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MASTER COURSE IN ENERGY ENGINEERING

Design and tuning of an easy-to-use application for sizing the heat pump of a single user residential unit

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Quasta tesi è dedicata a tutti coloro che mi hanno accompagnato in questo percorso:
Ai miei genitori, che mi hanno sostenuto sempre, nonostante la lontananza e le difficoltà. Mi avete insegnato cosa vuol dire amare
A mio fratello, che è sempre stato una guida ed un amico, a cui basta uno sguardo per conoscermi e capirmi.
A mia nonna, che è presenza costante nella mia vita e nel mio cuore
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A Matteo,Samuele e a tutti i miei amici, sia quelli fatti lungo la strada che uqelli che mi sono accanto da tanto. Siete il sale della mia vita.
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"Ohana significa famiglia e famiglia vuol dire che nessuno viene abbandonato o dimenticato"

Abstract

The objective of this work is to develop a tool for the feasibility assessment of the substitution between a traditional boiler and an air-to-water heat pump for the heating of residential buildings. The project has been commissioned by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile - ENEA) as part of an effort to promote the use of sustainable and renewable energy, with particular emphasis on the domestic heating sector. After an initial introduction to the current evolution of national and international policies, an analysis of the state of the heating market is proposed. Then, the Italian building scenario is discussed and an excursus on all the available technologies for domestic heating is presented, before focusing on the working mechanism of the heat pump. The main part of the thesis is then presented, which discusses the construction of an algorithm that evaluates the possibility of replacing a conventional boiler with a heat pump, while at the same time satisfying the user's heating needs. Great care has been taken to ensure that the programme remains user-friendly, requesting information and inputs that are as simple as possible and easy to find, a characteristic that was considered crucial to ensure the tool's widespread use. In the final part of the thesis, two analyses are carried out, covering the whole Italian territory, and the results are duly analysed.

Sommario

L'obiettivo di questo lavoro di tesi è lo sviluppo di uno strumento in grado di accertare la possibilità di sostituire una caldaia tradizionale, utilizzata per il riscaldamento domestico, con una pompa di calore aria-acqua. Il progetto è stato commissionato dall'Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), nell'ambito di uno sforzo per la promozione di un utilizzo dell'energia sostenibile e rinnovabile, con particolare attenzione al settore del riscaldamento residenziale.Dopo un'introduzione sulle politiche nazionali e internazionali, viene riportata un'analisi sull'attuale stato del mercato del riscaldamento. Successivamente, viene presentata un'analisi del parco immobiliare italiano e un excursus di tutte le tecnologie disponibili per il riscaldamento domestico, per poi concentrarsi sul meccanismo di funzionamento delle pompe di calore. La parte principale della tesi è poi dedicata alla creazione di un algoritmo in grado di valutare la possibilità di sostituire una caldaia tradizionale con una pompa di calore per soddisfare i bisogni di riscaldamento dell'utente. Particolare attenzione è stata posta nel garantire che il programma risultasse di facile utilizzo, richiedendo informazioni il più possibile semplici e agevoli da trovare, una caratteristica questa ritenuta indispensabile per una larga diffusione dello strumento. Infine, sono state condotte delle simulazioni su tutto il territorio italiano e i risultati sono stati riportati e adeguatamente commentati.

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Chapter 1

Introduction

To better understand the context in which the project has been developed, it is firstly necessary to fully comprehend the reason behind the choice of focusing on the heating sector, as well as to have in mind the political and technological background characterising the heating sector decarbonisation.

Historically, the generation of heat has consistently been a highly energy-intensive sector, currently accounting for approximately 50% of global final energy consumption. Of this percentage, approximately half can be attributed to industrial processes, while 46% can be attributed to the consumption of commercial and residential buildings [1]. This figure is set to rise further still, given the ongoing growth in both population and urbanised area, coupled with the fact that a significant proportion of the global population still lacks access to modern heating appliances. It is notable that, at the global level and also accounting for the most technologically and economically advanced countries, a significant proportion (in excess of 80%) of the heat sources exploited to meet these needs are still fossil fuels or non-renewable biomass. The high intensity of energy and the use of noxious fuels inherent to this sector contribute to its status as a major source of air pollution and CO_2 emissions. ”The need is urgent, then, to reduce and even reverse the growth in energy demand for heating [...], while rapidly scaling up the deployment of renewables” [1].

1.1 Global tendencies for heating decarbonization

As the problem of climate change has become an international primary objective, made official by the stipulation of the Paris agreement [2] in 2015, each country has embarked on a path to reduce its carbon footprint. The significance of the heating sector in this context is evidenced by the fact that the majority of strategies designed for this purpose allocate a pivotal role to the

decarbonisation of residential heat production.
For example, in recent years an increasing number of programs have been issued in the USA to electrify the residential sector, accounting for 13% of the country CO_2 emissions, by replacing fossil fueled systems with electrical equivalents. In the latest ACEE report [3], more than 40 programs have been identified, with 90% of them focusing on single-family air-source heat pumps.
Another notable example of this global trend is Japan: since the start of the century the Central Research Institute of Electric Power Industry of Japan, the DENSO corporation and Tokyo Electric Power Company (TEPCO) have joined forces to design a feasible substitute to the traditional gas boiler. The result is an innovative CO_2 heat pump layout able to supply hot water both for heating and sanitary use. Statistical results indicate that this solution has been installed in more than 20% of Japanese detached houses, showing a growing trend [4].
Furthermore, numerous countries with a greater reliance on coal, including China, have implemented decarbonisation strategies pertaining to the heating sector. In the last chinese Five-Year plan, the electrification of a vast system of district heating, installed in the northern part of the country, have assumed an important role, working as driving force for the transition to clean heating [5]. The aim is to substitute the coal fueled heating system in operation with high temperature heat pump, providing the needed hot water for two entire cities and increasing the air quality while abating the CO_2 emission.
The most ambitious environmental policy initiative at the international level is the European Union's (EU) commitment to reducing greenhouse gas emissions by 55% before 2030 and achieving net zero emissions across the entire Union by 2050. The strategy, designated the "European Green Deal," encompasses a multifaceted approach including social, economic and technological aspects, with the objective of ensuring a seamless energetic transition. Starting from the social security of carbon intensive industries workers and support to the inhabitants of regions frequently affected by climate events, the set purpose is a cohesive society progress, without leaving any member of the EU behind. The deal is of primary importance in the total scheme of the post COVID recovery plan, with an allocated budget of around six hundred billions euros.
From a technological standpoint, the primary objective is to enhance energy efficiency, expand the contribution of renewable energy sources to the energy mix and improve the energy performance of buildings. Regarding the last point, specific directives have been introduced to address the problem. Given the prevalence of poorly insulated buildings and the particularly harsh climatic conditions in the northern regions of the Union, which necessitate significant energy expenditure for home heating, this sector accounts for up to one-third of the total energy consumed in the Union. [6].

The decrease in the energy consumption of residential buildings can be seen as a key aspect to achieve the goal of decarbonizing by 2050. The chosen heating system foer this task has been the heat pump. With a ”call to evidence” and a ”public consultation” happened both in 2023, the European Commission has set the goal to accelerate the heat pump market and deployment. This target is ment to be achived by increasing the communication with the industrial sector and the R&I, developing a suiting legislation, enabling accessible financing to the user and setting up a virtual platform to bring all the stakeholder together [7]. With this proposition, the Commission’s goal is to install by 2027 at least 10 million unit, in addition to the 3 million heat pumps already installed in 2022.

The Italian legislation follows the prints traced by the European Commission, with particular attention to the riqualification of outdated buildings. In fact, in the 2020 budget law [8], a series of tax reductions have been put in place for those who performed a series of energy requalification measures on an existing building. In the same year, the so-called ”super-bonus” was implemented: this was a system that allowed the recovery of 110% of the riqualificarton expenses through tax deduction, making the allowed renovation works theoretically free for the house owner. This strong position served as fuel for the construction sector, stimulating the start of a staggering and partially overwhelming number of projects.
Regarding the possibility of boiler substitution, the driving force is, again, the presence of incentives and tax reductions. However, for now, no particular emphasis has been placed on the integration of renewables in the heating sector, as they fit the same incentives as a gas-fuelled condensing boiler.
Another barrier could be found in the lack of awareness in the supply chain and the ineffective promotions of the installers [9]. A push in this direction can be expected from the competent authorities in the coming years, and the project presented in this article can be seen as a step in Italy’s path to comply with the ”Green Deal” and ”Paris agreement”’s objectives.

1.2 Residential heating market composition

To better understand where the project stands in the actual Italian residential heating market, it is necessary first to determine how its composed on a national level, and how the heat pump compare against other possible technologies that can decrease heating emissions.
In Italy, the system with the highest spread is, by far, the traditional methane-fuelled boiler, which covers up to 70% of the market [10]. The remaining share is made up of biomass or alternative fossil fuel (i.e. LPG or diesel) boilers and a percentage of renewable energy.
In 2019, the European project HARP (Heating Appliances Retrofit Planning) presented an

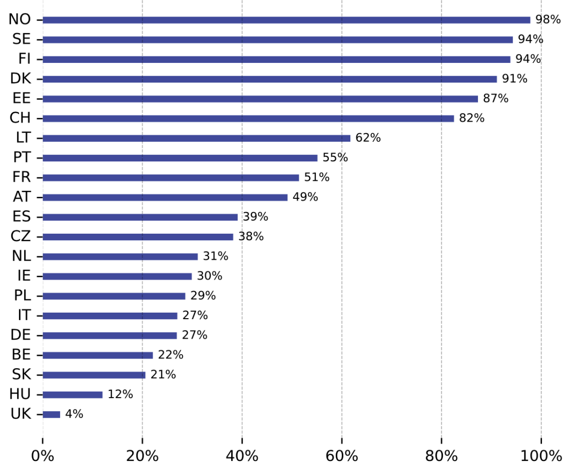
analysis [11] of possible replacement technologies for the phase-out of the traditional boiler, identifying several possibilities. These are: condensing boilers, heat pumps, biomass boilers and combined heat and power systems. Of these alternatives, only the first three have a adequate installation possibilities in the Italian context, each with its own characteristics.

The condensing boiler, probably the most commonly installed solution between the ones cited before, is a particular type of boiler. It is able to harness the latent heat of the water vapour present in the fumes, virtually exploiting the entire energy content of the fuel, increasing the heat provided to the user. Condensing boilers can cover all output ranges needed by a residential user, usually presented as wall mounted units. Although this technology displays an efficiency higher than that of a traditional boiler, it inherits the need for a fossil fuel, leading to a certain and unavoidable amount of emissions.

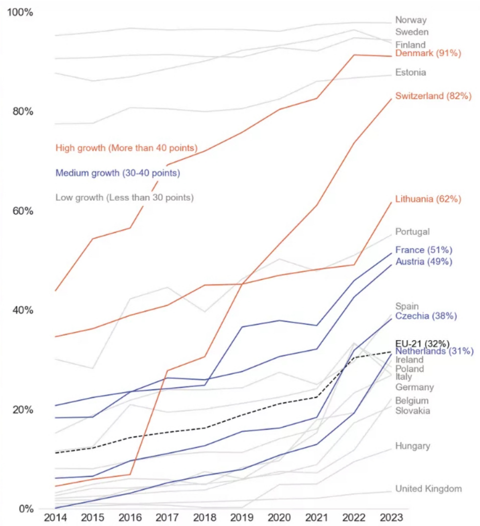
On the other hand, biomass boilers, because of the characteristics of the fuel used, are intrinsically carbon neutral. In fact, when biomass burns, it releases in the atmosphere the same quantity of CO_2 that has been absorbed during its growth [11]. Biomass-based heating systems have proven to be a reliable and flexible solution, able to respond to the heating needs throughout the year. Moreover, they can be easily combined with solar thermal systems. Most of the boilers available on the market achieve high efficiency, but a main drawback of this technology resides in the fuel supply and storage.

The last possibility is the heat pump, of which a detailed description of the working principle will be given in another section. In the context of the new heat production strategies put in place by the major governments, this technology is without a doubt the most promising and more taken into account in newest regulations and incentives programs. Suffice to say that, following the IEA ”net zero by 2050” pathways [12], before 2045 half of the global heating needs should be covered entirely by heat pumps. This should give the magnitude of the growth expected by this technology all throughout the planet.
In Europe, heating pumps has been selected as the centre of a variety of laws, ranging from the EU’s plans for greater energy independence [13], in the form of the REPowerEU plan [14], to its revised climate and energy targets for 2030 [15] [16]. This effort led to an increasingly high market share controlled by this technology. As can be seen in Figure 1.1a, that report the percentage of market share covered by the heat pump technology according to the most recent data, there are some virtuous examples of countries (i. g. Norway and Sweden) where a share of near 100%, is reached. In those countries the heat pumps are the predominant technology, to the point that it is practically the only viable choice when buying an heating system. Other

countries, in particular those located in the eastern or in the southern part of the Union, have a much lower presence of heat pumps. This distribution could have many different causes: it can be due to economical reasons related to the high initial cost of instalment or it could be linked to the interpretation and timing of reception of the European directives by the single states. Particular attention can be paid to Italy, that reach the value of 30%. Although over half of the reported countries have a percentage of controlled market lower than 50%, a reassuring trend can be seen by analysing Figure 1.1b where the trajectory of the curves indicates the variation in the technology market share during the years. As a first comment, it is important to note that the overall tendency of the curves show promising growth. In particular, the countries reported in red show a major rise in the percentage during the last years. Some other nations, in blue, are characterised by a medium increase that is almost equal to the average value of the continent, 32%. The remaining white lines refers to the group of countries with the lowest permeation of heat pumps. Among them it is possible to recognise the states that have already reached the maximum percentage, and do not have any more room for an increase, and those who have kept a low value during all the studied years. Unfortunately, Italy is part of this last group, even though its value place it on the top of his class.



(a)



(b)

Figure 1.1: Market share controlled by heat pumps per country during the years (1.1b) and focus on the year 2023 (1.1a). Source:EHPA.org

The heat pump sector has also been identified as a strategic industrial asset, as, in 2023, 60% of the heat pumps sold in the EU were produced internally. With the prospected growth of the market, this value expected to increase substantially. The trend of sold units, which can be seen in Figure 1.3a divided by type, shows a constant growth until last year, where a slowdown is appended. Following the study expressed in [17], the reasons for this downturn,

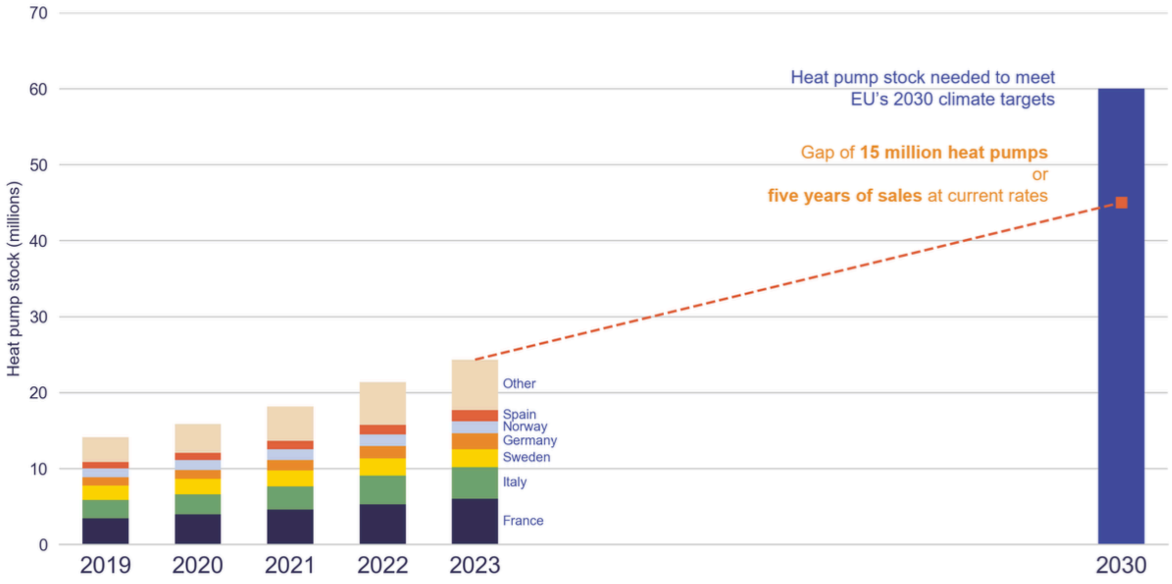
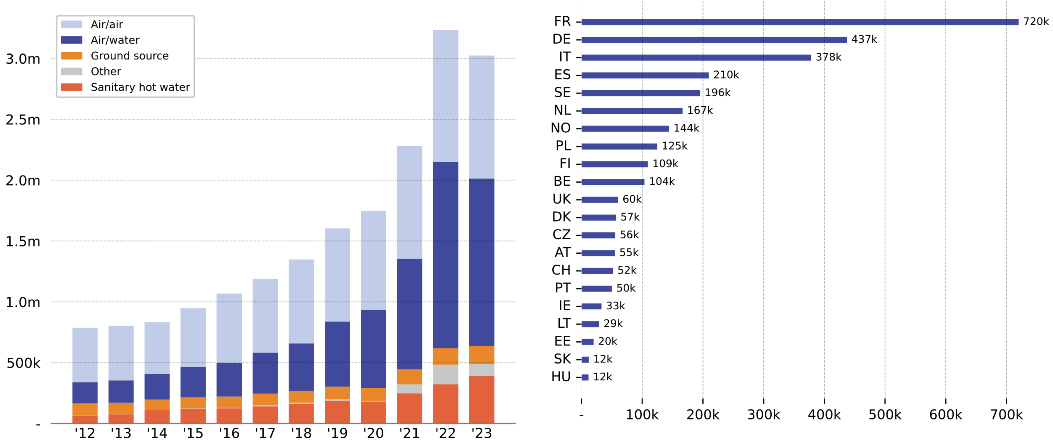


Figure 1.2: Trend of heat pumps sales reported to the EU 2030 objective. Source:`EHPA.org`.

after a decade of constant growth are to impute to several factors. From an economic point of view the energy price volatility and the economic stagnation dumped the confidence in the market. In particular, the fluctuation in gas prices, combined with high electricity cost, affected the financial attractiveness of heat pumps for consumers. Moreover, political uncertainty and regulatory challenges, together with the European Commission's postponement of the Heat Pump Action Plan [7] created further uncertainty and contributed to the decline in sales. In the report, country-specific analysis are reported, for an in depth compression of the phenomenon.

By analysing properly the figure 1.3a it is possible to note that the ratio between the various type of system has shifted during the years. The main heat source costantly remain the external air, and, initially, it was also the main heat sink. This type of machine was the first to be marketed, as the design knowledge was directly derived from the already widespread air conditioners, and this may have been the reason for its initial success. In the recent year a change in this paradigm has happened, with the increase of Air-water systems. One reason for this phenomenon could be found in the push for energy qualification of new buildings, which is at the core of this thesis.. In fact, when renovating, the safer and less invasive option is to replace the boiler, leaving the heating systems (radiators, radiant panels, underfloor heating, etc.) intact. The reasons why an air-to-air heat pump cannot be used in this case are trivial.
According to some experts [18], if annual sales do not increase above recent values, there is a high possibility that the EU will not be able to reach its goal of almost 60 million units installed by 2030. By following the PRIMES model in [19] and analysing the current sales trend, the

Union will lack around 15 million units. The projection of the existing sales patterns is reported in Figure 1.2 in relation to the targeted amount for 2030.



(a) (b)

Figure 1.3: European heat pump sales development by type (“Air/air counts heat pumps with a primary heating function) (1.3a) and Heat pumps sales by country in 2023(1.3b). Source:`EHPA.org`

In the EU scenario, Italy has one of the largest markets: until around 2020 it was in second place, just behind the French market [9]. Now the Italian heat pump market has been overtaken by the German one, making it the third force in the field. As can be seen in Figure 1.3b, that report the number of units marketed in each country in 2023, the total number of sold heat pumps was around 3 million. Of this total amount, around 24% were sold in France, 14% in the German market and around 12% in Italy.

In order to evaluate the composition of the Italian market, it is possible to analyse Figure 1.4. It represent the entirety of the Italian heat pump landscape divided by type of machine installed. Starting the analysis from the different energy sources, it is possible to observe that the air accounts for the vast majority of the market, followed by the ground source covering around 3% and a minor contribution by water [9]. Taking into account the heat sink, the most common technology is the air-to-air heat pump,in blue. In recent years an increase in the installation of air-to-water heat pump, reported in figure as ”other reversible tecnologies” in red, can be detected. Although they still represent a minority, their increase in numbers could be related to the Italian traditional adversity in using air conditioning, both for heating and cooling purposes. This reluctance could come from the common belief that this system is either inefficient or bad for the users health, even though no significant scientific proof of correlation could be found. Another driving force of the rise of this particular technology has previously been found in its compatibility with pre-existing heating systems. The percentage of ground-source heat pumps has remained low and stable over the years, with sales around the thousands of units [20]. Although Italy has a particularly high geothermic activity, barriers like high initial investments and difficult bureaucratic approval prevent further distribution on this technology.

