evaluate both building loads and energy consumption. The parametric model allows to apply the same calculation method for different scenarios, changing the parameters involved, like thermo-physical

ones or thermal systems technical specifications. It is defined as parametric also because it ensures the scalability of the model for each building analyzed. The third step includes the definition of different retrofit strategies. Applying the retrofit strategies different scenarios can be obtained, including also the BAU scenario. The fourth step includes the identification of some KPIs, useful to do the analysis and the comparison between all scenarios. The KPIs identification is accompanied by the use of the quadrant chart for their representation. The last step involves the spatial visualization of the results in urban maps, using a Geographic Information System.
The process of data elaboration to obtain a data set useful for the purpose has been done with Python. Also, the evaluation of building loads, the subsequent calculation of heating consumption, and the retrofit strategies have been modeled with Python. The urban maps have been obtained with the software QGIS. The steps mentioned will be described more fully in the following paragraphs.

2.1 Data preparation

Data preparation is the first step of the above mentioned methodology, but it represents a fundamental step for all works which use big data as model's inputs. Indeed, data have never a structure which allows their direct use, especially if they are open data. Despite open data represent a resource for the community, there is often a lack of interest in making sure that they are properly written. Indeed, open data may contain a lot of inconsistent information because often the collection process is not standardized. Before starting to directly use data, it is necessary to clean both data sets and remove wrong or unwanted information. The main step to follow are: collect the necessary data-sets, filtering the unnecessary columns, and recovering missing information not included inside the data-set. *Data filtering* is the process to reduce the data-set considering a smaller part of it to do analysis. Indeed, the quality of data is affected by different factors which depends on the type of data-set analyzed. To filter the correct information, as suggested by [62], the consistency checks considered are constraints rules for columns, physical thresholds, and rules involving analysis of values from several columns. The process of data filtering can involves also the elimination of duplicated data. Indeed, when data are stored, duplicates of records may appear, and they need to be eliminated, distinguish them between clones and representative sample. It may happen that there are also some contradictive data. To treat them and solve the problem, it is necessary to use the knowledge about the system. Another aspect to know doing the data filtering, is the presence of values out of bonds or outliers. In this methodology some boxplot have been constructed in order to know which are the outliers to eliminate. A boxplot is a standardized representation to graphically depict the distribution of a sample. A boxplot is characterized by five-number summmary: the minimum value and the maximum one, the sample median, and the first, second and third quartiles. It is used in descriptive statistics and the outliers may be represented as individual points. In this way it is easier to remove them. Using a large amount of data, it may happen that the information contained inside the data-set are not complete, and that implies the necessity to fill the empty field with real or statistical data, recovered by other sources. This process is generally called *data enrichement* and it consists of the recovery of missing information. In data analysis, this step is very complex, but in this methodology it consists only in allocating missing information taken from others sources, according to a certain criterion. Since the last step of the methodology consists of a spatial representation of the results, each rows of the data-set must be associated to latitude and longitude values. There are many ways to recover spatial coordinates, for example using a Geographic Information System or directly through the Open Street Maps tool. These two are both open to anyone, while others tools like Google Maps, are not easily accessible. Both Open Street Maps and Google Maps, require as input a default address format to correctly match it with a couple of coordinates. Open Street Maps is less accurate with respect to the Google Maps tool.

2.2 Calculation method

The second step involves the definition of a calculation method to obtain the energy consumption of buildings. It is defined a parametric model, which requires as input buildings envelopes parameters and specifications about thermal systems. The method chosen in this case is the bin method, because it is very useful in treating a large sample of buildings. The bin method is not the only known method to evaluate energy consumption. Indeed, ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) classifies different analysis methods to estimate energy use, grouping them in forward modeling and inverse modeling approaches [39]. The first approach evaluates output variables of a specific model, with well known structures and parameters, when subject to input variables. The main advantage is that it is useful during preliminary design and analysis phases, because the system involved does not need to be already built. To apply the second approach, input and output variables must be known and measured, in order to find a mathematical description for the system and its parameters. Bin method and the modified bin method are classified as steady state, which could be applied using both forward modeling or empirical/black-box inverse modeling, depending on the system involved. Indeed, compared to another simplified method, as the degree-day method, developed to avoid computationally intensive models, it takes account of the outdoor temperature influence on some parameters. Degree-day methods treat parameters like building use or the efficiency of HVAC equipment as constant, while bin methods consider them as dependent to weather variables. In this way, it is possible to account for equipment performance variations that may occur hourly in response to changes in the weather. It is largely used also to model building in which internally generated loads dominate, like large buildings [41]. For this reason the bin method has been chosen for this thesis work, because it is easy to apply for a big number of buildings. The bin method is also good for heating and cooling energy calculations, not only for residential sector, but especially for large commercial buildings. Steady-state calculation can yield good results for energy consumption in many cases, especially if different temperature intervals,

or time periods, are evaluated separately [42]. It calculates consumption at different outdoor temperature values, multiplied by the corresponding number of hours in the temperature interval, called bin, centered around that temperature. Then, monthly weather data are sorted into discrete groups, known as bins, which account the average hours of occurrence of outdoor temperatures or other weather variables, during the period of interest: a single month, a year, or an entire season. It is considered more accurate with respect to the degree-day method, because it is base on hourly weather data rather than daily average value. Bins are generally defined as temperature intervals of 2.8°C, with three daily 8 hours shift, if necessary [39].
The annual energy consumption can be easily evaluated applying the Bin Method. ASHRAE gives the following general formula to define how to evaluate the total heating consumption using the bin method [39]:

$$Q_{tot} = \sum_{i}^{n} (N_{bin} \frac{K_{tot}}{\eta_h} [t_{bal} - t_0]^+) \tag{1}$$

N_{bin} represents the number of hours correspondent to a single bin, K_{tot} is the total heat loss coefficient of the building, t_{bal} is the balance temperature, t_0 is the outdoor temperature and η_h is the efficiency of the heating system. The plus sign indicates that, when the balance temperature is higher than outer temperature, positive contributions are not counted, because no heating is needed in this situation. Equation (1) is evaluated for each bin, and then each contribution is summed to obtain the total consumption.

The total heat loss coefficient of the building, defined in the ASHRAE formula, generally it is not known. It takes into account all the different contributions which influence the thermal building load. These contributions need to be defined to estimate both heating and cooling building loads. Indeed, the thermal load profile is evaluated considering:

- Transmission loads (conduction).
- Solar loads through windows.

- Internal loads.
- Ventilation or infiltration loads.

Transmission loads (conduction) Thermal conduction is due to temperature difference between the outside surfaces temperature and inside temperature. It accounts for two different contributions: steady heat transfer load through windows, roofs and walls and unsteady heat transfer load by solar radiation through roofs and walls [43].

$$Q_{s,t} = \frac{\sum_{i=1}^{n}(A_i \cdot U_i)(T_{out} - T_{in})}{A_{floor}} \tag{2}$$

$$Q_{l,t} = \frac{\sum_{i=1}^{n}(A_i \cdot U_i \cdot CLTD \cdot SC \cdot FPS_m)}{A_{floor}} \tag{3}$$

$$Q_{UHL} = \frac{(Q_{UHL_7} - Q_{UHL_1})(T_{out} - T_1)}{T_7 - T_1} + Q_{UHL_1} \tag{4}$$

where $A[m^2]$ is the area, $U[\frac{W}{m^2 \cdot K}]$ is the coefficient of heat transfer, T_{out} and T_{in} $[°C]$ are outer and inner temperatures, $CLTD$ is the cooling load temperature difference, SC is the shading coefficient, FPS is the average sunshine rate, n is the number of wall/roof/window surfaces, k is the number of bins, m represents a specific month (1 is for January and 7 is for July), i is the i^{th} wall/roof/window considered. The subscript s means *sensible*, while the subscript l means *latent*.

Solar radiation loads through windows The traditional bin method evaluate this contribution as a linear relationship with the outdoor dry bulb temperature, while the modified bin method considers the solar radiation according to the following formula [43]:

$$L_{SR} = \frac{\sum_{j=1}^{n}[A_j \cdot SC_j \cdot \sum_{k=1}^{k}(n_i \cdot Cf_i)]}{A_{floor}} \tag{5}$$

where C_{f_i} $[\frac{W}{m^2}]$ is the solar radiation through windows, i is the i^{th} bin and j is the j^{th} window.

Internal load It is composed by different contributions by lights, equipment and heat sources from indoor equipments.

$$L_I = \frac{Q_{in} \cdot \sum_{i=1}^{k} n_i \cdot H}{24 \cdot A_{floor}} \tag{6}$$

where Q_{in} $[\frac{W}{m^2}]$ is the generation rate of internal contributions, n_i represents the i^{th} bin and H is the number of hours that equipments or lights are turned on.

Ventilation/infiltration load To simplify the method, natural ventilation it not taken into account and the total load is composed by infiltration and mechanical ventilation [43]. As for transmission load, it accounts for both sensible and latent contributions.

$$Q_{s,v} = \frac{\rho \cdot C_p \cdot V \cdot (T_{out} - T_{in})}{3600 \cdot A_{floor}} \tag{7}$$

$$Q_{l,v} = \frac{\rho \cdot \gamma \cdot V \cdot (D_{out} - D_{in})}{3600 \cdot A_{floor}} \tag{8}$$

where ρ $[\frac{kg}{m^3}]$ is the air density, c_p $[\frac{kJ}{kg \cdot K}]$, γ $[\frac{J}{kg}]$ is the latent heat of water vaporization, V $[m^3]$ is the volume of infiltration and D $[\frac{g}{kg}]$ is the moisture content.
Not all thermal inputs are always considered, but it depends on the type of load of interest, heating or cooling load.
As explained in [44] heating calculations are conservative, because they use simple worst-case assumptions, neglecting solar and internal gains. Then, heating load takes into account only sensible heat by transmission and ventilation/infiltration load.

Building energy consumption

After the evaluation of the heating or cooling loads, it is necessary to obtain the total energy consumption of the building, considering the type of thermal systems involved on building and space conditioning.

According to equation (1) the total load can be obtained by multiplying the thermal building load by the corresponding number of hours of each external temperatures and then dividing by the corresponding efficiency of each thermal system.

$$Q_{heating} = \frac{\sum_i^n (Q_{s,t} + Q_{s,v}) \cdot n_i}{\eta} \tag{9}$$

where $Q_{heating}$ $[\frac{Wh}{m^2}]$ is the total heating consumption of the building, n_i is the i^{th} bin and η represents the system efficiency (COP for heat pumps). If the thermal system efficiency varies with the external temperatures, it is possible to rewrite the equation to consider different values of efficiency for each temperature bin:

$$Q_{heating} = \sum_i^n \frac{(Q_{s,t} + Q_{s,v}) \cdot n_i}{COP_i} \tag{10}$$

2.3 Definition and analysis of scenarios

Before to introduce the map visualization, that allows to understand which are the census tracts which need larger improvements, it is necessary to define the approach used to define scenarios and do the analysis of them. A method useful to understand which are the correct actions to be taken at building level is to define some key performance indicators (KPIs), which are used to measure the improvements of a project. It represents a popular and validated tool, as explained by Kylili et al.[68] to define building renovations and sustainability of constructions. Kylili et al.[68] group different typologies of KPIs: economic, environmental, social, technological, time, quality, disputes, project administration. These indicators can be qualitative or quantitative, and they can be referred to building performances and their impacts at different levels. Considering this specific case, only environmental and energy-related KPIs have been used. From the environmental perspective, the indicator mostly used is the annual carbon emissions, or CO_2 emissions, which does not accounts for the whole greenhouse gases emissions, but it is the more relevant. It is indicated both as specific value $\frac{kgCO_2}{m^2}$ and absolute value $kgCO_2$. From the energy perspective the primary energy consumption is the mostly used. As for the environmental KPI, it is indicated both with its specific value $\frac{kWh}{m^2}$, and its absolute value kWh, considering both the thermal and the electric building consumption. Vergerioa et al.[69] highlight that the energy-related KPIs are the most diffused, and that both GHG emissions and energy consumption refer to the operational phase only.

To understand which are the critical buildings, a correlation between two variables is represented with a quadrants chart, to understand if there is a relationship between an absolute value and a relative value. Torabi et al.[70] use the quadrant chart (figure 5) as decision support tool, when a very large stock of buildings is analyzed. The quadrant chart helps to identify critical issues and energy performance levels of buildings under investigation. In this way, it is easier to plan some interventions and to understand which sample of buildings needs more urgent improvements with respect to the others. The graph is subdivided in four quadrants, by the average or median values, and each quadrant has a different level of priority. Buildings in the III quadrant are buildings or apartments with the highest performance inside the explored stock, while buildings in the I quadrant are the worst. The II and the IV quadrants contain buildings with lower priority with respect to the IV quadrant, but they need improvements, cause their specific and absolute values remain too high. This graph can be used also to group buildings with similar performances or common geometric characteristics.

Once the approach to make a correct analysis is defined, different scenarios can be evaluated, according to the chosen case study. The retrofit strategies will be defined not for a single building, but involving an entire sample, according to what has been said about the use of the quadrant chart. Even if the retrofit strategies will involve an entire sample of buildings, they will be scaled for each of them, considering the specific building parameters or its thermal systems specifications. In this way the model could be generalized and applied also in other case studies.

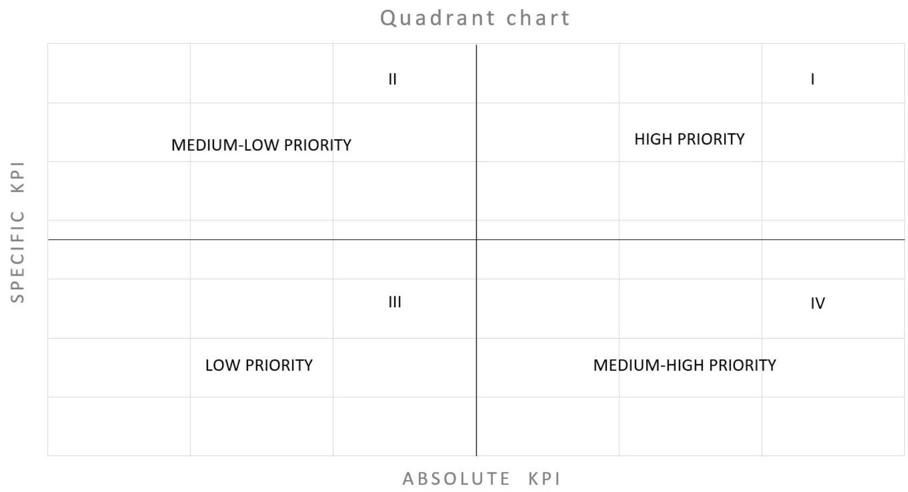

Figure 5: Quadrant chart.

2.4 Spatial visualization

The last step of the methodology includes the representation of the results through a spatial visualization. The representation of the results in a map allows the energy planners to make some targeted decisions for energy improvements of the buildings. For example, the energy planner could apply different retrofit strategies considering the areas in which the heating consumption or the carbon emissions are higher. In this sense, the map visualization is a tool useful both to obtain information about the spatial distribution of an identified key performance indicator for buildings, and to plan some strategies to adopt. There are many tool that provide the ability to represent georeferenced data. One of the most famous is GIS, which is the acronym of Geographical Information System. It is a conceptualized framework useful to collect, analyze and represent spatial and geographic data. GIS combines the common operations related to the use of database, like statistical analysis with the geographical analysis of the numerical cartography. It is a tool largely used by urban planners, because it is fundamental to the analysis of a territory. Some examples of the most diffused applications are the definition of: town development plans, environmental impact studies, territorial planning, geological mapping, etc. In a GIS system there are three types of information:

- geometrical: related to the representation of the cartographic objects, like the shape (points, lines, polygons), the dimension, and geographic position;
- topological: related to reciprocal relationship between objects;
- informative: related to the data information linked to an object.

All the spatial analysis must be done using a specific reference system. The projection and reference systems implemented by GIS are different. The most used is WSGS84, based on a reference ellipsoid elaborated in 1984. One of the most used functionality is the spatial representation using maps. It is possible to realize both static and dynamic maps; these latter are customized by the user. The most known not-open GIS software are ArcGIS, Global Mapper, Fielp-Map, and AutoCAD MAP 3D. The most known open-source GIS software are: GRASS GIS, QGIS, gvSIG, and Orfeto toolbox.
In this case the GIS system used is the open-source software QGIS, previously called Quantum GIS. The first step followed in this methodology for the spatial analysis, is the import of a georeferenced data-set, containing all the necessary information about the buildings. The imported data-set is composed only by points which correspond to a single EPC defined in the space with a couple of coordinates in WGS84 reference system. The second step involves the spatial join between these points and the polygons of buildings. The spatial join can be done also using the polygons correspondent to census districts. In this way it is possible to obtain the same information, but at different levels, at building or census districts ones. Especially when there are a lot of buildings analyzed, the building level does not allow to visualize correctly the information in the map. The spatial analysis involves many functions, like the estimate of the statistical information about the data aggregated at the chosen level. These statistical information may be for example the mean, maximum, minimum values or the standard deviations of the value of interest. This is the last step which allows to obtain a spatial visualization of the results. The polygons associated to buildings or census districts can be provided by the municipality. As explained, in this thesis work, these information where provided by the municipality as open data.

3 Case study

Bin methodology has been applied to Milan, a city located in northern Italy, which is the second most populated city in Italy. The city has a population of about 1.4 million inhabitants, while its metropolitan city reaches 3.26 million inhabitants. The population density is equal to 7674.81 $\frac{inh}{m^2}$ and the extension of the city is 181.76 km^2. The coordinates are (45°28'01"N, 9°11'24"E) and it is located in climate zone E, according to D.P.R. n. 412 (26/08/1993) [53]. In climate zone E, the heating period begins on October 15^{th} and ends on April 15^{th}. The city of Milan has been chosen because it provides open data available from the portal of open data created by the municipality in 2012. The data available cover different sectors, included energy and environmental ones. Data are open to increase the transparency of the Public Administration, according to the governing doctrine of Open Government. The city of Milan was one the Italian's first cities to make available to citizens such a large amount of data.

This thesis work focuses only on the heating period, and it does not investigate the building consumption during the cooling period. The group of building analyzed includes only residential users, neglecting commercial or public buildings with other intended uses. The residential buildings in Milan are 221891; in this thesis work around 96000 residential buildings have been considered.

3.1 Available data

The open data provided comes from the regional open data web portal[3], which allows to freely download Energy Performance Certificates (EPCs) and the technical specifications of thermal systems from the Cadastre of plants (CURIT). Since some information about the building envelopes was missing, they have been added to the EPCs dataset, according to the data provided by SIRENA20[4] web portal.

Climate data have been provided by the web site of the Photovoltaic Geographical

[3] `https://dati.lombardia.it/`

[4] `http://www.energialombardia.eu/sirena`

Information System (PVGIS)[5].

