POLITECNICO DI TORINO

Master of Science in Energy and Nuclear Engineering

Master Thesis

Optimization and multicriteria evaluation of carbon-neutral heat-only production technologies for district heating in Turin

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Abstract

The imperative to reduce emissions to counteract climate change has led to the use of renewables in more and more areas. Looking at district heating, there is a growing interest in coupling actual production system and carbon-neutral technologies. The thesis presents a methodology for supporting decision making of carbon-neutral technologies for district heating, specifically designed to consider uncertainties and dependencies, from modelling the initial system and alternatives to choosing the best one. In particular, the analysis is carried out considering several criteria, including economic, environmental and technical aspects. The proposed methodology is applied to the campus of Politecnico di Torino whose thermal load is satisfied by DH, with the aim to explore strategies for replacing gas boiler with more sustainable technologies. Considering that the campus represents only a substation of the DH system, introducing large-scale alternative in the actual DH network would not allow to directly evaluate benefits. To solve this problem, a smaller production system was simulated to cover campus heat demand and the methodology was applied. The process is organised in two stages, the first one simulates and optimizes the different alternatives, while the second one evaluates the previous scenarios according to multiple criteria. To optimize the alternatives, LP2 software was used and, to validate the models, results were compared to well-known software EnergyPRO, used in the district heating field. The output of the first part can be summarized in a matrix containing mean values and uncertainties for each criterion, and a correlation matrix that relates each alternative. Then, in the second stage, the alternatives were analysed using Stochastic Multicriteria Acceptability Analysis (SMAA), a simulation-based method specifically designed to consider imprecise information. The novelty of the approach is that differently from the most common multicriteria decision support methods, it can consider stochastic variables in the analysis, and in contrast to earlier SMAA applications in the energy field, it uses a correlation matrix, obtained after an iterative process, and decision makers preference information to strengthen the results. The most preferred alternative was the introduction of a solar heat plant coupled with an increase of daily storage, that add renewable capacity to the system while cutting the peak load. Solar heat can benefit from incentives, while reducing operational costs and emissions, maximizing the use of carbon-neutral heat thanks to the storage.

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Chapter 1

Introduction

The environmental issue is undoubtedly one of the most urgent problems that our society must face up to. Scientists agree in saying that the behavior of man is having important consequences on the climate and the global ecosystem and it has been demonstrated that the current economic model is not in line with the targets proposed by the Paris Agreement [97], that aims to keep the increase in global average temperature to well below 2 °C above pre-industrial levels. After the failure of the Copenhagen Agreement, the world realized that climate change was already happening and that actions to prevents climate change can drive innovation and improve the economic growth.
Despite the investments during the last few years, the large majority of world total energy consumption still relies on fossil fuels [41], [7].
Therefore, the design of the future energy system must aim to reduce the level of GHG emission by increasing energy efficiency or introducing renewable energy sources to support a new economic model.
In the Brundtland Report, also known as "Our common future", sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". In this regard, environmental sustainability should not be seen by companies as an additional cost to bear, but as a fundamental driver, as well as for reasons of economic convenience, also and above all for moral and ethical reasons.
In fact, sustainable development is founded on three pillars:

1. Social sustainability: ability to guarantee conditions of human well-being equally distributed by class and gender.

2. Economic sustainability: ability to generate income and labor for the sustenance of the population.

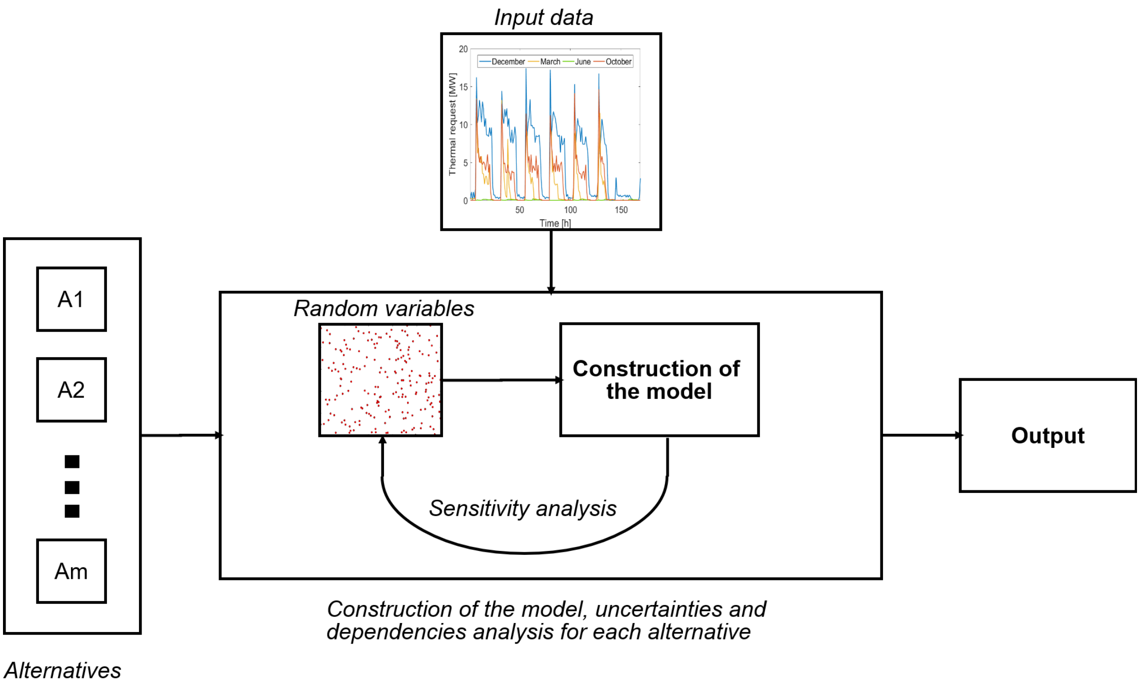
3. Environment sustainability: ability to maintain the quality and reproducibility of natural resources.

An energy system can be defined sustainable if it has a balance of energy production and consumption and has no, or minimal, negative impacts on the environment, but gives the opportunity for a country to employ its social and economic activities.
It is quite common to associate a sustainable economy to photovoltaic and wind power, that are well known technology used in the electricity market, however, as highlighted in Heat Roadmap Europe [15], [19], the role of thermal energy production is extremely important towards a sustainable society, due to the fact that nearly half of the energy production is thermal energy produced from technologies with high carbon dioxide emission factor. It was therefore decided to focus the attention on the heat sector, in particular on the district heating, seen as backbone for the energy transition [66].