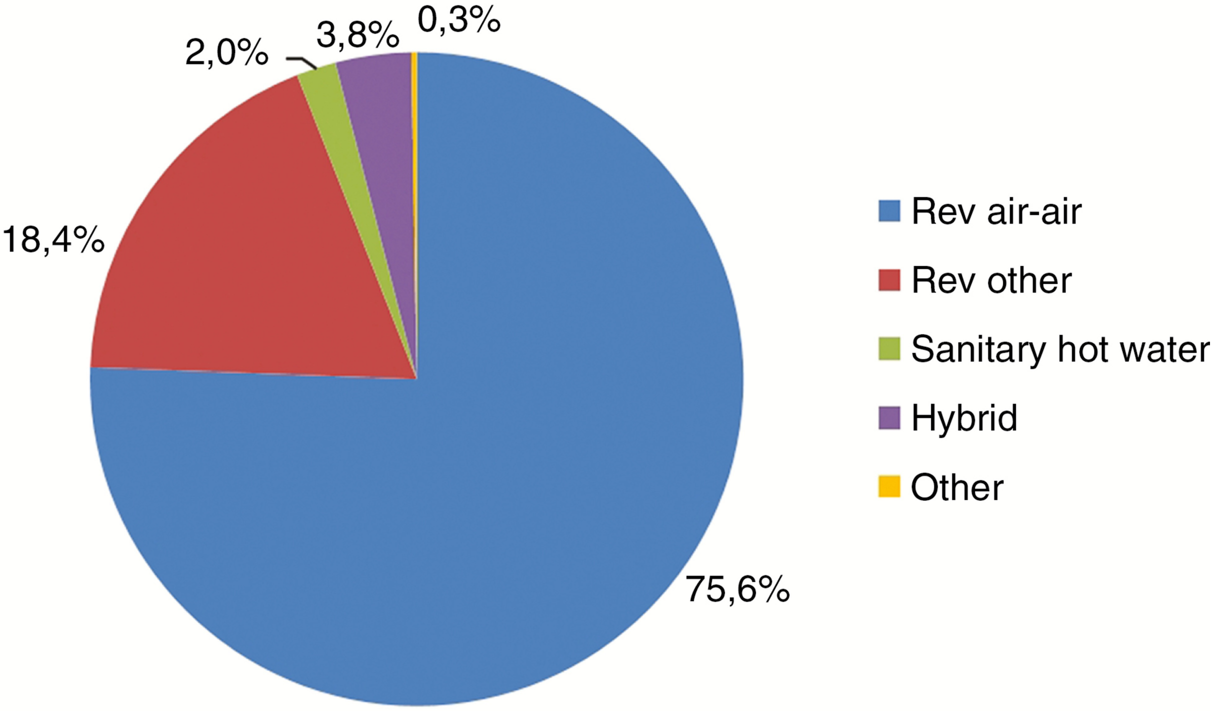


Figure 1.4: Share of italian heat pump market by type in 2017. Source: [9]

1.3 Italian Buildings landscape

To further analyse how the technology of the heat pumps can be essential to decrease the emission in the coming years, it is necessary to understand how the Italian building landscape is composed and how this technology relate to different possible installation sites.
Analysing the data from CRESME, the major entity in Italy for statistics, services and research on the building sector, it is possible tot note how old the Italian housing market really is.

A review of the data presented in Table 1.1, sourced from the CRESME document [21], reveals a striking observation: approximately 12% of Italy's total building stock was constructed prior to the outbreak of the First World War. An additional equal percentage was constructed during the period between the two world wars, while nearly 14% was built during the reconstruction phase following the last global conflict. This indicates that over five million two hundred thousand buildings, representing over 43% of the total stock, have been in existence for over eighty-five years. Further analysis reveals that the industrial growth of the

Building period	N. of buildings (millions)
before 1918	2,15
1919-1945	1,38
1946-1960	1,66
1961-1970	1,97
1971-1980	1,98
1981-1990	1,29
1991-2000	0,80
2001-2011	0,54
After 2011	0,16

Table 1.1: Number of building by year of construction. Source:CRESME.

period between the 1960s and 1980s led to a significant expansion of the construction market. Approximately one-third of the total number of structures were erected during this period, equating to three million, nine hundred thousand units. Following this period, a contraction of the market can be observed, with declining numbers.
In consideration of the year of introduction of the European Energy Performance of Buildings Directive (EPBD) [22], 2002, only a modest proportion of buildings were constructed subsequent to its implementation. The EPBD is regarded as a significant advancement in building performance regulation, adopting a comprehensive ”whole building” approach that considers a range of components, including ventilation and lighting systems. The relatively low proportion of buildings constructed in accordance with these regulations, at slightly over 11%, highlights the significant potential for energy savings in the construction sector. Furthermore, in 2010, a significant amendment to the directive was introduced [23], establishing nearly zero-energy standards. The aforementioned revision has been applied to a mere 1.3% of buildings.
In light of the fact that, according to CRESME, 79% of the building stock is composed of buildings used fully or predominantly for residential purposes, it became evident that the efforts undertaken to enhance the energy efficiency of Italian homes play a pivotal role in the overall impact on the emission reduction. To substantiate this assertion, it is sufficient to consider the evidence that, in Europe, it is estimated that buildings constructed recently require approximately 60% less energy than those built prior to the mid-1970s [24].

Italy is one of the most historically and architecturally rich countries in the world. Its city centres are renowned for their medieval, Renaissance, 1700s, 1800s structures, which are frequently integrated into the urban landscape. These edifices are used on a daily basis by the citizenry for a multitude of purposes, including cultural and academic institutions, commercial activities and even private homes. In light of their significance, the conservation of these edifices is important. They are frequently safeguarded by legislation that prohibits alterations

to their external appearance, employed materials, and construction techniques. Given their age, historical buildings are inherently less energy-efficient and require a greater input of energy, a combination that, when considered alongside their considerable numbers and the constraints that have been previously explained, represents a significant challenge that has inspired numerous authors. It is common for such structures to have a heating system already installed, which is often outdated. The installation occurred in years when regulations were less strict, and any modification is now more complex. Due to visual constraints, thermal solar panels are not permitted, thus the more selected renewable technology is the heat pump.
As evidenced in the literature, the majority of projects employ ground source heat pumps [25],[26], primarily due to the availability of large commercial units and their high COP values. Air source heat pumps are also utilized, as evidenced in [27]. [28] presented an overview of renewable technology integration in heritage buildings, with several case studies demonstrating the potential for enhancing energy performance in historic structures. [29] and [30] examined the energy efficiency measures employed in a historic complex at the University of Padova, comprised of offices, libraries, and classrooms. The interventions resulted in the installation of two air-to-air heat pumps and two ground source heat pumps coupled with a vertical heat exchanger, with the objective of achieving an energy efficiency rating of ”A”. Following the completion of the renovation works, The building was awarded the ”A Plate for Efficiency” prize by the GSE, in recognition of the ”complexity of the renovation work, carried out on a single building, and for having managed to combine energy efficiency with the preservation of the beauty of the architectural complex” [31]. Similar trends have been observed in other countries, including Poland [32] and England [27].

It is acknowledged that the necessity to retrofit energy systems in historic buildings presents a challenging and stimulating opportunity. The potential to enhance the comfort of use of these structures could increase their use in the daily life, helping their maintenance and increasing their cultural influence. However, if the objective is to achieve the sustainable targets set at the international level, this building category may not be the primary focus. A review of the data presented in [33] reveals that the highest number of structures, in terms of both quantity and energy consumption, were constructed between 1945 and 1991. When the specific consumption of each building is considered, it becomes evident that these periods exhibit the highest values. Table 1.2 presents the same values as Table 1.1, with the additional data just mentioned. This allows for the rapid assessment that, in order to reduce the energy consumption and, consequently, the emission of the residential sector, the main category to be addressed is that of buildings constructed in the second half of the twentieth century.

Building period	N. of buildings (millions)	Specific energy consumption [TOE/building]
before 1918	2,15	/
1919-1945	1,38	/
1946-1960	1,66	/
1961-1970	1,97	1,22
1971-1980	1,98	1,08
1981-1990	1,29	1,09
1991-2000	0,80	1
2001-2011	0,54	0,88
After 2011	0,16	/

Table 1.2: Number of building and specific energy cosnumption by year of construction. Source:CRESME,[33].

Upon analysis of the data published in the most recent ENEA report on energy efficiency [34], it becomes evident that the majority of interventions were limited to partial renovations. In particular, approximately 65% of approved Ecobonus renewals relate to the substitution of the heating system, while only 20% relate to the renewal of door and window frames and glass. A further 10% relate to shadings, and a negligible 1% relate to improved wall insulation. This evidence demonstrates that the majority of housing renovations are undertaken with a budgetary constraint or, in any case, with the objective of slightly increasing the energy efficiency rate. It is rare for a project to encompass a full renovation, as the ones applied to historic buildings, capable of achieving the maximum efficiency. Given that the majority of the buildings built from mid-century onwards are still in good conditions, it is far more common to focus the renovations on the aspect perceived as more lacking or under performing
This reasoning is crucial to understand the choice of the majority of citizens to select an heat pump that allows for straightforward integration with preexisting systems. Despite their high efficiency and performance, water and ground source heat pumps require a significant initial investment in terms of installation and system preparation. They usually occupy a considerable amount of space and necessitate a long authorisation process, as will be discussed in a subsequent section. The decision to focus on air-to-water heat pumps in this thesis is based on the aforementioned considerations.

1.4 Heat pumps overview

The heat pumps fit in a family of systems whose objective is to move heat from a lower temperature system to a higher temperature system. To do so, they exploit a so-called inverse cycle, meaning a cycle that uses a certain amount of energy to exchange heat between to bodies. The heat ”movement” in this cycle happens against the normal direction, that is from the hotter

body to the colder one. To have a more pragmatic example of this kind of processes, the common household refrigeration exploits the same principle to cool down a volume, the inside of the machine, that is already colder than the environment. To do so, it spends electrical energy to move the heat from the inside to the backside, where, in turn, the heat will be dissipated.
An heat pump work exactly in the same way, extracting heat from the colder external source, that is defined for this reason as the heat source, and release it to the ambient inside, the heat sink. To perform this process, it is necessary to spend a certain amount of energy; depending on the type of heat pump, it can be mechanical energy supplied by a compressor or thermal energy in case of an adsorption cycle. With regard to the two different types, only the Vapour Compression Cycle (VCC) will be studied in depth, while the Adsorption Cyle (AC) will be only cited. This choice follows the aim of the project to focus only on residential applications, thus excluding AC technologies that are more commercial and industrial in nature.

As already said, the main characteristic of the ACs is that they are thermally driven, meaning that the energy needed by the cycle to transfer the heat from the heat source to the sink is supplied by heat instead of electrical energy. Even if this technology is more frequent in industrial installations, where it is usually fuelled by high pressure steam or waste heat [35], it is still possible to find residential applications coupled to solar thermal systems [36].
The working mechanism of this technology exploit the ability of a given liquid, or salt, to absorb the working fluid's vapour. This second fluid is called absorbent, it does not participate in the heat transfer appending in the condenser or in the evaporator, as its role is only that of bond with the refrigerant vapour in the absorber (4) and release it in the generator (6). Generally, the most common fluid couple are water-lithium bromide, safer but with stricter working ranges, and ammonia-water, best performing but toxic.
As can be noted by the schematic in Figure 1.5, in this kind of systems the pressure increase of the working happens in liquid state, by means of a pump (5). This change permit to further decrease the electrical energy need of the system to an unremarkable level.

Focussing instead towards the VCCs, as can be seen in Figure 1.6, a basic vapour compression heat pump is composed mainly of four elements: the compressor, the condenser, the expansion device and the evaporator. Usually, for residential application, the selected expansion device is a thermostatic expansion valve because of its flexibility and ability to maintain optimal system parameters even in off-design conditions. In some cases capillary tube or short tube orifice devices can be used for simpler and low-cost designs, but they limit load regulation [39]. As for the compressor, normally scroll or rotary design are used [40], while in bigger applications piston type components could be selected. Regardless of the type,

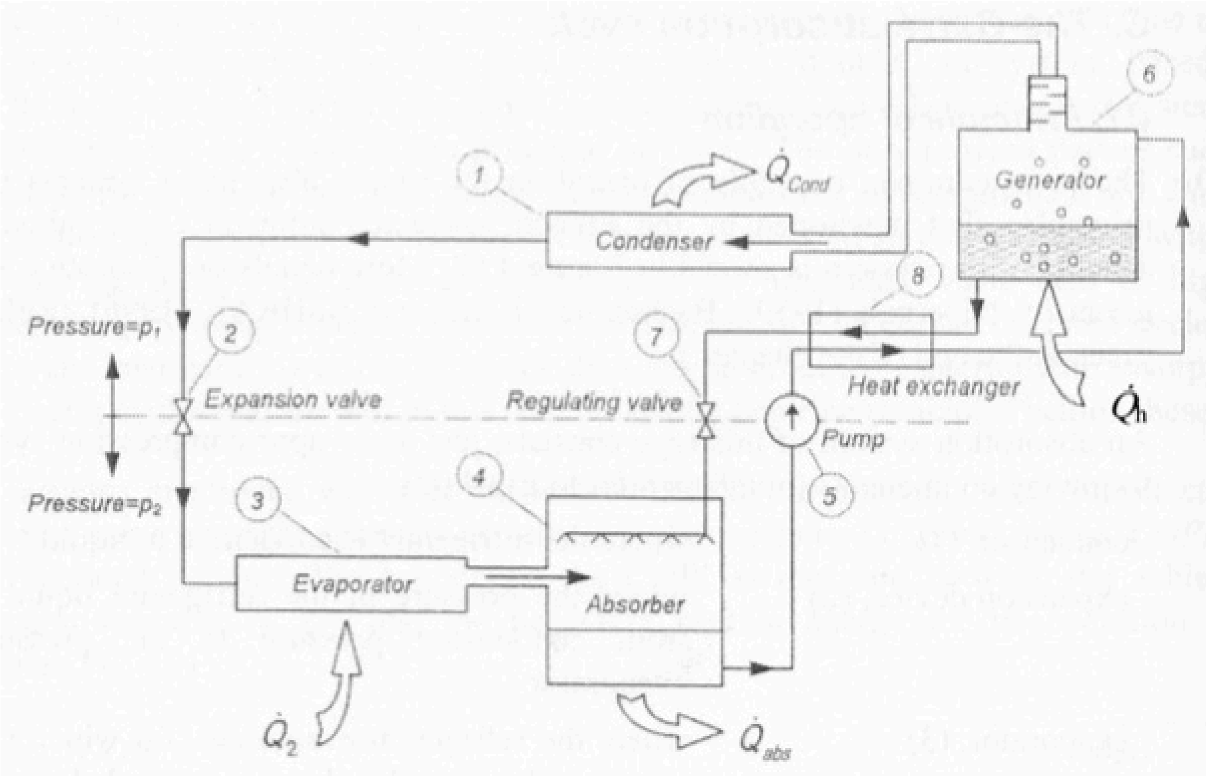


Figure 1.5: Schematic of a basic absorption heat pump. Source: [37]

the compressor must be able to vary its pressure ratio while maintaining high performance, a characteristic necessary to adequately follow the variable needs imposed by the user. The choice of the heat exchanges vary depending on the producers choice and on the secondary fluid the system work with.

Another fundamental component that has yet to be described is the working fluid. It can be defined as a component in its own right due to the numerous design aspects that follow the producer's choice of one fluid over another. As previously discussed, the working fluid serves as the medium through which heat is transferred across the circuit. The evaporation and condensation temperatures of a given fluid at a specific pressure, as well as the fluid's response to temperature and pressure fluctuations, determine the shape of the working cycle and, subsequently, the performance of the machines. The importance of the fluid selection cannot be overstated. Even before other components are selected, it is possible to fit the cycle to the design needs by carefully choosing a fluid, or a mixture of fluids, that exhibit the requisite phase change temperatures and respect the given specifications.
A number of other characteristics are crucial in the selection of an appropriate refrigerant. For instance, the molar mass of the fluid has a significant impact on the shape of the saturated vapour curve and, therefore, the magnitude of superheating at the exit of the compressor.

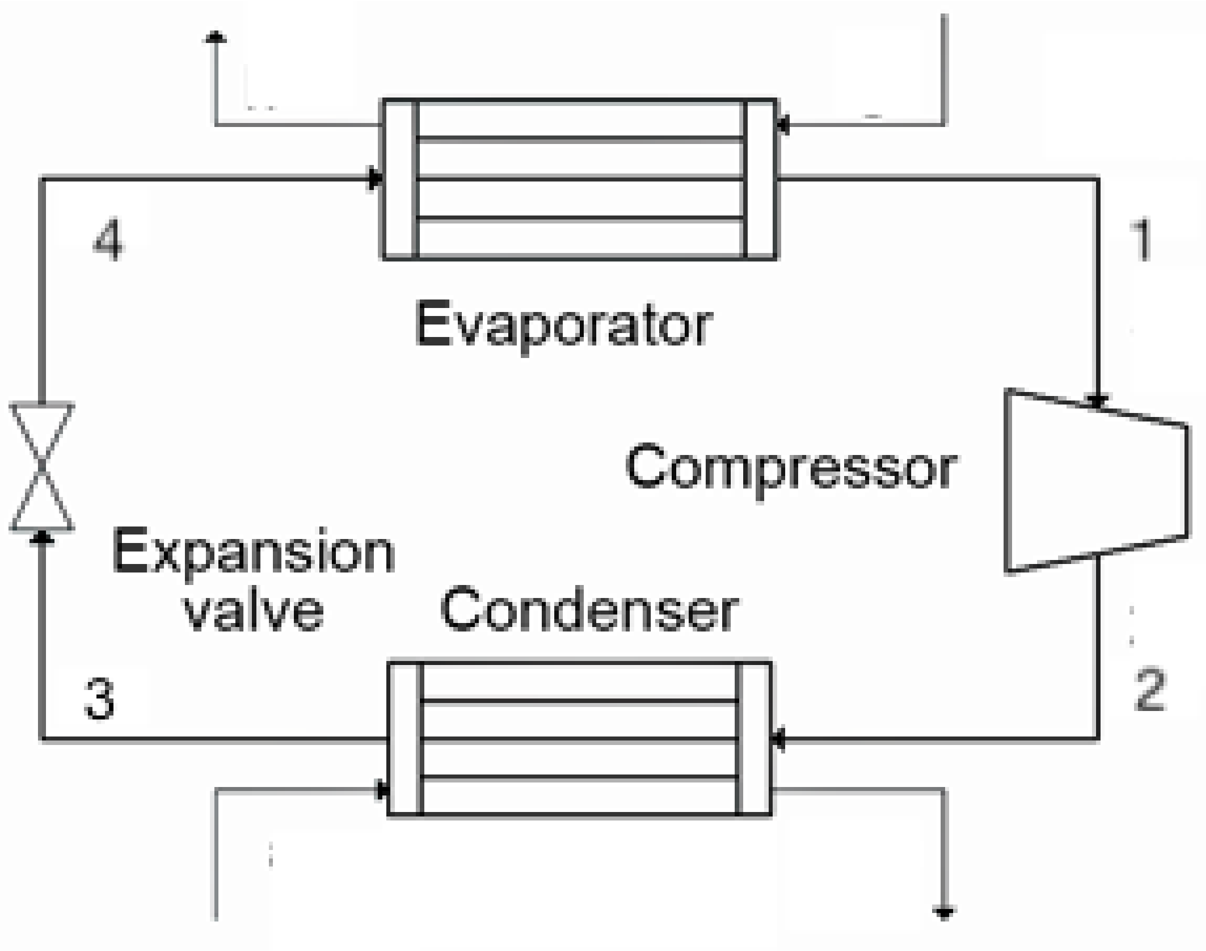


Figure 1.6: Schematic of a basic vapour compression heat pump. Source: [38]

This aspect alters the shape of the cycle, thereby determining the quantity of heat that can be released in the condenser. Other physical properties, such as miscibility with oil, viscosity, flammability and toxicity, are of great importance. Each of these attributes plays a significant role in the fluid selection process and must be subjected to meticulous analysis during the design phase. In recent years, starting from the Montreal Protocol [41] and continuing with the most recent F-gas regulation [42], particular attention has been paid to the environmental effects of such fluids. The most commonly used working fluids were chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), such as R-11 and R-22, which were selected for their exemplary performance and chemical stability. The high chloride content of these substances has resulted in their prohibition, due to the detrimental impact on the ozone layer and the elevated greenhouse effect. Subsequently, hydrofluorocarbons (HFCs) such as R134a, were introduced as replacements, as they did not contain chlorine. However, they were also banned due to their high environmental impact. At the time of writing, natural refrigerants such as ammonia and hydrocarbons (HC) are employed. The main drawback of those fluids are, respectively, flammability for HCs and toxicity for ammonia. Despite the undesirable characteristic, these fluid do not have any considerable environmental effect, a quality that leaded to a predominant use in Europe, where it is believed that the safety implication of hazardous refrigerants can be controlled by proper design and use [35]. In the United States, synthetic refrigerants with a low global warming potential (GWP) as R410a are preferred due to their safer nature.

Each of these components plays an essential role that can be recognised in the diagrams in Figure 1.7, reporting the two typical representation of the working cycle of VCCs heat pumps (Pressure-Entalphy and Temperature-Entropy diagrams). In particular, at point 1, the refrigerant

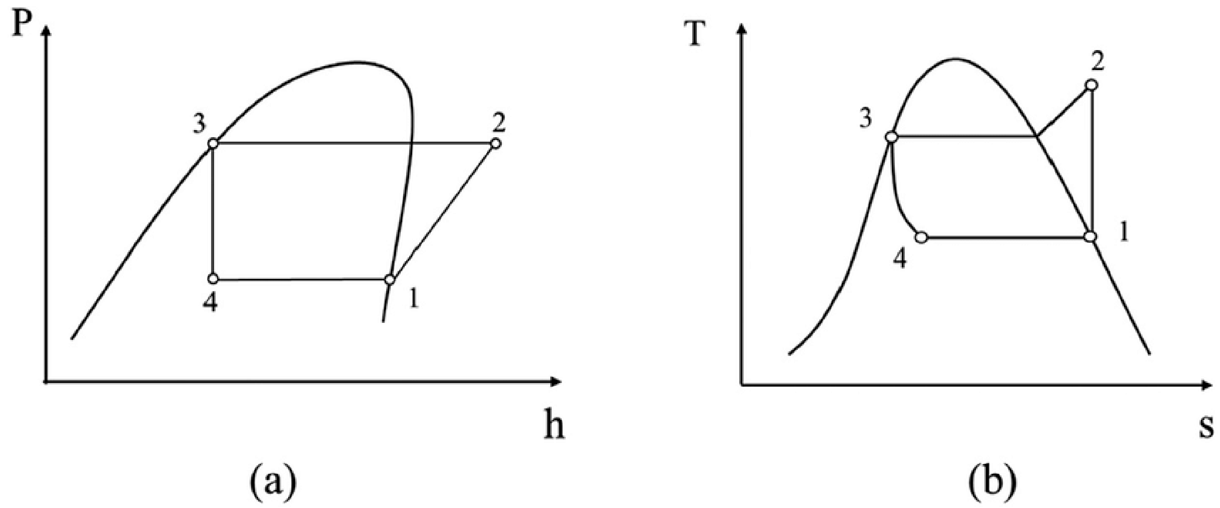


Figure 1.7: Pressure-entalpy and Temperature-entropy diagrams of a general fluid with heat pump cycle. Source: [43]

has just exited the evaporator and is in a saturated vapour state. Subsequently, the refrigerant is drawn into the compressor, which increases its pressure, resulting in the superheated vapour state observed at point 2. This increase in pressure results in an increase in temperature, as illustrated in the T-s diagram of Figure 1.7. This elevates the refrigerant to a higher thermal level than the ambient temperature, enabling heat transfer. The thermal difference enables the transfer of heat to the heat sink, which occurs within the condenser between points 2 and 3. At the exit of the condenser, the refrigerant is in a saturated liquid state. The thermal energy released during this process represents the useful product of the cycle. It is now necessary to reduce the fluid pressure via an expansion device until point 4 is reached. At this juncture, the temperature of the refrigerant is less than that of the heat source, facilitating the transfer of heat. after the vaporisation of the refrigerant and its return to point 1, a new cycle commences.