3.1.1 Energy Performance Certificates

EPCs of the Lombardia region are stored on a regional building energy register (CEER), according to Annex H-DDUO 2456/2017 [54]. The EPC is a useful tool to evaluate the convenience in carrying out building interventions of energy redevelopment, through a specific analysis of energy performances. Energy performances are evaluated based on the annual energy need for standard use of the building, which means to consider the annual primary energy for heating and cooling needs, for ventilation, and domestic hot water. If the calculation is done on a non-residential building, it is necessary to take into account also the contributions of lighting devices, elevators, and escalators.
The current methodology is explained in the Italian UNI TS 11300 and it can be applied to each typology of building. The most recent design software used for EPCs processing is CENED+2.0, which replaces the older versions.
The most important regulation at European level is the EU Directive
2002/91/EC [55], called also *Energy Performance Building Directive*, followed by EU Directive 2009/28/EC [56] and 2010/31/EC [57]. In accordance with the last directive, guidelines for the Italian nation have been defined, outlined in the Interministerial Decree of 26/06/2015 [58] to standardise energy performance calculation of buildings over the national territory. At the Regional level, the Lombardia region issued the above mentioned Decree [54] to replace the previous Decree 176/2017.
The EPBD (Energy Performance Building Directive) changed the concept of energy efficiency: the construction activity must pursue the reduction of environmental impact and GHG emissions. The rules contained in the EPBD directive paying attention on:

- the general framework for a methodology to calculate the energy performance of a building;
- the application of minimum energy performance requirements for new buildings;

[5] `http://www.energialombardia.eu/sirena`

- the application of minimum energy performance requirements for large buildings whose need a lot of renovation measures;
- the energy performance certificate for buildings;
- the periodic inspection of boilers and air-conditioning systems, and a report for thermal systems whose boilers have more than 15 years.

It explains also that the EPC must clearly indicate the energy performance of the building and recommendations on possible improvements to the envelope or thermal systems, which are economically available. The energy performance of the building is expressed through the non-renewable energy performance index $EP_{gl,nr}$, which refers to the non-renewable demand for the following services: heating and cooling (EP_H and EP_C), domestich hot water production (EP_W), ventilation (EP_V), artificial lighting (EP_L) and transports ($EP_{T,nren}$) for non-residential buildings. Heating and hot water production services are assumed to be always present in a building, while other services are added if necessary. If there are not thermal systems, they are simulated following a standard configuration. To classify the building performances it is applied the method of the construction of a reference building with same characteristics of the building analyzed, but with pre-set energetic parameters. The energy class of the real building is estimated using multiplication factors and the non-renewable index estimated for the reference building $EP_{gl,nr,Lst}$. This last value is the delimiter between the energy class A1 and B. Figures 6 and 7 represent the energy classes classifications, for the non-renewable index of the reference building, and just for the heating index. The first is used after the introduction of the [58], while the latter is refereed to the old classification used before 2015.

	Classe A4	$\leq$ 0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A3**	$\leq$ 0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A2**	$\leq$ 0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A1**	$\leq$ 1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe B**	$\leq$ 1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe C**	$\leq$ 1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe D**	$\leq$ 2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe E**	$\leq$ 2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe F**	$\leq$ 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
	Classe G	> 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$

Figure 6: Classification based on $EP_{gl,rn,Lst}$ index.

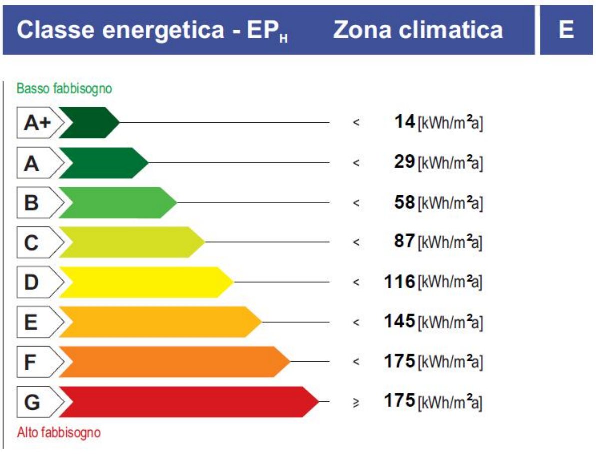

Figure 7: Classification based on EP_H index.

3.1.2 Cadastre of Thermal Systems

The cadastre of thermal systems is a computerized collection of data, which aims are to take stock of all thermal plants present in a region, and to allow simple interfacing with the land cadastre and EPCs register. The data set used here was created by Lombardia region in 2008 to collect and manage the data related to the thermal plants on regional territory, according to DPR 74/2013 [59]. To implement the Directive 91/2002/EC about energy performance of buildings, at national level they were issued the Decree of August 19^{th} 2005 [60] and then the Decree of February 10^{th} 2014 [61]. The last one illustrates which model of thermal system register to use. The plant typologies involved are:

- Fossil fuel boilers (> 5 kW).
- Wood biomass systems (> 5 kW).
- Heat pumps and/or thermal solar collectors for heating and domestic hot water production (> 12 kW).
- Chillers for cooling (> 12 kW).
- Heat exchangers of district heating substations.
- Cogenerators and trigenerators.
- Water heater for several users.
- Other devices which sum of powers of the single building units is equal or larger than 5 kW.

A structure of thermal plant register organized by region, offers the opportunity for the Public Administration to control thermal plants and to periodically manage their inspection operations. The register done by the Lombardia region contains some additional elements whith respect to the interministerial model: the thermal system plate, cadastral data about building location, the EPC code, and the identification codes of the energy meters, both for natural gas and electricity.

EPCs data set includes many information about buildings envelopes, geometries, construction years, energy performances and thermal systems.
Cadastral data set contains specific information about thermal plants used in each building, like number of generators, their categories and specific typologies involved, their rated powers, efficiencies and generator technologies.

Data filtering For these checks they have been imposed area and volume larger than zero, rated power of thermal systems always positive and thermal efficiency within correct thresholds. Both data sets have been filtered choosing only rows having the correct ISTAT code of Milan.
Since the cadastral data set refers to different generators of thermal installation of buildings located in Milan, its rows have been merged with the correspondent EPCs rows, through EPC identification code. The EPC identification code consists of 13 digits: the first 5 for the ISTAT code of the town, 6 for the total number of EPCs done during the year, and the last 2 identify the year during which the EPC was opened. Knowing these last two digits it is possible to filter EPCs before 2010. Indeed, according to paragraph 3 of Article 4 of Interministerial Decree 26/06/2015 [58], EPCs are valid for 10 years from the date of issue, and they are updated whenever any works are performed, which change the energy performance of the building or plant.
Most of EPC identification codes in cadastral data set are incorrectly written, or they are referred to older EPCs. Then only a small portion of the thermal plants are correctly associated with the correspondent building.
For this reason, the EPCs data set has been split between a real sample, composed by merged rows, and a statistic sample obtained analyzing the cadastral data set. The real sample contains both real information about thermal plants and building envelope.

Geolocation EPCs data set contains information about coordinates given in the WGS84 reference system. There are many empty cells, then NaN values have been replaced with the coordinates correspondent to address indicated on EPCs.
The process to convert physical address description to a geographic information in terms of latitude and longitude, called geocoding, is done with the help of Geopy and Geopandas libraries in Python. Geopy has different Geocoding services: in this case it is used Nominatim, which is built on top of OpenStreetMap[6] data.
The advantage of using Nominatim as Geocoding service is that it is freely available,

[6]https://www.openstreetmap.org

unlike other services that require API keys, but the main disadvantage is that it is not always able to find a couple of coordinates for a specific address.

Geocoding process is applied also to the cadastral register of thermal plants, with the aim to merge more data through latitude and longitude coordinates.

As illustrated in figure 8 it is correctly joined only a small portion of the entire data set, around 1%, cause to the disadvantage of Nominatim service previously explained. The spatial distribution of the EPCs correlated to buildings or apartments is more concentrated in the center of the Municipality of Milan.

The final data set is composed by around 95000 buildings not joined with the correspondent thermal systems and around 1500 correctly joined buildings. Cause to the presence of a large sample of buildings, whose information does not contain all the fundamental technical specifications of thermal systems, it is necessary to recover this gap analyzing statistically the cadastral data set, as explained in section 3.2.1.

In this case GIS (Geographical information system) helps to visualize and identify building consumption, which can be correlated to their characteristics in order to support decision-making at urban and regional scale.

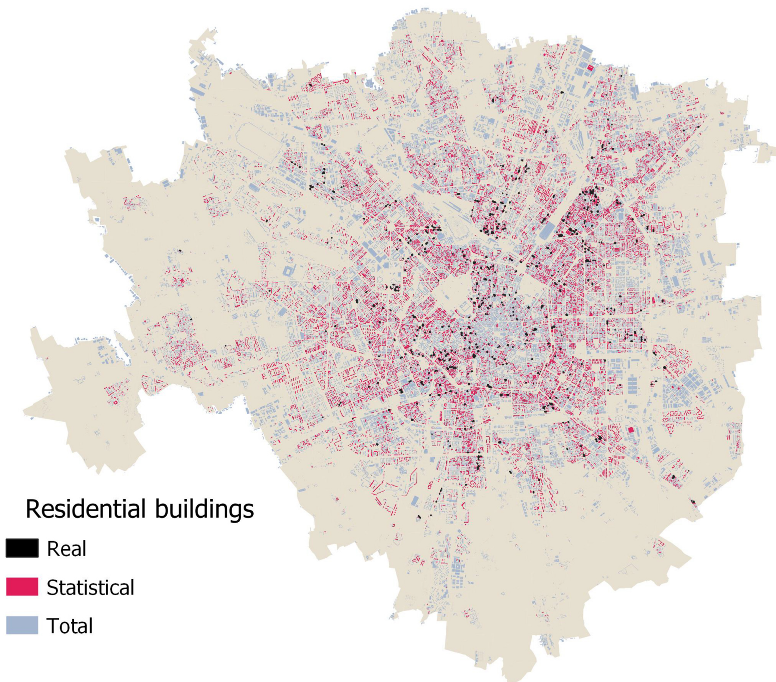

Figure 8: Spatial distribution of EPCs analyzed.

Missing information Data collected have been enriched with additional information from external data sources. In the most recent EPC, thermal transmittance of building envelopes are no longer being reported, then they have been provided from SIRENA20[7] web portal. Thermal transmittance are collected for each energy class and each specific use of the building (residential buildings of E.1(1) and E.1(2) classification groups).

Class	U_{cop}		U_{par}		U_{pav}		U_{serr}	
	E.1(1)	E.1(2)	E.1(1)	E.1(2)	E.1(1)	E.1(2)	E.1(1)	E.1(2)
A1	0.36	-	0.36	-	0.46	-	1.52	-
A2	0.36	-	0.35	-	0.41	-	1.49	-
A3	0.25	0.25	0.23	0.34	0.33	0.24	1.49	1.48
A4	0.20	-	0.24	-	0.27	-	1.20	-
B	0.45	0.5	0.6	0.99	0.65	0.53	2.02	2.555
C	0.72	0.535	0.88	1.17	0.9	0.62	2.49	3.63
D	0.92	0.57	1.07	0.94	1.05	0.71	2.72	2.84
E	1.07	1.29	1.17	1.01	1.1	1.32	2.99	4.24
F	1.18	1.01	1.23	1.13	1.15	1.15	3.32	4.12
G	1.41	1.56	1.39	1.44	1.32	1.26	3.79	4.36

Table 1: Thermal transmittance for residential buildings

Since the whole building stock analyzed is composed by 1% of real sample, containing both building parameters and thermal systems specifications, and by 99% of not joined EPCs. The latter do not contains some technical specifications that must be recovered by the registry of thermal systems, through a statistical analysis, as explained in section 3.2.1.

[7] `http://www.energialombardia.eu/sirena`

3.1.3 Climatic data

Climatic data have been taken from PVIGIS[8], which provides hourly temperatures considering a TMY (Typical Metereological Year). TMY represents a set of hourly meteorological data in a year for a given geographical location, whose data are selected from hourly data in a period of 10 years or more.

Hourly data have been elaborated to obtain temperature bins for each month of the heating period. In [39] it is suggested to use $2.8K$ as bin interval, but since heat pumps requires $1K$ as recommended by [50], it has been used this last value. Figure 9 represents temperature bins for the entire heating period, while figure 10 make a comparisons between different months.

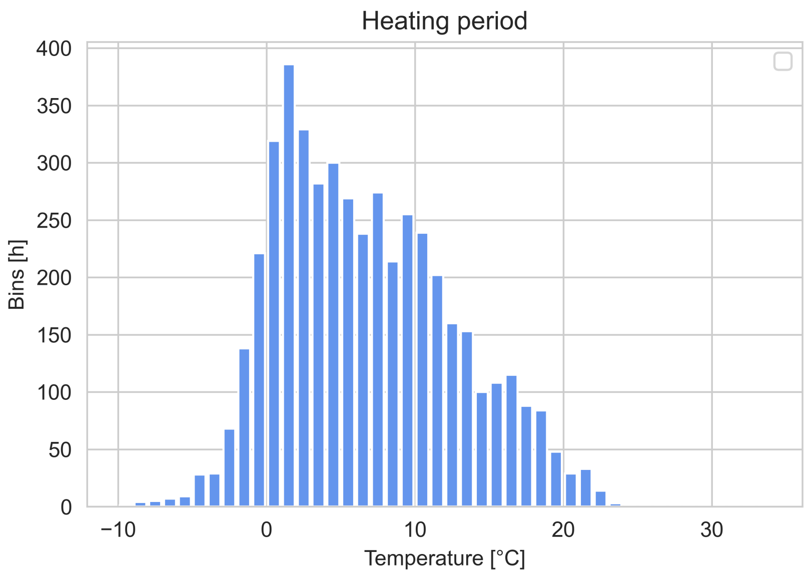

Figure 9: Temperature bins for heating period.

[8] https://ec.europa.eu/jrc/en/pvgis

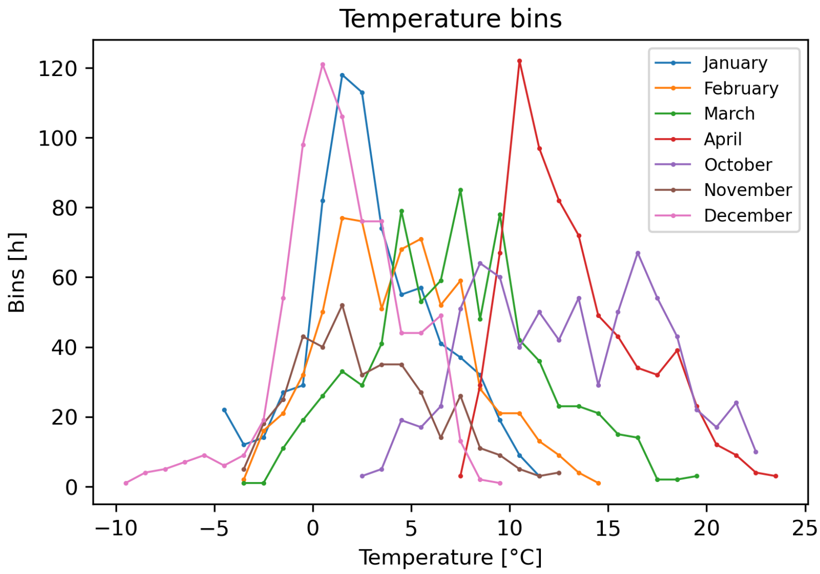

Figure 10: Temperature bins for each month.

In appendix A the histogram for each month are represented. December shows the lowest temperature, equal to -9.5°C, while the highest temperature in April is equal to 22°C. The most variable month in terms of temperatures is March, while highest peaks are in January and December.

3.2 Building's thermal systems model

The first sub-section 3.2.1 describes a simple statistical approach to recover other missing information in the EPCs about thermal plants, while the second sub-section 3.2.2 describes the modelling approach for the technology chosen for ACTIVE retrofit scenario, described in section 3.3. The modeling approach for heat pumps has been described in this section, because it has been applied also for the small number of heat pumps of the BAU scenario. There is not a sub-section dedicated to the heat combustion generators because they have not be modeled, because their parameters have been kept constant for all calculations done.

Figure 11 give a general overview of the main categories of thermal plant present in EPCs data set.

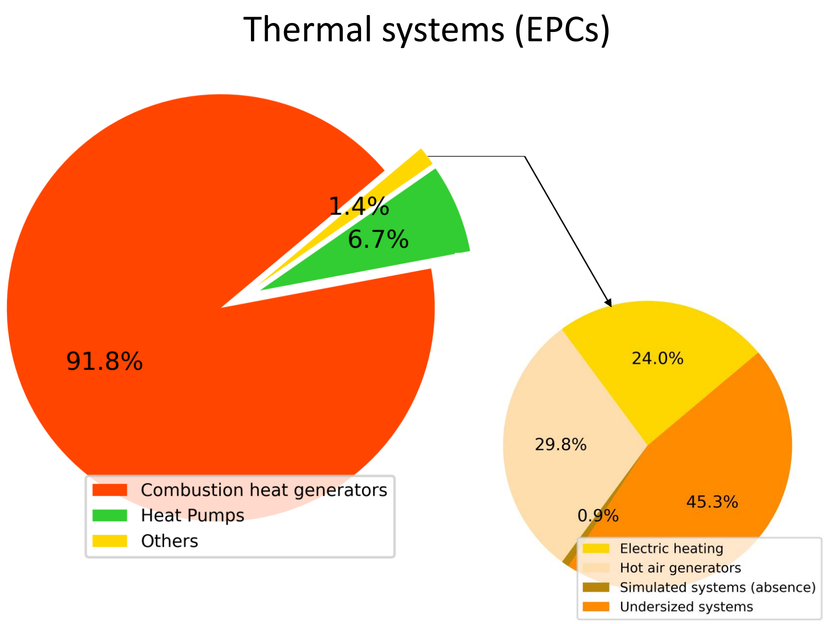

Figure 11: Thermal systems classification in EPCs.

Thermal plant typology	Number of units
Combustion heat generators	97819
Electric heating	366
Hot air generators	454
Simulated systems (absence)	13
Undersized systems	691
Heat Pumps	7160

Table 2: Thermal systems in EPCs

Following the process explained in the first sub-section about the analysis of the cadastral data-set, different values of efficiencies have been assigned to EPCs data set according to the same classifications and the same frequencies of occurrence. At the end of the frequencies classification and their correspondent allocation to the correct EPC field, the final EPCs data set is complete.

As mentioned above, the second sub-section focuses on the technologies used for the retrofit active scenario, but which are present also in the BAU scenario. Generally, both combustion thermal systems and heat pumps change their supply temperature according to the external air temperature. Every plant can be equipped with a thermoregulation system, which can change or maintain fixed the supply temperature to reduce energy losses. It is linked to a climatic curve, which is a characteristic of the building envelope and of the type of plant adopted. Figure 12 shows the climatic curve chosen from data-sheet [46].

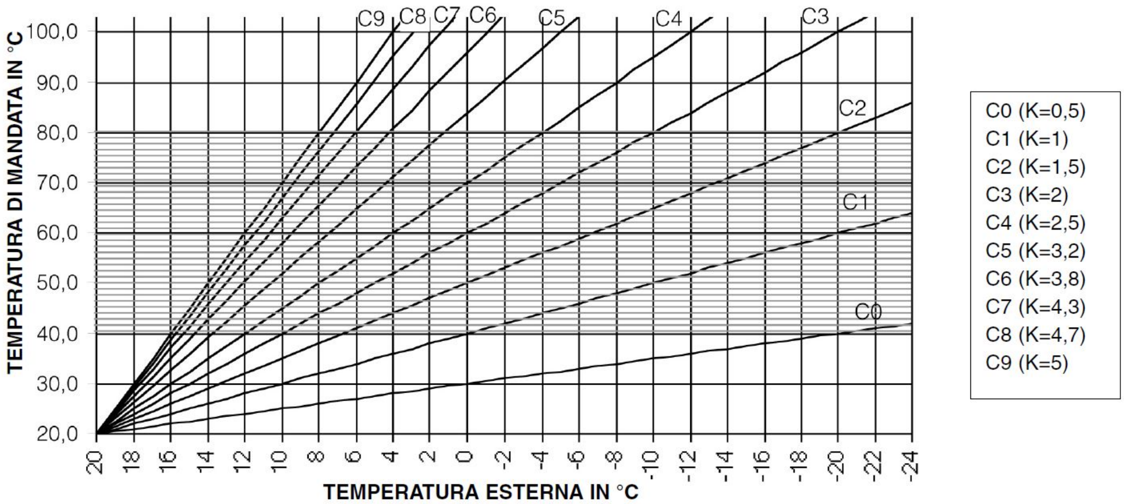

Figure 12: Climatic curve.