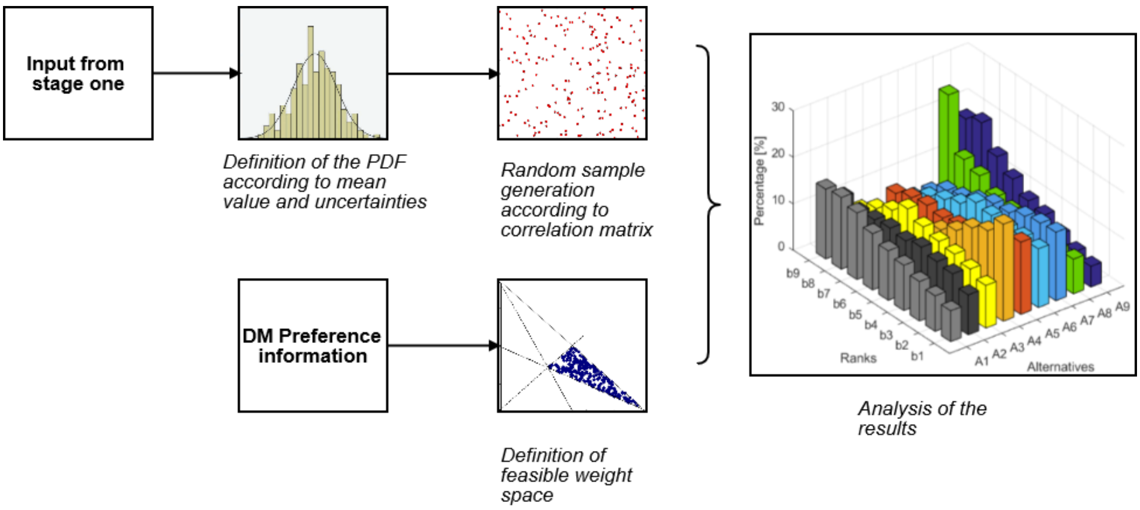
1.1 Structure and contribution of the thesis

The thesis aims to develop a methodology to support decision making of carbon-neutral technologies for district heating. The process is specifically designed to consider uncertainties and dependencies in criteria measurements and alternatives.
For the thesis, the methodology was applied to a case-study that analyzes Politecnico di Torino, a unversity whose thermal load is providd by district heating, scaling the actual DH system of the city and trying to substitute peak boilers with renewable or carbon-neutral technologies using a Multicriteria decision analysis.
The process can be divided in two stages, the first one that aims to model the base-case and the alternative, assessing uncertainties and dependencies, while the second one perform the multicriteria decision analysis under stochastic input variable. The framework of the methodology is shown in figure 1.1.
The first stage aims to reproduce the production system in a smaller scale, studying the thermal demand of the case-study and comparing it to the actual system. After that, the case-study is modelled using LP2 software. Consequently, a scenario-analysis is performed, describing all technologies used as alternatives and criteria considered in the second stage. Then, the Stochastic multi-criteria acceptability analysis (SMAA) is used, due to the stochastic nature of the problem and the lack of information. The methodology aims to combine the MCDM tool with the simulation-based software (LP2), assessing uncertainties and dependencies through special techniques. To choose the best alternative between the ones proposed, several simulations with an increasing level of detail are studied and compared, including also preference information from decision makers.
Finally, the analysis of the results is presented, and the best solution is critically analyzed.

The structure of the thesis is summarized as follows:
Chapter 2 analyzes the role of district heating towards a sustainable development, with an overview on Europe.
In chapter 3 the case study is analyzed, and the attention will be first focused on the problem formulation and then on the model creation.
In chapter 4 the main criteria chosen for the analysis are pointed out, then several technologies that could be implemented in the actual production system are studied, modelled and optimized. These information will be used in the second stage.
After that, in chapter 5, an overview on MCDM is provided, followed by a detailed description of the stochastic multi-criteria acceptability analysis (SMAA).
In chapter 6 several SMAA simulations are performed to find the best alternative, highlighting the important role of uncertainties, dependencies and preference information.
Finally, in chapter 7, the conclusions are presented, highlighting the results obtained and the possible future developments of this work.



(a) Framework of the proposed methodology (Stage 1):construction of the energy model



(b) Framework of the proposed methodology (Stage 2): selection of the best alternative

Figure 1.1: Framework of the methodology

Chapter 2

District Heating

District Heating is a system for distributing heat generated in a centralized location through a system of insulated pipes for residential and commercial heating requirements (*space heating and water heating*) [104]. The heat is very often provided by cogeneration plants, but usually also heat-only boilers are needed to cover peak demand. With the development of new technologies, DH has been successfully coupled also with geothermal heating, biomass, heat pumps, central solar heating and even nuclear.

It was demonstrated that district heating with combined heat and power (CHPDH) is the cheapest method of cutting carbon emissions, and has one of the lowest carbon footprints of all fossil generation plants [78]. In fact, substituting the distributed generation of heat with a centralized one there are benefits in terms of emission (*advanced system have better flue gas cleaning system with respect to traditional boiler*) and efficiency (*due to the combined production of heat and electricity*). Drawbacks are mainly related to the high investment cost that drive investors away, looking for a shorter payback time, but also to the impossibility to build DH everywhere, since it needs a high linear heat density to reduce specific costs. Looking at the urbanization rate in Europe, that was 74% in 2010 [96], DH should be favoured, however, only 13% [40] of the heat is delivered with district heating, as can be seen in figure 2.1.

2.1 District Heating in Europe

The history of District Heating started around 1870 in Lockport [14], while the first systems in Europe were introduced in Germany in the 1920s. The evolution of the DH lead to an expansion in different European cities and nowadays it is present in about 6000 systems [103] helping to save more than 200 millions tons of CO_2 per year [13].

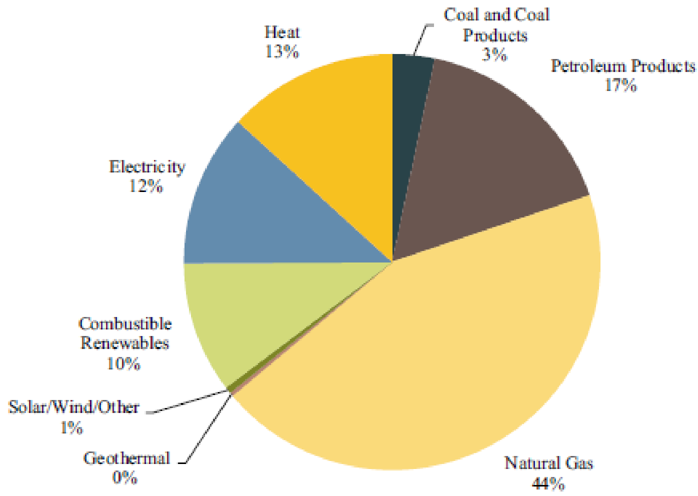


Figure 2.1: Proportions of all heat use in residential and service sector buildings in EU27. Heat denotes heat from district heating systems

Overview of share and technologies

- Austria: the share of DH is around 21% and 84.5% comes from direct renewable (*biomass*) and recycled heat, allowing a production of heat using CO_2-neutral or low CO_2 primary energy.
- Bulgaria: the Bulgarian DH market is mainly used in the capital city of Sofia, and in the entire country DH provides around 16% of heat, with 67% recycled heat.
- Denmark: it is definitely the European country with the highest development in DH market, accounting for 64% of share and with a direct use of renewable that covers almost 50% of the heat generation thanks to the high use of solar and heat pumps driven with renewable electricity. In the capital city of Copenhagen DH provides 98% of heat.
- Finland: it has a long tradition of CHPDH that covers around 45% of the demand and thanks to policy-makers, the share of renewable and recycled heat has reached 90% especially thanks to the use of wood in CHP plants. In the capital city of Helsinki DH share reaches 90%.