Since the systems takes as inputs two different energy types, meaning the thermal energy extracted from the external source and the electrical energy supplied by the grid, the definition of the machine performances is not trivial. Normally, instead of the electrical energy absorbed by the heat pump, the work done by the compressor is accounted. Theoretically, by energy conservation the heat released by the condenser should be equal to the heat absorbed by the evaporator plus the work expressed by the compressor, as in Equation 1.1.

$$Q_{cond} = Q_{evap} + W_{comp} \tag{1.1}$$

A common standard to evaluate the steady-state performances in the sector is to take into account the Coefficient Of Performance (COP) for this purpose. The COP is defined as the ratio between the thermal energy released at the condenser and the electrical energy absorbed by the compressor, Equation 1.2. The resulting value is, almost under every conditions, higher than one, with a normal value usualy above 3 [35]. This characteristic could seem odd and somewhat in contrast with the commonly understood concept of the first principle of thermodynamics. However, it is necessary to note that in the COP calculation the heat absorbed from the heat source is not considered and assumed to be ”free”. Taking into account all the energy streams interacting with the system, the global efficiency returns to a value lower than 1. The high value of the COP, in addition to being a good excuse for a theoretical revision of thermodynamics, holds an heavy practical value. It allows fewer energy to be spent in order to achieve the same value of thermal energy supplied to the user, therefore holding an economical advantage as well as contributing to increasing the energy efficiency.

$$COP = \frac{Q_{cond}}{W_{comp}} = \frac{Q_{evap} + W_{comp}}{W_{comp}} \tag{1.2}$$

It is possible to define a theoretical COP value, meaning the COP of in ideal machine performing a perfectly reversible and isentropic cycle also called called also COP of Carnot, as in equation 1.3. By referring the real COP to this ideal one, it is possible to evaluate the efficiency of the heat pump as in Equation 1.4

$$COP_{carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}} \tag{1.3}$$

$$\eta = \frac{COP_r}{COP_{carnot}} \tag{1.4}$$

These values refers to the machine’s instantaneous performance; however, another metric can be examined to have a deeper understanding of its behaviour over an extended period of time. The operational effectiveness of the heat pump over the period under analysis is referred to as the seasonal performance factor (SPF) or seasonal coefficient of performance (SCOP). It is defined as the ratio between the thermal energy delivered by the machine and the total electrical energy supplied to it, as illustrated in Equation 1.5.

$$SCOP = \frac{Energydelivered}{Energysupplied} \tag{1.5}$$

This value is particularly useful because it allows to calculate a unique coefficient that takes into account the variability of working conditions and energy demand, as well as other processes that may occur, such as frosting. In the European normatives, the calculation of the SCOP is explained in detail in [44]. In the procedure, a thermal power need is supposed, the machines' COP values are investigated at different external temperatures and, finally, the seasonal values are calculated with the aid of external temperatures fixed datasets.

1.4.1 Classification

Heat pumps can be classified according to a number of different criteria, depending on the purpose for which they are intended. For instance, they can be grouped according to their application, which may be residential, commercial or industrial. Alternatively, they can be classified according to their function, which may include space and hot water heating for residential or commercial applications, as well as drying, pasteurising and numerous other processes in the industrial sector.
In the context of this study, the focus will be on residential electrical heat pumps for space heating, as opposed to the numerous other types that exist. The most useful and clear differentiation that can be performed on the machines of this category is that referring to the heat sink type.
The following paragraphs will examine each typical residential heat source, with a particular focus on air-to-water heat pumps, which will subsequently be addressed in the algorithm.

Water source heat pumps exhibit an high COP due to the high density and heat capacity of the medium, in fact water is capable of containing a significant quantity of energy per unit of volume. Due to the high thermal properties and high heat transfer coefficient normally displayed by water, the working fluid is capable of absorbing a greater amount of energy, thereby increasing the performance of the machine. The secondary fluid may be groundwater, extracted from wells, or surface water, obtained from ponds, lakes and rivers. Groundwater is particularly efficient due to its almost constant temperature throughout the year [45]. However, the necessity to dig the wells, normally one for the extraction and another for the re-injection, implies a high initial cost and difficult authorisation. The temperature of surface water fluctuates significantly over time, which reduces the overall efficiency of the machine. However, the low initial cost and easier permission acquisition are notable advantages. A disadvantage of both configurations is the risk of refrigerant leakage through the heat exchanger, which typically necessitates the introduction of a third fluid between the heat source and the refrigerant.

Ground source heat pumps benefit from the same temperature stability observed in groundwater, particularly at greater depths where temperature fluctuations are less pronounced throughout the year.In fact, at a depth of around ten metres the temperature remains almost stable [46]. Furthermore, thanks to the so called geothermal gradient, the temperature increases with depth. The combination of these two characteristics explains why the ground has been considered one of the world's most efficient renewable energy sources [47]. There are two principal categories of ground source heat pumps: the ground-coupled heat pump and the direct expansion ground source heat pump.
In the former, a secondary fluid, typically comprising water and antifreeze, is pumped into a ground heat exchanger, where it exchanges heat with the surrounding environment [48]. The exchanger can be installed horizontally, in which case it covers a considerable area and the positive effect of the geothermic gradient is significantly diminished [49]. However, the excavation costs are considerably reduced. In the case of a vertical heat exchanger, all the potential benefits are exploited at the expense of a prohibitive initial cost.
An alternative design is the direct expansion ground source heat pump, in which the refrigerant is directly pumped into the ground heat exchanger, evaporating while it exchanges heat with the soil. In this configuration, the borehole heat exchanger essentially functions as an evaporator. While these systems exhibit higher COP and lower cost [50] than ground-coupled heat pumps, they also present significant challenges, including a high refrigerant charge, working fluid leaks, and heat exchanger corrosion.

In order to gain a comprehensive understanding of the various heat sources, it is essential to devote significant attention to the exploitation of air as an energy source. This technology is the most used, employed in both heating and hot water production, due to its relatively low installation costs in comparison to the other options. Additionally, the installation process typically does not necessitate intrusive works or specific authorisations. Two principal designs exist for exploiting the air source: Air-to-air and air-to-water heat pumps. In the former, one heat exchanger coil functions as the evaporator to extract heat from the external air, while the other operates as the condenser to heat the selected space. It is notable that this configuration is analogous to that used in cooling appliances. Indeed, the majority of air-to-air heat pumps are reversible heat pumps, capable of modifying their operational parameters to function as a heating system in winter and an air conditioning unit in summer.

Air-water heat pumps are predominantly utilised in the residential sector for the generation of hot water, used both for sanitary and heating purposes. As detailed in Section 1.2, the proportion of this technology has grown in recent years, largely due to its straightforward integration into existing heating systems, avoiding the need for significant changes. Indeed, this technology can be directly substituted to the existing boiler in order to provide the user with the necessary heating and hot water. To enhance the production of hot water, these heat pumps can be designed with multiple condensers. In particular, for higher sizes, a so-called hot gas cooler, a heat exchanger specifically designed to exploit the energy content of the superheated vapour exiting the compressor, is installed. For smaller machines, two different heat exchangers are mounted in parallel as can be seen in Figure 1.8. The condensers are designed with different specifications, so that they can supply hot water at distinct temperatures, simultaneously, in order to meet the user's requirements. It is uncommon for this type of heat

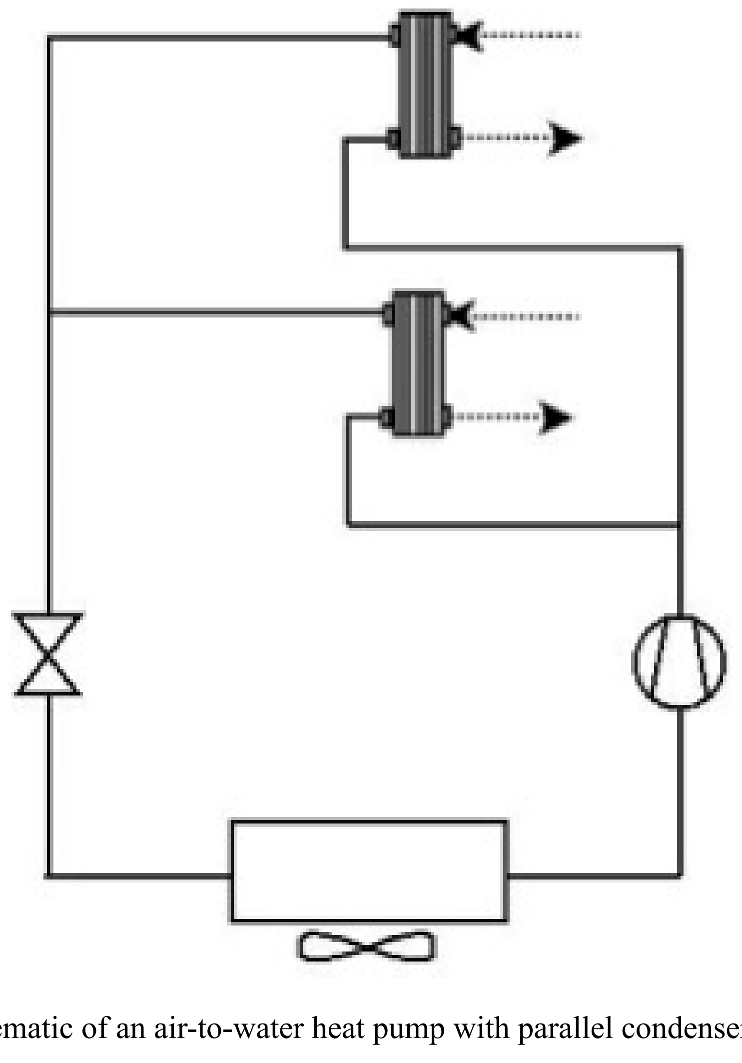


Figure 1.8: Schematic of an air-to-water heat pump with parallel condensers. Source: [37].

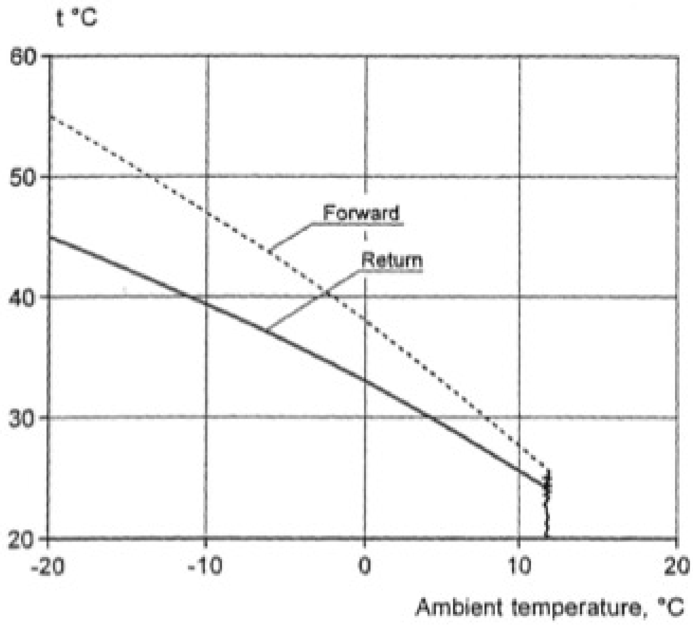


Figure 1.9: Sending and return temperatures diagrammed against external temperature as obtained from the method of compensated temperatures. Source [37].

pump to be installed as a standalone system; most often, a supplementary heat source, typically a electrical boiler, is employed. The optimal positioning of these backup systems is following the heat pump, ensuring that the primary heating system is consistently operational while the others are activated as needed. Another advantage of this configuration is that the heat pump is able to operate in the optimal conditions, given the lower temperature difference between the evaporating and condensing temperatures.

Another potential precaution to ensure optimal machine performance is the use of a method known as ”compensated” water temperatures. This entails modulating the temperature of the water requested to the heating system according with the actual thermal need. In contrast, conventional heating systems operate in a opposite way, they regulate the quantity of water demanded by the boiler, which supplies it at a fixed temperature. Before reaching the user, the flow of hot water is combined with a cold water supply from the municipal grid, delivering water at the desired temperature. Although this strategy is effective when used with a traditional boiler, it is not suitable for a heat pump, as it results in inefficient working conditions and a reduction of the COP. One disadvantage of this approach is that it is necessary to modify the control mechanism of the heating and hot water system. An example of the results of this method can be seen in Figure 1.9, where both sending and return water temperature are reported at different external temperature, thus at different thermal loads. Both the air-to-air and air-to-water heat pumps are subject to fluctuations in temperature on a daily and seasonal basis. This implies that the machine’s performance will vary considerably under typical

operational conditions, rendering it the technology with the lowest seasonal efficiency among the aforementioned alternatives. Nevertheless, due to its simplicity and affordability, air remains the primary heat source for heat pumps.
An additional intrinsic issue associated with the exploitation of the air source is the formation of frost on the evaporator, a phenomenon known as frosting. This phenomenon occurs when the external surface of the evaporator reaches a temperature near 0°C, which is indicative of an external temperature below +4 or +5°C. Frosting obstructs the airflow through the evaporator, forming a barrier that reduces the rate of heat transfer, resulting in a notable decline in the heat pump's performance [51]. Furthermore, it can result in a backflow of refrigerant within the system, which may lead to system failure [52]. To prevent a significant reduction in the efficiency of the heating system, a process to reverse the formation of frost is necessary, known as defrosting. The frequency of the defrosting process depends on a number of factors, including the type and design of the heat exchanger, the external air temperature and humidity and the presence of an anti-freeze coating. In the most unfavourable conditions, with an evaporator surface temperature approaching 0°C, a defrosting process may be necessary approximately every one and a half to two hours [37]. At lower temperatures, the interval between two defrosting cycles can extend to over five hours.
The principal techniques for defrosting are electric defrosting, hot gas defrosting by reversing operation, defrosting by subcooling refrigerant and hot gas bypass from the compressor.
The most straightforward of the technologies in question is that of electric defrosting. This involves installing an electrical conductor in the walls of the heat exchanger, thereby enabling the exploitation of the Joule effect to facilitate the melting of the frost. The melting process is relatively rapid, as it is sufficient for the inner layer of ice to melt in order for it to detach. During this operation, the heat pump must be idle, as the evaporator is unable to function properly. The most common solution is hot gas defrosting, which is employed particularly in air-to-air heat pumps. This involves inverting the machine's cycle, whereby the evaporator is transformed into a condenser. This process is is made possible by a special valve, known as a four-way valve, which ensures the correct functioning of the compressor. However, the primary disadvantage of this method is that, during the defrosting period, the heat source became the interior ambient, meaning that the machine will effectively absorbs heat from the user. To avoid this issue, a series of evaporators can be installed in parallel, enabling the defrosting of one while the others maintain the standard operational conditions. This solution is costly and is employed exclusively in high-capacity machines.
If the selected method of defrosting is by subcooling the refrigerant, an additional heat exchanger and tank must be incorporated. The refrigerant is subcooled at the exit of the evaporator and the extracted heat increases the temperature of a specific fluid, which is then

stored in an tank. When a defrosting process is required, the evaporator is filled with the heated fluid in substitution to the refrigerant, resulting in the heat exchanger becoming heated and the ice melting. An alternative approach is to introduce superheated refrigerant from the compressor exit to the evaporator, thereby providing heat to the latter. However, these last two solutions need additional connections between the components, which in turn increases the overall complexity of the design. Furthermore, it requires the machine to be halted during the process.
The final possibility is to allow the frost to melt naturally, assuming that the external temperature is above 0°C. However, this approach is highly inefficient, as it necessitates prolonged periods of inactivity due to the ice melting from the outer layer.

1.4.2 Dependency on heat source temperature

As can be deduced from what has been said before and by analising the working principle, the operating conditions of the heat pumps are strictly bounded to the thermal levels of the heat source and heat sink. The temperature difference between these two values dictates the pressure levels that must be reached inside the system, hence the work requested by the compressor. Modifying the pressures levels, the cycle change shape and the delivered thermal power at the condenser varies. For exemple, if the pressure ratio increases, meaning as the difference in temperatures between the two ends of the system rises, the thermal capacity of the machine tend to decrease. This leads to a variation in the supplied heat caused by a variation in the working conditions of the heat pump, a characteristic that is widely considered one of the biggest drawbacks of the technology.

The relationship between thermal power and the temperature of the heat source is dependent on the design of the system in question. This is a universal phenomenon that can be observed across all heat pump types, as previously discussed. However, the relationship between thermal power and the external temperature is a more complex phenomenon that requires further investigation. As illustrated in Figure 1.10, the external temperature exerts an influence on all heat pumps to a certain extent. In the case of ground water or vertical ground coupled heat pumps, as previously indicated, the temperature of the heat source varies only slightly throughout the year. Consequently, the trend depicted in the figure demonstrates a consistent power production. Conversely, surface water or horizontal ground coupled heat pumps are more susceptible to fluctuations in air temperature. This results in a more pronounced reduction in heating capacity in colder climates. In the case of air source machines, the relationship between heat pump capacity and heat source temperature is straightforward. In this configuration, the

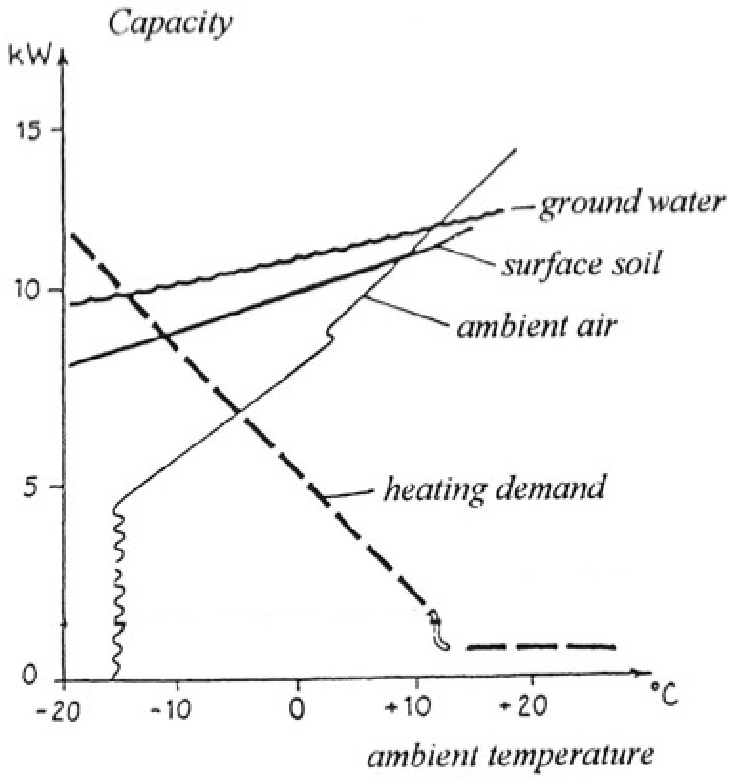


Figure 1.10: Thermal power as a function of external temperature for different heat sources. Source [37]

heat source and the ambient air are the same, so the depicted trend accurately represents the actual relationship between heat pump capacity and heat source temperature. By examining the trend for this particular machine, it becomes evident that there is a sudden decline in power output at approximately 4°C. This is attributed to the onset of frosting issues, which necessitate frequent interruptions and, consequently, a reduction in thermal capacity.

From the same figure, it can be observed that a hypothetical heating demand has been introduced. This allows for an evaluation of how the variation of thermal power affects the normal functioning of the machine. As can be observed, a reduction in temperature results in an increase in heating demand. Consequently, if the heat pump is not appropriately sized to prevent this particular issue, it will be unable to fulfil the thermal demand below a certain external temperature. In consideration of this specific case, the ground and water source heat pumps are capable of fulfilling the thermal requirements of the user unit until the temperature decline below -10°C. After that condition, the activation of a supplementary heating system is necessary. In the case of the air source machine, this limit temperature increase up to -5°C.

To avoid the excessive use of the backup heating system, it is possible to size the machines in a manner that the limit temperature at which they are unable to supply the entire load is sufficiently low to occur only a few hours per year. This ensures that thermal comfort is consistently maintained. A significant portion of the algorithm presented in this thesis is dedicated to performing this operation.

While the power varies by effect of the external temperature, the electrical energy absorbed by the compressor is modified in the opposite direction. For example, a reduction in the temperature of the heat source results in an increase in the power absorbed by the compressor. This phenomenon leads to a reduction in the COP of the machine. To better comprehend of this concept, it is helpful to present some general examples. With regard to the Italian geographical configuration, it can be observed that the climatic conditions vary considerably in accordance with latitude, thereby influencing the heat requirements of the residential sector. In the southern regions of the country, where climatic conditions permit more efficient operation of heat pumps, the demand for heating is relatively low, allowing smaller-sized machines to readily respond to heat requests. Conversely, in northern zones, the heating requirements are significantly greater, while external conditions limit the system's operational efficiency. This results in an increase in the required heat pump size, exceeding the one needed for the heating load alone. This situation leads to a lower COP and corresponds to a significant electrical demand.

Such behaviour of the COP is greatly treated in the literature, [53] have developed a linear relationship for the evaluation of the COP values in off-design conditions in water-water heat pumps, while [54] include a general estimation of the value for industrial heat pumps, including parameters regarding real variables as working fluid, compressor and heat exchanger characteristics. It is noteworthy that [55] present a number of equations for the assessment of COP values derived from real datasets. The data cover 16 European countries and a time span of ten years, from 2008 to 2018. Equations for calculating the COP for different heat sources (air, ground and groundwater) and different heat sinks types(floor heating, radiators and water heating) can be derived as a function of the temperature differential between the heat sink and heat source.
Other articles present empirical data on the impact of temperature on the COP. In [56], the performance of an air-to-air heat pump was investigated in the harsh Canadian climate for temperatures ranging from -19°C to 9°C. Additionally, [57] examined the behaviour of an air source heat pump in extremely cold climates, particularly in the coldest province of China, with temperatures ranging from -20°C to -10°C. The study identified the temperature difference between indoor and outdoor air to maintain a good COP to be approximately 40°C. In [58], the performance of an air-to-water heat pump was examined, with the objective of analysing the effects of varying the temperature of the water being sent through the system, while maintaining a constant ambient temperature. Furthermore, the analysis examines the performance of the system

under different operational modes, demonstrating that the instantaneous heating mode exhibits a COP 20% higher than the cyclic heating mode. Lastly, [59] have developed an innovative air-to-air reversible heat pump that integrates an air purification and dehumidification unit. The performance of this machine is then compared to that of a traditional air-to-air heat pump, with promising results.