A different straight line has been assigned for each building using the energy class as criteria to differentiate. Lines with lower slope refers to buildings with higher energy class.

Combustion heat generators are the largest percentage of thermal systems of studied buildings or apartments. In EPCs data set combustion heat generators are treated separately with respect to hot air generators, electric heating and undersized or absent thermal plants. In this thesis work they are treated as their functioning parameters were kept constant. Indeed, unlike the case of heat pumps, all the combustion heat generators were not modeled to obtain different values of thermal power and efficiency according to external temperature bins.

3.2.1 Analysis of cadastral data set

To recover missing information about thermal systems in EPCs not joined with their respective data from the cadastral data-set, this latter has been statistically analyzed. The statistically analysis of the cadastral data-set is a fundamental step to apply correctly the methodology. Indeed, the Italian guideline for drafting energy performance certificates recommends to indicate in the final document the seasonal performance factor of thermal systems, without the thermal efficiency, COP or EER. In this sense, EPCs data set results to be incomplete to apply properly the Bin Method. For this reason, and cause to the difficulty to merge all the EPCs with the correspondent cadastral document of thermal systems, this statistically analysis is fundamental.

The cadastral data set is composed by around 182000 rows, of which around 169000 are referred to residential buildings and each row represents a generator of a thermal plant. The EPCs data set contains only general information about thermal plant and not technical specifications concerning them, although the field correspondent to thermal system typology should contain more detailed information. Micro cogenerators, district heating systems and solar thermal plants are not analyzed to simplify the study. The cadastral data set has been analyzed according to the main categories of thermal plants (figure 11) specified in the EPCs data set and to the energy vector for each category. The cadastral data set contains a further subdivision of combustion heat generators and heat pumps, then the same typologies and technologies classifications have been assigned to EPCs, considering the category *Thermal groups* as the category *Combustion heat generators* of EPCs data set.

As far as possible, a good diversification in terms of thermal plants typologies and efficiencies has been retained, to simulate a more realistic case study. Some of the thermal system typologies have been necessarily grouped and they have been included in larger thermal groups. For example, different types of fireplace like boilers and stoves have been grouped in a category called *Single thermal group*.

At the end of data filtering and simplification, the main categories of cadastral data set and their correspondent typologies are illustrated in figure 13. Each identified sub-

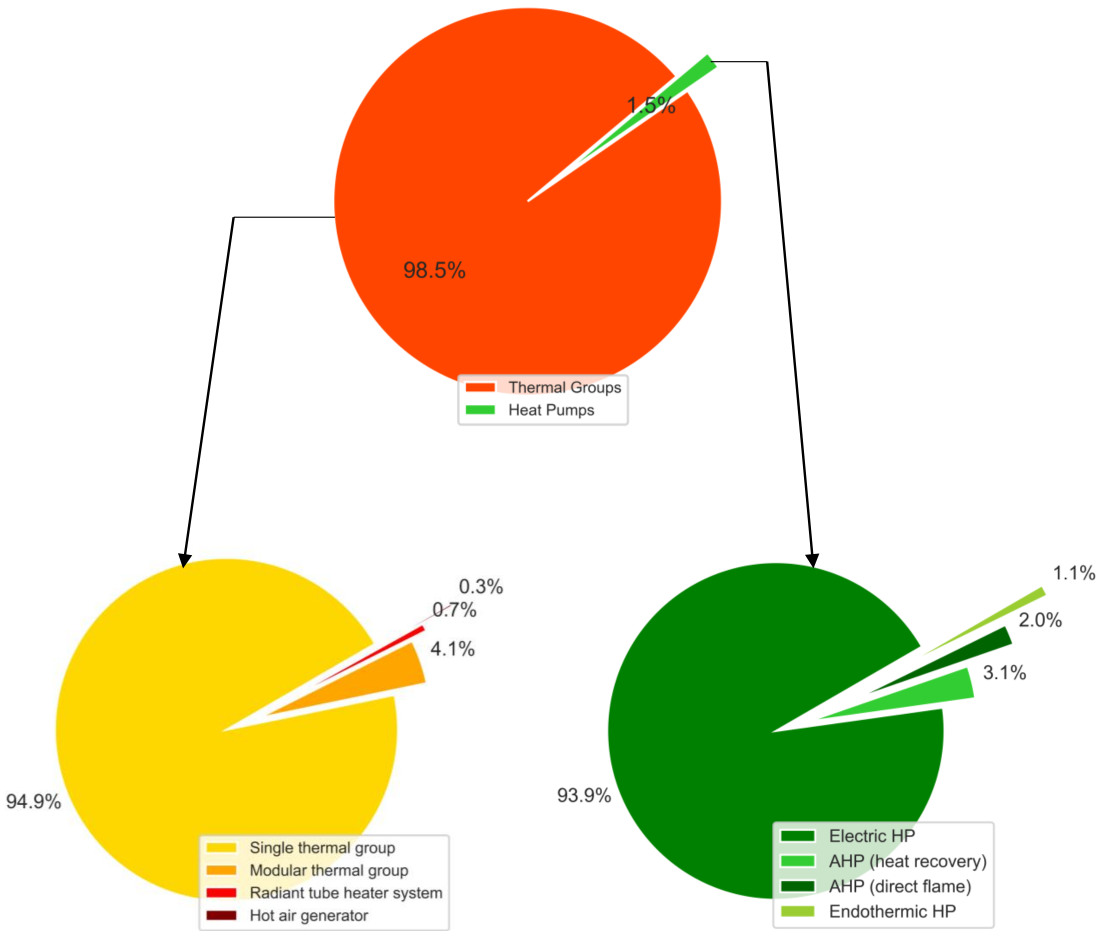

Figure 13: Cadastral thermal systems classification.

group uses different energy carriers, simplified as in table 3. A further sub-classification of technologies adopted has been made for thermal groups, by analyzing traditional and condensing technologies separately. Cause to a small percentage of EPCs combustion thermal systems, which energy vector is wood or biomass fuel, stoves and groups using solid fuel have been neglected, and only combustion systems, included in traditional or condensing technologies, have been studied. Then, the reduced data are illustrated

Type	Number of units	LPG	NG	Diesel	Wood
Single	107911	117	106880	891	23
Modular	4710	2	4653	55	-
Radiant	783	3	779	1	-
Hot air	286	1	284	1	-
Stove	168	-	-	-	168

Table 3: Energy vectors for combustion thermal systems (CURIT).

in table 4. As shown in table 5 heat pumps use only two type of energy vectors: nat-

Type	Number of units	LPG	NG	Diesel
Single	94474	96	93681	697
Modular	4054	2	4001	51
Radiant	698	3	694	1
Hot air	286	1	284	1

Table 4: Energy vectors in combustion thermal systems post filtering (CURIT).

ural gas and electricity. Efficiency values have been filtered before classifying them to remove outliers. First, they have been kept only significant values: for traditional thermal groups or boilers thermal efficiencies between 40% and 100%, for condensing boilers between 40% and 300%, for heat pumps COP between 1 and 20.

The reason why condensing equipment turn out to have high thermal efficiencies is due to the approach in their evaluation. Indeed, for boilers the primary chemical energy in thermal efficiency formula is calculated on the basis of the lower heating value.

$$\eta_{comb} = \frac{Q_{comb}}{m_{comb} \cdot PCI} \tag{11}$$

The lower heating value is measured without taking into account the condensing process, which means to subtract the heat of vaporization of water from the higher heating value: this difference is around 11% of the higher heating value. For this reason, when

Type	NG	Electricity
Electric HP	-	1333
Absorption with heat recovery HP	44	-
Absorption with direct flame HP	28	-
Endothermic HP	15	-

Table 5: Energy vectors for heat pumps (CURIT).

a condensing boiler efficiency is evaluated according to equation 11 the result can be larger than 1, that is at odds with the second law of thermodynamics. Thermal efficiencies of condensing boilers have been modified in order to obtain values lower than 1, by multiplying each of them with the ratio between heating values of different energy carriers. Table 6 summarize the lower and higher heating values adopted.
LHVs and HHVs for LPG (Liquefied Petroleum Gas) and natural gas have been taken from [63]; those for diesel from [64] and for wood from [65]. Then, boxplots have been

	LHV $[\frac{MJ}{kg}]$	HHV $[\frac{MJ}{kg}]$
LPG (propane)	46.373	50.402
Natural Gas	33.9	37.66
Diesel	42.7	44.4
Wood	17	18.5

Table 6: Lower and Higher heating values.

adopted to identify and remove outliers of thermal efficiencies. Figure 14 shows the boxplots for traditional thermal groups or boilers typologies and figure 15 for condensing typologies.

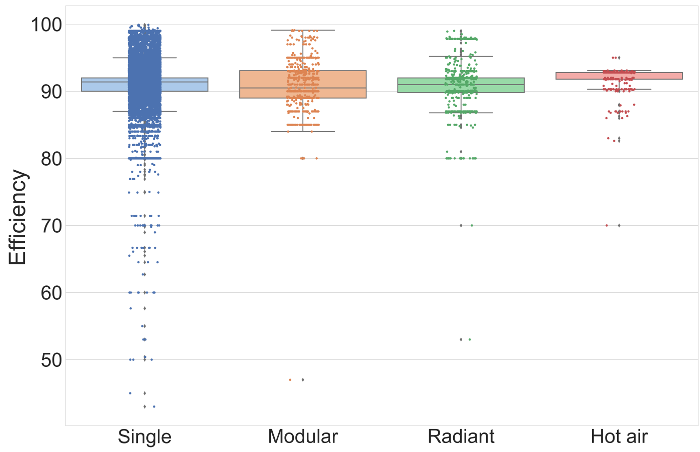

Figure 14: Efficiencies of traditional systems by typology.

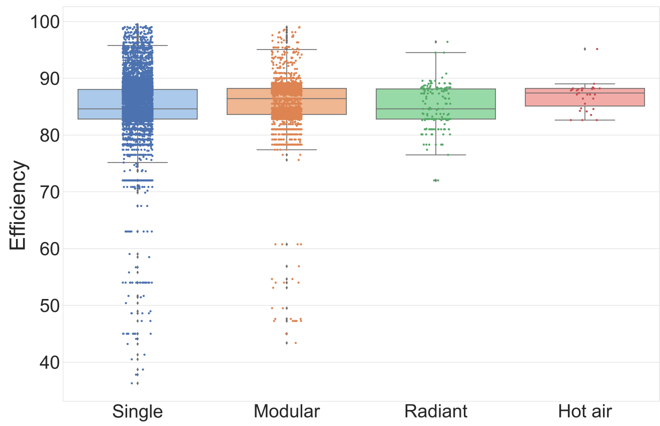

Figure 15: Efficiencies for condensing systems by typology.

While for thermal groups it has been maintained a differentiation to delete outliers, for heat pumps outliers have been filtered considering the boxplot of the entire category (figure 16), cause to very slight difference in maximum and minimum acceptable values of each heat pump technologies (figure 17).

For each energy vector, for each typology, and each technology it is applied a simple procedure to know the distributions of efficiency values for each sub-group:

- Calculation of maximum values of thermal efficiency (COP_{max}, η_{max}).
- Calculation of minimum values of thermal efficiency (COP_{min}, η_{min}).
- Splitting of the vector $[\eta_{min}, \eta_{max}]$ or $[COP_{min}, COP_{max}]$ into n intervals.

- Grouping of efficiency values into n intervals identified.

- Calculation of the frequency of occurrence for each interval identified.

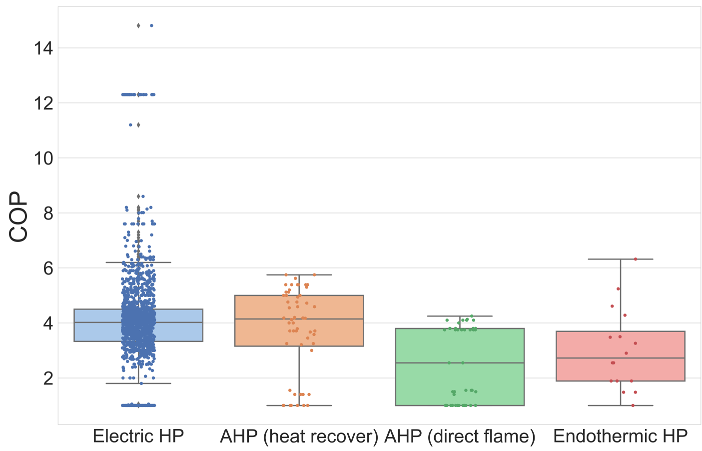

Figure 16: Heat Pumps efficiencies by technologies.

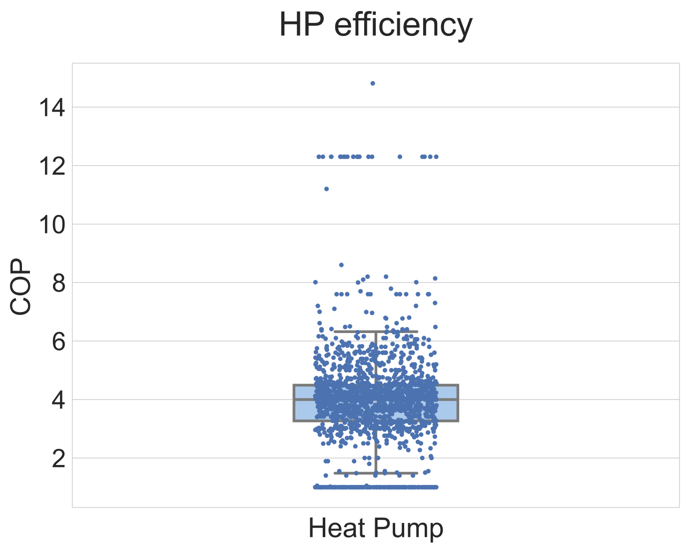

Figure 17: Box plot for heat pumps efficiencies.

3.2.2 Heat pumps

As mentioned above, it has been dedicated a single sub-section to thermal systems considered in this thesis work, because the combustion heat generators were not modeled. Indeed, their technical specification were kept constant without variations with

respect to the external temperature bins. Instead, heat pumps need to be modeled in a proper way because their technical parameters are strongly influenced by the external temperature bins. Heat pumps have been described here because they are a technology used both for the BAU scenario and for the retrofit ACTIVE scenario.
Heat pumps represents now a proven technology, widely used also in residential sector, thanks to a large number of regulation and incentives introduced to increase energy efficiency and energy savings. They are classified according to their operating principle: compression heat pumps or absorption heat pumps. A compression heat pump uses a classic refrigeration cycle to compress a cooling fluid, with a consequent increasing in temperature; the compressor can be moved by an electrical or endothermic motor, supplied by natural gas or liquefied petroleum gas (LPG). In this case the typical cycle can be the Otto cycle or Diesel cycle. The refrigerant fluid chosen must be compatible with the environment and they must have low freezing temperatures. An absorption heat pump uses a mixture of two fluids, with different vapour pressures, and the mechanical compression phase is replaced by a series of transformations, to separate and then recombine the most volatile with the least volatile fluid. The most used fluids combinations are water-lithium bromide and water-ammonia [45]. Heat pumps can be classified also according to the thermal sources, which are usually air or water.

Air source heat pumps They are the most efficient and innovative technologies from the point of view of energy production and energy saving. Air is mostly used in thermal plant with short circuits, with a direct expansion. There are two main categories: air to air and air to water. An air to air heat pump uses the external air as working fluid, with the advantage to reduce the losses due to a presence of an heat exchanger. The main disadvantage is that it is not able to produce domestic hot water, and then its use is limited to heating or cooling. An air to water heat pump uses water as refrigerant fluid, and it can be used also for domestic hot water production. It ensures higher temperatures and it can be coupled with different type of emission systems.

Water source heat pumps The working principle is to collect heat extracted from the building during the summer and to transfer it to water source. In this case, during winter, the heat can be extracted from the same source, which usually is groundwater.

Ground source heat pumps They extract the heat from the ground and vice versa, which allows to have a constant temperature around 12°Cand the heat pump can work at maximum efficiency. The heat is extracted vertically at great depths, that can reach also 100 m, but many installations are horizontal to achieve the desired temperature at lower depths. Ground source heat pumps can be used both for heating and cooling, but also for domestic hot water production. They have highest efficiencies if compared to air source heat pumps, and their electrical consumption are quite negligible.

The main categories considered in this case study are four, according to the classification done in the cadastral data set.

- Absorption Heat Pumps (AHPs) with heat recovery fed by natural gas.
- Absorption Heat Pumps (AHPs) with direct flame fed by natural gas.
- Endothermic heat pumps fed by natural gas.
- Electric heat pumps

Heating performances of a heat pump are evaluated by the Coefficient Of Performance (COP), defined as the ratio between the useful heat supplied and the electric power required by the heat pump to work. The Energy Efficiency Ratio (EER) is the coefficient use for cooling performances; in this case the numerator represents the heat removed by the heat pump.

$$COP = \frac{|Q_H|}{P_{el}} \tag{12}$$

$$EER = \frac{|Q_C|}{P_{el}} \tag{13}$$

Another performance indicator has been introduced with the European Directive 2005/32/EC [47], called Seasonal Performance Factor. It is defined for heating (SCOP) and cooling (SEER) and it consider the performance of the thermal system during the whole year. It is calculated as the annual load for heating or cooling, divided by the annual electric consumption. Through the application of the bin method and by knowing the technical specifications of the heat pump, a SPF is easy to evaluate. As previously explained, EPCs data set contains a seasonal coefficient for each thermal system, and not the correspondent COP or EER.

There are two main technical regulations to analyze and calculate seasonal performances of heat pumps and to study their operation: European UNI EN 14825 and Italian UNI TS 11300-4:

- UNI EN 14825: European regulation which defines the methodology to evaluate the Seasonal Energy Efficiency Ratio (SEER) and the Seasonal Coefficient Of Performance (SCOP). It accounts only for winter heating service and not for domestic hot water service.

- UNI TS 11300-4: Italian regulation which defines standards for the use of renewable energy sources and other energy generation methods. It accounts both for winter heating service and domestic hot water service.

Heat pumps performances depend not only on operational thermal limits and on heat pump technology chosen, but also by the building load behavior [48].
Standard UNI TS 11300-4 proposes two different energy load calculation methods depending on type of service (heating, domestic hot water production or both), on hot source (air or water) and cold source (air, water or ground) and on heat pump technology (steam compression, absorption or electrically driven) [49]:

- Monthly calculation based on average monthly quantities.

- Monthly calculation based on frequency distribution on hourly quantities.