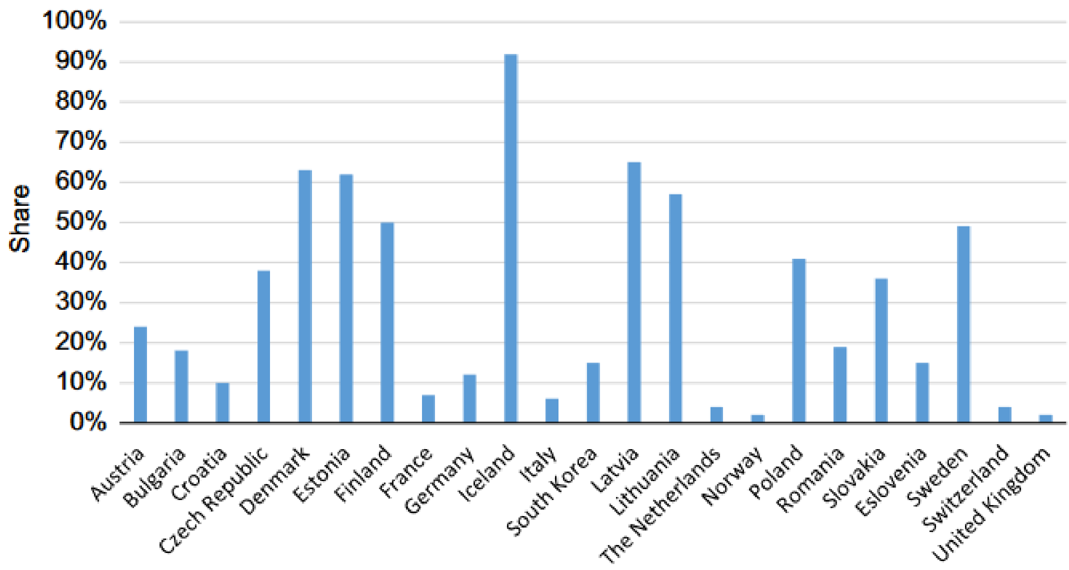


Figure 2.2: Percentage of citizens who have access to district heating networks for different countries of the OECD (2012)

[26]

- Germany: it has the largest market in terms of absolute figures, serving around 10 million people, however it account only for 14% of heat demand, with a high use of fossil fuels, that still dominate the DH market.

- Hungary: the share of DH is around 12% but natural gas playing an important role in both heat demand in residential sector and in DH, where it covers 78% of productions.

- Iceland: it is the nation with the highest DH share in the heat market, with an astounding 92% and a 100% of DH that comes from direct renewable and recycled heat, thanks to the massive use of direct geothermal.

- Ireland: DH covers less than 1% of heat demand, with the few plants built during the last ten years. There are no national level targets for district heating, with some possibility to use it only in some arease of the capital city Dublin.

- Italy: it has developed DH very recently and it has kept an upward trend, however only 3% of heat demand in residential sector was provided by DH. Around 77% of the energy comes from direct renewables and recycled heat, with around 68% from CHP.

- Netherlands: heat supply is mainly provided with natural gas, in fact only 4.4% of the heat demand is satisfied with DH, where 90% of the heat was generated from direct renewable source and recucled heat.

- Norway: it is characterised by the highest share of electricity in heat sector, thanks to the dominant hydro power system, therefore DH has a minor role, covering only 3.3% of share, however 94% of the energy comes from renewable energy sources
- Poland: the share of DH is 41% and around 70% of the district heat was generated from direct renewable sources and recycled heat, while almost another 40% is covered with coal.
- Romania: due to a combination of legal, administrative, financial and social issues, DH sector is in decline, in fact during the last 40 years due to political decision around 250 no more use their DH system, leading to a 23% DH share, with 90% of the heat coming from CHP.
- Serbia: it has achieved a continued growing in the DH capacity, reaching 27% of share with also a high share of renewables, heat pumps and electricity, due to the low cost of power.
- Sweden: it has a heat market leaded by DH, that covers 51% of demand, with the totality of production supplied by renewable,biomass and waste. The heating system uses also electricity and renewable, becoming one of the most green nation in Europe to provide heat.
- United Kingdom: it relies mainly on natural gas, with a DH system underdeveloped, that covers only 2% of the heat sector and it is mainly fueled by natural gas in CHP. Despite the low presence the UK recognize the role of DH and aims to increae the share up to 14% by 2030

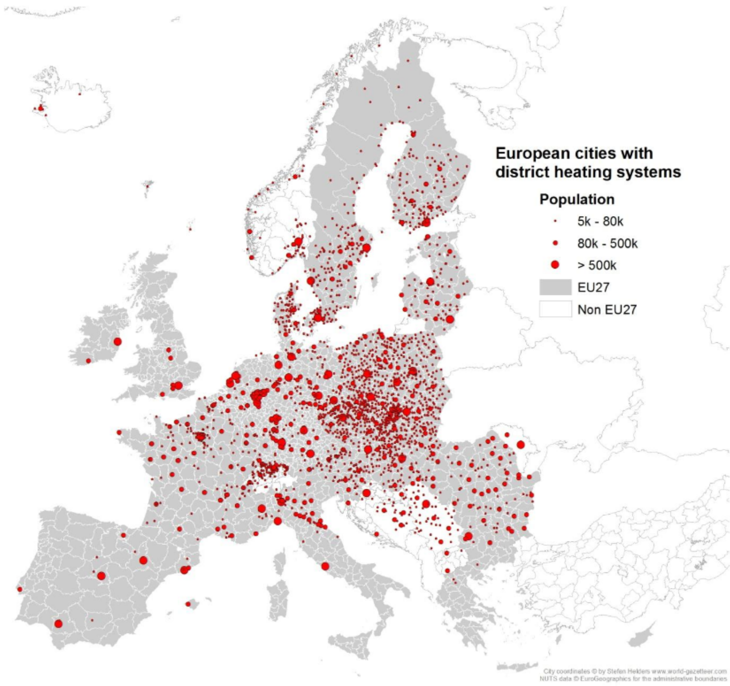


Figure 2.3: Distribution of DH system all over the Europe [26]

In particular, around two-third of the heat supply relies on fossil fuels, with a large share of natural gas. This could be explained looking at the climates and the availability of fuels in Europe, which have led to different kind of network both for heat and electricity supply. In fact, share of DH varies significantly between EU members; looking at figure 2.2 can be seen that in Scandinavian and Baltic country this value reaches 40 − 60%, while in country like France, Italy, Netherlands and Norway it does not reach 10% .
In general in Northern Europe (*except Norway* [88]) DH contributes way more than 13% to heat supply, leading Europe towards sustainability in the heat system. Many research have suggested that heat demand in Europe is sufficiently high in major city to install district heating networks [80] and, as said by Lund et al. [66], DH is considered *the backbone of future energy systems* due to the high flexibility and the possibility to use renewable.
Nowadays DH supplied by Cogeneration Heat Plants (CHP) is among the most efficient solution for providing heat to buildings [67] and can reach efficiency up to 90%. Currently CHP represents the main production technology for DH in Europe, allowing both to distribute heat and increase energy efficiency of existent plants, however as said before CHP are mainly run on fossil fuels, a trend that is reversing thanks to the introduction of biomass CHP and new renewable energies.