1.4.3 Interaction with the electrical grid

With the electrification trend displayed by the recent decarbonization policies, an important aspect to take into consideration is that the energetic burden that previously was posed on the shoulders of the fossil fuels is now expected to fall on the electrical grid. Several studies have tried to quantify the magnitude of the additional load coming from heat pumps installation and its effects, but the modelling has revealed quite complex and most importantly strictly related to the methodology and initial assumptions[60]. For example, often in literature the electrical grid is supposed to be able to deliver the required electrical demand without any problems, as in [61], which may result in misleading conclusions. By considering additional investments act at strengthening the grid infrastructure, the expected benefits from the introductions of heat pumps decrease consistently [62]. Accordingly, also the cost of CO_2 abatement by means of this technology increase when grid reinforcements are taken into account [63].

The majority of research has been directed towards the study of load management, rather than analysing the possible distribution grid technical constrains. In particular, [64] and [65] have studied the capability of the heat pumps to variate their load in order to increase the possibility of self-consumption, if associated to photovoltaic panels, even though possible discomfort, as shown in [66], would probably prevent the direct control of the heating system.
[67] discussed the possible application of a Demand Side Management (DSM) concept at a district level, accounting for the grid current conditions. Furthermore, it proposed the institution of a platform to analyse such control strategies. The main drawback of this approach is the computational time, which impose the use of simplified models and narrows the spectrum of examples that can be investigated.
Few studies have been actually carried out on the impact of heat pumps: for example in [68] the result of installation of domestic system for the production of heat and electricity on the German grid was studied, using some simple building models and a balanced grid. [69] performed analysis on the effects of the transient voltages developed during the start up of the machines, while [70] investigated the impact on harmonic power quality. In [71] several studies on the voltages levels and profiles have been performed, varying the degree of penetration of the heat pumps. In all these studies detailed networks simulations have been employed, but variation in

the network configuration is poorly represented.

Beside scholars, also other bodies have started an analysis of the possible effects of heating electrification. The International Energy Agency (IEA) have recently published a report, called ”Electricity Grids and Secure Energy Transitions”, which investigate precisely this issue and reveals that worldwide electrical grids are not able to follow the rapid growth of green technologies. Specifically, ”Without greater policy attention and investment, shortfalls in the reach and quality of grid infrastructure could put the goal of limiting global warming to 1.5 °C out of reach and undermine energy security” [72].
The same report has already identified ”a large and growing queue” of project waiting approval for grid connection, showing that the problem is actual and concrete. The agency is paying so much attention to the issue that it developed a new scenario for the 2050 objective, called ”Grid Delay Case”. This take into consideration the possibility that the grids aren't able to keep up with the renewable technologies installations. The analysis count almost 60 billions tonnes of CO_2 more than the target, with a rise in temperature well above 1,5 degrees permitted by the Paris agreement and a 40% probability of exceeding 2 degrees.

From a technical point of view, some studies results showed that, with an higher heat pump penetration, overloading and voltage stability, problems increase.
In particular [60] used the Montecarlo method, a statistical method typical of simulation where random variables could intervene, to assess and quantify the impact of technologies, such as heat pumps and PV, on the low-voltage distribution grid as a function of building properties.
The possible vasriation of many aspects was taken into account, as resident behaviour, building characteristics, morphology of the heating system and of the grid itself. Particular attention has been paied in the modelling methodology of the buildings. Starting from the sampling of different building parameters, and following a complex procedure, 100 building cases were created.
The models of both the buildings and the neighbourhood are implemented using the Modelica IDEAS library and simulated with the Dymola software. The feeders loading and stability were, than, examined as a function of the peak demand, the beck feeding and associated total annual energy demand, while the grid stability was assesed by analysing the voltage. The results shows that, depending on the the feeder size and cable type, overloading and voltage depletion occurs at different heat pump penetration. For small feeders supplying up to 20 users, a low probability of problem has been calculated. However, increasing the number of buildings, from 30 on, crucial conditions develop from 20% to 30% Heat pump permeation in weak cables, while even the strongest cable encounters problems in 40-building feeders,

starting from 40% penetration. Moreover, especially in less interconnected and rural areas, particularly in large rural feeders, overloading can be expected from penetration percentage as low as 20% or 30%. The authors of the reported paper warn that the result could vary slightly depending on the rated carrying capacities of the cables, as reported in [73].

It is important to remember that, it the future scenarion of a diffused electrification , the heating sector is only one of the numerous fields that will be affected. Another important area of interest for the emission abatement goals is transportation, with particular attention to electric vehicles. Adding this new and considerable burden to the electrical grid could only lead to a further worsening of the aforementioned problems. For this reason, combined effect of electric vehicles and heat pumps have been studied in the literature. Some example of those studies are reported here for completeness.
The majority of the studies focus on the impact of the technologies on the distribution grids, as for example [74] that apply the Monte Carlo method to assets the effect on low voltage feeders. Similarly, [75] have assested the future impacts of electric vehicles and heat pumps on distribution networks in Great Britain. In [76] different scenario of fast and slow-charging electric vehicles, in association to electric heating, has been analysed to model future energy demands.

Several documents report a more comprehensive analysis of the issue by analysing both the presence of heat pump and electric vehicles in the demand side, and the presence of the solar panels in the supply side. This combination of technologies is the most challenging, as the grid is stressed both during the peak use by the users and during off-peak periods by the power flow inversion caused by the photovoltaic panels.
A single paper [77] analysing the above conditions is reported, considering as bottom-up approach to investigate the grid impact of those technologies. As a first step, an accurate model of the three technologies is created, as the bottom-up method request, later the distribution grid were defined and the different scenario set-up. The results indicate that the load has a seasonal trend, with winter being the most hazardous period. Three times more over-loading problems and more than twice the voltage deviation can be expected during heat pump peak use, with again rural and suburban area being the most vulnerable. Moreover, while heating seem to have, in general, a greater impact compared to electric transportation, electric vehicles cause more prolonged violations.

To cope with this recognised issue, the IEA have estimated that around 80 million kilometres of power lines should be substituted or upgraded, an amount dangerously close to the entire

existing global grid [72]. To carry on this demanding task, the annual funding on power infrastructures is estimated be doubled. The opportunity has been seen also by several Private companies that have already started to increase their investments.
The European Union is also a central player, as always in the energetic transition, and is set to invest around 580 billion euros on the matter [78]. In particular, ENTSO-E's 10-year network development plan (TYNDP) [79] state that the capacity ot thetransmission infrastructure crossing the borders of the member countries should doubled in the years prior 2030, with 23 GW incorporated by 2025 and another 64 GW by 2030. Moreover, the Commission have presented a 14-point action plan [80] to make Europe's electricity grids stronger, more interconnected, more digitalised and cyber-resilient.
In TERNA's 2023 Grid Development Plan [81] a series of more that 30 infrastructural projects have been presented to improve the situation of the Italian grid. A total of 23 billion euros are set to be invested in the next 10 years to achieve the European targets set by the "Fit-for-55" package, improving connections between the different regions of Italy, rationalising the grids in the big cities and strengthening interconnections with foreign countries.

1.5 Literature review

Given the importance of the heat pump topic in the recent scenario, both from a political and a technological point of view, a considerable number of articles have been published on the subject. A particularly thriving area of studying refers the possible modelling of the heat pumps, a fundamental step in the study of the performances of the machines. In this regards [82] states that it is possible to divide all the available models in three categories: Calculation methods, dynamic simulations and HP design models, each one with peculiar characteristics, degree of accuracy and objectives. On the other hand, [83] classify the various proposed methodologies based on their mathematical approach as: Characteristic curve, Equation-fit, Parameter estimation-based and Physical. In this section neither of the two classifications is adopted, as the aim is just to report how the model used in this document pose against ones already published.

The majority of the articles present in literature cover very detailed models of heat pumps, performed with specific software and complex dynamic equations. [84] have developed a quasi-dynamic model, by integrating dynamic equations and steady-state models, to evaluate the correct size of a residential CO_2 heat pump using Matlab. With the same tool [85] have developed an algorithm to forecast and process external inputs, such as temperature and solar radiation, in order to predict the room temperature and the thermal demand of buildings.

The study is than extended in [86] to incorporate electrical energy cost and economical considerations.
Other programs such as TRNSYS, Energy Plus, IDA ICE and PYLESA are often employed. Using the first one, in [87] a model of two houses served by a gas absorption heat pump in Canada has been developed. After a complete analysis of the models behaviour, the data have been validated by comparison with real recorded data. A similar procedure has been applied by [88],[89] for the same buildings, as they serve as testing ground for the Toronto and Region Conservation Authority (TRCA) [90]. The same software has been used by [91] in some preventive simulations regarding the peak loads of different building studied. Subsequently, a calculation method described by [92], and implemented in the EnergyPlus software, has been used to evaluate the COP of two heat pumps, one Air-Air and the other geothermal. By comparing the two models behaviour in different conditions, the author was able to analyse the COP dependency on the building insulating characteristics.
Employing the IDA-ICE simulation environment [93] defined a Water-Water heat pump model based only on performance maps, meaning data deriving directly from the manufacturer catalogues. The model has been later validated using data collected in the program "Warme Pumpe Effizient" coordinated by Fraunhofer Institute for solar energy systems [94]. The heat pump data collection in this article result quite similar to the one adopted in the project, the only difference is that the COP and thermal power values are defined as a function of both condenser and evaporator temperatures, meaning heat sink and heat source thermal levels. Given the assumption carried on in this thesis of a constant heat sink temperature, the values aforementioned have been defined as dependent only on the external temperature. Finally, in [95] the Pyton-based PyLESA tool to study, on a planning-level, the correct sizing of heat pumps and hot water tanks.
As can be seen, the context of modelling software is various, leading to different approaches and complexity. Some programs, such as TRNSYS or IDA-ICE, permit to create complete models, containing several sub-models referring to each individual component, reaching impressive realism. The main drawback is that, to achieve such complexity, a professional knowledge is needed, as well as selected technical data. This aspect conflict with the project's final objective to build a simple tool accessible to all the interested users. Another important drawback is the computational time, often extended, and power needed to perform the requested task. Given the necessity to present the algorithm as a web app available freely on the ENEA site, the reason is clear for the impossibility to use computational-heavy programs. Other tools, as EnergyPlus, are more focused on whole energy systems. The same drawbacks presented before can be applied also to this case.
Matlab and Pyton are more suitable for the needs of this projects, as their implementation

is easy and less demanding in therm of computational power. Although the presence of the PyLESA library favours the second software, the first one has been chosen due to an higher familiarity of the author.

Some studies focus only on the mathematical modellization of the machines, without the use of preexisting sub-models or ad hoc programs. Among those, the majority focus on the characterisations of the systems only by means of the calculations of the COP or the Seasonal COP (SCOP). For example [96] follows the bin-method suggested by the European standard EN 14825 [44] and the Italian UNI/TS 11300-4 [97]. These norms consent to characterise the external conditions as a distributions of bins, each one representing the number of hours the external temperature stays in a give range. To characterise the thermal behaviour of the buildings, the article use the the Building Energy Signature (BES), which can be defined as the value of thermal need corresponding to each external temperature. Concerning the heat pump, a model based on the data sheets given by the manufacturer is used. The document than continues the due calculations specified in the norms, but it is already possible to note some similarities between [96] and the methods explained in this thesis. In particular, the use of the BES, or ”firma energetica” as will be called later, is the selected method of the building modellization, as it presents the simplest implementation. A major difference lies in the implementation of the method, as the BES is constructed by tracing a straight line between the design thermal power of the building and a null request at 16 °C. In this project, real consumption data are taken into consideration for the ”firma energetica” evaluation, leading to a different trend.
The modelization of the heat pump also present some differences as, in addition to the COP, the thermal power was a needed parameter in the calculations. Moreover, a multitude of machine is taken into account, while in the article only a single heat pump was considered. This choice lead to a broader spectrum of application, but inevitably results in a lower fidelity of the outcomes. Furthermore, the external temperatures used in the article derives from the one identified by [97], thus referring to standardised values, in contrast to what is done in this document where real temperature data have been found and elaborated to construct a suitable temperature database.

Given the complexity of the developed algorithm, several models needed development. In addition to representing the behaviour of the heat pumps, it was necessary to develop a standard year for each Italian city considered. In literature, several data-set and models are presented to build a typical temperature year. Historically, the main methods, specifically designed for use in building energy simulations, were developed in the us by the National Climatic Data Center (NCDC) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers

(ASHRAE) [98]. In particular, the NCDC (now NCEI [99]) developed the Test Reference Year (TRY), considering information about dry and wet bulb temperature, dew point temperature, wind, pressure and humidity. In this preliminary model, no solar data were included. The model took an actual historic year, selected using a process of elimination of the years with progressively too high or low temperatures among the one considered. Due to its construction methodology, the TRY is known to result in particularly mild years.
To remedy this limitation of the TRY, the same institute created the Typical Meteorological Year (TMY), including total and horizontal solar radiation and composing the year of typical months rather than entire years. The single months were chosen considering the values of solar radiation, temperature and wind velocity and comparing them to the general trend of the the same values in the whole studied period, typically more than twenty years.
Simultaneously , the ASHRAE developed another model, called Weather Year for Energy Calculations (WYEC), based on the TRY format with the addition of the solar data [100].
Numerous works have been inspired by these standard methodologies, in particular by the TMY, among which [101], [102], [103], [104] and [105]. The majority of the literature articles are based on the works from [106], that apply the statistical method Filkenstein–Schafer [107] to select the most fitting months and construct the standard year. As will be explained later, also the methodology employed in this thesis, reported in [108], belong to this family.

As this analysis have demonstrated, although the methodologies illustrated in this work shares multiple similarities with works already present in the literature, they showcase some unique features. The ability of the algorithm to extrapolate the thermal needs of the building from the consumption data given by the users, the elaboration of the same data in compliance with the national regulations as well as the attention devoted to maintaining the needed inputs as simple as possible, grant this thesis the needed uniqueness. Moreover, the development of an heat pump's coefficient database, that tries to describe the entire Italian market, and the construction of a typical year for the hourly temperature value of each city in the peninsula, fills literature gaps present at the time of writing.

Chapter 2

PdC-Risc algorithm

In this chapter, the main objective of this thesis will be treated. The goal is the construction of a simple tool that allows to evaluate the possibility of substituting a traditional boiler with an air-water heat pump for the heating of residential buildings. The algorithm evaluate the proper size able to fulfill the user's requirements, while maintaining the interaction user-friendly. It means maintaining the requested information and inputs are as simple as possible and easy to find, a characteristic deemed crucial to grant large-scale use of the tool.
In light of the potential for input inaccuracies introduced by users, it is evident from the start that the precision of the results would not permit to use the tool as a actual design tool. Instead, it should be treated as a suggestion for the feasibility of the renovation of the heating system and as a guideline for its possible size. Further design steps and certifications would have to be carried out by a legally qualified expert following the current regulations.
The following sections will provide a comprehensive account of the design and creation process of the script, along with the calculations employed to achieve the desired output, the used values and the pertinent databases. The methodology employed to request user input and to upload the databases will not be addressed, as these processes do not impact the program's operational and computational mechanisms. The selection of an implementation strategy for these features was conducted by an external IT company and is therefore not pertinent to this work.

2.1 Project restrains

The project has been commissioned by the Italian public agency for technology, energy and sustainable economic development (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile - ENEA), as part of an effort to promote sustainable and renewable energy use, with particular attention to the decarbonisation of the domestic heating sector. In order to ensure that the project aligns with its intended objectives, ENEA has stipulated that

it should operate within defined boundaries:
It is a prerequisite that the heating system is autonomous for each individual treated building. The case of district heating has not been considered, while the possibility of a centralized heating system covering different apartments has been addressed with the aim of increasing the number of potential users. This specific option also permitted the assessment of energy efficiency in accordance with the regulatory requirements [109].
The heat must be supplied by a fixed-point boiler, which operates on a selected number of fuels. The case of a condensing boiler is not considered, given that its conversion into a heat pump would not result in a significant enhancement.
In this analysis, only radiators are considered as heating bodies, as they represent the most common solution in the Italian housing market. This constraint implies that only air-to-water heat pumps can be considered, as the user-side secondary fluid must be water for trivial reasons. With regard to the secondary fluid on the ambient side, a number of possibilities have been considered, including ground-to-water or water-to-water systems. However, the regulatory issues and scarcity of market solutions for these configurations were deemed to be too prohibitive. The use of radiators poses a significant challenge in relation to the temperature of water supply. In standard conditions, the fluid exiting the boiler reaches 70°C, whereas the typical maximum temperatures of commercial heat pumps are considerably lower, typically around 50°C. A reduction in the temperature of the circulating water within the radiators will inevitably result in a corresponding decline in their efficiency.
It is essential that the building in which the heat pump is to be installed has undergone restoration in recent years, with the objective of improving its energy efficiency. Such renovations may include, for example, the replacement of fixtures and windows or an improvement in the insulation of the roof or walls.
In addition, the house must have been inhabited after the said restorations for at least a year, proving that the currently installed heating system is able to respond to all the user thermal needs.
Lastly, complete and coherent data regarding the fuel consumption of the boiler in question must be available. these data should cover an adequate period of time in order to facilitate an accurate evaluation of the energy consumption in question. In the event that the aforementioned requests cannot be met by data from a single year, information from different periods may be used as an alternative.

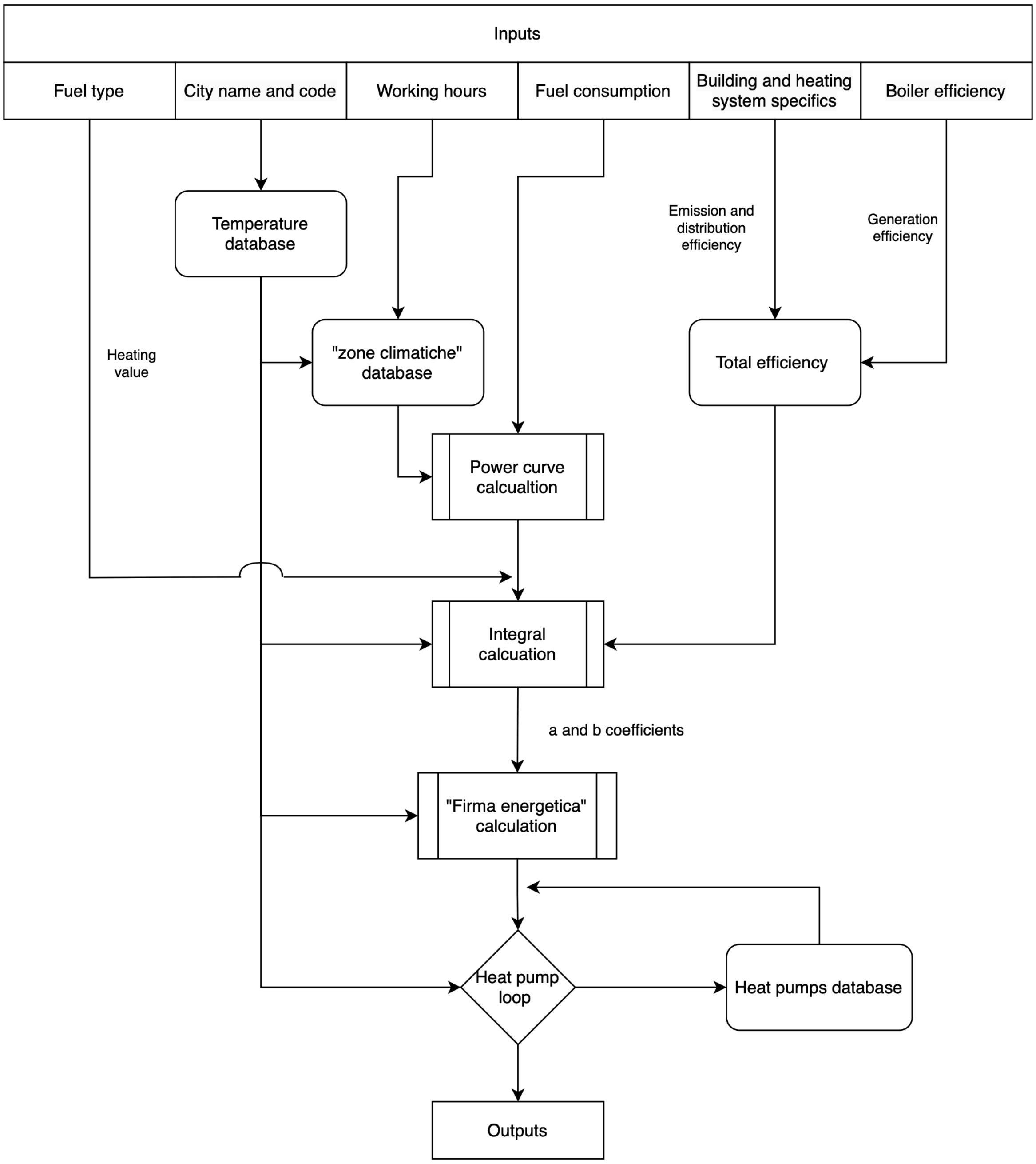


Figure 2.1: Schematic of the working principle of the PdC-Risc algorithm

2.2 Projects schematic

In accordance with the specifications provided by ENEA, a schematic of the algorithm's operational principle was devised, as illustrated in2.1. Each individual passage will be subjected to a comprehensive examination in the subsequent sections, accompanied by a detailed account of the necessary calculations. In this initial paragraph, however, a concise overview will be provided.

Upon examination of the requested input, it becomes evident that each input leads to a distinct set of calculations. The primary computational branch commences with the fuel consumption values, which are subsequently elaborated in consideration of the coefficients extrapolated from the ”Zone Climatiche” database. The database is accessed via an elaboration of the city name, code and temperatures, and is then used to evaluate the validity of the provided working hours as well as the permitted heating period.
From the fuel consumption data, the power curves are derived, which subsequently serve as the primary components in the integral calculations. To proceed with this block, a number of additional values are required, beginning with the total energy efficiency of the building in question. The emission, distribution and generation efficiencies are evaluated as products of the aforementioned values, which are retrieved from various building information sources. The remaining requisite for the integral calculations is the hourly values of the external temperature, which are retrieved from the pertinent database.
The subsequent phase of the algorithm is the evaluation of the building's ”Firma Energetica”, a process made possible by the coefficients a and b derived from the preceding step and once more by the knowledge of the external temperature.
Once the thermal behaviour of the building has been described, it is possible to proceed with the selection of the appropriate heat pump size. This process, known as the heat pump loop, is an iterative process that takes as initial information the machine parameters, the building's thermal signature, and the external air temperature. The initial values are extracted from a specific database, which is the result of an in-depth analysis of the Italian air-to-water heat pump market. The remaining values were already contained within the aforementioned calculations.
Upon completion of this final step, a hypothesis regarding the optimal size of the heat pump is formulated, and the results are then subjected to further analysis. The user is presented with a series of elaborations of the resulting data from the algorithm, to provide a comprehensive understanding of the advantages and disadvantages of heat pump substitution.