Choose the correct methodology means to define the calculation interval to adopt and the relative temperatures of hot and could sources. When the calculated interval is not sufficient to make a precise assessment, it can be divided into smaller intervals (bins) as previous explained. These intervals correspond to temperature ranges of 1 K.
The evaluation of energy load is statistic, because real values will always deviate from average values based on multi-years averages.
Heat pumps work in different conditions, depending on multiple factors, like climate data and internal load to be covered, and no domestic equipment always works in nominal conditions at full power. For these reasons their performances are described by a capacity factor, which takes into account the deviation of real operations with respect to those declared.

$$CR = \frac{P_{th}}{P_{max}} \tag{14}$$

Where P_{th} is the thermal heating load to be covered by heat pump and P_{max} is the maximum thermal power deliverable. According to UNI-TS 11300-4 [50], the capacity factor must be calculated for each temperature bin:

$$CR_{bin_i} = \frac{P_{th_{bin_i}}}{P_{max_{bin_i}}} \tag{15}$$

There is a temperature limit imposed during the design phase called $\theta_{cutoff,min}$: for energy optimization purposes, or to avoid frost when the circulation fluid used is water, the heat pump can be deactivated if the cold source temperature is lower of this limit. There are three cases to consider from the estimation of the capacity factor:

- CR > 1 and $T_{cold} > \theta_{cutoff,min}$: heat pump works at full load, but it is not able to supply the total requested power and it is necessary the intervention of the integration system, if available. Then $COP_{bin_i}(T_{ext})' = COP_{bin_i}(T_{ext})$ and the heating consumption at that specific temperature must be calculated dividing the building thermal load by the $COP_{bin_i}(T_{ext})'$. In this case a portion of the building load is not covered, then, if there is another thermal equipment it must satisfy the difference between the total load and the load met by the heat pump. If there is not another thermal system, the building thermal plant is undersized.

- CR $= 1$: heat pump works at full load and, as for the first case, $COP_{bin_i}(T_{ext})' = COP_{bin_i}(T_{ext})$, then the heating load is totally covered by the heat pump.

- CR < 1 and $T_{cold} > \theta_{cutoff,min}$: heat pump is activated and it is able to supply the entire heating load requested for that specific bin, but it works at partial load. COP must be corrected through the evaluation of the part load factor.

$$f = \frac{CR_{bin_i}}{CC \cdot CR_{bin_i} + 1 - CC} \tag{16}$$

  CC is a correction factor generally declared by the installer; in absence of such information it is assumed equal to 0.9. The heating consumption is evaluated by multiplying the building heating load by the capacity factor for the specific bin and by dividing by the new efficiency $COP_{bin_i}(T_{ext})' = f \cdot COP_{bin_i}(T_{ext})$.

The same process has been adopted for each typology of heat pump. It has been use a Baxi data-sheet [51] to correlate the COP with the external temperatures. According to UNI EN 14511 [52], producer companies of heat pumps must provide values of COP, thermal power and absorbed power at 7°C of cold source and 35°C of hot source. UNI TS 11300-4 [50] suggests to provide these values at different values of cold and hot sources. If the cold source is air, they must be provided at -7°C, 2°C, 7°C, 12°C of cold source, and at 35°C, 45°C and 55°C of hot source. Baxi data-sheet [51] provides these values also for additional values of temperatures. Figure 18 shows the COP trend at different supply temperature, while 19 for thermal power.
With the aid of the specific building climatic curve in figure 12, the correct supply temperature has been selected as function of external temperature. Since each EPC has a thermal system with different technical specifications, COP and P_{th} trends have been normalized with respect to rated values of Baxi heat pump. In this way, curves can be rescaled for every building or apartment. COP and P_{th} values have been selected considering the supply temperature closest to that choice from climatic curve. Figure 20 summarizes the process adopted for heat pumps to evaluate the heating energy consumption for each bin.

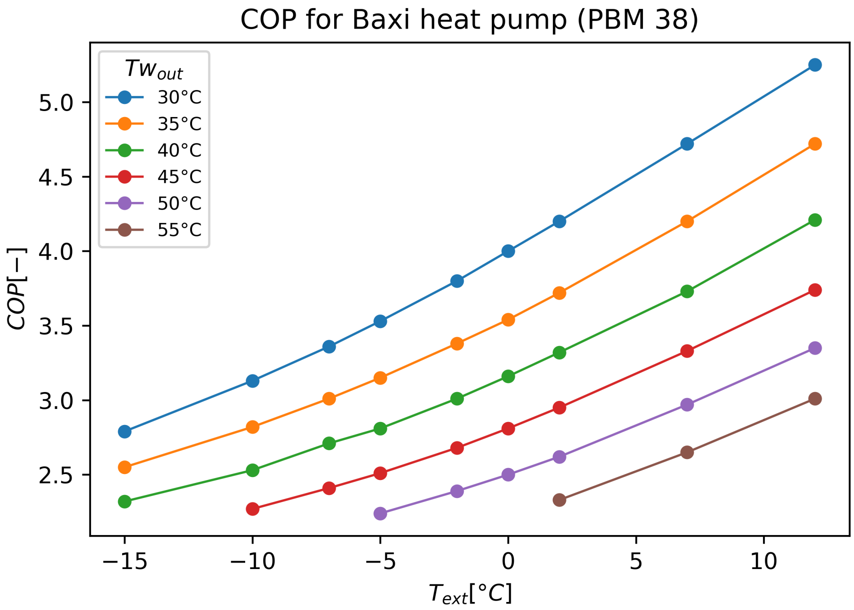

Figure 18: COP for Baxi heat pump.

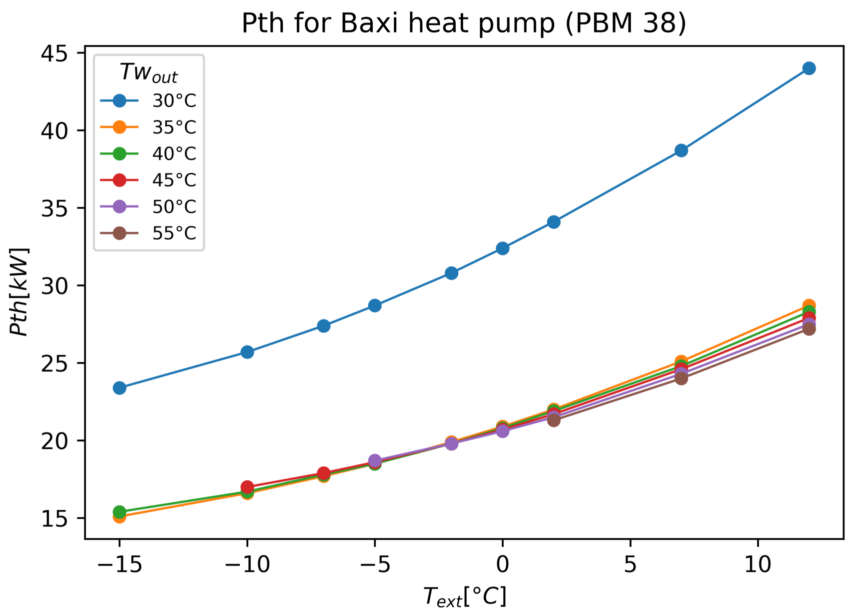

Figure 19: Maximum thermal power for Baxi heat pump.

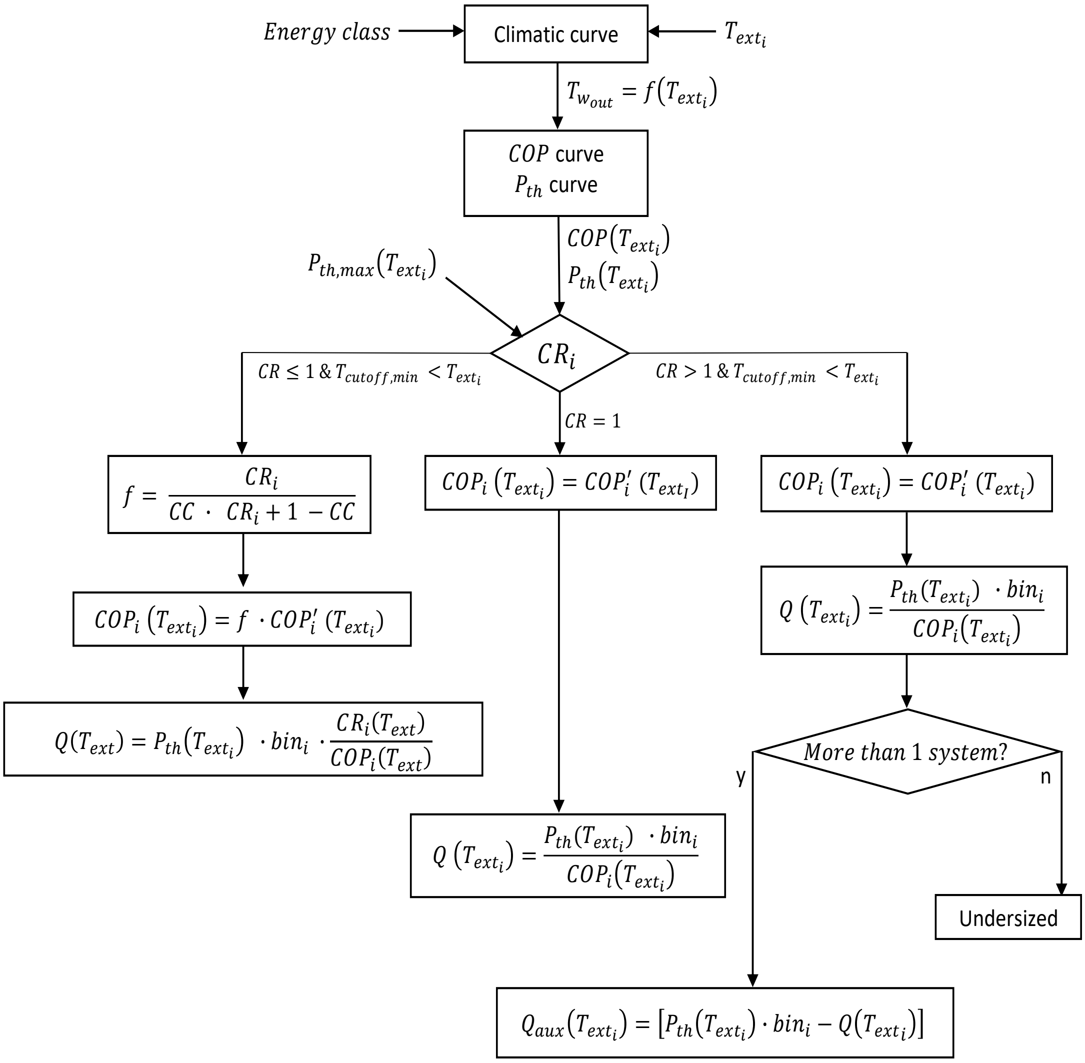

Figure 20: Flow diagram for heat pumps.

3.3 Scenario models

In this sub-section the main retrofit strategies adopted to obtain the final scenarios have been described. The final scenarios are six: one for the BAU case, two from the application of passive strategies, one from the application of an active strategy and two from the application of a mixed solutions. This latter is an integration of the mixed scenario with the introduction of a photovoltaic plant.

For the case study some assumptions must be done before to apply the calculation method defined in section 2.2 and to obtain different scenarios. Since this study analyzes only the heating period, from October to April, the heating building load has been calculated neglecting the solar and internal load contributions. The calculation for transmission load must be done for each wall and roof. Cause to the wrong and inconsistent information written on EPCs fields about the type of building, it is impossible to understand if the EPC is referred to a single apartment, an entire building or portion of building. There are some fields which should contain these information, but they came often into conflict each other. Instead of evaluating transmission load separately between walls and roofs, it has been considered an unique opaque surface with an heat transfer coefficient as average value between those of walls and those of roof.

$$A_{opaque} = A_d - \sum A_{w_i} \tag{17}$$

Where A_{w_i} is the i^{th} window surface and A_d is the dispersing surface taken from EPC fields. The total windows surface is not specified, then it has been obtained from window-floor surface ratio, equal to $\frac{1}{8}$ according to the Decree of Healt [66]. It imposes that opening surfaces must not be lower then $\frac{1}{8}$ of floor area.

Building load and heating consumption have been evaluated through a Python class, which logic is explained in the flowchart in figure 21. To achieve substantial reductions in building energy consumption, massive retrofit actions in building stock must be done. Buildings energy retrofit is a complex process that involves a large number of decision variables related to technical and technological aspects, but it is also strongly influenced by environmental, social and cultural aspects [67]. In this case, only technical aspects have been taken into account, cause to limited or missing information related to buildings use and social differentiation of users.

The retrofit strategies have been chosen according to the most diffused solutions and they can be grouped in two categories.

- **Passive** solutions: including an improvement of opaque elements of building envelope and its glasses or frames. The goal is reduce the thermal transmittance.

- **Active** solutions: including a substitution of thermal plants of building, to improve their efficiencies and then, if possible, reduce consumption.

- **Combination** of both solutions: only for building with high consumption, after the first two retrofit strategies.
- **PV integration** in the mixed solution: only a rough estimation of the possibility to integrate photovoltaic plants has been done.

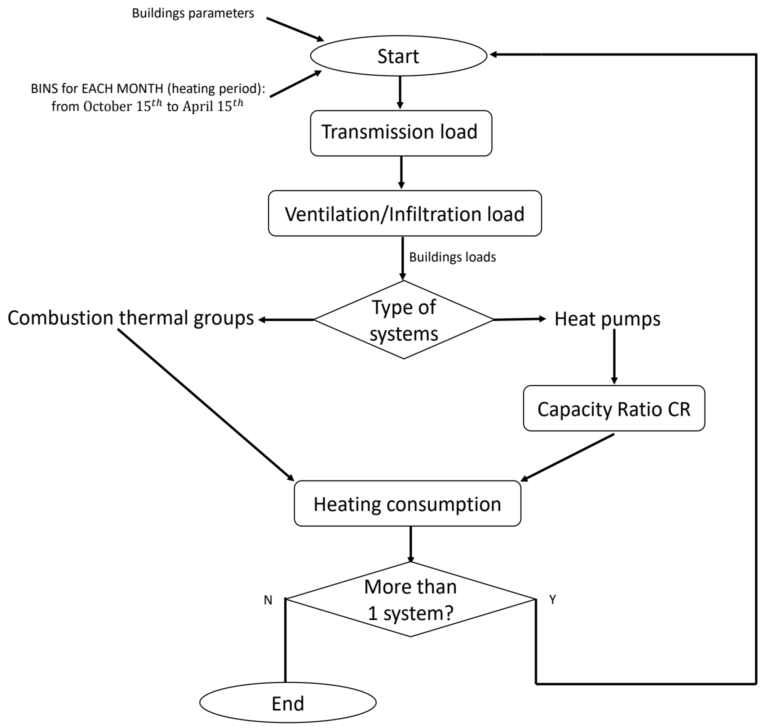

Figure 21: Flow chart for heating consumption calculation.

Not always the selected solutions represent the best choices, especially for the active ones. The major limit derived from the model is that the thermal load is related only to the winter season, but it neglect the cooling season, which can be higher, especially after the retrofit actions.

Passive retrofit strategies Since the stratigraphy and the area of each wall or roof, and the presence of a roof, are not known from EPCs data set, it is used a web tool called TABULA[9] to select the correct value of transmittance. It groups Italian buildings stock according to the year of construction and the typology of buildings. It evaluates a series of retrofit strategies, showing the change in thermal transmittance from the existing state to the usual or advanced refurbishments. Since the TABULA web tool is referred to the entire national building stock, the values of transmittance, differentiated by year of construction, do not match with the same values of the stock analysed in this thesis work. Then, values of transmittance of each apartment block typology, have been taken and assigned to the building stock of this thesis, according to the most similar thermal transmittance. This choice has been done, because apartment block is the most diffused typology of building in Milan, and probably the most diffused in the EPCs data set analyzed. Table 7 and table 8 represent the thermal transmittance of BAU scenario, and the corresponding value after retrofit strategies. Two different scenarios have been defined: a PASSIVE MILD scenario and a PASSIVE HIGH scenario. The second have thermal transmittance values stricter with respect to the first. Thermal transmittance values, in both scenarios, have been divided also if the final values are so similar, to associate a different thickness of insulation, which determine a different cost for each intervention. Indeed, to obtain the same value of thermal transmittance, a building with a lower value in BAU scenario needs a smaller thickness of insulation material.

BAU $[\frac{W}{m^2 \cdot K}]$	PASSIVE MILD $[\frac{W}{m^2 \cdot K}]$	Thickness $[cm]$
$0.44 \leq U_{value} < 0.59$	0.29	6
$0.59 \leq U_{value} < 0.88$	0.3	7
$0.88 \leq U_{value} < 0.94$	0.33	7
$0.94 \leq U_{value} < 1.23$	0.31	9
$1.23 \leq U_{value} < 1.44$	0.31	10

Table 7: Variations of thermal transmittance of walls (P1).

[9]http://webtool.building-typology.eu

Table 1
Typical insulating materials used in Italian residential buildings

Insulation material	ρ (kg/m^3)	λ (W/m K)
Glass wool panels (PLV)	20	0.043
Glass fibre mat (FFV)	11	0.053
Rock wool panels (PLR)	40	0.042
Rock fibre mat (FLR)	50	0.044
Extruded polystyrene (XPS)	33	0.038
Expanded polystyrene (EPS)	15	0.045
Expanded polyurethane (PUR)	30	0.038

Figure 22: Italian insulation materials from [71].

BAU $[\frac{W}{m^2 \cdot K}]$	PASSIVE HIGH $[\frac{W}{m^2 \cdot K}]$	Thickness $[cm]$
$0.44 \leq U_{value} < 0.59$	0.24	9
$0.59 \leq U_{value} < 0.88$	0.23	11
$0.88 \leq U_{value} < 0.94$	0.25	11
$0.94 \leq U_{value} < 1.23$	0.24	13
$1.23 \leq U_{value} < 1.44$	0.25	13

Table 8: Variations of thermal transmittance of walls (P2).

BAU means business as usual scenario, *PASSIVE MILD* means a usual refurbishment and *PASSIVE HIGH* means an advanced refurbishment.
TABULA does not specify the type of insulation material to use to obtain the new thermal transmittance, but since it is well known the effective thermal conductivity associated to the insulation material used ($\lambda = 0.04[\frac{W}{m \cdot K}]$), it can be associated to a real insulation material and its related cost. [71] demonstrates the benefits related to the use of insulation materials and the cost reduction associated to a high-performance building envelope. It explains which are typical insulation materials used in Italian residential buildings and their costs, as in figure 22. According to the thermal conductivity from TABULA, the insulation material of interest could be an extruded polystyrene (XPS), an expanded polyurethane (PUR) or a rock wool panels (PLR). The cost associated to

these technologies are 1.91 $\frac{€}{m^2}$ for floors, and 2.21 $\frac{€}{m^2}$ for walls. Both scenarios includes also the substitution of the glasses and their frames. In this case, since the windows must be replaced, the final thermal transmittance are equal for each building, as in table 9.

BAU $[\frac{W}{m^2 \cdot K}]$	PASSIVE MILD $[\frac{W}{m^2 \cdot K}]$	PASSIVE HIGH $[\frac{W}{m^2 \cdot K}]$
$2 < U_{value} < 4.36$	2	1.7

Table 9: Variations of thermal transmittance of windows (P1 and P2).