Generations of DH

A strongly connected topic to the type of fuel is the generation of the district heating networks. As explained by Lund, Werner et al [67], the first generation of district heating systems used steam as the heat carrier, this can be considered an outdated technology, due to several problems with maintenance and efficiency related to the high temperature of the steam. The second generation used pressurised hot water as the heat carrier, with supply temperatures mostly over 100 °C, changing the material of the pipe to allows more flexibility. The third generation of systems was introduced in the 1970s and still uses pressurised water as heat carrier, but often the supply temperature are below 100 °C. The third generation is sometimes referred to as "Scandinavian district heating technology", since the components are often prefabricated in Scandinavia.
Following the trend, that aims to reduce operative temperature, use new material and reduce losses, the fourth generation combines economical and environmental aspects
The main features of a 4th generation district heating are:

1. Capability to supply low-temperature district heating for both space heating and domestic hot water (DHW);
2. Capability to reduce thermal losses with respect to the previous generation;
3. Ability to recycle heat from low-temperature sources;
4. Ability to integrate renewable heat sources such as solar and geothermal heat and to be integrated in a smart grid.

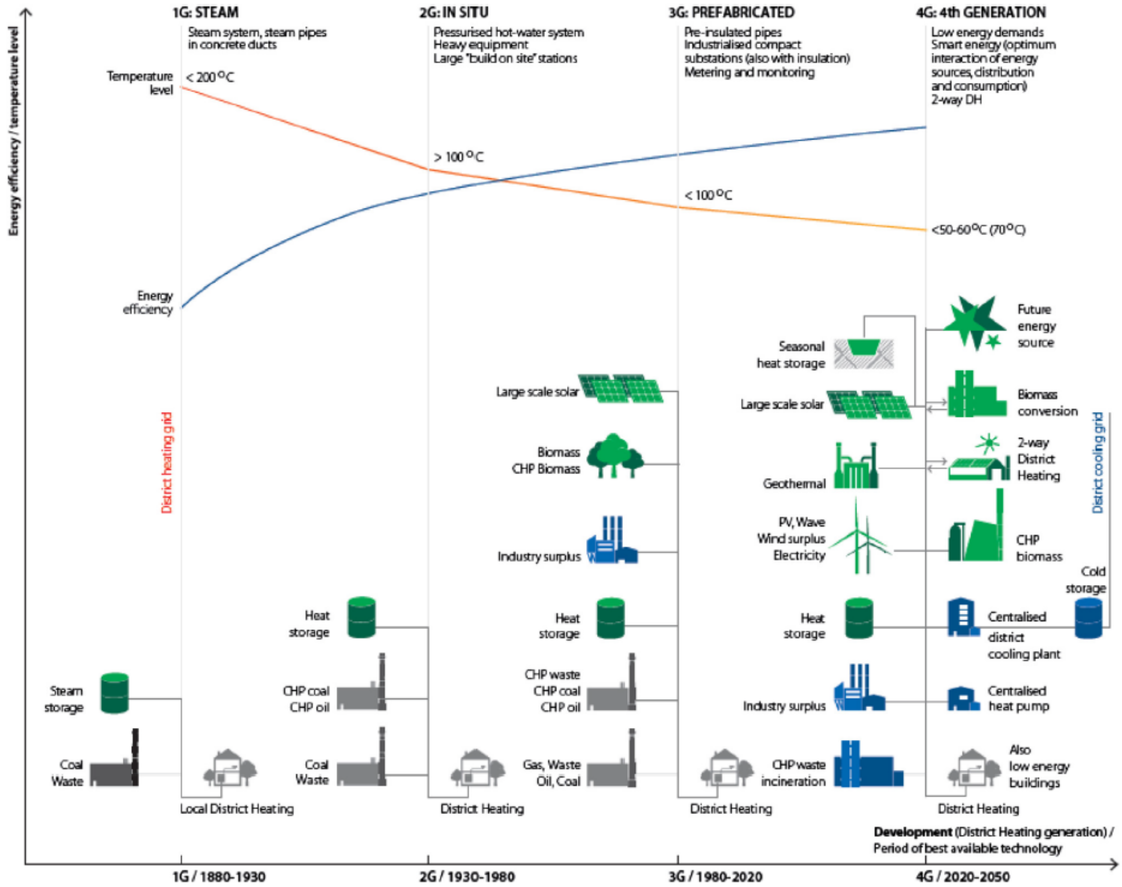


Figure 2.4: Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations [67].

Looking at the past, the integration between DH and renewable energy sources is already present from 2nd generation, as can be seen from figure 2.4. Some examples in literature [73, 74] show that it is possible to reduce the emission through the integration of renewable. In fact, in dense urban areas, district heating networks may offer the only option for using a significant share of renewable and other low-carbon heat, as individual biomass boilers, solar thermal systems or heat pumps may be constrained for reasons such as lack of available space . Even if renewable heat has grown fast during the last five years (2013-2018), with an increase of 12% it accounts for only 9% of the global demand (*including heat generated from renewable electricity*) while during the same period renewable electricity has grown for around 31% [42], underlining the fact that electricity is a much more discussed object.

In the next section an overview on district heating in Italy will be presented.

2.2 District Heating in Italy

In Italy DH was seen as an immature technology until the 1980s, when the first plant was built in Modena in 1971 [3]. Since 1972, it has kept an upward trend, but the share covered is still very low with respect to other European countries (*2.8% compared with an average of 10% in European residential sector*).

Today there are more than 300 networks and it is present in every northern region (*excluded Friuli Venezia Giulia*) and also in Tuscany, Lazio and Marche.