2.3 Database

One of the fondamental step in constructing the project was to build a number of databases that were necessary for the proper functioning of the algorithm. The databases allowed to store an high amount of data, referring to single italian cities or to particular working condition of the system, and retrieve them easily when needed for the code elaboration.

The initial database delineates the so-called ”Zone Climatiche.” These zones represent a method of subdividing Italian municipalities based on their annual external temperature, thereby enabling the implementation of differentiated regulations depending on the climatic conditions. The discrepancies between the ”Zone Climatiche” pertain to the initial and final dates of the permitted heating period, which encompasses the interval during which the heating system may be activated, as well as the number of daily maximum operating hours. The value used to define the town climate is termed ”Gradi Giorno,” which is equivalent to ”heating degree days.” This value is calculated as the annual sum of all positive differences between the room temperature, which is legally defined as 20 degrees Celsius, and the hourly external temperatures, as illustrated in Equation 2.1.

$$GG = \sum (20 - T_{ext})^{+} \tag{2.1}$$

In accordance with the stipulations set forth in [110], art. 2, the boundary values of degree days for each climatic zone could be defined. Furthermore, from [110] art.9, it was possible to extrapolate the maximum number of hours per day that the heating system is allowed to operate, as well as the dates on which the heating period is to commence and conclude. The aforementioned information was used to populate the database, as illustrated in Table 2.1. In particular, columns 5 and 7, labelled ’Eco start’ and ’Eco end’, represent the dates as varied in [111]. The amendment was implemented in the wake of the 2022 energy crisis, with the objective of reducing the permitted heating period and, consequently, fuel consumption.

ZC	Min DD	Max DD	Start	Eco start	End	Eco end	Duration	Hours
A	0	600	01-12	09-12	15-03	08-03	104	6
B	601	900	01-12	09-12	31-03	24-03	120	8
C	901	1400	15-11	23-11	31-03	24-03	136	10
D	1401	2100	01-11	09-11	15-03	08-23	165	12
E	2101	3000	15-10	23-10	15-03	08-23	182	14
F	3001	∞	01-01	01-01	31-12	31-12	365	24

ZC:”Zona Climatica”, DD: Degree Day

Table 2.1: Values of different parameters specific of each ”Zona Climatica”

Another database was necessary to describe the behaviour of the heat pumps corresponding to each variation of the external ambient temperature.
To realize this database, the first step was to evaluate which type of information were openly available from the technical sheets of the producers. Searching the normative landscape, it was possible to identify the two main norms: [112] and [44]. Those documents define a standard methodology to express the working point of each machine, calculated at common external temperature points and fixed conditions. In particular, in each technical sheet, the working condition of the heat pump must be tested at -7° C, 2° C, 7° C and 12 ° C, with evaluation of both the thermal power and the performance coefficient. Exploiting this homogeneity in the available data, it was possible to gather information of several different models of heat pumps, from different producer, and to compose the wanted database. Since the program has been built to be operated in the Italian market, the heat pump database had to respect this direction. For this reason, the models and producers taken into account were chosen from a document [113] published by the public company "Gestore Servizi Energetici" (GSE), summarising all the machines commercially available in the country.
Once all the raw data were acquired, it was necessary to divide them by rated thermal power. By performing this process several data-set were created, one for each nominal power present in the Italian market. In order to collapse the data into the behaviour of a single fictitious machine, a variety of statistical methods were subjected to analysis. A review of the literature, in particular [37], indicated that the variation in power could be assumed to follow a linear relationship with the temperature of the heat source. Given this information, it was then possible to select a suitable methodology for the subsequent data analysis. This involved the application of a polynomial interpolation, analysing the thermal power in relation to the external temperature. In particular, a first-degree polynomial interpolation was selected, thereby enabling each curve to be defined by two coefficients. The application of this modelling method to each data set enabled the representation of the complete market possibilities.
During the data collection process, it was observed that the producers reported the working points for different delivery water temperatures, which had a significant impact on the machine performance. In particular, it was observed that as the temperature difference between the forward water and the external environment increased, there was a corresponding decrease in efficiency. As the heating bodies under consideration in this study are radiators, which require a high temperature to operate effectively, and in order to size the heat pump in the most unfavourable scenario, the data employed were limited to those pertaining to the maximum temperature.

$$K = x * \cdot T_{external} + y \tag{2.2}$$

The database is obtained in tabular form, as reported in Table 2.2, where the value of *a* and *b*

Size	P_{th}		COP	
	x	y	x	y
4	0,0782	4,1437	0,0781	2,4613
6	0,0926	5,3828	0,0669	2,2914
8	0,1266	6,7554	0,0640	2,3541
10	0,1643	8,4944	0,0745	2,4335
12	0,1447	10,5197	0,0657	2,3924
14	0,1614	11,1506	0,0697	2,3112
16	0,2139	12,8920	0,0733	2,4305
18	0,2655	14,5109	0,0789	2,1712
22	0,2951	19,9514	0,0806	2,3933
26	0,3127	23,3884	0,0839	2,3726
30	0,4237	26,5045	0,0936	2,3006

Values obtained with forward temperature of 55°C

Table 2.2: *a* and *b* coefficients for the construction of power and COP curves for different heat pump sizes.

are the two coefficient of the linear interpolation described in Equation 2.2.

In Figure 2.2 it is possible to note that all the sizes considered for the heat pump present the same general behaviour, with thermal power production that increases linearly with increasing external temperature. It is also possible to see that the higher sizes present a slight variation in the slope towards higher values. This characteristic denotes a decrease in the flexibility of the machines, which means that larger heat pumps will work less effectively in the colder regions. In fact, the steeper the curve the higher the variation of thermal power resulting from a variation of external temperature. The rage of external temperatures considered in figure has been chosen to give an immediate idea of the magnitude of the power variation, it doesn't take into account the limits of the working conditions of the machines.

One of the input information the user must supply are the identifying information of the town in which the building is located: those information allows the program to evaluate the hourly external temperature to which the building is exposed and must respond in term of delivered thermal power. The process can take place thanks to a specifically designed database containing a temperature vector for each Italian municipality.
The construction of this database involved a complex automated procedure, based on reference articles. The first step was the acquisition of a considerable amount of meteorological data for the selected location. This process was automatized through a dedicated Matlab script that performed an API (Application Programming Interface) call for each town, requesting the me-

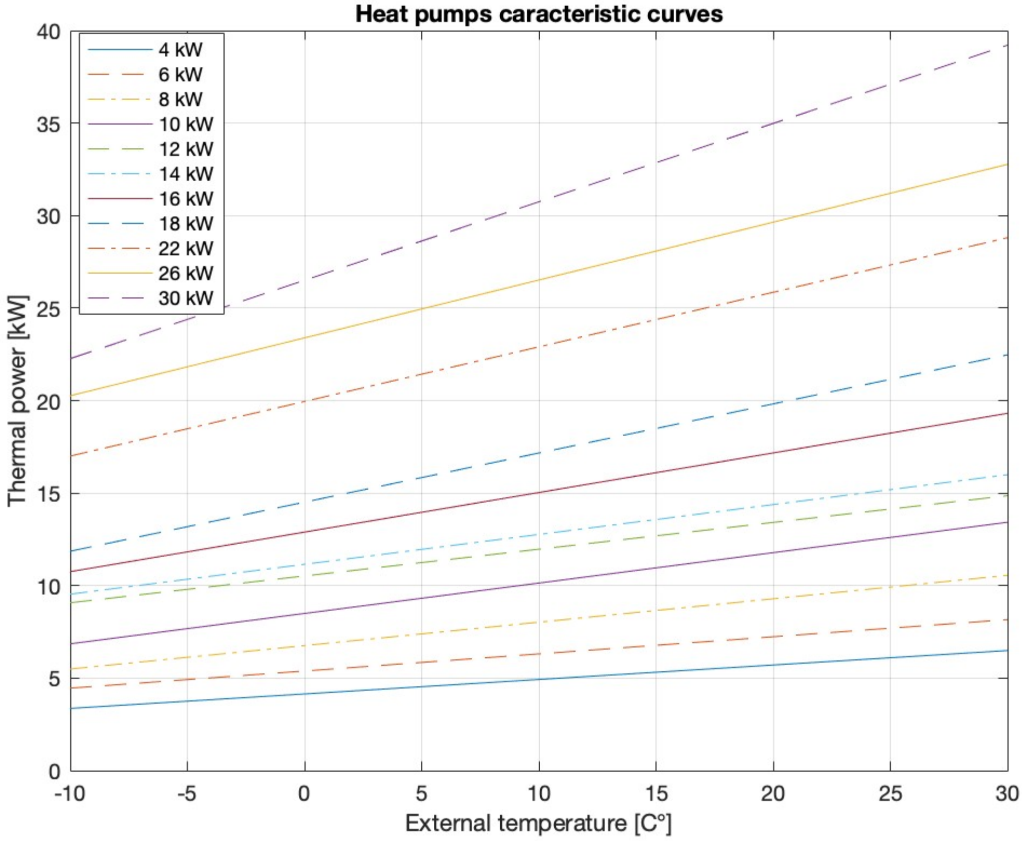


Figure 2.2: Characteristic curves of different sizes of heat pumps at a sending temperature of 55 °C.

teorological data of the last 10 years, from January 2010 to December 2019, from a open-source weather database [114]. In order to correctly submit the request, it was necessary to know the latitude and longitude of the selected location. For those information, a direct elaboration [115] of the official Italian data was taken into account. It contained the geographical location of all the towns halls, as well as the official name and town code of the municipality. With these information the API call could be submitted, returning not only the external temperature, but also the apparent one, the relative humidity, the precipitation values (comprised of both rain and snow) and the velocity of the wind calculated at ten meters of height. The whole data set for each locations was saved into a single file named $CityName - CityCode$ to be automatically retrieved afterwards.

The discrepancy between the actual number of towns in Italy and the number of files generated (7896 versus 8454) is to be attributed to two factors. Some smaller cities share the same city code, while larger ones have different codes for different districts. This discrepancy did not result in any significant issues, as the user inputs are subject to the same process, leading only

to a higher degree of geographical precision in areas with a greater number of city codes.
Once all the data from the various years had been collected and organised, it was necessary to elaborate them in order to create a single fictitious year that would represent the statistical behaviour of the gathered values. In order to do so, it was adopted the method described in [108] that will be briefly presented here for the sake of completeness. The method can be divided in two main parts. The first one focused on the selection of the twelve best months to compose the typical year, based on some specific statistical tools, while the latter corrects and adapts the hourly values in the transaction zone to achieve a smooth progression of the temperatures. This passage was aimed at avoiding step and uneven variation in the common case the chosen months belong to different years. The method uses a main parameter P to perform the primary calculations and a secondary parameter S for further choices. In the case in analysis, the principal variable is the external temperature while the secondary is the wind speed.

The first step is to calculate the first empirical cumulative curve of the daily temperature means for each month, taking into account every year. The procedure can be summarized as:

1. Sort all the values of each month of each year,
2. Evaluate the daily mean of each day i of the selected month for all the available years,
3. Arrange all the values in a crescent order,
4. Assign to each value a rank $K(i)$, equal to the position in the ordered list,
5. Evaluate the $\Phi(P, m, i)$ as in Equation 2.3, where P is the main parameter, m is the month of the year, i is the selected day of the month that varies from 1 to n and N is the total number of daily mean values calculated.

$$\Phi(P, m, i) = \frac{K(i)}{N+1} \tag{2.3}$$

This cumulative curve represents the trend of the temperature of the specific month selected throughout all the analysed years and will be used as reference. An example of the final result can be seen in Figure 2.3 for the month of January, using the data for the city of Padova.

The second empirical cumulative curve follows the same concept, but it considers only the selected month of a single year. The procedure is:

1. Divide all the values of each month of each year
2. Evaluate the daily mean of each day i of the selected month for the chosen year
3. Arrange all the values in a crescent order

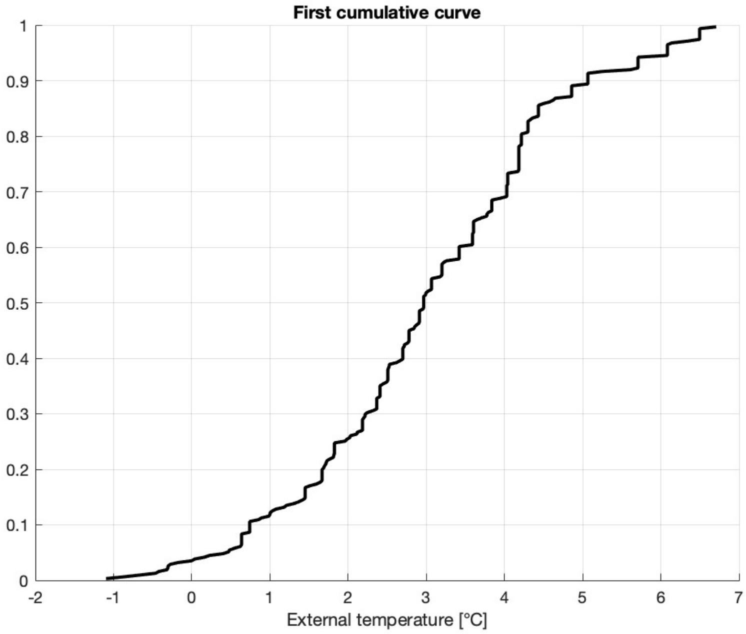


Figure 2.3: First cumulative curve calculated for the month of January in Padova.

4. Assign to each value a rank $J(i)$ equal to the position in the ordered list
5. Evaluate the equation $F(P, y, m, i)$ as in Equation 2.4, where P is the main parameter,y is the selected year, m is the month of the year, i is the selected day of the month that varies from 1 to n.

$$F(P, y, m, i) = \frac{J(i)}{n+1} \tag{2.4}$$

This second curve depicts the behaviour of only a single month and, analised in contrast to the first one, can be used to determine how close the period selected is from the statistical mean. As can be seen in Figure 2.4 different months have trends more or less similar to the first cumulative curve.

This faithfulness can be mathematically identified by means of the Finkelstein-Schafer [107] statistical method $FS(p, y, m)$ for the comparison of the cumulative curves. This procedure is based on the calculation of the daily difference between the two curves as in Equation 2.5.

$$FS(p, y, m) = \sum_{i=1}^{n} |\Phi(P, m, i) - F(P, y, m, i)| \tag{2.5}$$

For each month, the computation is carried out and the value of the respective $FS(p, y, m)$ is saved and organized. To a lower value of the parameter is associated an higher truthfulness of the temperatures to the mean. Once the three month with the lower $FS(p, y, m)$ have been selected, it is necessary to use the secondary parameter to choose the more fitting one. In order

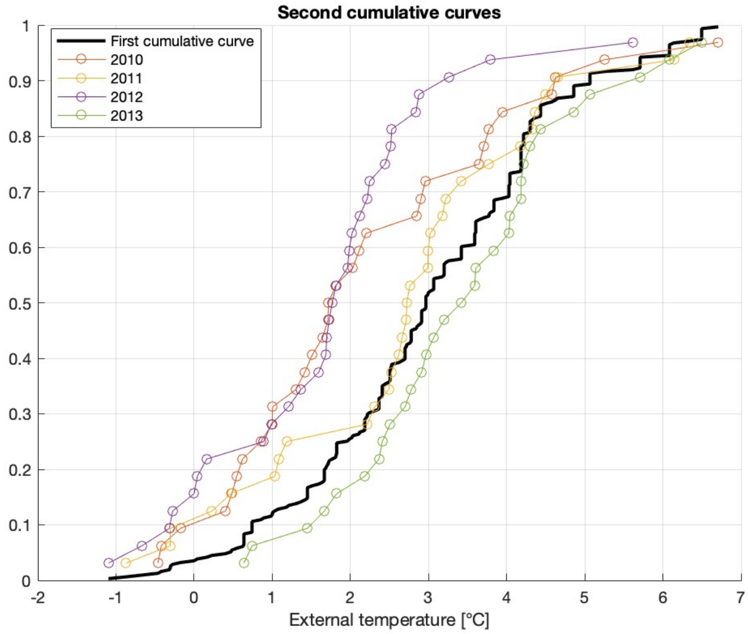


Figure 2.4: First cumulative curve of January and different curves for the years 2010, 2011, 2012 and 2013.

to achieve this, it is necessary to evaluate the mean wind velocity for each month over the entire period of observation. The standard deviation between each monthly mean and the calcuated value is, then, evaluated. The month with the lowest value is selected to represent a typical year. It is highly probable that the selected months belongs to different years, leading to a lack of continuity in the temperature trend between the end and the beginning of two adjacent months. The normal temperature difference in the month changeover, on an hourly scale, is around 1 or 2°C, while using the presented method can be as high as 5 or 6°C [108]. Smoothing the transition sector is, therefore, necessary. To do so, it is necessary to delete the first and last eight values of the two neighbouring periods and substitute the sixteen temperatures with the ones evaluated through an interpolation process.
After the elaboration each typical year is saved in a vector, named using the just mentioned rule, and stored in the database.

2.4 Inputs and known data

As already stated, the input requested from the users should be as simple as possible, assuming that they do not have, nor are able to obtain, any technical information. For this reason, all the requested data should be retrivable through simple actions or by a quick inspection of technical manuals.

The first request of the algorithm is the identification of the city in which the building is located through the name and city code. Based on this information it is possible to enter the ”temperature database” created for the program, as previously explained. It contains the hourly value of external temperature for each city of a ”typical” year. This value will later be used to analyse the building and heat pump behaviour.
The second input regards the buildings specifications, such as the construction year, it’s type (i. g. single home or apartment) and other information that allow an estimation of the building thermal behaviour. Such informations link the actual energy demand of the building and the amount of energy that must be supplied in the boiler. This process is done through the value of the building energy efficiency, evaluated as the product of three different efficiencies, as can be seen in Equation 2.6.

$$\eta_{tot} = \eta_{emision} \cdot \eta_{distribution} \cdot \eta_{generation} \tag{2.6}$$

In particular, the emission losses include stratification losses, due to a non-uniform temperature in the rooms, embedded losses, related to thermal exchange between rooms and with the external environment, and finally control losses, associated with the installed control method. The values associated to each possible input are collected in the following tables (Tab. 2.3, Tab. 2.4, Tab. 2.5), as reported in [109]:
The total emission efficiency can be evaluated, as in Equation 2.7.

$$\eta_{emision} = \eta_{str,1} \cdot \eta_{str,2} \cdot \eta_{emb} \cdot \eta_{ctr} \tag{2.7}$$

Since, as previously stated, for safety reasons all the project calculations suppose to work under the less favourable conditions. The values of $\eta_{str,1}$ and $\eta_{str,2}$ are taken as the lower between the possible ones.

For the evaluation of the distribution losses, it is important to consider the construction year of

Temperature in the radiators	$\eta_{str,1}$
90/70	0.88
70/55	0.93
55/45	0.95

Table 2.3: Values of the stratification efficiency component based on the working temperatures of the radiators

the building. The following Table 2.6 reports the values considered. In the case of the generation losses, the regulation provide a table containing a numerical values corresponding to a certain number of stars, as in 2.7. This value can easily be individuated in the technical documents of the boiler. The number of stars, from one to four, represent an easy method to display the

Radiator Position	$\eta_{str,2}$	η_{emb}
Internal wall	0.87	1
Normal external wall	0.83	1
Glass external wall w/out insulation	0.88	1
Glass external wall w insulation	0.95	1

Table 2.4: Values of the stratification efficiency component based on the installation position of the radiators.

Type of temperature control	η_{ctr}
Thermovalves	0.80
Single thermostat	0.88
A thermostat per room	0.93

Table 2.5: Values of the control efficiency based on the temperature control technology installed

Year	$\eta_{distributed}$				
	Single house	1*	2*	3*	4* or more
Earlier than 200	0.99	0.97	0.96	0.95	0.94
between 1990 and 2000	0.97	0.94	0.93	0.92	0.91
later than 1990	0.95	0.91	0.90	0.89	0.88

** number of floors covered by the centralized system*

Table 2.6: Values of the distribution efficiency based on the type and construction year of the building, as well as the number of floors.

performance of the boilers in a user-friendly way. Due to the limited options, this value can not be particularly precise. Yet for the purposes of this work its accuracy is sufficient, moreover it can be easily individuated by the users that want to operate the program.

N. of stars	$\eta_{generation}$
1	0.76
2	0.81
3	0.89
4	1

Table 2.7: Values of the generation efficiency based on the stars value of the boiler.

To describe the efficiency of the boiler, a calculation method inspired by the Italian laws [116] was also considered for the implementation. This methodology followed the general Equation 2.8 where P_n is the rated thermal power of the installed boiler, and η_0 a base efficiency. The Italian law varies the η_0 value by reason of the construction year of the boiler. This information is harder to obtain than the number of stars of the boiler. Moreover, a choice was made to maintain an homogeneous methodology for all the efficiencies. This calculation method was discarded for these reasons.

$$\eta = \eta_0 \cdot 2\log(P_n) \tag{2.8}$$

The following request takes into account the daily amount of hours the system is used: It is important to evaluate this value, as it will later be used to evaluate the instantaneous power supplied by the boiler. In case the user is not able to provide the data, a full 24 hours working period is taken into account. Although this second option could seem a strong hypothesis, the input will later be elaborated following some standards, decreasing the supposed daily number of working hours to a lower value.

The last needed information regards the fuel type and its consumption details. Due to the physical and supply differences of the energy sources accepted by the algorithm, it became necessary to implement a consumption request for each typology. As a general classification, it is possible to define two different possibilities:

The first and more simple one refers to the situations in which the consumption is regularly evaluated by the supplier, in the case of grid connection, or by the user. For this specific case it is possible to construct a year-round consumption behaviour, by either monthly or bimonthly datasets, that will later be adequately analysed. In this first methodology the time span of each period is fixed, thus the only value that must be requested and stored is the fuel consumption.

The latter case concerns the fuels that are supplied in a batch-like behaviour, meaning that the fuel needed for a extended period of time is provided in a single load and stored for later use. The creation of a full year description in this case is more complex due to the discontinuity

of the data; therefore, for the input request, the algorithm settles for a limited number of said periods and analyses them in a peculiar way. Given the unpredictable duration of the considered interval, it is necessary to acquire more information. In particular, besides the mere consumption value, the precise date of the load and the presumed date in which the stock was exhausted are requested.
It is important to remember that the sourcing of the data from the same year, although preferable, is not a necessary condition as long as the time periods from different years fit adequately with each other.
For each fuel category, a different methodology is needed also for the data rielaboration, as the difference in the periods length impose different calculations and should properly be taken into account.