The PASSIVE MILD scenario refers to a new window, double glazed, argon filled with low emissivity, while the PASSIVE HIGH scenario refers to the same window but triple glazed.

Obviously only buildings whose transmittance are higher than targets imposed by TABULA have been modified. This means that buildings belonging to the energy classes A or A+, maintain the same thermal transmittance of BAU scenario, because often they have lower values than targets imposed.

Active retrofit strategy The active strategy involves the total substitution of the thermal systems used. Since the majority of the buildings use combustion thermal systems like boilers, which are fueled by natural gas, diesel or LPG, a transition to electrically driven thermal systems has been planned. The strategy proposed is composed by an air to water heat pump with an electric boiler as auxiliary system.

It is well known that electric boilers are a very energy intensive technology [72], but the heat pump has been sized to cover as much heating demand as it is technically possible, then the boiler must be used only when the heat pump cannot work. The sizing process is the same for all buildings, but the parameters change for each building to obtain a scalable sizing model. The size has been done considering only the thermal energy to cover during the worst month, without assessing the economic aspect, which surely influence the sizing of the heat pump. To define the correct size, it is necessary to define the amount of thermal power deliverable by the heat pump. This can be defined

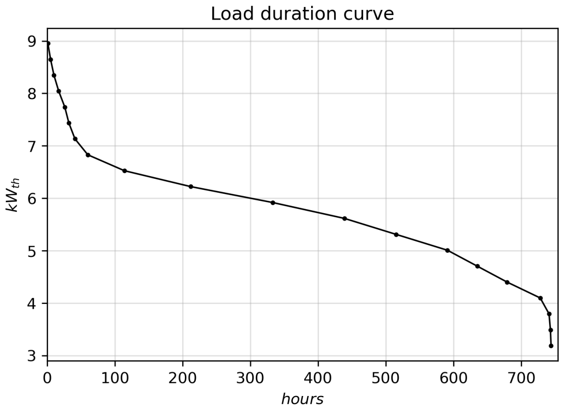

Figure 23: Load duration curve.

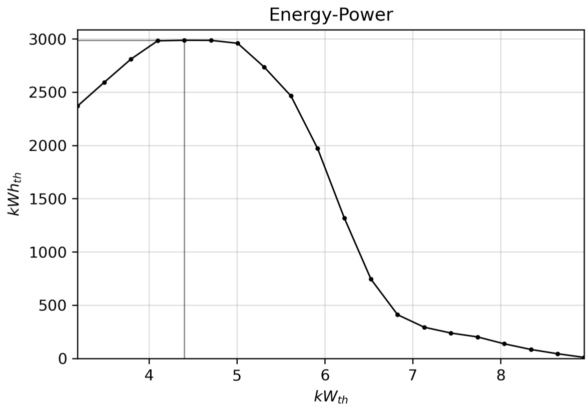

Figure 24: Energy-power plot.

knowing the building thermal load of December, which is the worst month in terms of temperature. The minimum temperature of the whole heating period has been registered during December and it corresponds to a temperature of -9.5°C. Starting from the building load, the thermal load duration curve has been built. The heating and cooling load duration curves are fundamental tools to define the correct size of thermal systems and to decide which systems must cover different portions of the demand curve [75]. In this case it has been assumed that the heating demand will be covered by two type of systems, the heat pump and the electric boiler. The logic followed is to consider the maximum area under the load duration curve, to be sure that the heat pump will works for the larger period of time. The area under the curve is the energy associated to the load duration curve. The load duration curve obtained for a random EPC is represented in figure 23. The load, expressed in kW_{th}, is represented in descending order on the y-axis, while the hours are represented in ascending order on the x-axis. Once that powers have been ordered from the highest to the smallest value, hours correspondent to the $i^{th}+1$ interval have been summed with the hours of the i^{th} interval, to obtain a cumulative of hours. Then, the power vector has been multiplied by the ordered hours of cumulative vector, to obtain the energy, expressed in kWh_{th}. From the energy-power curve, the thermal power correspondent to the maximum value of energy has been taken. If there are two points of maximum, only the smallest has been considered. In this way, it is possible to size the heat pumps assuming that it is

able to cover the maximum amount of thermal demand of building.
The heat pump chosen has the same COP and thermal power curves of [51] used in BAU scenario, but the nominal COP value is equal to 4.2 for the whole stock of heat pumps introduced. These parameters changes according to the bins temperature, as explained in section 3.2.2. The electric boiler need to cover the heating load not covered by heat pump and its efficiency is equal to 0.998, according to [73]. The thermal powers deliverable by heat pumps, have been evaluated for each case, then there is not a common value for all heat pumps. The same has been done for electric boilers, whose powers derive from the amount of demand that heat pumps fail to meet.
Electrification of the systems shall be justified, especially if the new system introduced entails larger consumption or a small reduction with respect to the BAU scenario. In this sense, it may be important to analyze the amount of electrical energy consumed by both systems, but separating them, to understand if the system could be better sized. The electrical consumption is useful to understand also the size of an eventual photovoltaic system, which can mostly justify the presence of a total electrified thermal plant. The PV system has been introduced only in the last mixed scenario.

Mixed retrofit strategies The previous strategies can be combined in order to obtain a MIXED scenario. The application of a combination of these strategies represent an optimized scenario with respect to the previous ones. The correct approach is explained in section 4.3, because it has been defined starting from the results obtained from the BAU scenario, the PASSIVE HIGH scenario, and the ACTIVE one. Indeed, the MIXED scenario has been evaluated considering the buildings whose energy consumption in the PASSIVE HIGH scenario has not reached a significant reduction with respect to the BAU scenario. For these buildings the ACTIVE strategies have been applied in order to reduce a lot their consumption.

Mixed strategies with photovoltaic plant The MIXED scenario obtained by the application of the mixed strategy implies the introduction of a lot of thermal plants supplied by electricity. To cover the electricity demand, an estimate of the possibility

to introduce a photovoltaic plant has been done. It has not to be realized a complete sizing of the photovoltaic plants, cause to missing information about cooling demand or positioning and orientation of buildings. A rough estimation of the area necessary to cover the entire electric demand has been done, comparing it with the real available area. The available area has been calculated from QGIS, considering only the buildings with heat pumps or electric thermal systems. In QGIS points related to EPCs have been spatially joined with the polygons associated to buildings. These polygons are available from the Geo-portal of the city of Milan, which provides the planimetry of each building. In this way, each point or a group of points have been associated to a building's area. As most likely, the roof is two-pitched, only half of the available area must be taken. Generally, the area of a roof is not completely usable, due to the presence of some obstacles as skylights and due to the limits derived from the rules for the assembly of panels. For this reason, only 80% of the area has been taken.
Knowing the electricity demand, the peak power of the photovoltaic plants of interest has been estimated. The annual production of a PV for 1 kW_p is equal to around 1200 kWh if it is located in Milan, with an inclination of the panel equal to 33°. From [74], the maximum power intensity used is 350 $\frac{W}{m^2}$ for a monocrystalline panel. Then, dividing the peak power obtained by electricity consumption to the power intensity of this specific module, the required area has been obtained.

4 Results

The result obtained for each scenario will be described in the following sub-scetions. The first is dedicated to the BAU scenario. The second is dedicated for both the passives and active scenarios called respectively PASSIVE MILD and PASSIVE HIGH, and ACTIVE. The third sub-section describes two scenarios obtained from the mixed strategies, called MIXED and MIXED+PV. The last sub-section is dedicated to a general comparison of the results obtained from different scenarios.

4.1 BAU scenario

The business as usual scenario is the base case; it is the scenario in which no actions have been taken to reduce the heating consumption or CO_2 emissions, and it represents the starting point to make some evaluations about buildings improvements. Figure 25 and figure 27 show the quadrant charts, previously introduced in section 2.3, for both primary energy consumption and CO_2 emissions of the whole Milan's building stock. In figure 25 the straight lines, used to divide the plot into four quadrants, are the medians of the sample analyzed. The median values were preferred with respect to the average ones because it allows to exclude outsiders. Indeed, the sample of buildings is very large and it contains different typologies of constructions, with different thermo-physical and geometric parameters, and an average value could prove not enough significance [69]. The median allows to neglect the influence of the extremes values to the sample. The median for the absolute value of primary energy demand is equal to 10023.72 kWh, while the specific value is equal to 159.16 $\frac{kWh}{m^2}$. The median for the absolute value of carbon emissions is equal to 2024.12 $kgCO_2$, while the specific value is equal to 32.15 $\frac{kgCO_2}{m^2}$. Each dot in the figure represents a building. The percentages refer to the number of buildings inside each quadrant: more than half of the sample needs an urgent retrofit action, while 33.7% have heating consumption below the average. As previously explained, the quadrant on the bottom left represents buildings with both low absolute and specific consumption, while the quadrant on the up right represents buildings that need urgent actions, because they have poor performances and high

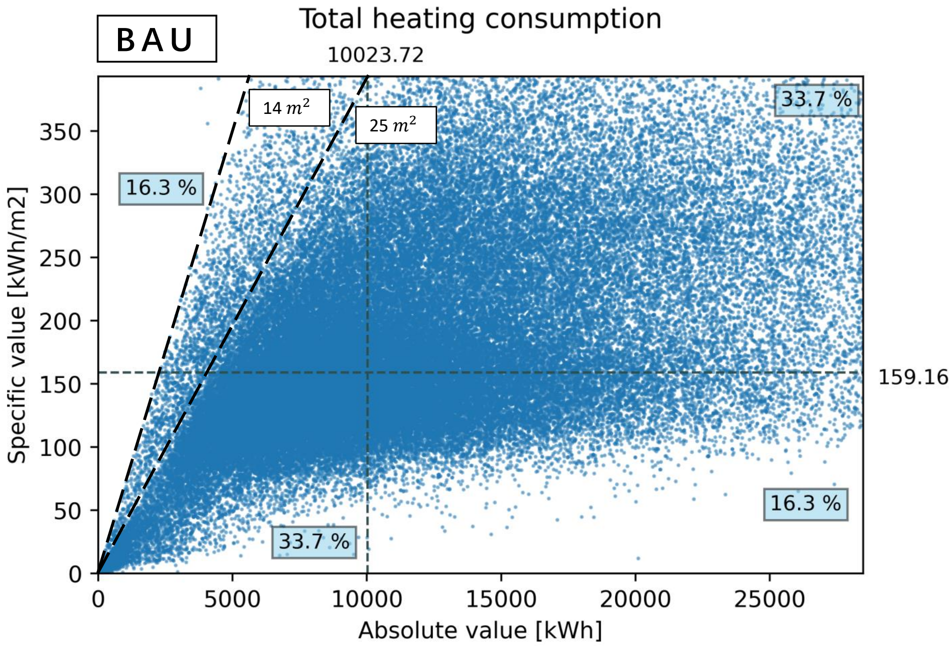

Figure 25: Quadrant plot for BAU scenario: primary energy consumption of the Milan's building stock. Each dot represents a building.

energy consumption. In figure 25 it is possible to observe two straight lines with a label that specify an area, equal to 14 m^2 and 25 m^2. These areas are common to all points distributed along straight lines. In this case only two straight lines have been represented, but it is possible to draw other lines starting from the origin of the quadrant, but with different slopes. Lines with reduced slope are associated with big buildings and then with larger areas, then their high consumption and consequent emissions may be linked to their great extension. Their position in the graph is on the bottom right and up right boxes, identified in section 2.3 as HIGH PRIORITY and MEDIUM-HIGH PRIORITY buildings. Lines with highest slopes include buildings with small extensions, but with high specific consumption. They are positioned on the up left box, defined in section 2.3 as LOW PRIORITY buildings. These considerations will be proved after the application of passive and active strategies separately. The same plot can be seen highlighting the typology of thermal plants, dividing them into two larger categories: combustion thermal plants and heat pumps. Heat pumps are less energy-intensive with respect to the combustion thermal systems, which are the larger portion of the systems involved (figure 26). Each dot represents a building's thermal system.

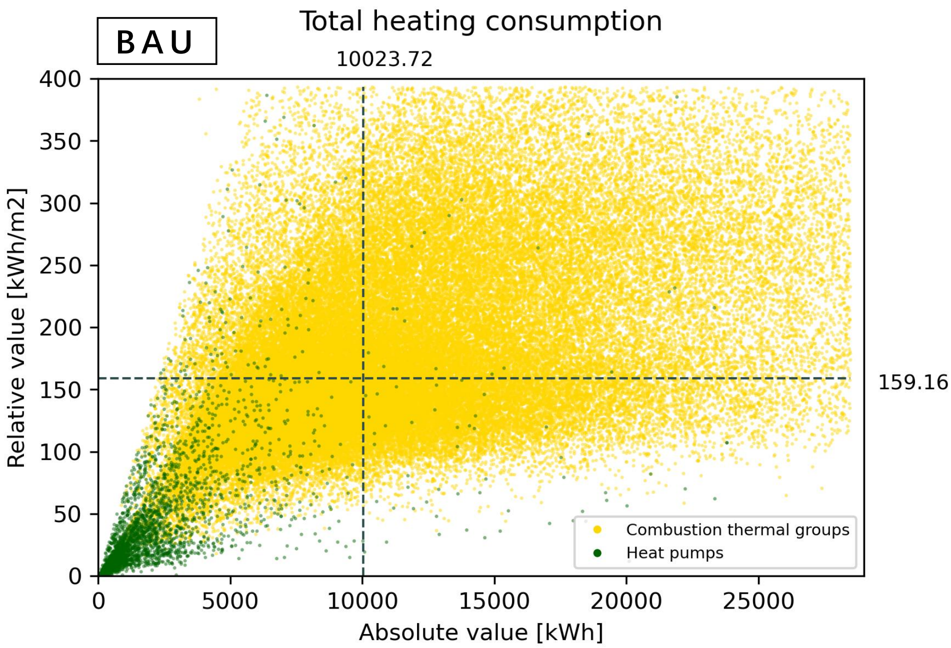

Figure 26: Quadrant plot for BAU scenario by thermal systems typology. Each dot represents a building's thermal system.

The greenhouse gas emissions of CO_2 are estimated by multiplying the primary energy consumption with a correspondent carbon emission factor. Through the evaluation of the carbon emissions in the BAU scenario and the successive scenarios, it is possible to compare the difference after the retrofit measures. Each energy vector, it has been associated with a carbon emission factor, as in table 10.

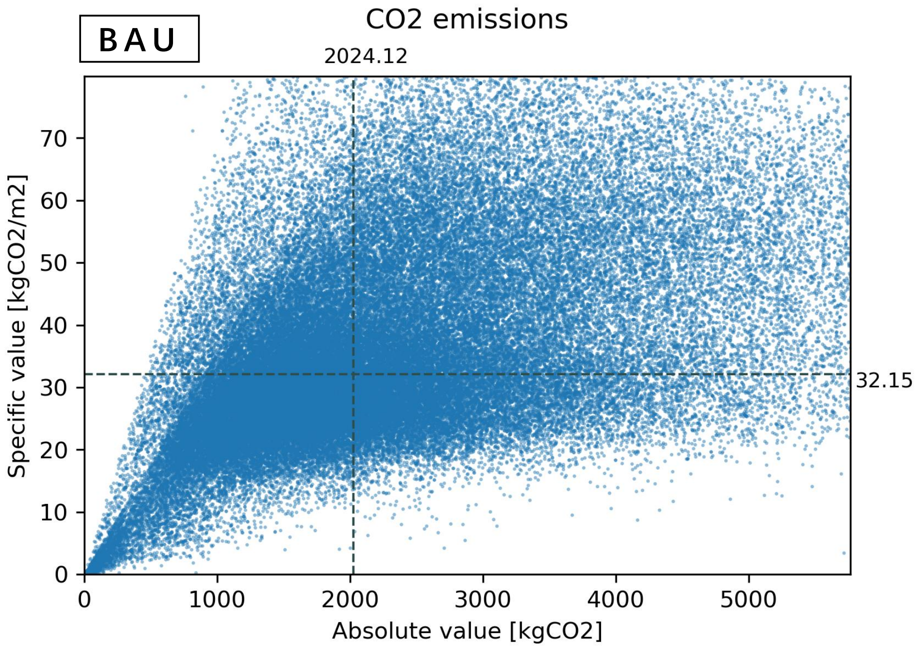

Figure 27: Quadrant plot for BAU scenario: carbon emissions. Each dot represents the carbon emission associated to the building.

Energy carrier	Natural gas	Diesel	LPG	Electricity
CO_2 emission factor $\frac{kgCO_2}{kWh}$	0.1999	0.2704	0.2252	0.2845

Table 10: Carbon emission factors for different energy carriers.

Carbon emission factors associated with natural gas, LPG and diesel, have been derived on a regional basis, from the SIRENA20 web portal [10]. The carbon emission factor of electricity cannot be assigned for each region, because it refers to the national production and it depends on the energy mix of the current year. The Italian institute for protection and environmental research (ISPRA [11]) provides it, based on the data from TERNA [12]. Tables 11 and 12 show the statistical value associated to different boxes

[10] http://www.energialombardia.eu/sirena
[11] https://www.isprambiente.gov.it/
[12] http://www.terna.it

for some thermo-physical, geometrical and technical values. Labels HIGH PRIORITY, MEDIUM-HIGH PRIORITY, MEDIUM-LOW PRIORITY, and LOW PRIORITY include the buildings which belong respectively to the up right, bottom right, up left, and bottom left quadrants. The priority indicates the urgency to improve buildings with retrofit strategies.
As explained in chapter 2, a GIS software called QGIS has been chosen to represent the results in urban maps. Urban maps focus the attention on the distribution of the primary energy demand for heating and carbon emissions in the territory analyzed. In this way, the results can be represented both in quadrant charts, considering the distribution of the buildings according to their KPIs, and considering their specific location in the city. To improve the readability of the figure the data are aggregated at the level of census district, which contain a variable number of buildings. Heating consumption are classified according to the energy class derived from the EPCs data set. Intervals have been chosen according to the classification defined by Article 2 of DPR 412/93 to identify energy class from A+ to class G. Groups represent energy performance indexes for the heating season, defined starting from the definition of degree days for each thermal zone. Generally, the standard groups are eight, but inside the EPCs data set used in this thesis work buildings are classified considering the subdivision of the A class in A1, A2, A3, and A4 classes. The map shows approximately the same distribution of the pie chart obtained from the EPCs data set, with some differences due to the fact that to establish the energy class many contributions must be considered, like cooling or hot water consumption. Since buildings are aggregated by census tract, the presence of buildings with low consumption, which probably belongs to class A or A+, is not sufficiently emphasized. There are few sections in which all buildings have low consumption, but it can be due to the fact that the section contains just one EPC. The quadrant graph represented under the map, is the same previous plot but differentiating by energy class. Low energy classes are located in the more consuming box up to scale to lower values and then higher classes. These graphs have been represented together because they give different information but using the same KPI. Indeed, the urban map gives a spatial information about the positioning of the

	A_u $[m^2]$	V_l $[m^3]$	$\frac{S}{V}$ $[\frac{m^2}{m^3}]$	U_{wind} $[\frac{W}{m^2 \cdot K}]$	U_{wall} $[\frac{W}{m^2 \cdot K}]$	U_{floor} $[\frac{W}{m^2 \cdot K}]$	U_{roof} $[\frac{W}{m^2 \cdot K}]$
HIGH PRIORITY							
mean	89.48	476.53	0.56	3.49	1.29	1.23	1.27
standard deviation	159.97	19013.8	0.205	0.35	0.11	0.104	0.16
median	68.276	272.38	0.55	3.79	1.39	1.32	1.41
min	14.04	30.79	0.01	1.52	0.36	0.46	0.36
25%	52.71	212.87	0.42	3.32	1.23	1.15	1.18
50%	68.28	272.38	0.55	3.79	1.39	1.32	1.41
75%	91.23	368	0.66	3.79	1.39	1.32	1.41
max	9594.9	3450005	4.93	4.36	1.44	1.32	1.56
MEDIUM-HIGH PRIORITY							
mean	132.93	510.58	0.29	3.15	1.19	1.13	1.11
standard deviation	211.3	826.41	0.33	0.376	0.132	0.11	0.18
median	108.07	410.9	0.27	2.99	1.17	1.1	1.07
min	64.438	3.81	0.01	1.52	1.2	0.24	0.27
25%	89.3	335.025	0.23	2.99	1.17	1.1	1.07
50%	108.07	410.9	0.27	2.99	1.17	1.1	1.07
75%	136.32	523.6	0.32	3.32	1.23	1.15	1.18
max	6580.7	27595.26	39.39	4.36	1.44	1.32	1.56
MEDIUM-LOW PRIORITY							
mean	37.7	152.19	0.49	3.47	1.29	1.22	1.26
standard deviation	10.61	44.31	0.18	0.37	0.12	0.11	0.17
median	37.47	151.2	0.43	3.32	1.23	1.15	1.18
min	9.92	20.34	0.11	1.49	0.36	0.46	0.36
25%	30.3	121.19	0.35	3.32	1.23	1.15	1.18
50%	37.47	151.2	0.43	3.32	1.39	1.32	1.41
75%	45.39	181.5	0.53	3.79	1.39	1.32	1.41
max	63.97	495	4.61	4.36	1.44	1.32	1.56
LOW PRIORITY							
mean	59.49	230.3	0.31	2.86	1.05	1.02	0.97
standard deviation	29.98	121.52	0.289	0.64	0.31	0.26	0.31
median	56.055	214.02	0.27	2.99	1.17	1.1	1.07
min	14.05	2.13	0.01	1.2	0.23	0.24	0.2
25%	43.48	169.4	0.22	2.72	1.07	1.05	0.92
50%	56.055	214.02	0.27	2.99	1.17	1.1	1.07
75%	69.69	267.39	0.33	3.32	1.23	1.15	1.18
max	2691.39	10390.9	31.06	4.36	1.44	1.32	1.56

Table 11: Statistical information about thermo-physical properties of buildings, divided by their priority for taking retrofit actions.