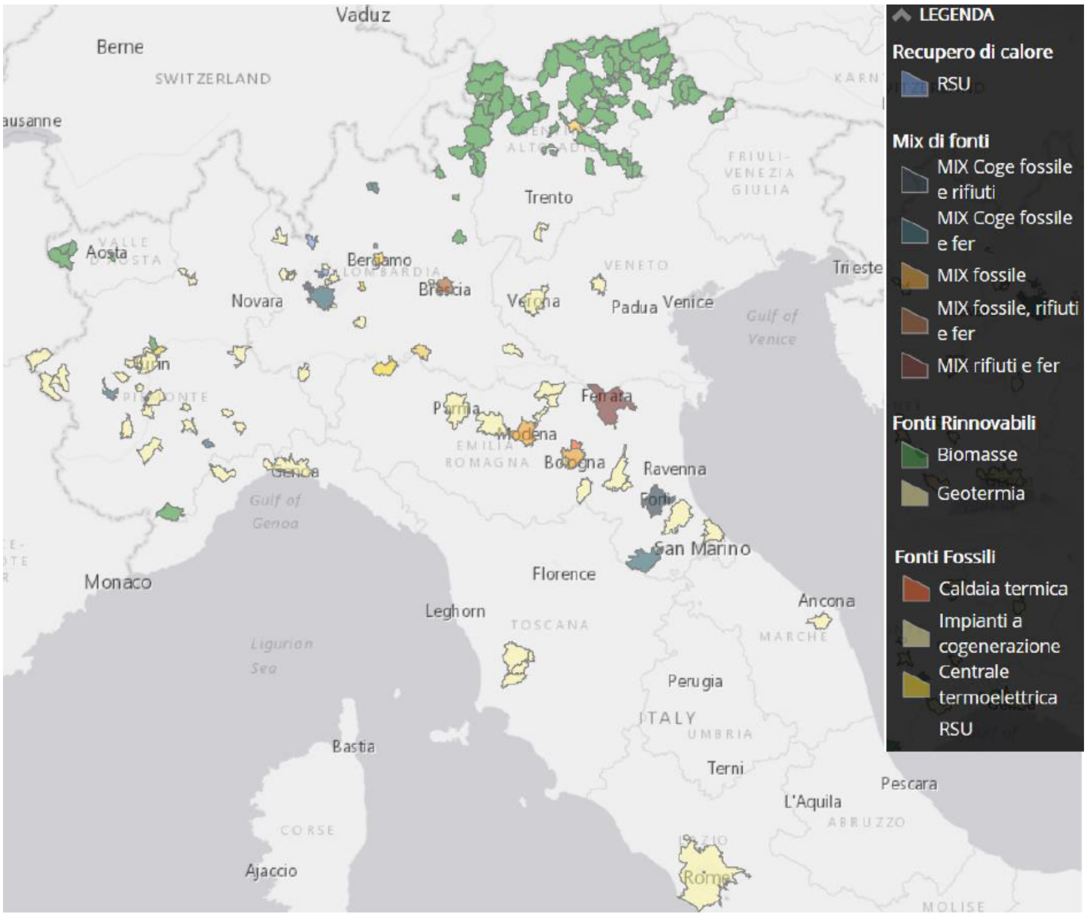
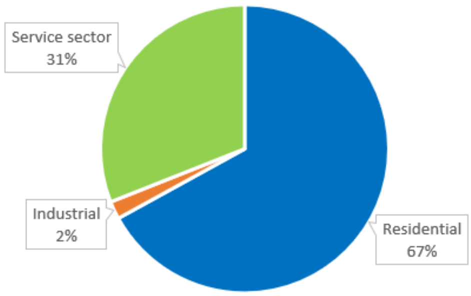


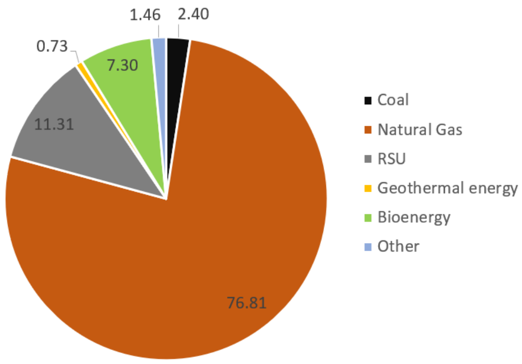
Figure 2.5: District heating networks in Italy, distribution and energy source [21]

In particular 78% of networks are distributed between Lombardy,Piedmont and Trentino alto Adige and from figure 2.5 can be seen the presence of renewable DH networks mainly in Tuscany, thanks to geothermal heat, and in Trentino alto Adige, thanks to biomass obtained from the processing of wood waste.

Around 95% of the total energy provided by DH network is used for space heating and hot tap water. Figure 2.6a highlight that 2/3 of the heat is used in residential sector, while for industrial sector there are minimal benefits. Figure 2.6b shows the high dependence from fossil fuels, that represents the main source for DH network with the 77% of share. However, last years have seen an increase in renewable with RSU (Municipal Solid Waste) as the second fuel used in DH covering 11.3% of the total share, followed by biomass with a 7.3% share. Coal and Geothermal energy represent only 3% share and while the first is expected to decrease, geothermal energy is not expected to increase in the future.



(a) Thermal energy supplied by sector



(b) Thermal energy supplied by source

Figure 2.6: Share of sectors and energy sources in DH in 2013 [11]

The production system depends heavily on the analyzed region, in fact, the use of renewable is mainly confined in two region, Tuscany and Trentino alto Adige, while in the other region there is the prevalence of cogeneration plants and boilers. Figure 2.7 shows that cogeneration plants (*both RES and not*) represent 86% of the installed capacity serving DH, that however does not consider back-up boilers, that produce around 25% of the total energy used in DH. It is also interesting to notice that heat pump nowadays represents only 1% of the capacity installed, while according to HRE it should cover around 30% by 2050. At the moment, also due to the higher temperature of Italian district heating, there are only few heat pumps employed in DH networks.

Several studies have been conducted to analyze the interaction between the already existing DH and renewable heat sources [52, 37, 79] assessing the possibility to reduce primary energy consumption and reduce emissions [38, 98] coupling the stochastic nature of renewable with storage.

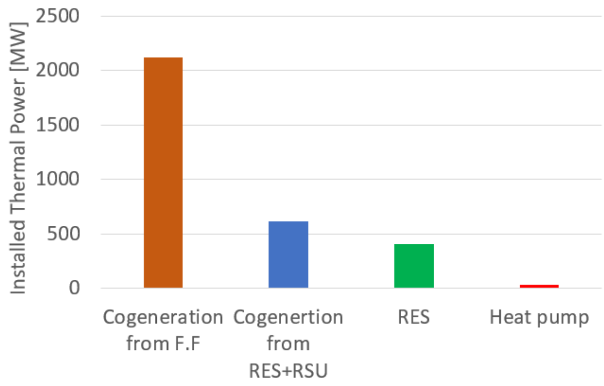


Figure 2.7: Installed capacity serving DH

The advantage of DH is highlighted by two main parameter: the primary energy saving and the avoided emissions. Primary energy saving is translated into higher efficiency of the system and economic saving due to fuel saved. In addition to a higher efficiency and the economic savings, there is an environmental benefit, since DH in 2012 avoided 1528 Mt of CO_2. As highlighted from figure 2.8, around 60% of the CO_2 avoided came from Turin DH, that is the largest DH network in Italy, able to deliver about 1.9 GWh of thermal energy to users, accounting for 23% of the national total. Moreover, can be seen that in Lombardy and Trentino alto Adige there is a higher PES with respect to avoided emission if compared with Piedmont case, this because in such regions there are more small systems, that allow a higher energy saving.