The first considered fuel is methane, which is the most common and easily handled fuel for residential heating. In the vast majority of cases, the buildings are connected to the methane grid, and the fuel supply arrives directly at the user without it's manual intervention. For those cases, the methane consumption can easily be deducted from the billing documents. In Italy, there are three main types of gas supply bill: monthly, bimonthly, or by self-reading.
The cases of Monthly and Bimonthly billing are more common, and their operation is trivial, but in recent year more and more costumers have adopted the Self-reading methodology. It allows to communicate the precise values of consumption to the gas provider, avoiding over or under billing that must be balanced at a later time. Self-readings can be communicated by the user at any given moment, leading to a variable length of the time periods associated to each consumption data.
The case of methane is the only one between the fuels that, due to the different possibilities in billing, require the use of both methodologies previously cited. In particular the first one is adopted for the monthly and bimonthly billing, while the latter for the self-reading case. For this last possibility, in order to have a substantial amount of data, three winter and three summer time-period are requested, each with its associated consumption value. It is important to note that all requested consumption values must be provided in standard cubic meters, as that is the *IS* unit of measurement and it is also the one compulsorily reported in the billing documents.

Other types of fuels are taken into account to cover the most used alternatives in Italy, such as dried wood, pellet or general biomass. Although finding complete heating systems exploiting this kind of source is not so common, few examples are present in the market that are capable of providing hot water both for sanitary purposes and for supplying radiators. In the case in which those fuels are in use, it is possible to treat the consumption as a monthly bill by asking the user to provide an estimation of the period's fuel use. This method can be easily implemented and covers all the possible methods of resupply that a private consumer can have; being, for example, buying all the stock at the start of the winter or supplying each time the stockpile decreases. In these cases, the inputs are requested in kilograms, as it is normally the unit of measurement on which the bill is calculated, and permits the inputs to be uniform for pellets, usually sold in twenty-five-kilos bags, and the other fuels sold at quintal.

The last types of fuels implemented in the calculations are LPG (Liquefied Petroleum Gas) and Diesel. Less spread for residential heat production than methane,they posses a major quality that still allows their presence in certain market conditions: their high energy density. It allows the user to stock an amount of fuel high enough to supply the household for a remarkable period of time. In fact, in areas not attached to the main gas grid, the presence of these fuels is concentrated as they are one of the only viable solutions. Since the supply method of these fuels varies from pressurized tanks that can be transported by hand to buried vessels that hold up to thousands of litres, the method used to track consumption is equal to the one implemented for self-reading. The only difference lies in the fact that the number of data sets to be inserted is not fixed, as it depends on the user organization of supply.

To each of the considered fuels, an extremely important characteristic must be identified: the calorific value. This fuel propriety is mandatory for the calculations, linking the physical amount of fuel burned and the quantity of energy supplied by the same amount.
For hydrocarbons the access to these information is not too complex, as extensive literature data exists on the argument, while for less common spread fuels the selection of the right value is more complex. The composition of marketable natural gas, LPG and diesel fuel used in household heating is strictly regulated, thus unambiguously leading to a single value of the heating value. On the other hand, natural resources present a highly variable nature resulting from species, moisture content or processing differences. In particular, for the selection of the values of wood and biomass, a mean between the types most used has been performed, leading to the reported values of Table 2.8.

Another important information that must be supplied by the user to guarantee a correct elaboration of the data is if the heating system considered for the switch is regularly used also in summertime. The information, supposing the user strictly follows the law-imposed start and end date for the allowed heating period, enable to understand if the fuel consumption is also associated to an application different from heating. The most probable example is the production of sanitary hot water that, if performed by the boiler, will require the heating system to work also

Fuels	LHV				
	[Mj/kg]	[kWh/kg]	[Mj/l]	[kWh/l]	[kWh/m^3]
Methane	-	-	-	-	10.94
LPG	46.10 [a]	12.80	23.63 [a]	6.56	-
Diesel	43.25 [a]	12.01	35.9 [a]	9.97	-
Wood	15 [b]	4.16	-	-	-
Pellet	17 [b]	4.72	-	-	-
Biomass	14.4 [b]	4	-	-	-

a: Ramadhas, A.S. (Ed.). (2011). Alternative Fuels for Transportation (1st ed.). CRC Press.https://doi.org/10.1201/b16260

b: Del Col, D. 2022. Energy from biomass [Lecture presentation]. University of Padova.

Table 2.8: Heating values of the fuels considered in the algorithm.

in summer. Assuming that the secondary use of the system is associated with an year-long demand, as happens for hot water, it became necessary to obtain this consumption and extrapolate it from the winter-time data gathered previously. If this process is not correctly implemented, an overestimation of the needed thermal power is probable.

Moreover, it is necessary to determine if the same fuel used by the boiler is employed in applications different from heating: this is the frequent case of methane, that is normally used also for cooking. Since the user has only a single bill in which the whole amount of fuel used in the house is reported, the possibility of having information about the consumption during the summer can help determining the average amount of fuel that is used for those purposes. For example, we can consider again methane, used for cooking and heating, while we suppose that the hot water is supplied by an electric heater. During summer, the fuel should be used just for cooking purposes, since the heating system does not work. By recovering the data for all the periods of the year is possible to understand which is, approximately, the amount of fuel consumed for cooking. This amount will later be deducted from the consumption of the heating system in order to avoid over-sizing the energy need of the building studied. For other fuels, different from methane, the use in summer is less common. To comply with needs different from heating, usually less energy intensive, electrical solution are commonly installed.

2.5 Algorithm

The following section explains in detail each step performed by the algorithm to achieve the wanted output.

The first stage is the extraction of the information regarding the climatic zone from the dedicated database. Once the user has entered the location of the building, the system is able to

automatically retrieve the temperature information from the Temperature database. Following the calculations expressed in Equation 2.1, and using the limits expressed in Table 2.1, is possible to identify in which climatic zone the building is located. With this information, from the same table, it is possible to retrieve the law-imposed values of the starting and ending date of the heating session and the maximum allowed daily working hours, parameters that will be used in following passages.
In the case in which the building result in the F zone, the coldest one, the system switch automatically the zone E. This action is due to the fact that the zone F does not have limits in the use of the heating system, as it was thought to be applied in alpine and extremely cold regions. This particular characteristic would have prevented the correct applications of some of the following equations, thus the problem has been avoided as explained.

It is, than, necessary to check if the working hours stated by the user in the input section are consistent with the values of [110]. In the event that the stated value is higher than the maximum legal one presented in Table 2.1, it can not be taken into consideration. In this case the inputs are overwritten by the maximum values expressed by the law.

Now the bills value received in input must be elaborated, to compute the daily fuel consumption of the system. The treatment of the data in this section varies depending on the fuel selected, following the same subdivision applied before.
In case of regular consumption, the starting and ending date of the months are fixed, thus the duration of the month. Starting from the period's consumption, it is possible to evaluate the daily value by means of a simple ratio. Using the daily values of the summer months, meaning May, June, July, August and September, it is also possible to calculate the average consumption disjointed to the heating process. By evaluating the difference of the two results, the actual heating consumption is extracted.
In the case of methane it is supposed that there is always a summer use, due to the production of sanitary hot water and the needs for cooking, while for others fuels this information is specifically asked to the user.
Taking into account the winter months, a further elaboration of the data is performed, in case the studied period falls outside the heating time-span. In this case all the consumption are set equal to zero, as it can not derive from the boiler heating process. On the other end, if the start or end date falls in-between the studied period, consumption needs to be scaled, as in the days before the start of the heating season the system should not have worked, and a mere ratio would lead to wrong conclusions. If this possibility occurs it is necessary to evaluate the difference between the heating period boundaries and the actual start of the consumption

period. The total fuel use value must be decreased accordingly. Once the overall consumption is scaled, by supposing a non-heating daily use constant and equal to the summer mean, the calculations continue unaffected.
On the case the fuel is handled in a batch supply methodology, the concept of the calculations remain the same, but there are different precaution to be taken. In fact, the user could insert any winter or summer bill without needing to specify which month it covers, leading to the necessity of study the period boundaries to better understand how to manipulate the consumption value. In case of summer bills, the procedure is much easier, as it is only necessary to evaluate the length of the period each bill covers to calculate their daily consumption values and total mean. For the winter bills, instead, each set of values must be treated differently. The control of the starting and ending date of the heating period is performed, following the method already explained, respectively in the first and last bill. For the remaining ones, as well as in the case in which there is only one data set, both the procedures must be put in place to assure that every possibility is explored.

Once the elaboration of the input data is completed and the daily consumption have been extracted, it is necessary to proceed in the creation of the so-called power curves. The power curves are vectors containing all the hourly values of the instantaneous power needed by the building in the selected period of time. This construction process is comprised of two main stages: the creation of the vectors containing all the daily fuel consumption and the conversion of those values of consumption into power values.
In case of constant monthly or bimonthly billing, the initial vectors are simply composed by the values of the daily consumption, net of the summer mean value, divided by twenty-four hours to get the hourly data. This hourly consumption data, when positive, is considered constant for the whole period taken into account. Using the period's duration multiplied by the hours in a day, the right amount of vector's slots will be filled. In case the net value between the daily consumption and the summer mean is negative, a null value is set. The process is repeated for the time period covering up to the end of the year for the data inserted into the first vector, and the one from January to April filling up the second vector.
All the Winter months are taken into account independently of the climatic zone of the building. This simplification is made possible by all the previous steps in the data elaboration. In fact, the considered duration of each billed period has already been modified accordingly to the heating season boundaries. In the case in which it is completely outside the boundaries, its consumption value has already been set to zero, thus it will not intervene in the subsequent calculations. The same concept applies if the consumption is so low that its net value with the summer mean result negative.

Moving to non-continuous fuel resupply, the case is more complex than the previous one, as the two vector content varies depending on the period covered by the different dataset. The first step of this procedure is to check the actual order of the dates inserted by the user. Even though there is an explicit request in the Input section to insert the values in precise time order, the consequences of not following that specification are so important on the final result that the expanse of computational time to perform a further check is justifiable. For each subsequent bills a comparison between the initial and final dates is done and, in case it results that the time order is not respected, their position is switched. After this important step, the creation of the actual vectors can start. As a general rule, the first consumption data always belongs to the first vector, as the last to the second one, while the remaining value position depends on it's covered period. Consistently to what has been done in the previous methodology, the separation between first and second vector take place at the new year date. It means that, if the analysed time span falls before the end of the year, it belongs to the first vector, otherwise to the second.
If there is only one fuel filling in the entire heating season, it is necessary to split the consumption evenly between the two vectors, each containing a number of values equal to half the bill duration multiplied by twenty-four. In this way, the creation of both power vectors is assured, a necessarily condition for the further develop of the calculation.
Once the two vectors are created, independently from the method used, each of the contained values is multiplied for the respective fuel's heating value and the energy efficiency evaluated starting from the user's input. In this way the consumption values are translated into the instantaneous power needed by the system.
Although the result of this analysis is somewhat approximate and the hypothesis of considering the thermal power needed by the building as constant for entire months may appear somewhat simplistic, given the data that was possible to collect from the users and taking into consideration what was explained in the preliminary section of this chapter, the developed method was deemed to be the more appropriate and suitable approach. Furthermore, as will be discussed subsequently, the data present in the power curves will not be employed as the building's requirements directly, but rather subjected to further processing to develop a mathematical model reflecting the heating system's behaviour, thereby compensating for the lack of precision.

The next calculations are those that allow to fully understand the thermal power needs of the buildings and how they vary depending on the external temperature. To do so, it is first necessary to resolve the system of equations 2.12, so that the two coefficients a and b can be evaluated. The theoretical explanation of the creation of such system of equation can be found starting from the basic definition of energy as the temporal integral of the power, in this case thermal. So the total thermal energy requested by the building can be given as Equation 2.9.

$$En_{th,tot} = \int_{period} P_{th} dh \tag{2.9}$$

The two values *a* and *b* are the coefficients of a polynomial curve, created as Equation 2.10, and called *Firma Energetica*. This curve is able to relate the thermal power needs of the building under study for each external temperature. This information, in association with the knowledge about the external temperature derived from the interrogation of the dedicated database, leads to a complete characterization of the annual requirements of the system, as can be seen in Figure 2.5.

$$P_{thermal} = -a \cdot T_{external} + b \tag{2.10}$$

By means of simple mathematical passages, reported in Equation 2.11 , it is possible to

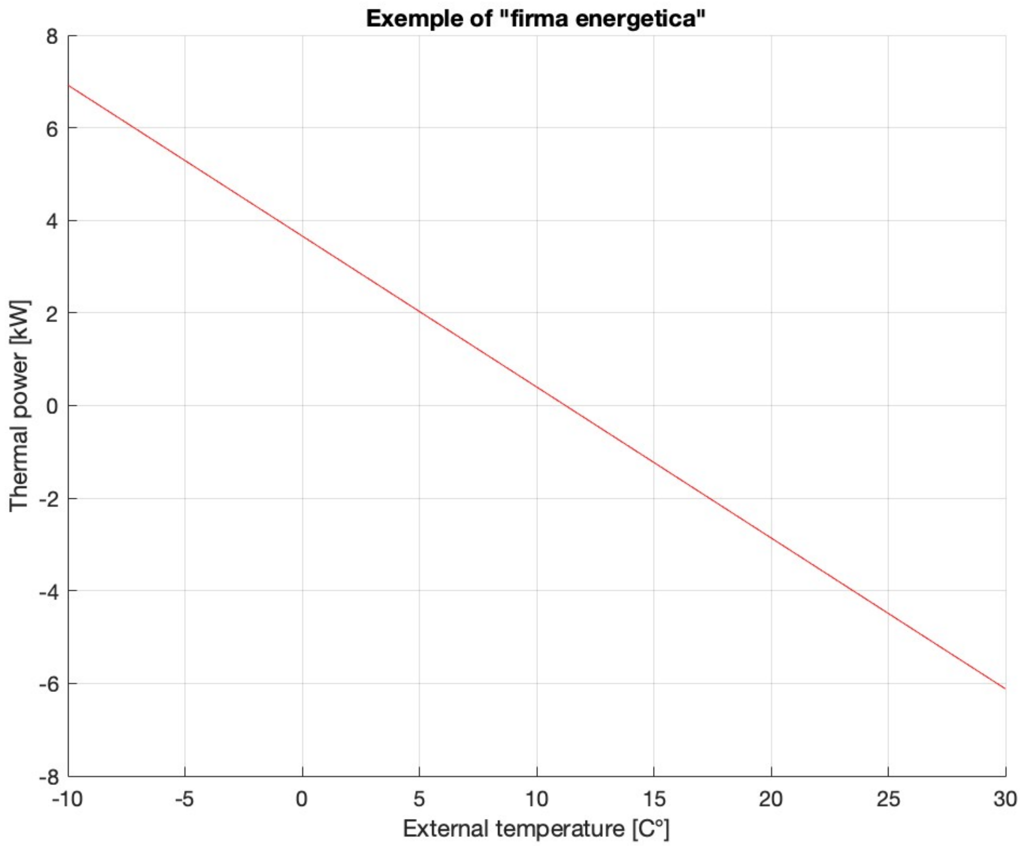


Figure 2.5: Example of a ”firma energetica” calculated following the explained procedure for the city of Padova, starting from methane consumption elaborated as in Section 3.

comprehend the final writing of the formulas composing the system. Since the variables are two, the same number of periods must be studied.

$$
\begin{aligned}
En_{th,tot} = \int_{period} P_{th} dh = \int_{period} (-a \cdot T_{external} + b) dh = \\
= \int_{period} a \cdot T_{external} dh + \int_{period} b dh = -a \int_{period} T_{ext} dh + b \cdot Duration
\end{aligned}
\tag{2.11}
$$

As can be seen in Equation 2.12, before having the possibility to resolve the system, it is necessary to compute the values of all integrals.
The integrating intervals of these calculations must be correctly evaluated, as its variation heavily impacts the final result. In this regard, the whole Chapter 3 has been dedicated, while on the current one the intervals chosen after the appropriate analysis have already been applied. To perform the integral calculations the trapezoid method has been used for its simplicity in the script implementation.

$$
\begin{cases}
-a \int_{firstperiod} T_{ext} dh + b \cdot Duration - \int_{firstperiod} P_{th} dh = 0 \\
-a \int_{secondperiod} T_{ext} dh + b \cdot Duration - \int_{secondperiod} P_{th} dh = 0
\end{cases}
\tag{2.12}
$$

For the case of fixed duration periods, the procedure of integration is quite simple because of the starting and ending date of all the bills. The value of the total thermal energy consumed by the system is calculated by the integral calculation of the power curve on the considered interval, in this case December for the first period and January for the second. The same process is applied to the vector of the external temperature to calculate the relative integrals. The last values needed in the equations, called "Duration", are referred to the number of hours contained in each considered time-span.
As explained in Chapter 3, there could be an interaction between the values of the external temperature and the consumption given by the user such that *a* or *b* assumes negative values. In this condition, it is necessary to change the integration intervals, repeating the whole procedure for the months of November and February.
For the fuels that don't fit in the previous condition, the general Equations 2.12 can still be applied. In those cases, as already hinted, the floating nature of the starting and ending dates of the periods makes it more complicated to identify the right integration intervals. To do so an auxiliary value, calculated as the time difference between the starting date of the considered year and each date of the datasets, is used. It allows the integral to be evaluated between the two auxiliary values, referring to the starting and ending dates of the given period. In the case in which several loads are aggregated into a single power curve, it is necessary to account for the right dates also in the external temperatures and duration calculations. In the case of a single load throughout the winter season, the intervals of the calculations are derived by splitting the

time period into two symmetrical elements, each assigned as an integrating interval.
The final result of this operation is the calculation of the two values *a* and *b* and the creation of the ”Firma Energetica” for the precise scenario evaluated. This curve represent a mathematical model mimicking the behaviour of the heating system. It can be seen as a virtual boiler used only for space heating. It is this virtual boiler the base on which all the consideration for the heat pump switch are done.

In particular, the evaluation of the right size of the heat pump capable of providing the thermal power needed for the building is performed by an iterative loop. Since the calculation of the two coefficients *a* and *b* is the standardized end for all the different calculation cases seen until now, this last calculation doesn’t need any variation.
The heat pump selection is performed by assuring that the heat pump is able, in its more critical condition, to supply the power requested by the building in the coldest temperature possible. The two scenarios happen simultaneously, as can be seen from the curves trend depicted in Figure 2.6, thus the calculation is reduced to a simple equation as seen in 2.13. The factor *1.1* is a safety factor inserted to ensure that the goal is reached even if some thermal losses have been underestimated.

$$P_{heatpump} > Max(-a \cdot T_{external} + b) * 1.1 \tag{2.13}$$

The program performs this loop with each pair of coefficients reported in Table 2.2, starting from those associated with the smaller heat pump size, until the above condition is satisfied. As can be seen in Figure 2.7, this occurs when the highest thermal request of the building, which is the one corresponding to the lowest external temperature, is still covered by the worst operating condition of the heat pump. When it happens, it means that the selected Heat Pump can be used as a replacement for the previous boiler while guaranteeing the same thermal load coverage. Based on this calculation, all the output are evaluated.
When the condition is not met by a certain pair of coefficients, the system automatically switches to the pair reflecting an higher heat pump size, and the process restarts.
In the case where none of the current sizes of the heat pump is able to supply the required thermal power, it means that the switch between heating systems is deemed not feasible and the user will be notified on the outlet screen. The calculations will stop and the system will automatically jump to its conclusion.

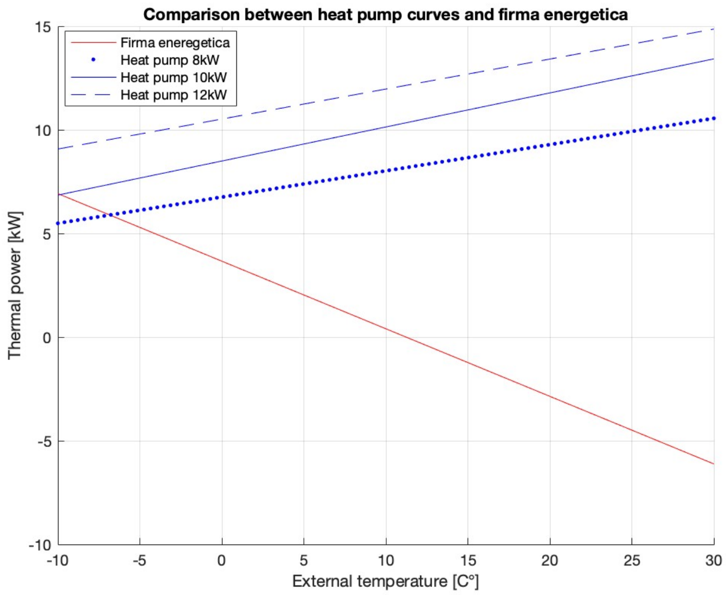


Figure 2.6: Example of the interaction between the needs of the building and the production curves of different heat pumps sizes

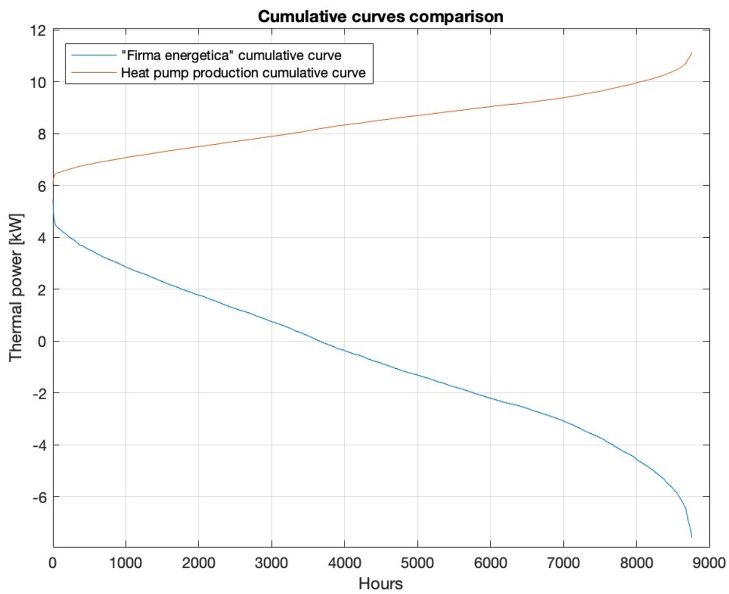


Figure 2.7: Example of two cumulative curves obtained by calculating the values from Figure 2.6 with the real external temperature. It refers to the city of Padova and an heat pump of 10 kW.