	P_{nom_1} $[kW]$	η_1 $[-]$	P_{nom_2} $[kW]$	η_2 $[-]$	Heating $[\frac{kWh}{m^2}]$	consumption $[kWh]$
			HIGH PRIORITY			
mean	429.7	0.89	0.56	370	271.04	22509.02
standard deviation	1353.98	0.076	793.7	1.08	1065.45	107199.3
median	168	0.88	157	0.925	251.33	16659.2
min	0.96	0.78	0.3	0.78	164.51	10557.95
25%	25.6	0.88	52.6	0.875	202.59	13235.44
50%	168	0.88	157	0.925	251.33	16659.2
75%	350	0.925	460	0.925	305.4	22619.88
max	40000	4.55	9792	6.05	193577.77	18587472.89
			MEDIUM-HIGH PRIORITY			
mean	533.9	0.9	357.73	1.47	134.41	17507.11
standard deviation	2847.13	0.192	738.97	1.16	20.43	29034.93
median	250	0.876	194	0.925	137.067	14005.1
min	1	0.776	0.6	0.776	12.01	10559.54
25%	96.5	0.875	59	0.875	121.06	11994.38
50%	250	0.876	194	0.925	137.07	14005.13
75%	460	0.925	439	0.925	150.94	17595.86
max	186000	6.55	9320	6.55	164.51	945779.83
			MEDIUM-LOW PRIORITY			
mean	318.15	0.908	0.49	314.07	221	7977.45
standard deviation	891.55	0.25	400.9	1.13	57.23	1728.1
median	120	0.876	147	0.925	203.2	8198.18
min	0.12	0.777	0.4	0.776	164.52	2472.3
25%	24	0.875	55	0.875	180.42	6819.48
50%	120	0.877	147	0.925	203.2	8198.18
75%	320	0.925	461.5	2.5	243.28	9400.03
max	24620	6.05	2907	6.05	654.76	10557.71
			LOW PRIORITY			
mean	321.97	1.32	212.15	2.44	108.96	6095.53
standard deviation	918.8	1.12	406.79	1.62	43.41	2815.26
median	918.8	1.12	406.8	1.62	43.41	2815.27
min	0.02	0.78	0.07	0.776	0.331	17.10
25%	24	0.875	44.4	0.925	93.23	4334.55
50%	153.7	0.925	112.8	2.5	120	6483.95
75%	343.3	0.925	284	4.05	140.23	8332.72
max	69767	6.55	9864.5	6.55	164.51	10557.89

Table 12: Statistical information about technical properties of buildings' thermal systems, divided by their priority for taking retrofit actions.

buildings according to their consumption and the quadrant chart gives an information about the distribution of the heating consumption of buildings. The pie chart is just a support for the other two plots to prove that the results obtained from BAU scenario match with the information given by the EPCs data-set.

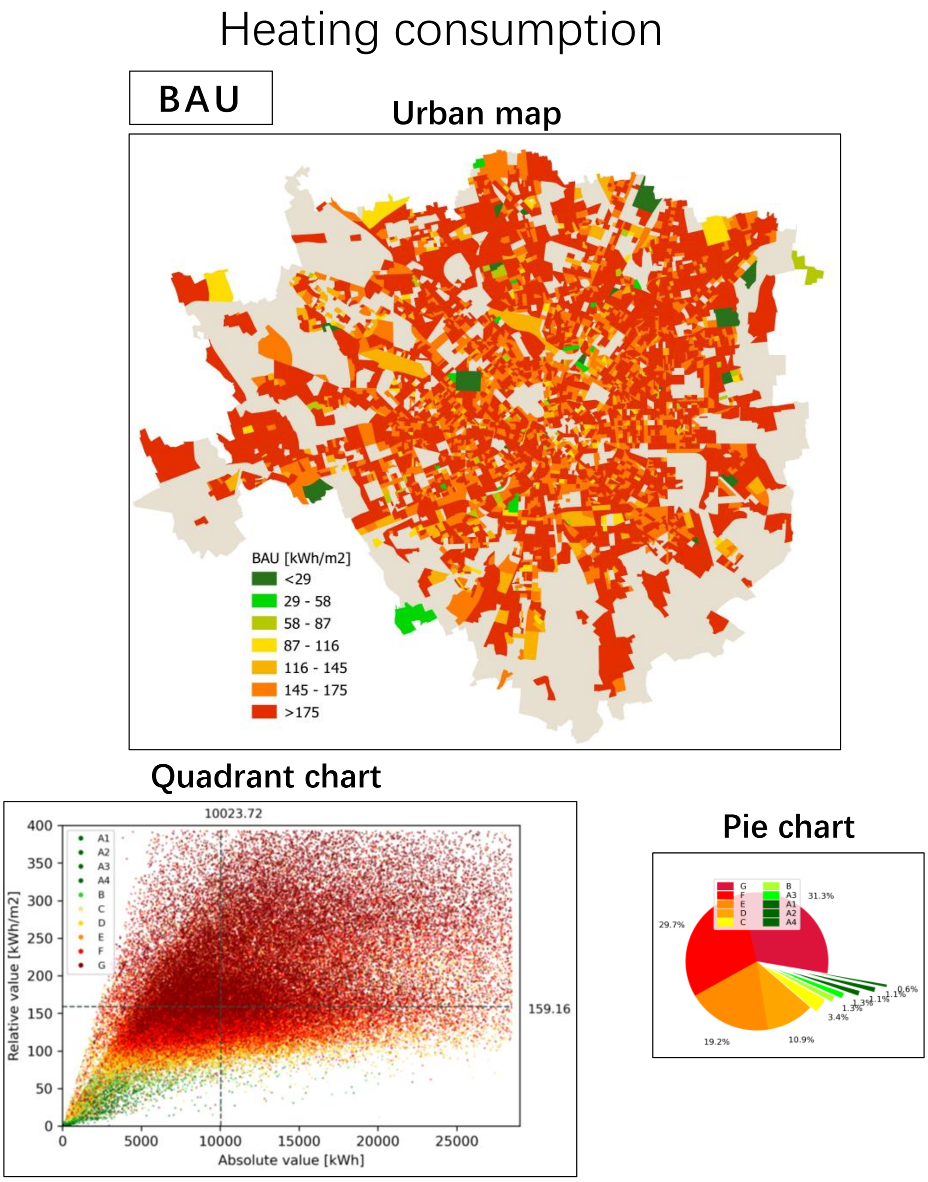

Figure 28: Different ways to view the information about the heating energy consumption for BAU scenario: urban energy map, quadrant chart classified by energy class, pie chart for energy class by EPCs.

4.2 Passives and active scenarios

After the application of the passive retrofit strategies, two passives scenarios have been obtained, the first is PASSIVE MILD and the second the PASSIVE HIGH. The ACTIVE scenario, has been obtained from the application of the active retrofit strategy, equipped with a conveniently sized heat pump, as described in 3.3 supported by an electric boiler during peak demand. Figure 29 shows the results obtained for passives and active scenarios, in terms of total heating consumption and carbon emissions. The quadrant chart is the same defined for the BAU scenario, with the same values for absolute and specific median, in order to have a reference system to make comparisons. The PASSIVE MILD and the PASSIVE HIGH show similar distribution shapes, both for heating consumption and carbon emissions. The heating consumption and carbon emissions of all buildings have been reduced, but there is a sample of them which continues to have their absolute values greater then the median related to the absolute KPI. These buildings are in the bottom right quadrant. The ACTIVE scenario shows a different shape with respect to the passives ones. The reduction for both heating consumption and carbon emissions, is high for all buildings, but in this case the shape is more homogeneous and localized in the bottom left quadrant.

In the PASSIVE MILD and PASSIVE HIGH scenarios, EPCs in the bottom right box continue to have high consumption because they represent large buildings with inefficient thermal systems, which need more improvements to reach a significant energy saving. Indeed, buildings of the up left box, consume a lot of energy to heat 1 m^2 of floor surface, then a decrease n in building demand is sufficient to reach a considerable reduction. As proof of what has been said, the average surface to volume ratios for each box has been calculated. Observing the tables 11 and 12, the up left and right boxes have a surface to volume ratio close to 0.5 (0.56 for the up right box and 0.5 for the up left box), while the values for bottom right and left boxes are between 0.29 and 0.31. The dispersing surfaces for the first two are too high with respect to their volumes, and that affects the building energy performances. Moreover, the thermal

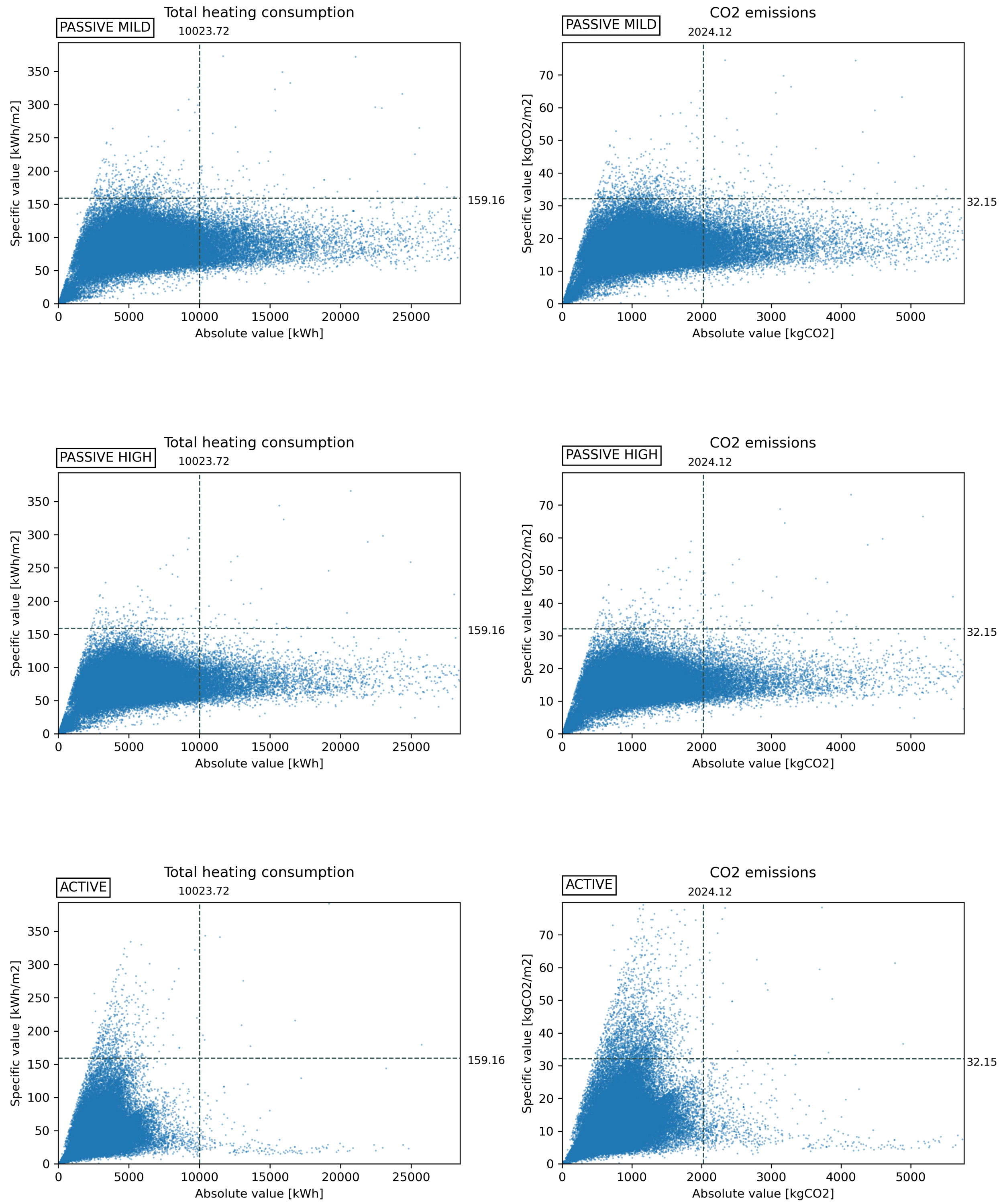

Figure 29: Heating consumption (left) and carbon emissions (right) for passives and active scenarios: PASSIVE MILD, PASSIVE HIGH, ACTIVE.

transmittance has the highest values in these two quadrants, then the passive strategy impacts especially these areas.
To better understand the influence of different retrofit strategies on buildings, the quadrant chart has been represented coloring the points belonging to various boxes, and observing their shift with respect to the BAU scenario (figure 30 and 31). The graph related to PASSIVE MILD scenario is not shown because, as previously explained, the distribution is very similar to the PASSIVE HIGH, but the reduction is less marked. The red color is for the up right box, the orange for the bottom right, the yellow for the up left and the green for the bottom left one. It is evident that big buildings of the bottom right quadrant are more influenced by the substitution of the thermal systems, with respect to the small ones.

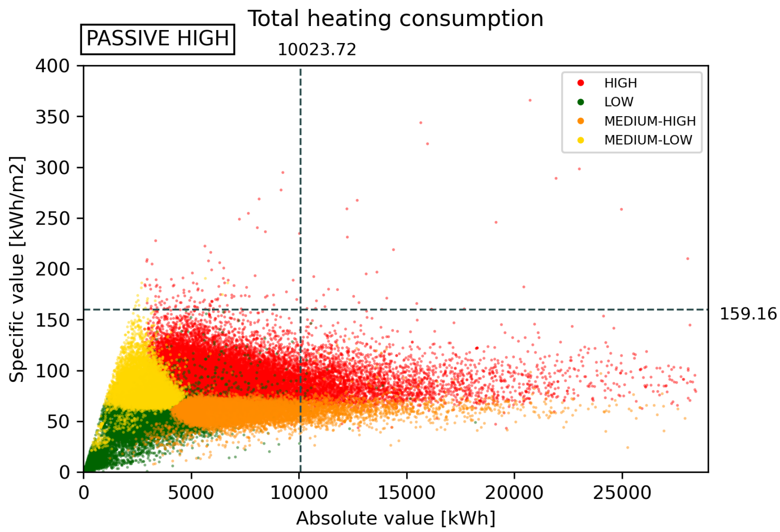

Figure 30: Quadrant chart for PASSIVE HIGH scenario: consumption shift with respect to BAU scenario.

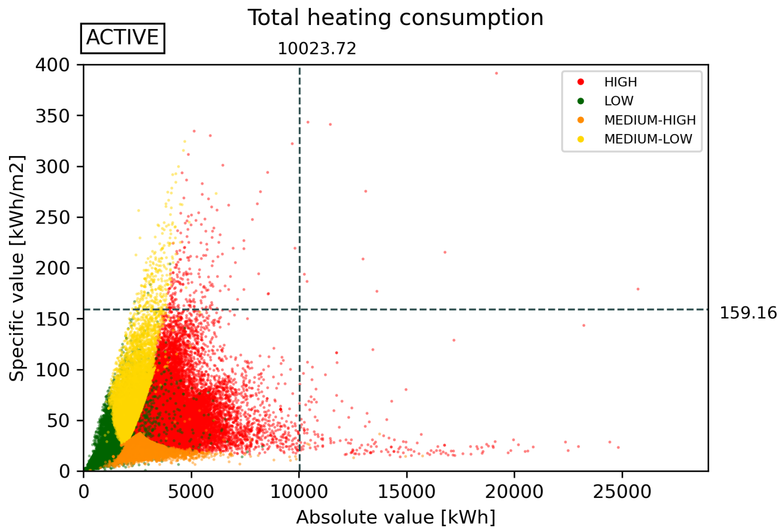

Figure 31: Quadrant chart for ACTIVE scenario: consumption shift with respect to BAU scenario.

Some points do not move with respect to the BAU scenario and they remain fixed in the same initial position. This happens in the case of the application of the passives strategies because they are already present some buildings with high performances, even better than the post-retrofit case.

4.3 Mixed scenarios

After the application of passive and active strategies, different responses have been observed. The two strategies have been combined, starting from the passive one and then applying the active one. To reduce the heating consumption, especially in the bottom right quadrant, the active solution has been applied only to the buildings whose have their specific and absolute value even greater than the initial median values. Thermal plants of this sample, have been replaced with a conveniently sized heat pump and an electric boiler. The heat pump sizing is different for each building, with different thermal power, electric power and COP. The results are shown in figure 32. As expected, the reduction in heating consumption is absolutely evident, with a shift towards very low absolute and relative values. All the points are inside the bottom left quadrant, with absolute and relative values lower than median of the BAU scenario.

From the carbon emissions perspective, some buildings continue to have values greater then the median, but it is a problem related to their great extension.