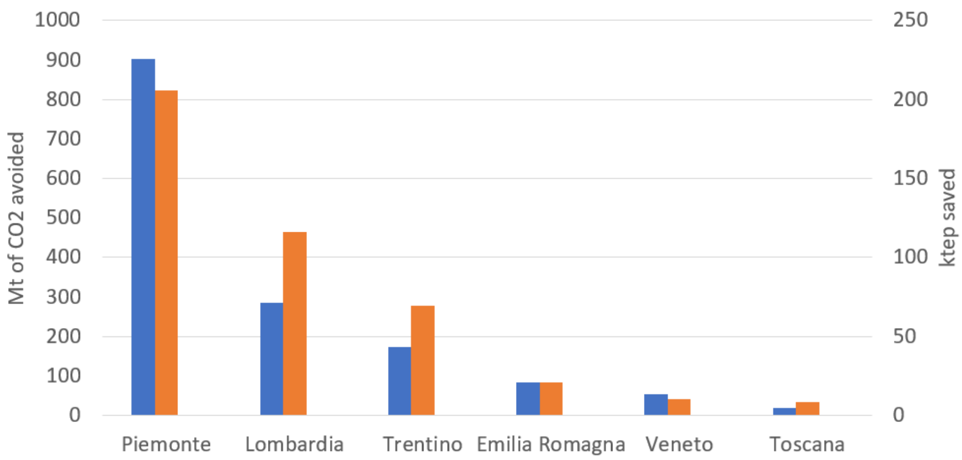


Figure 2.8: Mt of CO_2 avoided (*blue*) and PES (*orange*) thanks to DH for different region in Italy

DH perspectives

According to HRE, the potential of DH in Italy is one of the highest in Europe, due to the match between excess heat and heat demand; moreover, the dense built environment decreases cost associated to pipelines, increasing the advantage of a high penetration of DH in the heating sector. The projection provided states that DH should be expanded to cover up to 71% of the heating market in Italy by 2050, compared to 2.6% in 2015 and that the new DH should have compliant characteristics to the fourth generation, trying to lower distribution temperature and deeply decarbonise the heating sector.
It is recognized the importance of cogeneration, in particular in Italy (*where a vast expansion of DH is suggested*), that represent the cheapest way to cut emissions and the fundamental role of heat pumps, that will help the integration between the electricity market and the thermal market.
In figure 2.9 are represented the main sources that should be used according to HRE.
As can be seen the share of boiler is almost the same, with the difference that they are fueled by biomass, while there is a high increase of heat pumps, from 1% to 23%. Lastly, the other technologies (*except electric boiler*) are mainly used to cover base-load.

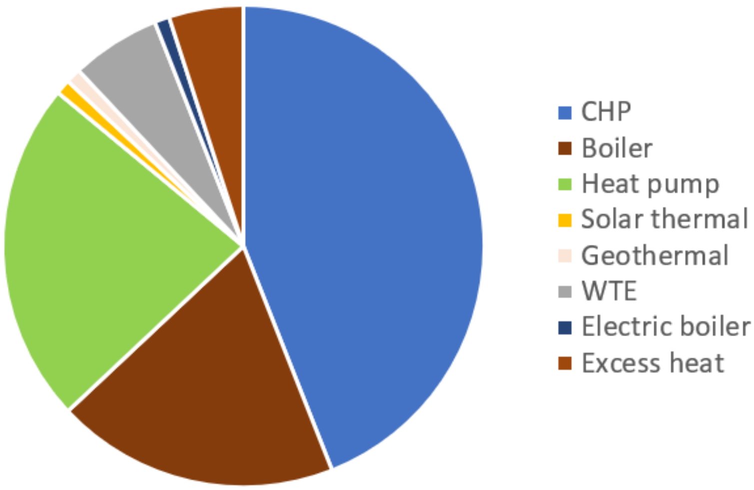


Figure 2.9: Heat sources for DH in HRE 2050 in Italy

Chapter 3

Case study

The case study focus the attention on Politecnico di Torino, a university based in Turin. The heat demand of the building complex is satisfied with DH and represent around 1.5% of the peak demand of the entire city. In this chapter a first glance is given to the Turin production system, then the input data are analyzed and used in the first stage of the methodology.

3.1 Polytechnic heat demand

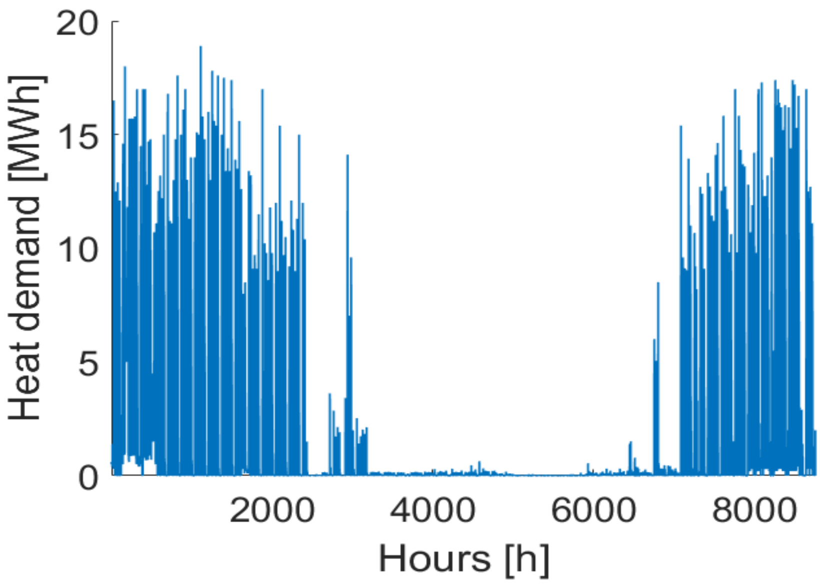


Figure 3.1: Polytechnic heat demand in 2017

Thanks to the data provided by LivingLAB [64], it was possible to measure the hourly heat demand

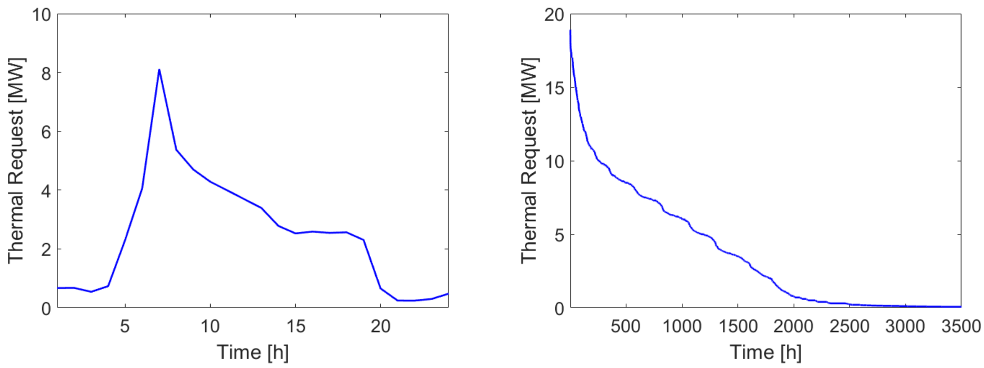
in the different stables of Polytechnic and recreate the total demand during the year,that can be seen in figure 3.1.
Polytechnic heat demand is characterized by:

1. Absence of a base load;

2. Absence of demand when Polytechnic is closed (*Ex: during the night and on holidays*);

3. Decreasing demand after a morning peak.

In figure 3.2a the average heat demand is shown and can be seen how after 8 p.m. there is almost no demand. The absence of a base load will affect the cumulative (*that can be seen in figure 3.2b*) and the operation of the production system.