Chapter 3

Analysis on the integrating intervals

The choice of the right integration intervals was a crucial step to obtain a proper estimate of the thermal power needs of the building. In fact, any change in the modelled ”Firma Energetica” would have lead to a substantial change in the chosen heat pump size. It was important to note that the choice of the period covered by the integrals is possible only in the case of a complete power curve, which means scenarios of fuels that allow for a constant period load.

The possibilities taken into account for the integration intervals were various, starting from a seasonal integral, passing through single months or considering only the single coldest days or weeks. The last two possibilities have rapidly been discarded, as they were based on the coldest conditions of the standard year and not those of the year to which consumption is related. In this way the analysis was not representative of what happened in the actual billing period and leaded to taking into account the behaviour of the system in two random moments, different from the ones of highest stress for the heating system. By further analysing the situation it was clear that, even if the problem was resolved by retrieving the actual temperature data, the instantaneous power value used for the calculation would have resulted in a mean consumption of the belonging month. This leaded to the conclusion that any calculation taking into account a period shorter than a whole month was not suitable for the procedure.
The other two possibilities: analysing three months or a single one per integral, have been studied by means of a sensitivity analysis. This procedure consisted on applying the program to different buildings and different consumption patterns and, for each set of variables, varying the interval used for the calculations. It allowed to understand the effects of the change and evaluate which was the most appropriate method for the considered application.

The choice of the reference cities was a crucial point in the sensitivity analysis. In this regard, the towns selection was aimed at an even distribution both geographically and from

Figure 3.1: Italian geographical map with highlights on the cities taken into consideration in the sensitivity analysis

a temperature point of view. In particular, the selected cities were Bolzano, Lecce, Livigno, Padova, Palermo, Roma and Trieste as can be seen in Figure 3.1. They represent each Climatic zone except the *A* and *B* ones, the less populated and the ones with a lower heating need, and most of the Italian climate types.

$$Consumption_{town} = Consumption_{province} * \frac{DD_{town}}{DD_{province}} \tag{3.1}$$

It was also necessary to have an suggestion of the typical consumption in all those towns: to achieve that, some data from the Italian regulative authority for the energy, ambient and grids (ARERA) have been exploited. In particular from the ARERA website [117] it was possible to derive the methane monthly consumption values for each Italian province. Data for other

Input	
N. of stars	4
Temperature control	A thermostat per room
Construction year	earlier that 2000
Type of house	Single house
Working hours	7
Resulting efficiencies	
$\eta_{generation}$	1
$\eta_{distribution}$	0,99
$\eta_{emission}$	0,71
η_{tot}	0,70

Table 3.1: Starting input of the sensitivity analysis

fuels have been far more complex to retrieve since, as already explained, the Italian heating market is vastly controlled by the methane boilers. Due to the scarcity of installation of other technologies, and possibly the opposition to disclose confidential data from the citizens, a lack of data coverage on the topic have been observed. For this reason, the sensitivity analysis has been carried out only for the methane case, applying the results on all the other possibilities.
Given that, due to the diversified morphological nature of the Italian territory, within each province the geographical and elevation profile can vary greatly, and so the climatic conditions, simply referring the province data to a single city would not have lead to accurate results. For this reason, a method to re-scale the given consumption was developed: for each selected town, the values of degree days *(DD in the equation)* have been manually evaluated following Equation 2.1 and inserted in Equation 3.1. The value of the degree days corresponding province has been evaluated as a mean of the values of all the single town belonging to it.

Before carrying on the calculations, it was essential to define some standard values of all the other input information, so that the resulting outputs could be comparable. After all the hypothesis and design choices explained in Section 2.4 regarding the energy efficiency values, the only informations needed by the algorithm were: the efficiency value of the boiler, the type of temperature control, the approximate construction year of the house and the morphology of the heating system, as well as an estimation of the daily working hours of the system. The chosen values are reported in Table 3.1. The resulting efficiencies are also reported in the table, calculated as reported in the corresponding section.

With now all the information collected, it was possible to perform the analysis. As can be seen in Table 3.2 and Figures 3.3 and 3.2, the use of a monthly integration interval covering only the coldest months of the year, December and January, led to a higher peak of thermal

Town name	DD	Climatic zone	Integration interval	HP size	*a*	*b*
Bolzano	2821	E	Dic-Jan	6	0.114	1.8387
			3 Months	4	0.0849	1.6651
Lecce	1509	C	Dic-Jan	6	0.3093	5.0513
			3 Months	6	0.2617	4.6505
Livigno	6507	F	Nov-Feb	12	0.0826	2.0064
			3 Months	12	0.1428	2.1592
Padova	2782	E	Dic-Jan	8	0.326	3.6616
			3 Months	8	0.2034	3.315
Palermo	1243	C	Dic-Jan	4	0.1242	2.1143
			3 Months	4	0.0764	1.5104
Roma	2023	D	Dic-Jan	4	0.1675	2.1262
			3 Months	4	0.105	1.7359

Table 3.2: Resulting values of the sensitivity analysis

demand from the building. This, in turn, results in an increased thermal demand on the heat pump, needing a size that is either larger than, or at least equal to, the three-month case. On the other end, using the wider integration interval, the slope of the thermal request result is lower, resulting in a lower sensibility of the thermal needs in regard to the temperature. This lead to a lower peak in the coldest scenario but an higher overall request throughout the whole season, meaning that choosing this method would have given a lower sized heat pump and would have overestimated the yearly consumption, affecting the output calculations. The use of the interval November-February has been analysed as well, resulting in a lower peak that the December-January one, but a similar trend.

During the analysis, a peculiar behaviour emerged, causing a negative result in the calculation of coefficients *a* and *b*. This specific trend could be explained by looking at the values of the integrals of external temperature and instantaneous power. In the case where these two values were not in phase with each other, which means that the consumption peak and the lowest temperature did not occur in the same period, the only valid solution to the equation system 2.12 was to have one coefficient, or both, as negative values. To explain why this condition could occur, it was necessary to remember once again that the external temperature taken into account was a statistical mean value, while the fuel consumption was based on real values that may have a different trend.

To follow the same path already used for other similar choices, as result of this analysis, it was selected the value that put the system in the most stressful condition, meaning the interval December-January. In the already explained case in which that scenario wasn't applicable, as in

the third row of Table 3.2, the November-February time interval was applied, as it was the one with more similar trend and the closest values.
In a more general view, it is possible to note that the trend showed by the data follows, with the due uncertainty caused by the simplistic nature of the data retrieval, the wanted behaviour: the decrease in the thermal power needs follows the decrease of the fuel consumption and, thus, the external thermal power. A confirmation of the veracity of the project's general direction.

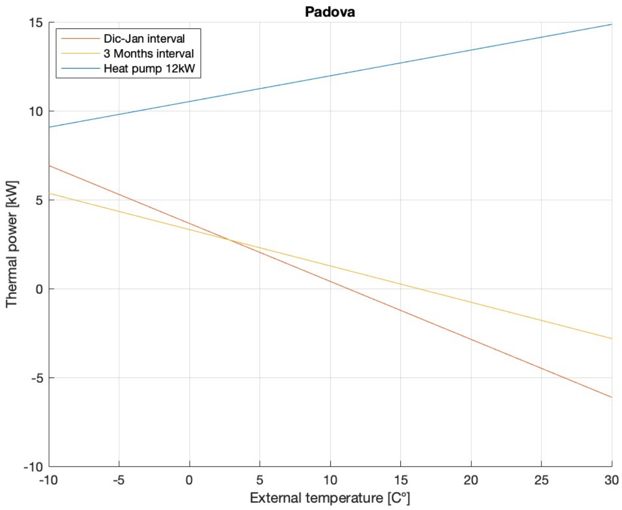


Figure 3.2: Difference in the "Firma Energetica" curve due to change in the integrating period for the town of Padova

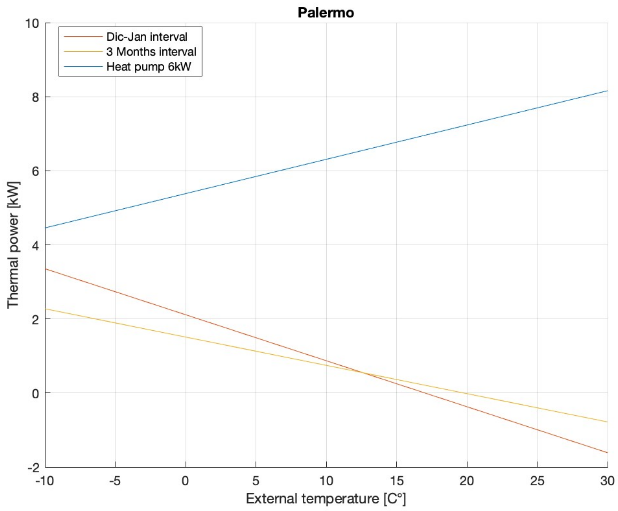


Figure 3.3: Difference in the "Firma Energetica" curve due to change in the integrating period for the town of Palermo

Chapter 4

Output and analysis of the results

Once the program have completed all the calculations and the best size of heat pump has been selected, the results must be presented to the user in a concise and clear way. In the output screen some reworking of the final data are also present, to create a more complete picture of the actual effects of the heating systems change on various parameters.

As a first and most important step the user is notified whether the actual interchange between the previous boiler and an heat pump is theoretically feasible, a result obtained directly from the heat pump loop. Such a claim is based only on theoretical calculations and the data supplied by the user, it doesn't take into consideration the actual morphology of the system or any other physical aspects, thus doesn't hold any thermotechnical or legal value. Before the choice of the actual model and size of the machine, the user is advised to ask a specialist opinion. In parallel to this information, also the supposed fitting size of the heat pump is communicated.

Another possibly useful information is the electrical power consumption of the heat pump during the heating period. A value that, associated with a standard cost of the electrical energy, lead to the calculation of a supposed yearly cost of heating. This cost can, than, easily be compared with the fuel bills directly by the user.
To evaluate such values it is mandatory to know the heat pump's Coefficient of Performance (COP) and it's behaviour at different external temperatures. Those information have been retrieved following the same procedure explained in the heat pumps database for the thermal power, starting from the data given by the machines producers, and are reported in Table 2.2. By using Equation 2.2 to calculate the instantaneous value of the coefficient of performance and multiplying it by the power needed by the system, it is possible to evaluate the electrical needs of the heat pump.

This important parameter could be used to evaluate the amount of primary energy saved by the system substitution, by retrieving a conversion factor that account for the electrical grid losses and production efficiency. However, to express a value more understandable to the user, the savings have been expressed in terms of avoided emissions. Two parameters expressing the specific CO_2 emissions for each kWh, thermal in case of the boiler and electric in case of the heat pump, have been chosen and used to perform the calculations.
Associated to these calculations, it is also possible to estimate the peak of electrical energy absorbed by the machine during the working year. This information could be useful for a study of the power load management in the building: the majority of the Italian residential buildings are attached to the power grid with a contract that permit the withdrawal of maximum 3 kW, by adding the load of the heat pump it could be necessary to modify this contract with the electricity provider, incurring in higher costs.

The subsequent elaboration of the outputs given by the script is intended as a push to peruse the emission abatement of the building taken into consideration and it regards the possibility of installing solar panels. For this purpose, an had-hoc database containing all the specific solar irradiance was put in place. The values, downloaded in the same process as the temperatures from [114], have been elaborated following the same method used for creating the thermal typical years in Section 2.3. With this irradiance value, multiplied by the nominal area of a common solar panel, meaning $1,6m^2$, and its efficiency, 22%, as well as the whole system efficiency, 75%, it is possible to estimate the energy production of a single panel throughout the year. Using this value is possible to evaluate a rough estimation of the needed installed power to cover the whole heat pump consumption: by simply dividing the annual electrical consumption of the system by the production of a single panel, a reckoning on the total size of the photovoltaic system needed to completely compensate the heating system is given. It is clear that this calculation have meaning only as a outline of the actual value, having the only goal of intriguing the user in further studying regarding the possibility of actually installing solar power.

The last calculation of this section aim at give to the user a monetary estimation of the possible savings it could achieve if the photovoltaic system was installed, to better understand the timing and magnitude of the return of its investment. Analysing the market, it is possible to see that the most frequently installed sises of solar systems produce 3 kW or a multiple of this power. To reach this production, normally around 7 panel are used, thus by assuming the installation of a 3 kW and a 6 kW system, an estimation of the possible economic savings can be done. The calculation is simple: based on the previously found production of a single panel. The electricity consumption covered by the two systems is estimated. The net value between the solar production and the heat pump consumption is then evaluated, and with the use of a supposed cost of the electricity, the total expenditure is determined. It is also necessary to do a rough estimation of the total boiler fuel cost, as this value was not asked to the user. To do so the total requested thermal power is extrapolated by the ”Firma Energetica” and, by calculating its ratio with the fuel heating value and the energy efficiency of the building, the total amount of burnt fuel is found. By multiplying this value with a supposed cost of each fuel unit, the total expenditure results and can be compared to the savings of installing the Photovoltaic systems. The case in which the ”optimal” sized PV system was installed is also taken into account, with its saving being the whole yearly cost of the fuel.

4.1 Results analysis

Once the algorithm has been completed it is necessary to perform an accurate analysis of the results and their behaviour variation based of the different climate, in order to understand if the working principle, the hypothesis and the writing of the code is correct.

A first analysis can be carried out for the case of the methane boiler. This scenario is less complex to analyse in respect to the one referring to other fuels because, as already explained, the data regarding the consumption can be easily retrieved from [117].
For this specific analysis it has been chosen to use the vales of monthly consumption refereed to the climatic zones, and not those referred to the single provinces as done before. This choice is due to the fact that each climatic zone group together a much higher number of cities, and so of data, leading to a value that is less susceptible to variation caused by factors other that the climatic conditions. During the sensitivity analysis has been noted that some provinces had a consumption value higher or lower than the one expected following the global trend. In particular, some data-sets referring to the southern part of the country had values quite high, while some provinces of northern Italy consumption too low.
Reasons for this discrepancy were quite complex to find, as the seasonal pattern of the values respected the bell-shaped trend, with December and January in the middle, found in all the available data. This characteristic leaded to think that the reason for the discrepancy in the values came from an external factor. An hypothesis that could explain the behaviour traces the problem back to the energy efficiency of the buildings, meaning that zones where the majority of the houses have been renewed and the boilers have an high efficiency would express a lower consumption than what expected from their temperatures. On the other end older buildings and heating systems could cause an increase in the fuel burnt. By analysing the geographic wealth distribution in Italy [118] it was possible to recognise the provinces with a lower efficiency as

January consumption	301	February consumption	277
March consumption	246	April consumption	92
May consumption	95	June consumption	28
July consumption	31	August consumption	54
September consumption	52	October consumption	56
November consumption	126	Dicember consumption	321

Table 4.1: Input value for the analysis based on methane use

the ones with the lower GDP (Gross Domestic Product) per capita, thus presumably with the lower economic possibilities to perform renovation works. As can be expected, in the case of particularly high GDP the consumption values resulted lower, adding a proof to the hypothesis. As said, by choosing the data based on the climatic zones, the intention was to lower as much as possible the inference of external parameters. in this case by taking into account values from different provinces or regions belonging to the same climatic zone thew effect of the wealth distribution was mitigated.

Starting from the consumption data, it is also necessary to adjust the values using a scaling factor. This coefficient has been evaluated as the ratio between the value of degree days of the specific city taken into consideration and an average value between the boundaries values of the climatic zones, as reported in Table 2.1. The calculation is necessary to increase the accuracy of the input information, as their statistical nature carries a certain degree of uncertainty.

The algorithm has been modified accordingly to the needs of the analysis, so that in could be ran by a loop cycling among all the Italian cities. Regarding all the other needed inputs, the same values used for the Sensitivity analysis in Section3 have been selected.
After the computing process finished, the data analysis revealed that the suggested heat pump size for the vast majority of the cities analysed was the smallest one, 4kW. This result is clearly not plausible, as the variation of temperature caused by the different Italian climate is a well established concept in the culture of the country. It impose a strong differentiation in many aspect of the building techniques, as well as different layout of the heating systems. Supposing that this strong variation do not affect the size of a plausible installed heat pump would be highly inaccurate.
For the second time in the analysis it is necessary to research the cause of the error. Although this time a far simpler answer can be found: by comparing the values of consumption reported by [117] and a set of real data available for the city of Padova (Table 4.1, it is possible to note that the first ones are nearly four times lower, for the same climatic conditions.

This difference cannot be attributed to statistical discrepancies, neither to a particular high consumption of the real user, so the only explanation is a flaw in the dataset retrieved in the ARERA database. Some hypothesis can be done on the reason for values so low, the first idea is that among the gathered data some were referred to systems which had another heating device other than the boiler, thus decreasing the total consumption values. Since the calculation methods of [117] are not disclosed, further analysis were not deemed beneficial.

Given that the analysis is a mandatory step in the correction process of the algorithm, it was chosen to continue using the only real data set available. As already said, it's referred to the city of Padova, so the implementation of a scaling factor to report the consumption values to other climate type was necessary. This factor has been implemented seemly like explained before, meaning as the ratio between the value of the heating degree days of the studied city and the corresponding one of Padova (2782). This substantial change in the input data leaded to a much higher differentiation among the results. As can be seen in Figure 4.1 the average size of the heat pumps remain contained, around 4-6 KW. In the South and in the islands, as it can be expected, the size stays pretty small while around the Alps regions, the Appenini's line and in general the mountain regions an increase in the average size of heat pumps can be noticed. A non trivial result can be seen in the plain regions of Pianura Padana and Lombardia, where the size of the heat pump remain quite constant and similar to the hotter climates, despite the higher latitude. The most energy demanding area seems to be the north-east part of the country, while the peaks of sizes are reached in the north-west border, where the highest mountain rages are located. In the southern part of the country the effect of the highlands present, due to the high volcanic activity, is substantially decreased, with still some examples of higher values, while on the islands it seems to be completely abated, as the results oscillate between 4 and 6 kW.

In figure 4.2 is possible to see two different drawings: the first one (4.2a) refers to the geographical distribution of the degrees day's value, as calculated in the algorithm. accordingly to what may be expected, temperatures are lower near mountain regions in the northern part of the country and alongside the Apennines area, while the value of the coefficient rise towards the coastal zones and in the islands. It is possible to notice that the values cover an extremely high range, a proof of previews statement regarding the variability of Italian climate, with maximum values as high as 7000, while the lower ones drop below 900. Remembering Equation 2.1 it is easy to understand that a value as low as the last one means the external temperature dropped below 20°C only around one eighth of the total number of hours a year.
In the second image (4.2b), the values follows an extremely similar trend, with the same geographical and values distribution all through the peninsula. This shows that the theoretical association between the external temperature and the thermal needs of the building is respected also practically in the results. The linear correlation showed in the figures can also be seen

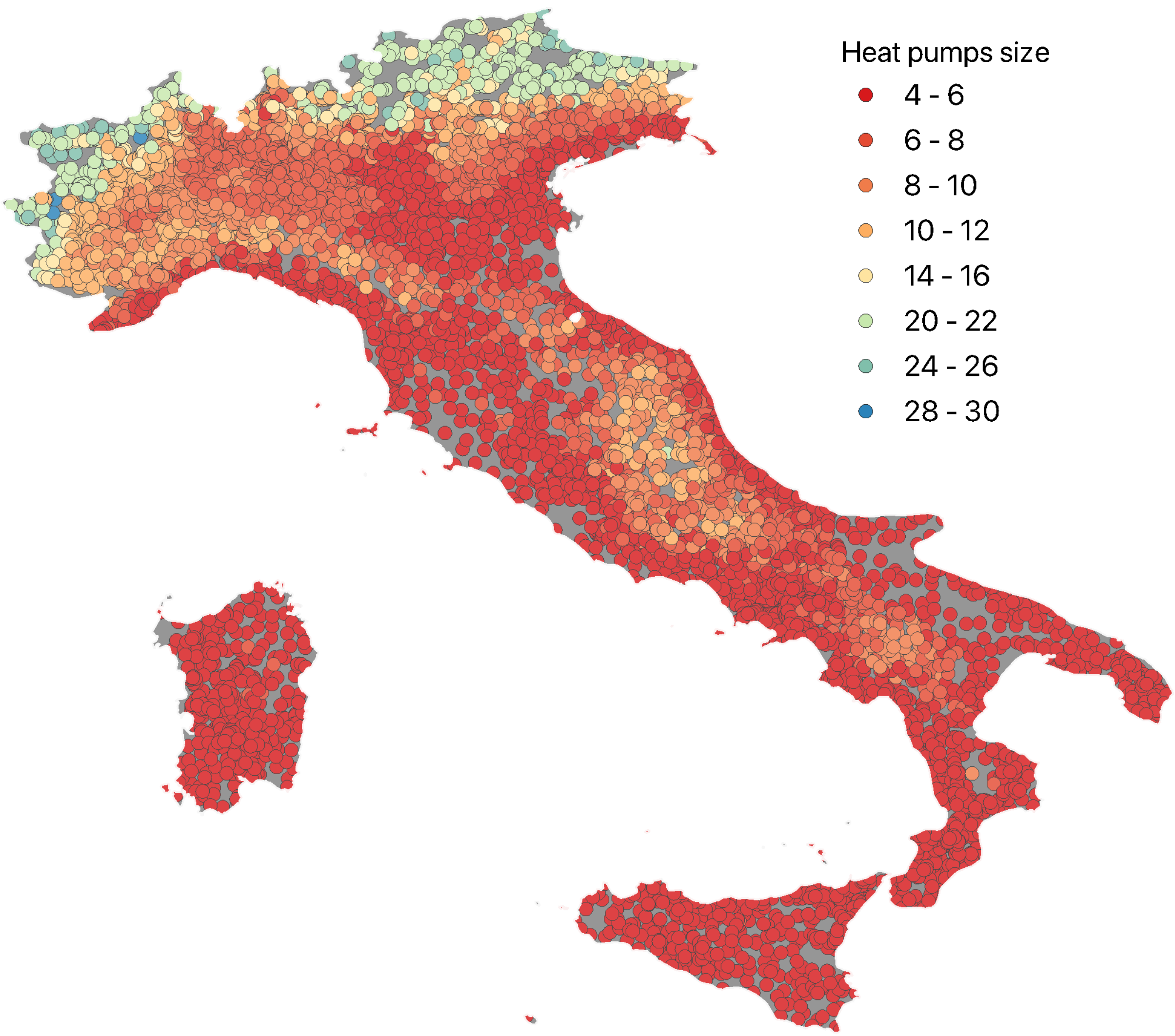
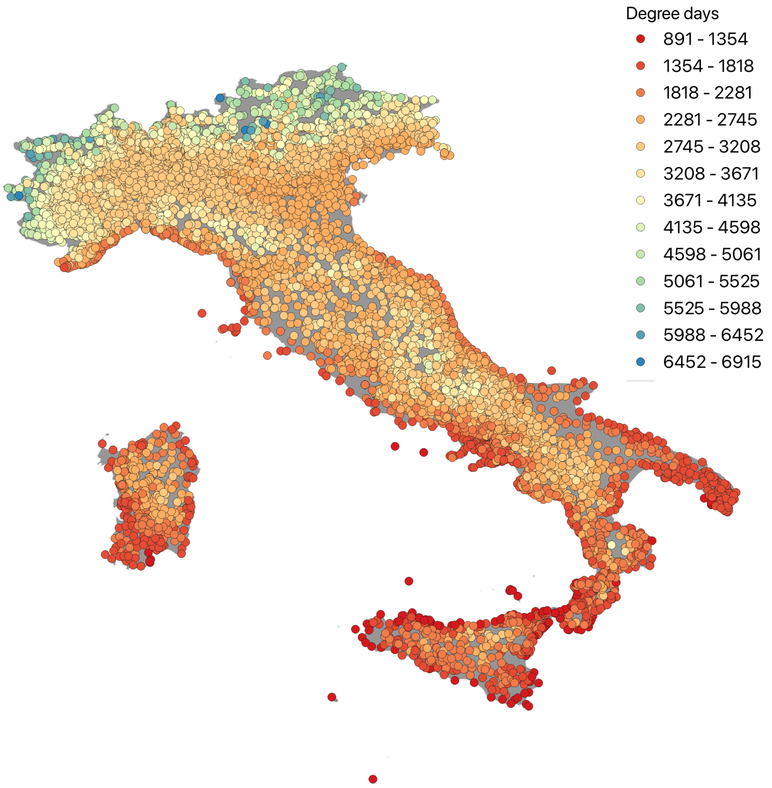
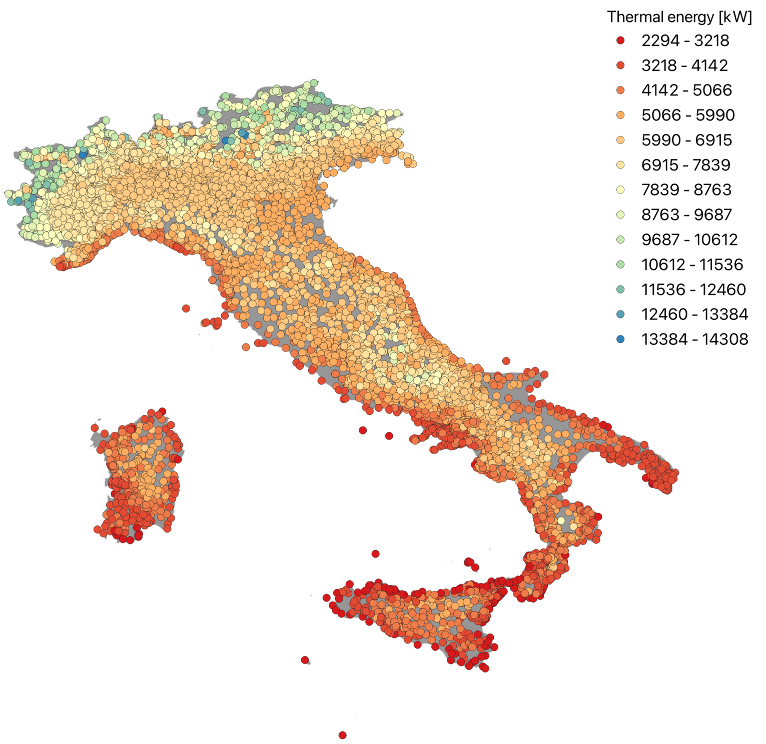