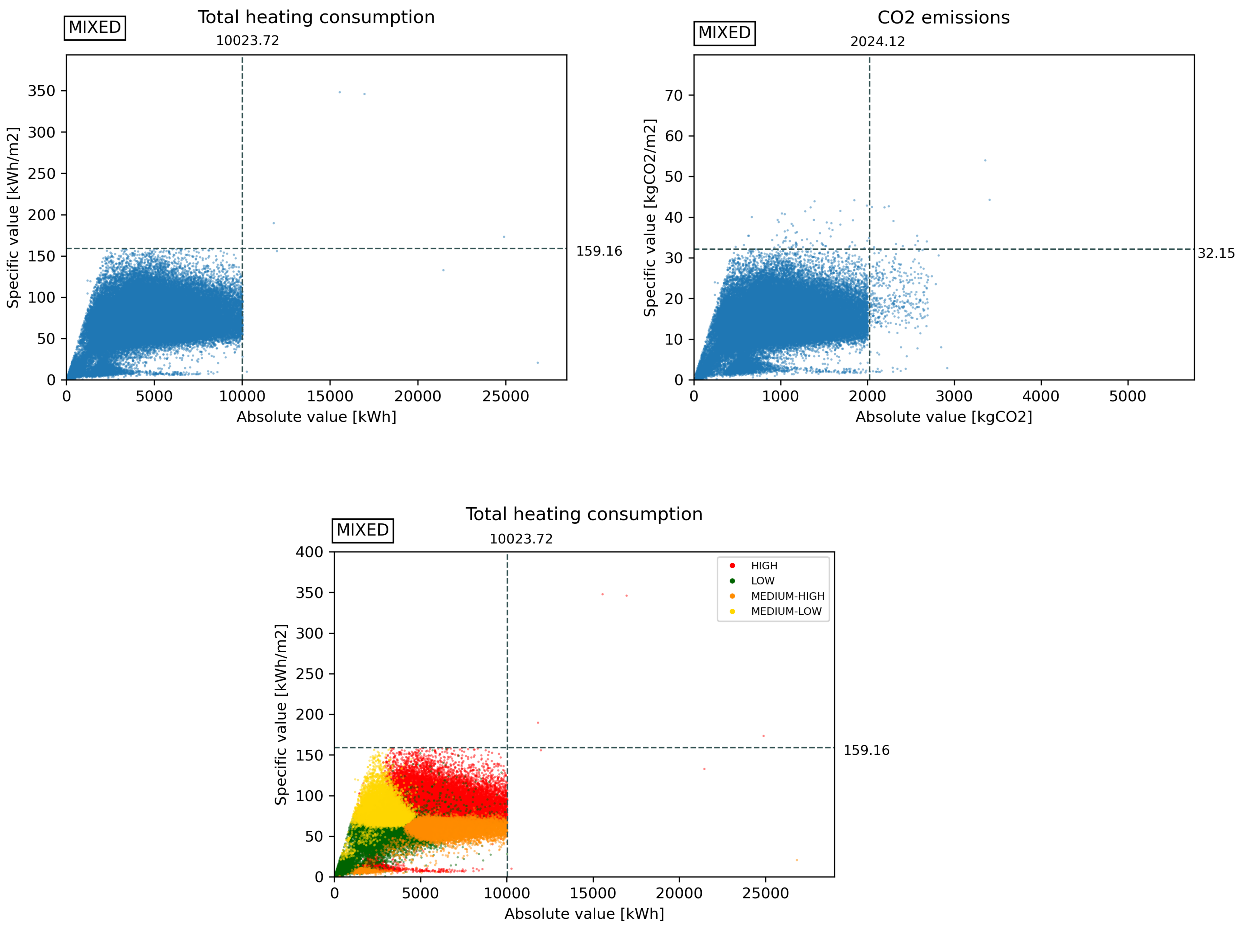

Figure 32: Quadrant chart for MIXED scenario: heating consumption reduction (up left), carbon emission reduction (up right), consumption shift with respect to BAU scenario (bottom).

Since a portion of the thermal consumption has been shifted towards electrical consumption, an assessment of the possibility to introduce photovoltaic modules, to cover the electricity demand, has been done. The evaluation regards the estimate of the area required by heat pumps or electrical systems, as explained in section 3.3. Photovoltaic modules must meet electricity demand of both already existing heat pumps and those newly introduced with the optimized scenario. The required area for the PV panels is equal to 179323 m^2 ($\sim 16.84 \ \frac{m^2}{building}$), while the available area is equal to 548082

m^2 ($\sim 51.49\ \frac{m^2}{building}$), then it possible to install the 100% of the photovoltaic modules required to supply the electricity required for heating purpose. This evaluation does not consider many aspects, which are fundamental to evaluate the energy production from a photovoltaic plant, as the cooling consumption or the real area available. The estimate should be done for each EPC, in order to know if for each building or apartment having a heat pump, has enough space to install the corresponding photovoltaic system. There may be some cases in which the PV plant could not satisfy the whole electricity demand of an entire condominium, especially considering that it is located in Milan. Another information to know should be the orientation of the roof, to place correctly the PV modules.
The carbon emission factor in this case, is assumed to be equal to zero, because the emission factors do not take into account the greenhouse gas emissions derived from the modules production. The new carbon emissions are represented in figure 33, distinguished by energy carriers. The absence of the electric energy is due to the assigned carbon emission factor, equal to zero.

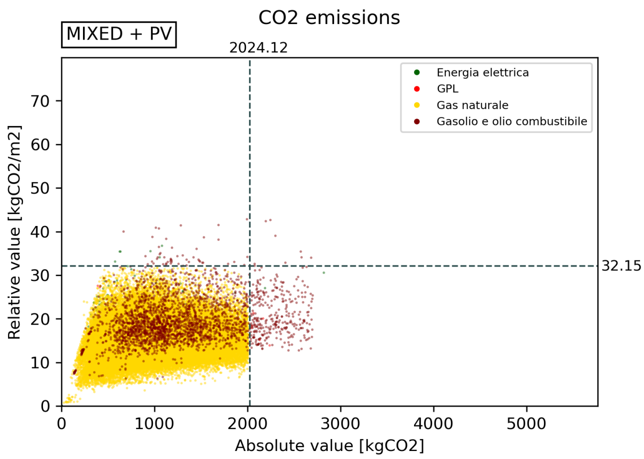

Figure 33: Quadrant chart for MIXED + PV scenario: carbon emissions reduction.

4.4 Comparison between scenarios

Figure 34 compares different scenarios with respect to the BAU case. The color bar represents the reduction of the specific value in $\frac{kWh}{m^2}$. The results of emission reductions are visible in the appendix B. The figures show different shapes with respect to the previous quadrant plots. Indeed, the samples represented in the quadrant plots for each scenario, have been represented always maintaining the same x and y limits, and the same median for both KPIs. The same approach has been applied to represent the energy and carbon emissions savings. Then, some points are not more visible in the plot.

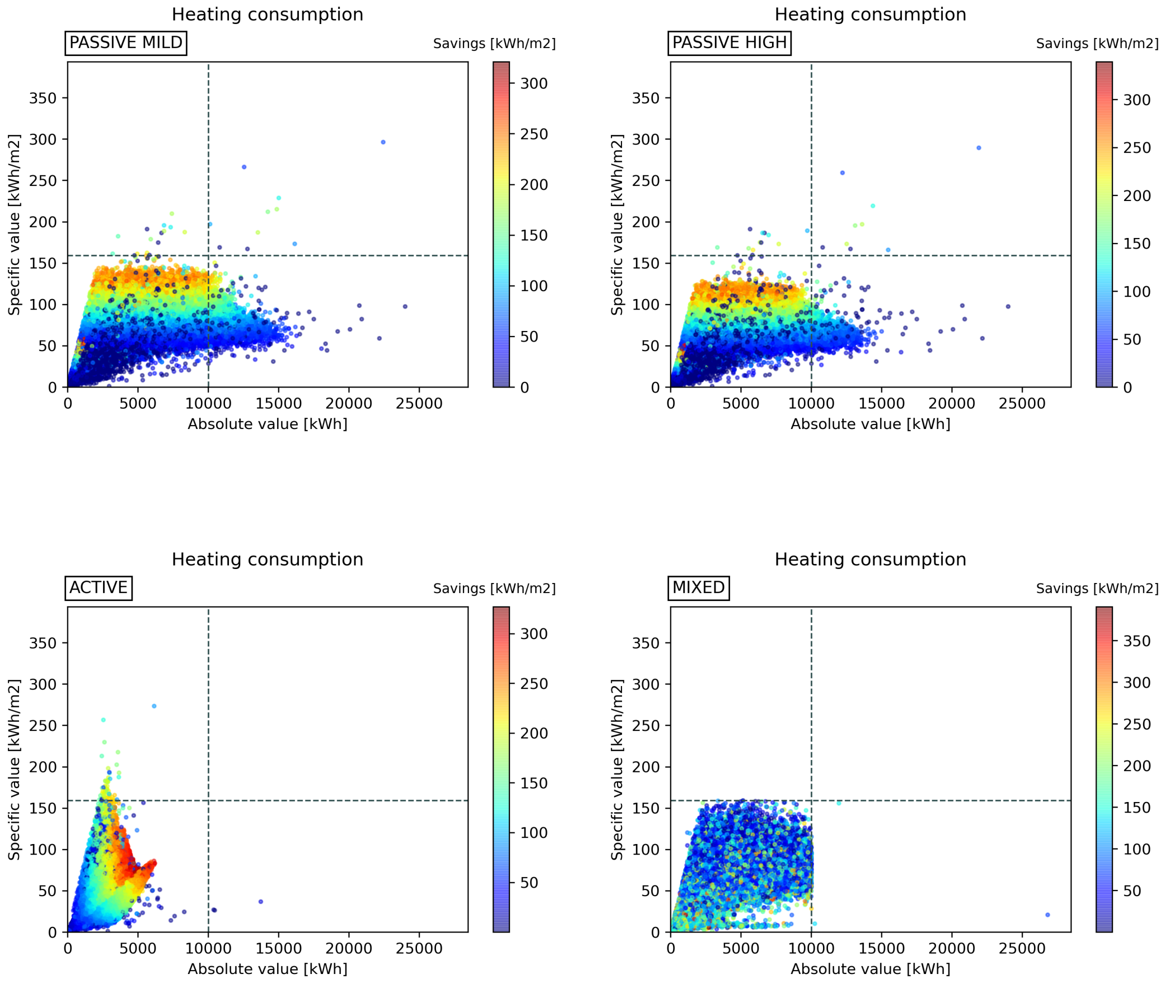

Figure 34: Primary energy savings for heating for PASSIVE MILD scenario (up left), PASSIVE HIGH (up right), ACTIVE (bottom left), MIXED (bottom right).

For all scenarios the range of visible energy savings values is concentrated near the

lowest ones. The reason of this behaviour is due to the large sample of data, which includes buildings with very different geometrical and technical features. For the MIXED and MIXED+PV scenarios it is difficult to distinguish different colors, because it is the optimized scenario and there are a lot of overlapping points.
Table 13 compares different scenarios and their reduction in terms of consumption and emissions reduction. Heating consumption has been divided between thermal and electric ones. Figure 35 and 36 show the same information of the above mentioned table. The highest reduction for heating consumption and emissions reduction is given by the ACTIVE scenario, because is the most invasive solution because it involves the replacement of thermal systems of the whole building stock.

	Thermal		Electric		Total		CO_2 emissions	
	TWh_{th}	%	TWh_{el}	%	TWh	%	$ktCO_2$	%
BAU	1324.46	-	9.849	-	1333.99	-	270978.38	-
PASSIVE MILD	1169.97	-11.64	5.261	-46.59	1175.23	-11.9	240.91	-11.1
PASSIVE HIGH	1041.594	-21.34	4.781	-51.46	1046.37	-21.56	214.54	-20.83
ACTIVE	0	-100	34.701	+252.33	34.7	-97.4	875.98	-67.67
MIXED	385.159	-70.91	44.069	+347.33	429.23	-67.82	90.39	-66.64
MIXED + PV	385.159	-70.91	44.069	+347.33	429.23	-67.82	77.99	-71.22

Table 13: Heating consumption and CO2 emissions by scenarios.

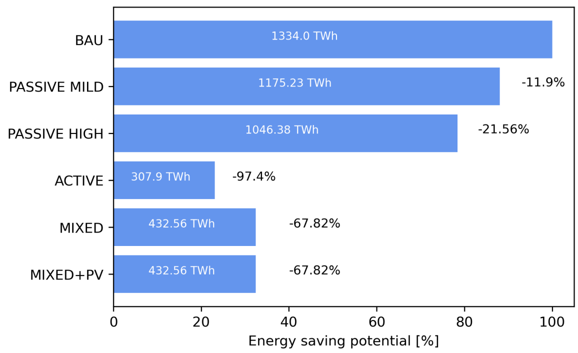

Figure 35: Energy savings for different scenarios.

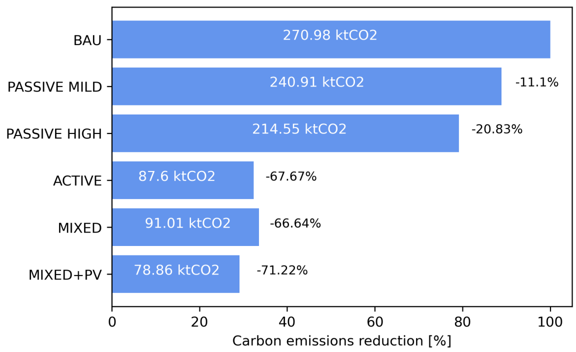

Figure 36: Emissions reduction for different scenarios.

Comparing the result with the targets imposed by the European Union and the national NEPC, only the last three scenarios respect the limits.

The map representation are reported in appendix C, both for BAU and post-retrofit scenarios. The energy maps shows the specific KPI of heating consumption, classified according to this old parameter used to identify the energy class of a building. The post-retrofit scenarios determines a large improvement in terms of energy efficiency, especially for the ACTIVE one. Through the spatial representation it is possible to identify the census tract that had larger improvements. For heating consumption, in the optimized scenario, these buildings are localized near the center of the city, which corresponds to the oldest buildings. Figure 37 shows respectively the heating consumption and carbon emissions for the MIXED+PV scenario. As previously said, the largest reduction is located near the center of the city and also in the north-west zone. The north-west zone correspond to the location of one of the newer neighborhoods. This means that, the oldest buildings reach performances very similar to buildings recently built. It is evident in the emission maps. Indeed, in the BAU scenario the emission related to the north-west zone and the center-north zone were already low. In the MIXED+PV scenario this reduction involves also the buildings in the center of the city. Indeed, to understand it, it is sufficient to observe the map with census tract classified according to the year of construction (figure 38).

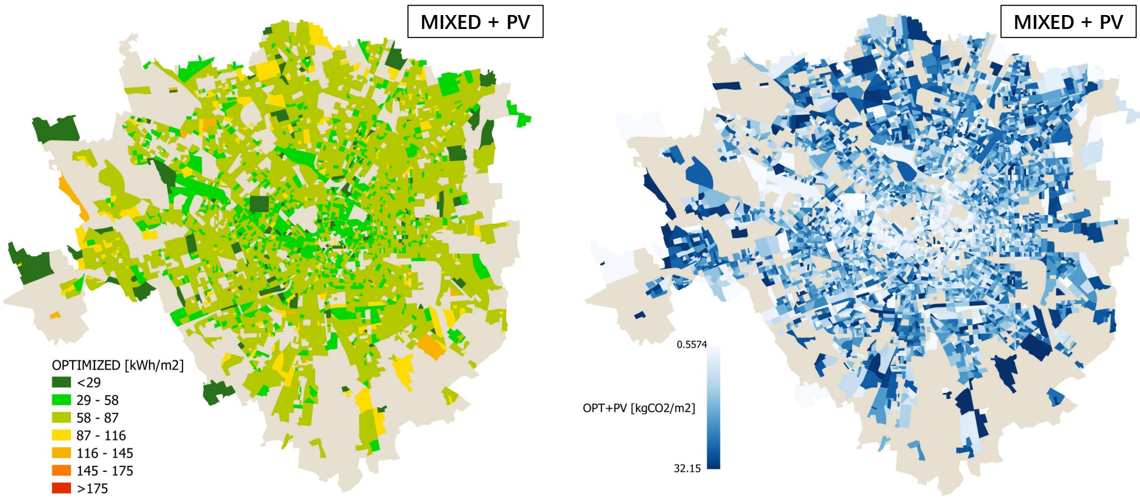

Figure 37: Urban maps for MIXED+PV scenario on the top: heating consumption on the left and carbon emissions on the right.

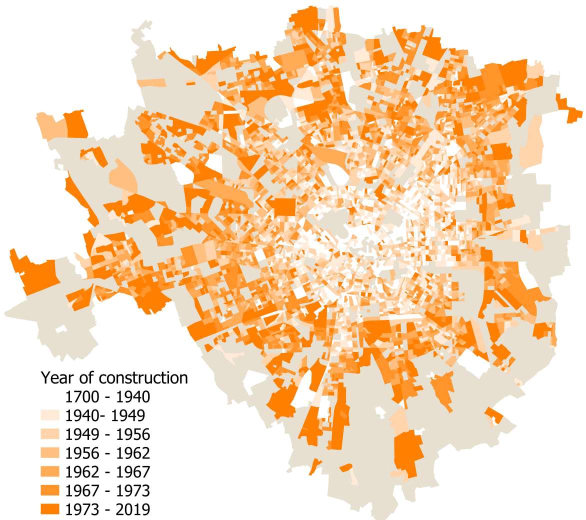

Figure 38: Urban map classified by year of construction.

5 Conclusions

This thesis work wants to define a methodology to evaluate the heating consumption of a sample of buildings located in an urban area, starting from open data, and through the use of some KPIs, to define retrofit strategies. Energy performance certificates are useful to understand the performances of existing buildings and they could be a very powerful tool for urban energy planning. The main problem found during this work was related to how data have been written in the EPCs data set. A lot of information was miswritten and often they were inconsistent whit other information reported in the same EPC. Certain data, belonging to different EPCs, were written in different orders of magnitude and this means to reduce a lot the sample considered. The most relevant aspect, which is also an alternative to the reduction of the sample, is that the computational time to manage a huge number of buildings increases a lot if the data set fields are badly compiled. Thanks to Python it is possible to reduce the computational time if compared with other spreadsheets like Excel. The reason why the number of buildings treated was still high is linked to the fact that only residential buildings were analyzed and that only heating consumption has been calculated. This ensures to have homogeneous information because the conditions imposed guarantee the use of a small set of fields of the EPCs data set. Energy performance certificates should be done using a standardized system, imposing a preset format of data, and a series of options to choose. In this way, the possibility to access to open data can become a resource for energy planning or other purposes.

Another obstacle was the difficulty to correctly merge the EPCs with their correspondent cadastral documents for the thermal system. It is not necessary to provide data sets already joined, but it is fundamental to transcribe the identification code of the EPC in the right way. The correct join phase was possible only for a small fraction, equal to the 1% of the entire sample of EPCs.