(a) Polytechnic average heat demand for a winter day

(b) Polytechnic cumulative

Figure 3.2: Daily profile and cumulative of the case study

The next section will analyze the production units in Turin's DH, then the information about the CHP, HOB and storage will be used to construct a model able to cover the heat demand of the case study and, last, the models will be benchmarked.

3.2 Production units in Turin's DH

The city of Turin is the most district-heated city in Italy, and one of the most district-heated in Europe. Turin's network extends for about 550 km and is able to supply a volume of 60,3 million cubic meters, corresponding to around 600 thousands of inhabitants. Thanks to the increase of storage capacity, Turin's district heating system is mainly fed by three CHP plants, able to satisfy around 98% of the heat demand [47] while the remaining part is satisfied using heat-only boilers. In this section, a more detailed look at the plants and their description is provided.

Figure 3.3: Turin District Heating Network [45]

3.2.1 CHP

The CHP plants have similar characteristics, in particular there are two twin plants, called 2^{nd} GT and 3^{rd} GT that are part of the bigger plant "Moncalieri" and another CHP plant called TON

"Torino Nord" Plant, that is located in the northern part of the city.

2GT

The 2^{nd} GT is part of the Moncalieri cogeneration plant, that is made up of two combined-cycle cogeneration units. The 2^{nd} GT has a 400 MW_e capacity, and it was built by upgrading the existing cogeneration plant that had a capacity of 141 MW [43]
The plants is made up of:

- Gas Turbine able to generate about 270 MW_e with an efficiency of 39%
- Heat recovery steam generator with three pressure levels, fed with exhaust gas from the GT
- Condensation steam turbine with a capacity of 141 MW_e with extraction of steam system
- Heat production system for DH network 260 MW_t

In figure 3.4 the operating range of the 2GT is shown and can be seen that the minimum load allowed is 45%. Moreover, the production of 240 MW_{th} leads to the lack of production of 50 MW_e. In order to properly model the plant, not only the efficiency at full load is required, but also the one at partial loads and, since these data were not available, they have been assumed according to the technology used and their standard efficiency at partial load [25].

	P [MW]	Q [MW]	η
me	200	0	0,4
mc	180	200	0,76
ME	400	0	0,58
MC	340	260	0,9

Table 3.1: Characteristic points of 2GT

The different operating points are defined as follow:

- me: Minimum load in electricity mode
- mc: Minimum load in cogeneration mode
- ME: Maximum load in electricity mode
- MC: Maximum load in cogeneration mode

3GT

The 3^{rd} GT is part of the Moncalieri cogeneration plant, that is made up of two combined-cycle cogeneration units. The 3^{rd} GT has a 383 MW_e capacity, and it was built by upgrading the existing cogeneration plant that had a capacity of 138 MW [44].
The plants is made up of:

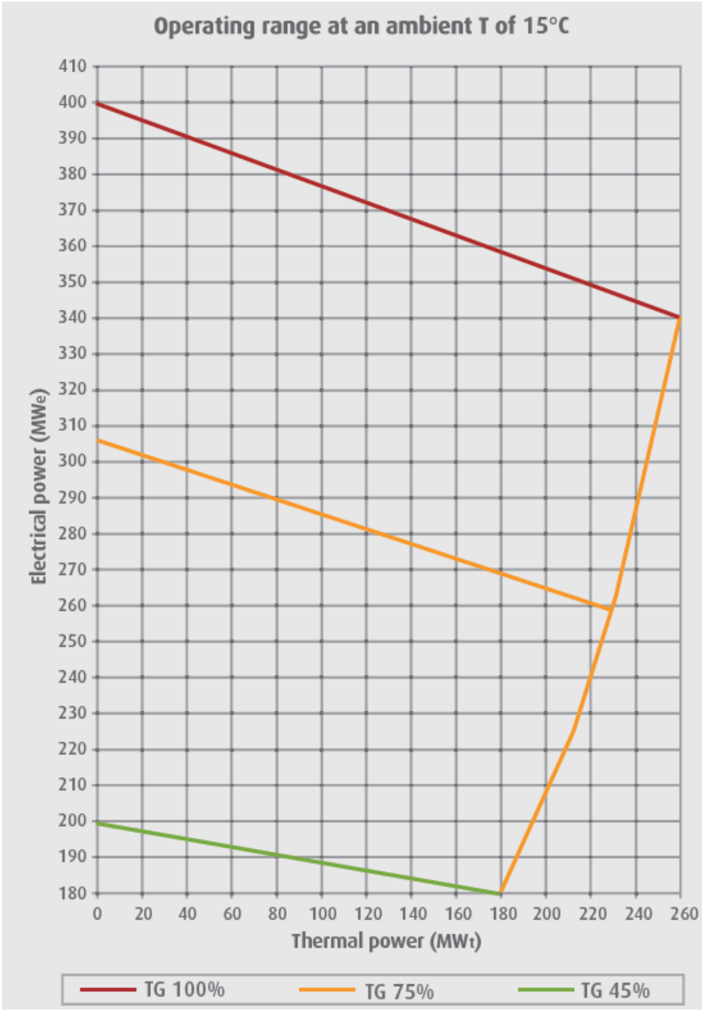


Figure 3.4: Characteristic points of 2GT in Moncalieri CP

- Gas Turbine able to generate about 260 MW_e with an efficiency of 39%
- Heat recovery steam generator with three pressure levels, fed with exhaust gas from the GT
- Condensation steam turbine with a capacity of 138 MW_e with extraction of steam system
- Heat production system for DH network 260 MW_{th}

In figure 3.5 the operating range of the 3GT is shown. The same consideration of 2GT can be applied to the 3GT, however, as can be seen, the main difference is that turbine 3GT operates at lower efficiency at partial load. Moreover, the minimum load allowed is 60% at partial load the production of heat leads to a decidedly lower production of electricity than the 2GT turbine. The resulting operating points are listed in table 3.2.