Figure 4.1: Geographical distribution of heat pumps sizes on the Italian territory substituting methane boilers



(a)



(b)

Figure 4.2: Geographical distribution of Temperature, trough the value of degree day, 4.2a and Requested thermal energy 4.2b on the Italian territory

First winter bill start	01/09/23	First summer bill start	01/04/24
First winter bill end	24/11/23	First summer bill end	31/05/23
Second winter bill start	25/11/23	Second summer bill start	01/06/24
Second winter bill end	31/12/23	Second summer bill end	31/08/23
Third winter bill start	01/01/24		
Third winter bill end	31/03/24		
First winter consumption	90	First summer consumption	60
Second winter consumption	385	First summer consumption	30
Third winter consumption	230		

Table 4.2: Input value for the analysis based of LPG use

as a proof of the truthfulness of the methodology put in place in this project. In particular, it shows that the theoretical modernisation of the buildings trough the ”Firma Energetica” holds practical sense.

In order to have a more complete understanding of the algorithm results, it was chosen to perform a further analysis with LPG as a fuel. Supposing that the algorithm performed similarly for fuels included in the same (wood, pellet and biomass), this choice was meant to give an overall comprehension of the program outputs
The consumption data collection has been challenging due to the already noted lack of literature information. Since the only reliable data were the ones used in the previous analysis referring to methane boilers, it was made an attempt to mimic the same consumption for a LPG system. To achieve this, a trial-and-error method has been applied, changing both the consumption values and periods, and obtaining a ”Firma Energetica” as close as possible to the real one. The resulting input values are reported in Table 4.2 and, by running the script, the coefficients a and b have been computed. The method has been successful in displaying coefficients that are extremely close in value to the real ones. This result is also shown in the almost overlapping of the two curves contained in Figure 4.3.

The same methodology as in the previous analysis has been used and the results were obtained for each Italian municipality. As can be seen in Figure 4.4, the resulting suggested size of the heat pumps is considerably lower then the one reported in Figure. In particular, the vast majority of the Italian territory is covered in red spots, meaning that the average size can be approximate to 4 kW. The only exceptions are the Apennines line, were medium size heat pumps can be installed, and the far north of the country were lies the Alpine arch. Here, peaks of 24-26 kW can be found. In the more southern part of the peninsula the results show a value that remain undisturbed by the morphological changes of the territory, with only few values of 6 or 8 kW shattered here and there. In the islands, probably due to a more homogeneous altimetry or to the

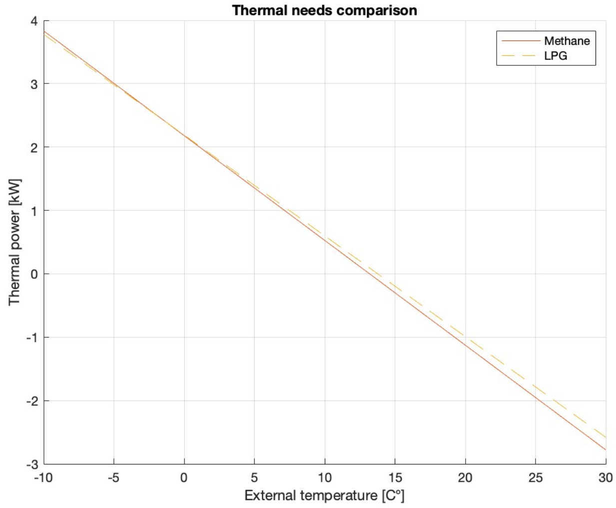


Figure 4.3: Comparison between the curves obtained for the real data and from the supposed LPG consumption

effect of the higher wind intensity, not even those sizes are reached.

In Figure 4.1 the results showed much more variability of the heat pumps across all the nation, while the latter analysis suggested a more homogeneous use of small heat pumps. It is possible to note that even the areas characterised by a colder colour in the first figure, like the region of Piedmont or the hilly area near Naples, in this last map have been uniformed to the rest of the country.

To explain this difference it is necessary to look at the periods covered by the LPG consumption data taken into account. Since, in the method used to elaborate the data-set covering periods of variable length, the power curve is taken into account in its completeness, the time span covered by the consumption data is the same used for the calculation of the integrals. Analysing the periods covered by the data reported in Table 4.2, it is possible to note that they cover the whole winter periods. An integration on such interval has already been studied in the chapter 3 and the resulting knowledge is useful in understanding the problem. By taking into account the full season in the calculation, the minimum temperatures reached during the colder months will be mediated by the more mild ones. In the same way, the maximum thermal power required by the building will be mitigated. In this process, the ”firma energetica” decrease in steepness and the Thermal needs that it represent will increase slower when the temperature drops. Although this second analysis of program output was not successful in its initial intentions, it can be exploited to clearly show what the sensitivity analysis suggested. The difference in figures 4.1 and 4.4 is a proof, based on the data from over 8000 cities, that

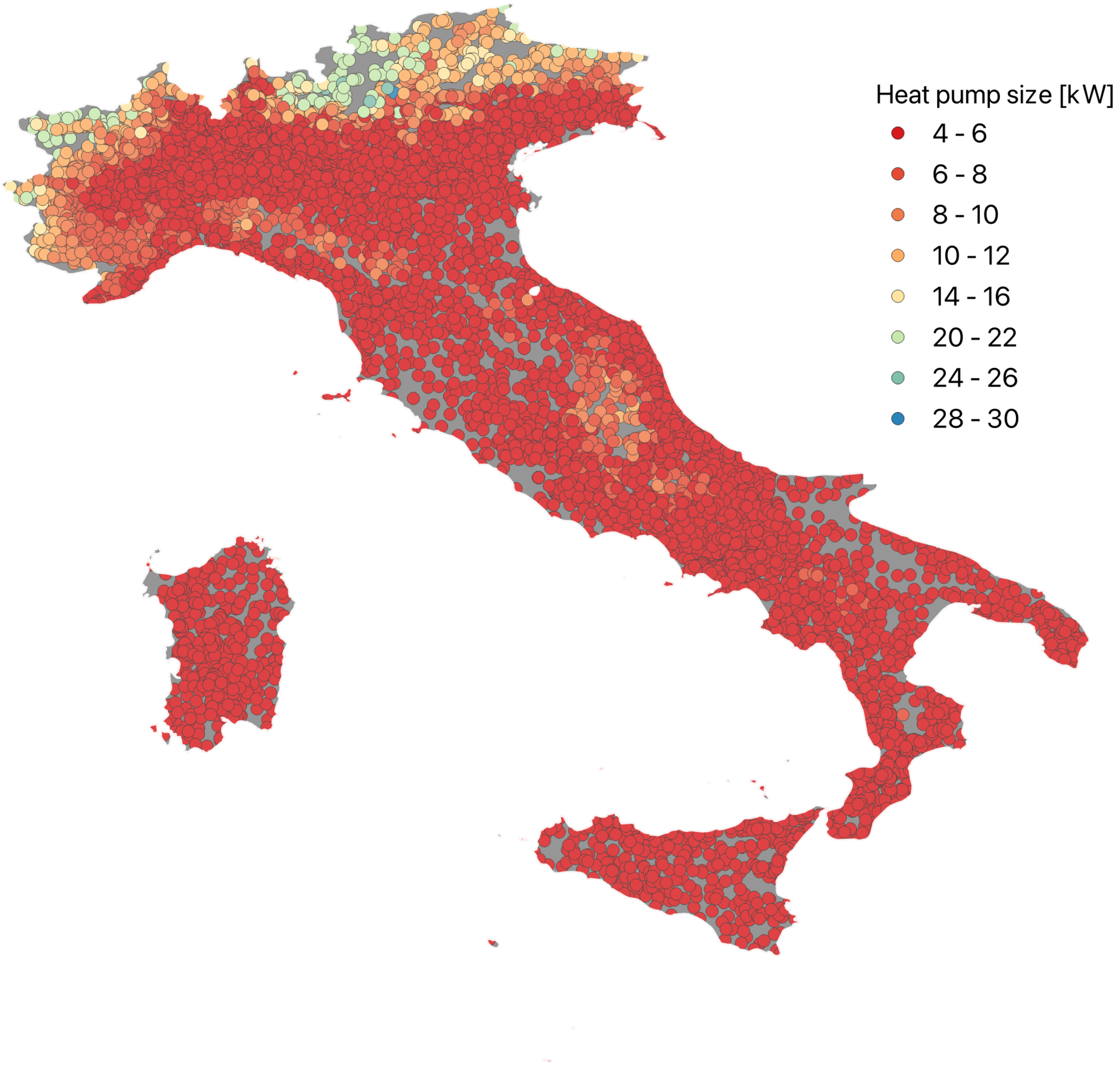


Figure 4.4: Geographical distribution of heat pumps sizes on the Italian territory substituting LPG boilers

the integration interval has an extremely important effect on the Algorithm analysis of the building. Moreover, it shows that the choice of considering only the coldest months for the calculations leads to an higher size of the suggested machines, favouring safety against possible overestimation of the buildings thermal efficiency.

Having understood that the reason behind the difference in the resulting size of the heat pumps was an error in the initial data supposed for the LPG consumption. An attempt to correct the aim was made by transposing the same period covered by the methane case to the LPG consumption. Unfortunately, due to the several degrees of freedom, deriving from the starting and ending date and from the values of consumption, develop a data set that respected the natural gas case was more complex than initially supposed. few combinations were analysed and the results for the city of Padova were acceptable, but the methodology to refer those datasets to the other cities revealed itself to be unfitting for this use. The calculation methods developed for the fuels with batch like billing, as LPG, were designed to take into account larger time spawns. By forcing the consumption to fit in a two month period, as so to reflect the same analysis carried out for methane, the resulting algorithm sensibility is increased. Due to this problem the simplistic method of scaling the consumption linearly with the ”gradi giorno” values give rise to a series of results that do not follow the real trend of the Italian heating needs.

The result of this analysis still is reported for the sake of completeness. In Table 4.3 the initial datasets used to perform the calculations are reported, while in Figure 4.5 the results are reported in graphical manner. As can has already been discussed, it can be seen in the figure how the size distribution do not follow the same trend of Figure 4.1. In particular, in the north-western part of the country numerous small heat pumps are present. That particular area, referring to the Turin city in the Piedmont region, in known for it’s cold climate. Also the region of ”Valle D’Aosta”, on the French border, is predominantly a mountainous area, with the notable presence on the ”Monte Bianco”, the highest peak in the whole country. The program result for these two areas shows heat pumps of four or six kilowatts in Piedmont, and around twelve in ”Valle D’Aosta”. Examining the results form the initial analysis a significant difference can be noted, in fact, the areas have a much more gradual shift towards highest sizes, reached in the Alpine border.

Another notable difference is the north-east region, where a diffuse decrease in the machine dimensions happened. This region displayed lower results even in the initial case, although a more smooth distribution were present. The Appennini’s region still display the same overall trend with the with the appearance of a high size zone in the region of Abruzzo. the same zone in the previous analysis was affected by a similar phenomenon, but with considerable lower magnitude. Likewise, the Basilicata region, a increase in the global size can be extrapolated from the results. Similar effects can be detected, even if in smaller scale, in the islands of Sardinia and Sicily, where cluster of higher size heat pumps can be found. all those differences can be attributed to the higher sensitivity of the calculation methodology applied in this specific case, as explained.

By combining the results showed in Figure 4.4 and 4.5 is possible to conclude that, with the approved initial result, the methodology constructed for this other category of fuels works as intended. This leads to the end of the Results analysis, as both calculations methods have been proved and the results deemed acceptable

First winter bill start	01/12/23	First summer bill start	01/04/24
First winter bill end	15/12/23	First summer bill end	31/05/23
Second winter bill start	16/12/23	Second summer bill start	01/06/24
Second winter bill end	31/12/23	Second summer bill end	31/08/23
Third winter bill start	01/01/24		
Third winter bill end	31/01/24		
First winter consumption	106	First summer consumption	25
Second winter consumption	186	First summer consumption	10
Third winter consumption	350		

Table 4.3: Input value for the new analysis based of LPG use

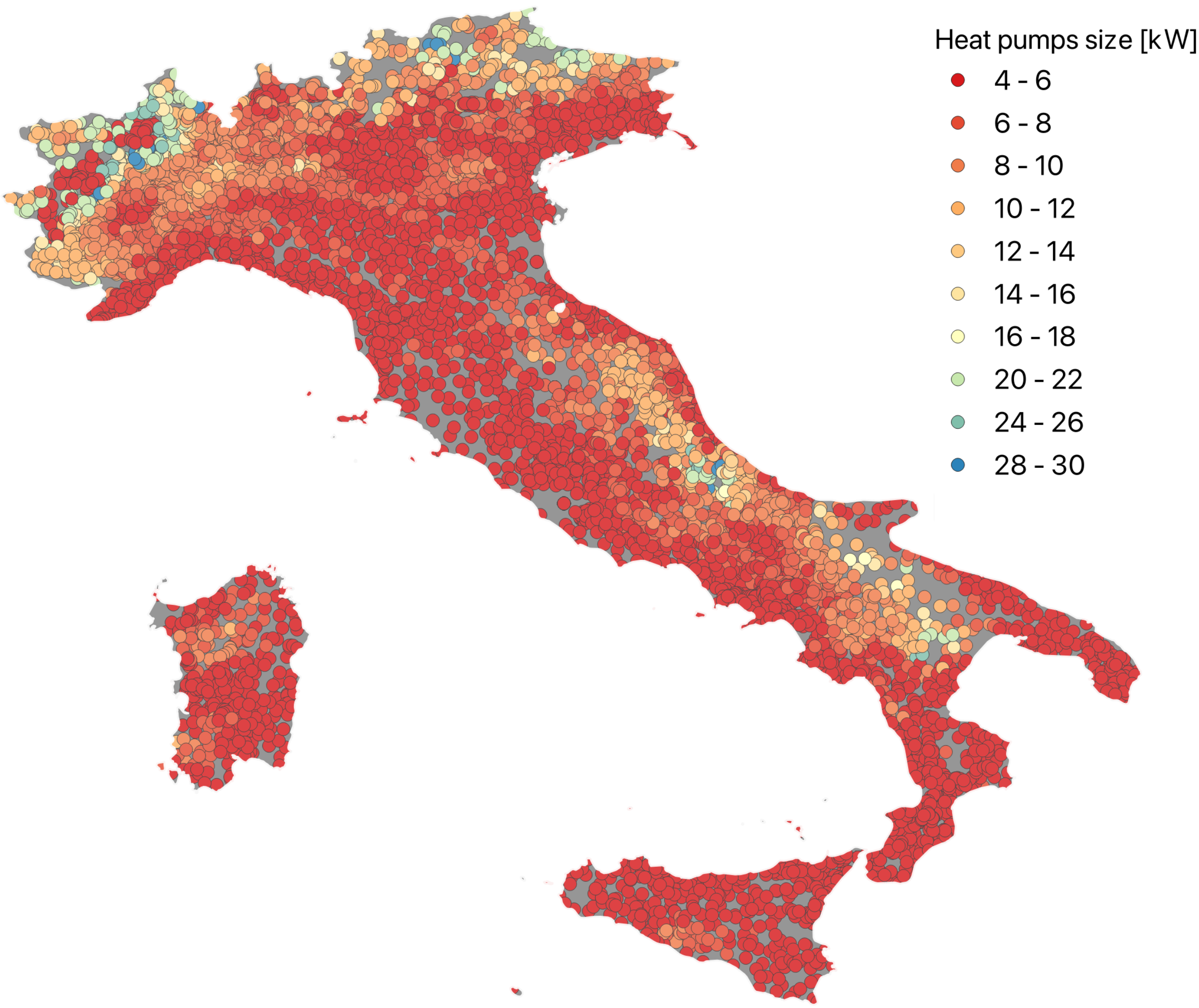


Figure 4.5: Geographical distribution of heat pumps sizes on the Italian territory substituting LPG boilers according to the new analysis

Chapter 5

Conclusions

This thesis was centred on the construction of an algorithm for the evaluation of feasibility of replacing traditional boilers with air-to-water heat pump. The study, requested by the ENEA and focused on the production of hot water for heating purposes, addressing the context of decolonisation of the residential heating market and following the energy policies outlined by national and international bodies.

The first part of the work started highlighting the growing importance of renewable energy sources, especially in residential heating currently dominated of fossil fuel-based systems. After an explanation on the current heating market composition, a review on the possible substituting technology was presented. The Italian building landscape was also examined, as well as the challenges it presents in terms of energy efficiency, given the significant number of older buildings. Heat pumps were identified as a promising solution to these challenges due to their ability to reduce greenhouse gas emissions and increase efficiency compared to traditional heating methods such as boilers. Major attention has been paid to this technology, presenting the various types and possible designs. The working principle was explained in depth and a considerable part of the chapter has been spent analysing the effects of the variable external temperature on the heat pumps performance. The impact of the future diffusion of the technology on the electrical transition grid has been taken into account, also in connection to other electric driven renewable technologies. The final part of this initial chapter was used to present an extended literature review on works and models similar to the one presented in the project.

The core section of the thesis is the development and tuning of the ”PdC-Risc” algorithm. The program was carefully constructed to remain accessible for a wide range of users, by requiring inputs that are easy to obtain, while maintaining the needed accuracy to determine the appropriate heat pump size for their specific building and climate conditions. By taking into account various parameters, such as fuel consumption, building proprieties and heating systems

characteristics, and exploiting the extensive database created specifically for it, the algorithm is able to promptly perform the needed calculations.
A tuning analysis has been done to analyse how to selected integration periods affected the final results. Shorter intervals, focusing on the coldest months, were selected leading to a higher peak thermal demand and resulting in larger heat pump sizes. This ensured that the system was designed to handle extreme conditions, enhancing reliability.
The algorithm also incorporated the analysis of the heat pump Coefficient of Performance to estimate the electrical consumption during the operation periods. It provided the users with useful insights on potential costs and saving of the suggested actions, particularly through comparisons with current fuel expenses. A suggestion to potentially install photovoltaic panels was also inserted, combined with the calculation economical and environmental advantages, to spur the user into considering other environmentally friendly actions.
Trough a simple method to re-scale available methane consumption base on climate, the algorithm was successfully adopted to perform an analysis on all the over 8000 italian municipalities. The system correctly identified smaller heat pump sizes in southern and coastal regions, where milder winters reduce heating demands. In contrast, larger systems were suggested for regions with harsher climates, such as the Alps and the Apennine mountains. A comparison of result for methane and LPG consumption profiles further illustrated the algorithm's flexibility in adapting to different fuel sources. The Algorithm successfully handled both case, providing consistent results in the two scenarios, though some discrepancies in the input data led to further refinements in the analysis.

In conclusion, this study has successfully developed a tool that, while not intended as a design tool, serves as a valuable first step for users considering the transition to heat pump technology. While focusing on ease of use, the algorithm provides accurate recommendations by incorporating comprehensive climate and building data. Further refinements could be made in therms of data availability, expanding the heat pump database, and accuracy in the energy modelling of the building. moreover, additional analysis on the heat pump size selection criteria could be performed to increase the accuracy of the software.
The hope of the author is that the tool will be adopted on a wide scale, contributing to Italy's and ENEA efforts to transition into a greener residential heating sector.

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