The bin method allows to define a parametric method to calculate heating and cooling consumption. Different scenarios can be obtained just changing a parameter, like thermal transmittance, thermal power, or efficiency. This ensures a generalization of

the methodology, easily applicable to other scenarios or case studies. It is a good alternative when the consumption was not provided by the energy supplier, with some limitations due to the lack of knowledge of hourly values. The heating consumption has been displayed both on the map and in a quadrant chart. The latter allows understanding the buildings which require more attention, and which would suffer the highest reductions. The application of the simple scenarios, the passive and active ones, allows understanding the behaviour of the heating consumption if the saving was due to the reduction in building demand or thanks to the use of more efficient technology. The highest reduction was observed for the latter, but the consumption was shifted to an electric source. The passive scenario shows that the buildings with the worst energy class suffer a great reduction after the application of passive saving measures. These measures are fundamental to increase the energy efficiency, because the main problem is related to the presence, in urban areas, of buildings with old building envelopes. Passives scenarios show that these measures are not sufficient to reduce the consumption, and consequently the carbon emissions, in large buildings.
The quadrant chart highlights those small buildings that have high specific consumption but low absolute values, and vice-versa for large buildings. Another aspect highlighted is related to the fact that small buildings have a dispersing surface greater than large buildings, as demonstrated by the surface to volume ratio. Then, their majors' problems are losses through dispersing surfaces, cause to their shape but also the large numbers of walls exposed to the external ambient or unheated environments. So, an action in terms of reduction of thermal transmittance of walls, roofs and windows is urgent. Some buildings are not sufficiently influenced by the reduction of thermal transmittance, because they are very large but their surface to volume ratio is quite small if compared to the previous ones. Since they probably have undersized or inefficient thermal systems, which do not satisfy anyway the heating demand of the building. The third scenario applies to all buildings the passive solution, but only for these, it is previewed the substitution of the thermal systems with the heat pump and the electric boiler. The heat pump has been sized according to the climatic parameters of the heating season, but it has not considered the cooling season. This represents surely an

underestimation with respect to the real case. Indeed, to complete the work should be correct to evaluate also the other services of the building, like cooling consumption or those due to domestic hot water production. In this way it possible to calculate the new index after the application of retrofit actions, and consequently the new energy class. Indeed, after 2015 the energy class is evaluated on the basis of the non-renewable index and not the heating index.
The larger reduction in terms of consumption and carbon emissions has been seen for the two last scenarios. The latter is characterized by the introduction of a PV plant, just for the heating systems supplied by electric energy. QGIS allows evaluating the potential useful area of the building interested by these systems since the building are geolocated according to their WGS84 coordinates. They have been considered only the half surfaces of roofs, because they are assumed to be two-pitched and only 80% of the area has been taken. The results have shown that the area available is larger than the necessary area for the PV. A more refined sizing is not feasible because there is a lot of missing information, like the orientation of the roof and the cooling demand. Another fundamental element to understand if the retrofitting packages are feasible is the cost linked to the proposed solutions. To find specific solutions for aggregated buildings, the use of a KPI associated to the expenses of the measures could determine different choices. Indeed, the local community can be influenced by the related costs.
The amount of thermal demand and electricity demand have been calculated for each scenario. The third, fourth and last scenarios show a great increase in electricity consumption, but they could be justified by the introduction of a photovoltaic system. They are also the only scenarios which achieve a consistent reduction to reach the 2030 goals, both for the European and Italian targets. It is important to stress again that they are partial results, cause the cooling demand is absent.

As future work might be interesting to develop a complete model that include the cooling demand too. To reach this goal it might be necessary to integrate other information about the building consumption. This process is feasible if information in EPCs and in the regional registry of thermal systems, are correctly written. Indeed, the bin method can be applied also for the cooling evaluation, while domestic hot water consumption can be calculated from the knowledge of the thermal system used to produce it, and statistical information about domestic habits. It might be possible also to aggregate buildings with very similar characteristics and compare the result with respect to the more generic and less refined methodology like that. The aggregation can be a useful resource for the interpretation of the information reported in the quadrant chart, and to support energy planners to take more effective solutions at urban scale.

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A Climatic bin data

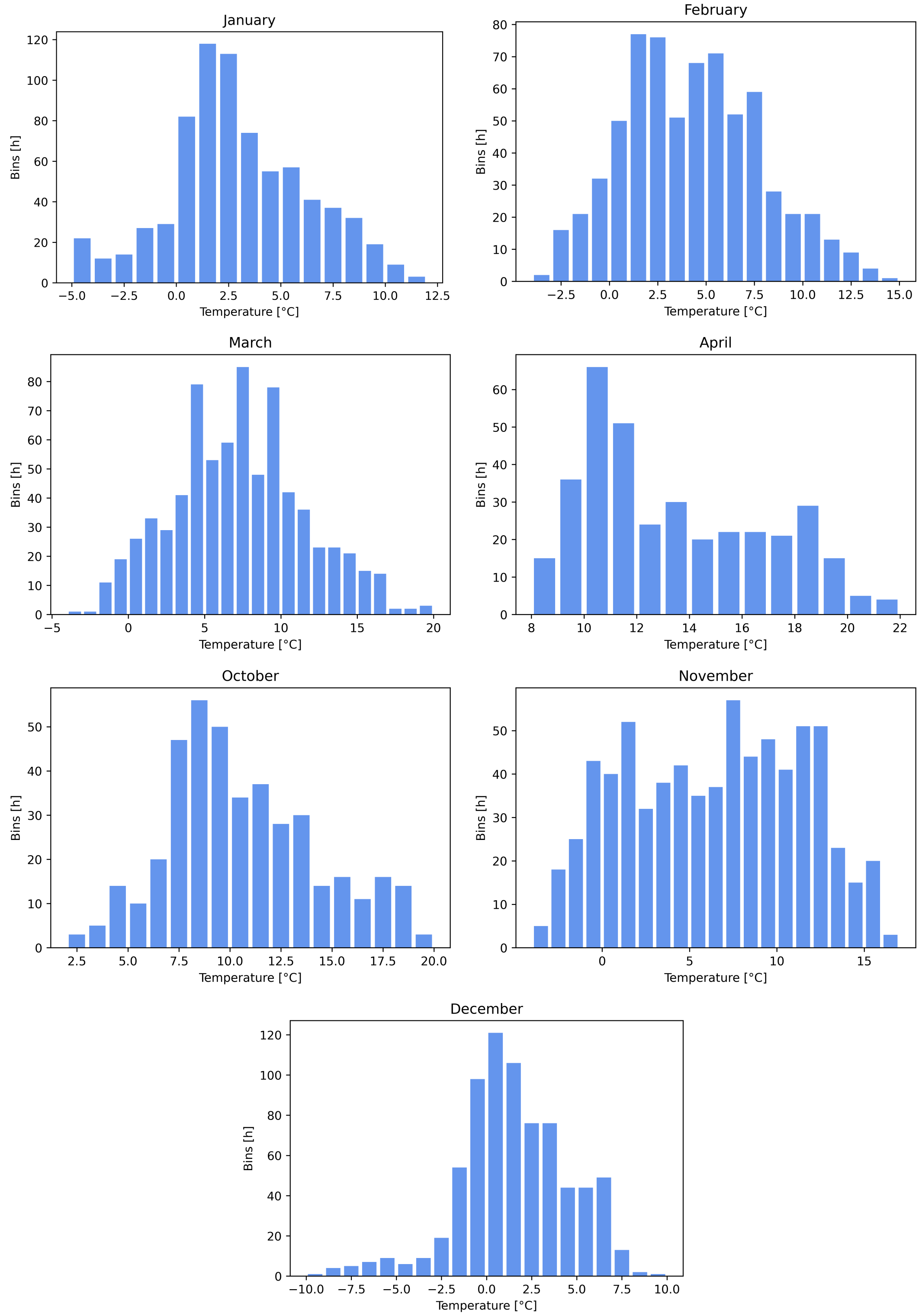

Figure 39: Climate bin data divided by month.

B Carbon emissions reduction

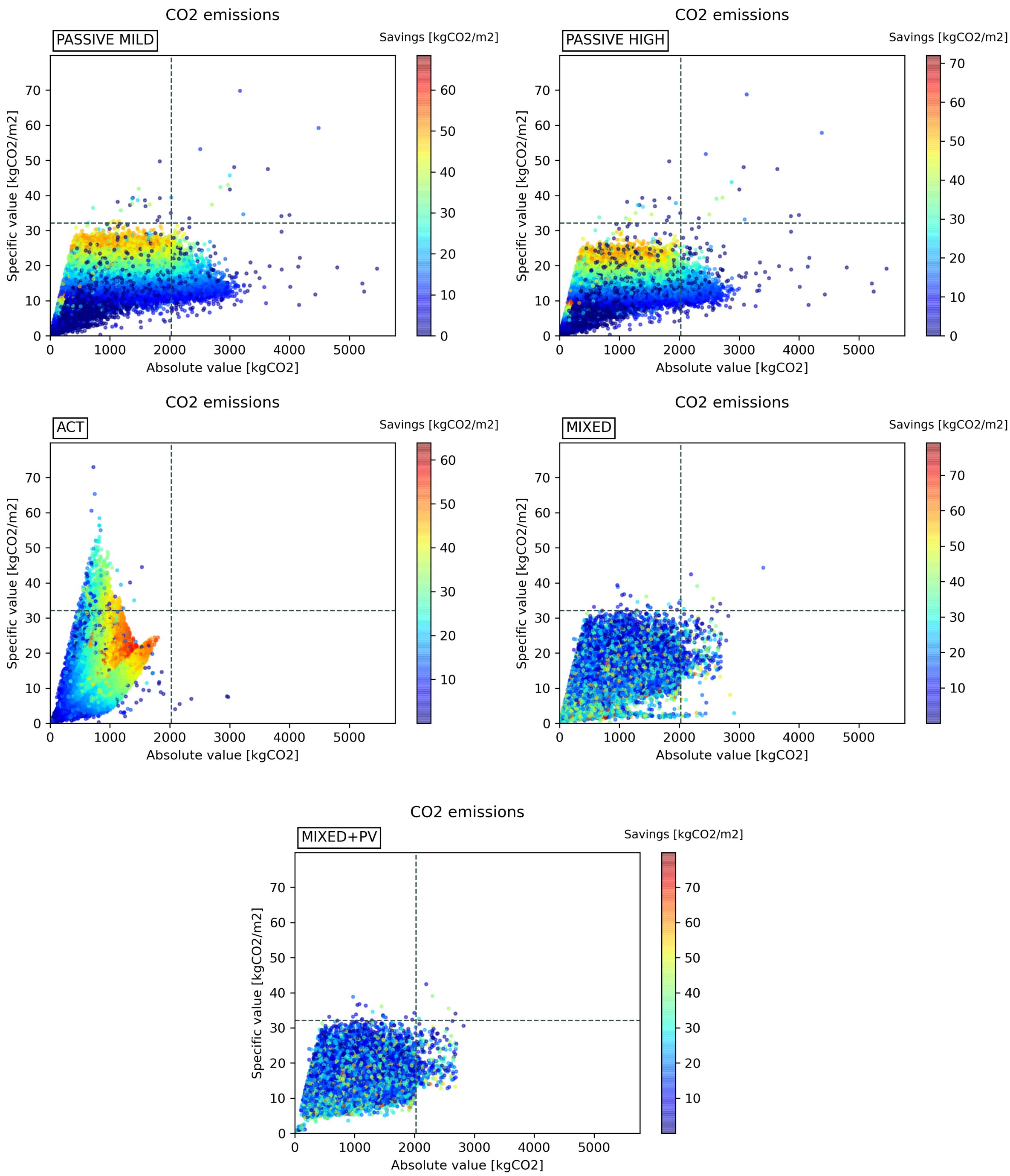

Figure 40: Carbon emission reduction for each scenario: PASSIVE MILD (up left), PASSIVE HIGH (up right), ACTIVE (center left), MIXED (center right), MIXED+PV (bottom).

C Map visualization

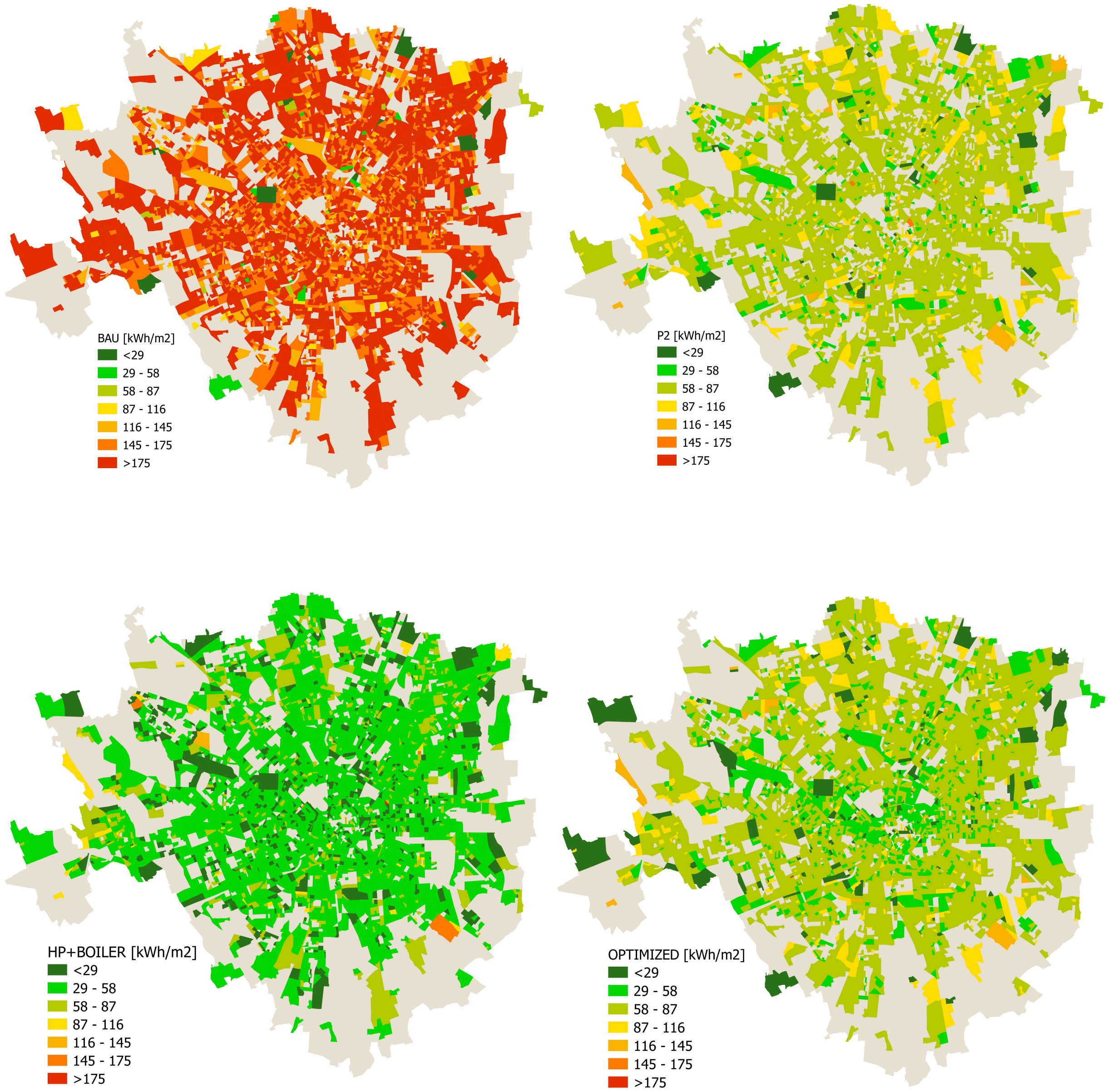

Figure 41: Energy maps with heating consumption by scenario: BAU (up left), PASSIVE HIGH (up right), ACTIVE (bottom left), MIXED (bottom right).

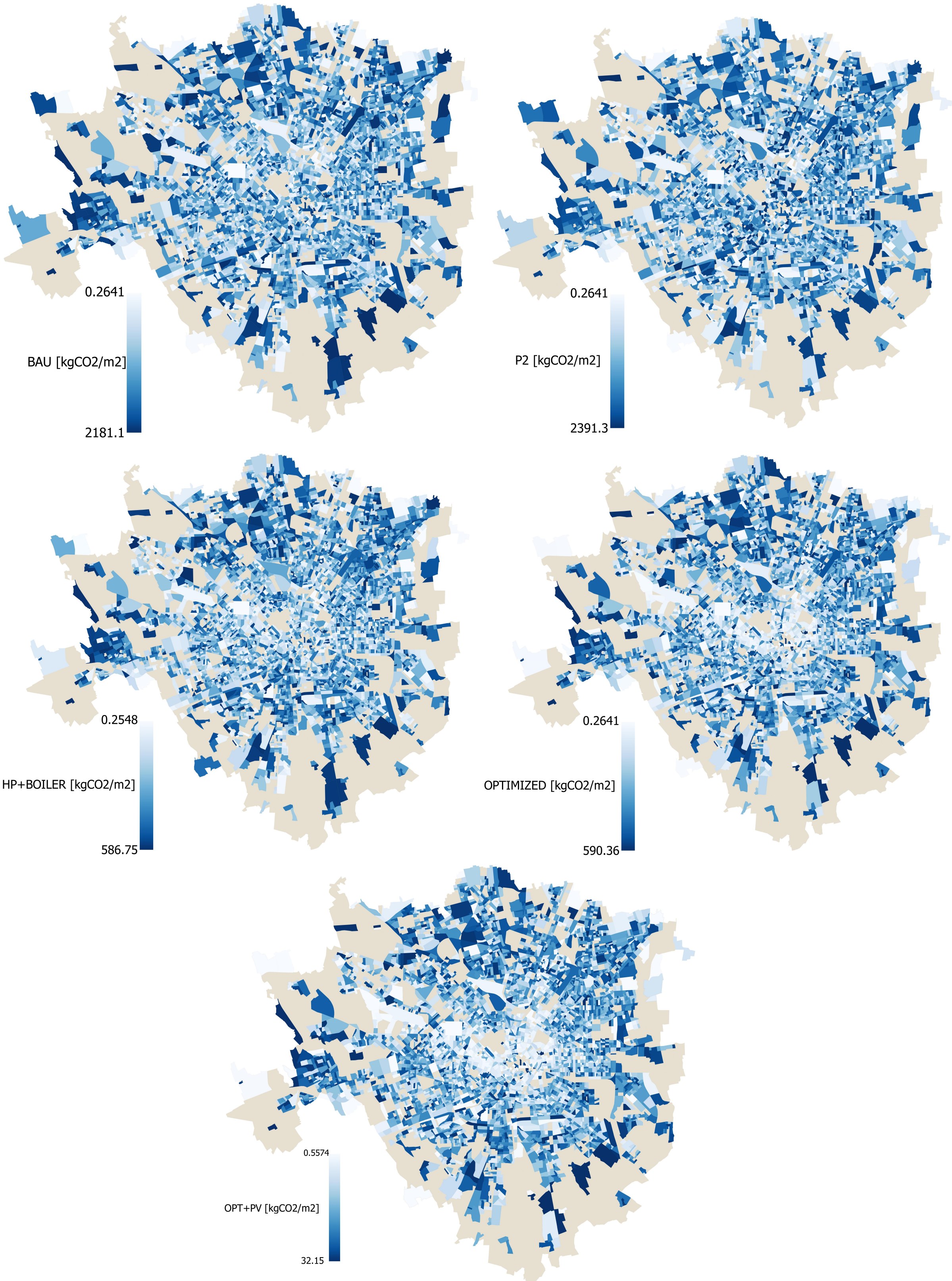

Figure 42: Carbon emission maps by scenario: BAU (up left), PASSIVE HIGH (up right), ACTIVE (center left), MIXED (center right), MIXED+PV (bottom)