	P [MW]	Q [MW]	η
me	260	0	0,4
mc	185	190	0,75
ME	383	0	0,57
MC	322	260	0,87

Table 3.2: Characteristic points of 3GT

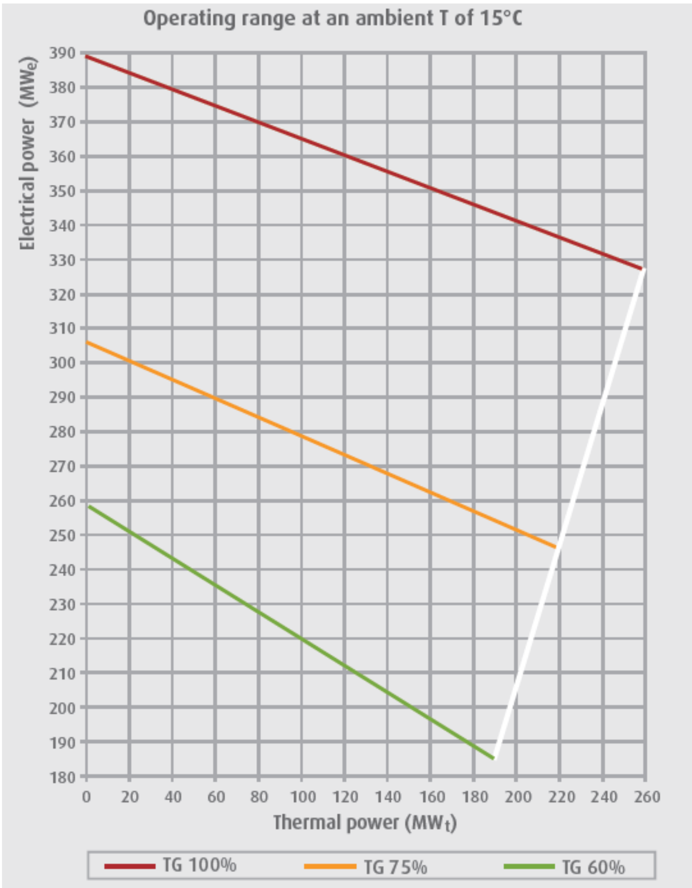


Figure 3.5: Characteristic points of the 3GT in Moncalieri CP

TON

The Torino Nord cogeneration plant is made up of:

- A combined-cycle unit with a 400 MW_e
- A gas turbine with electrical power of 270 MW
- Heat exchangers for district heating of 220 MW_{th}

The cogenerator has an efficiency of over 85% in cogeneration mode and 56% in electricity only mode [46], however the operation points are not given,except from maximum electrical power and its efficiency. Using also the data from [48] it is possible to reconstruct the operating range of the TON plant, shown in table 3.3.

	P [MW]	Q [MW]	η
me	200	0	0,4
mc	160	180	0,75
ME	390	0	0,56
MC	340	220	0,85

Table 3.3: Operating points of TON

3.2.2 Boiler

Several boilers, fed with natural gas, are used to cover peak demand. They are located in strategic places in Turin, such as BIT, Mirafiori Nord and Polytechnic itself. However, the role of boilers is decreasing more and more due to the need to maximize the utilization factor of CHPs and to reduce emissions, goal achieved through the increase of storage capacity. In table 3.4 are shown the main characteristics of the boilers.

	P [MW]	η
BIT	255	0,87
Mirafiori	35	0,87
Moncalieri	140	0,87
Politecnico	255	0,87
Torino Nord	340	0,87

Table 3.4: Boiler capacity and yield

3.2.3 Heat storage

A thermal energy storage can bring a lot of benefit if integrated in a DH system.

- Maximization of the efficiency of the system
- Reduction of heat generation installed capacity
- Increase the flexibility of CHP plant
- Reduction of the emission with respect to HOB

The system of heat accumulators has the function of storing the thermal energy generated by the thermoelectric plants in cogeneration at night, when the heat demand is less, to sell it during the hours of maximum load of the district heating network, reducing the use of integration boilers. It has a maximum delivery temperature of 120 °C and a return temperature of 70 °C. In table 3.5 the storage volume for different sites are shown.

	Volume [m^3]
Martinetto	5000
Politecnico	2500
Torino Nord	5000

Table 3.5: Heat storage volume

Summary

Looking at thermal power, the entire system can be summarized in the table 3.6 and as can be seen, since the peak demand is almost 1400 GWh, outages of CHPs or boilers can be taken into account.

	CHP [MW]	HOB [MW]	STORAGE m^3
BIT	-	255	-
Martinetto	-	-	5000
Mirafiori	-	35	-
Moncalieri	520	140	-
Politecnico	-	255	2500
Torino Nord	220	340	5000
TOT	740	1025	12500

Table 3.6: Turin heat production and storage for DH

3.3 Input data of the model

The starting point is the representation of Turin's production unit scaled to the case study and the resulting composition of the system is summarized in table 3.7.

	CHP [MW]	HOB [MW]	STORAGE m^3
BIT	-	3,46	-
Martinetto	-	-	67,86
Mirafiori	-	0,47	-
Moncalieri	7,05	1,9	-
Politecnico	-	3,46	33,92
Torino Nord	2,99	4,61	67,86
TOT	10,04	13,90	169,64

Table 3.7: Polytechnic heat production and storage for DH

After the analysis of the production unit of the case study, the attention is focused on several information needed to built the model, such as:

- Heat demand
- Economic aspects
- Environmental aspects

3.3.1 Heat demand

The Polytechnic heat demand has been previously shown in figure 3.1 and the main feature is the small need of heat from April to September, mainly related to the use of hot tap water. Focusing on space heating season (*October-March*) a detail of the previous graph is shown in figure 3.6. It can be seen that the heat demand follows a daily profile, with a peak in the morning and a decrease, due to the increase of external temperature; this trend is almost constant during the week with the exception of Sunday in which there is no need of heating. In figure 3.7 a comparison between heat demand in January and March is shown, and can be seen a decrease in the heat demand, mainly related to an increase of the external temperature.

3.3.2 Economic aspects

The purpose of this section is to provide information necessary for the construction of the model, including the prices of technologies and fuels and the main factors that influence them.

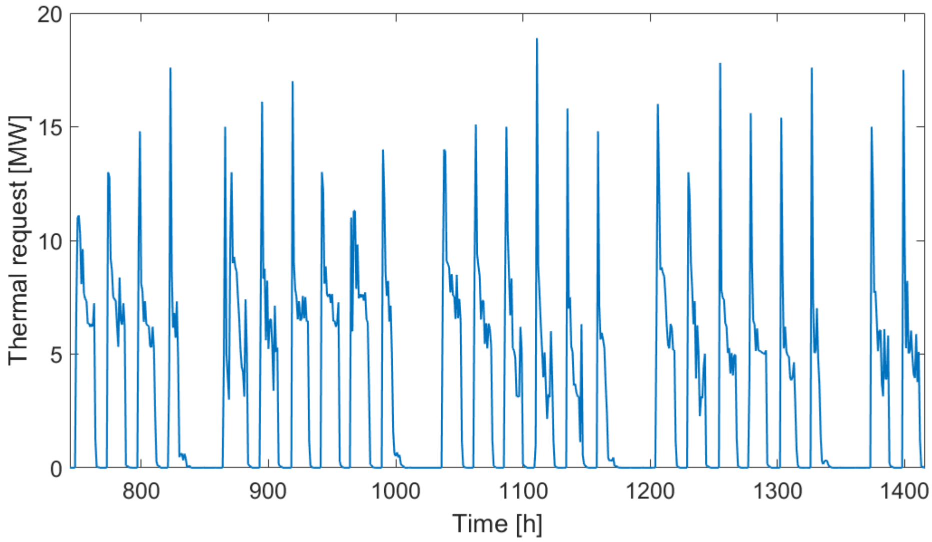


Figure 3.6: Polytechnic heat demand in February

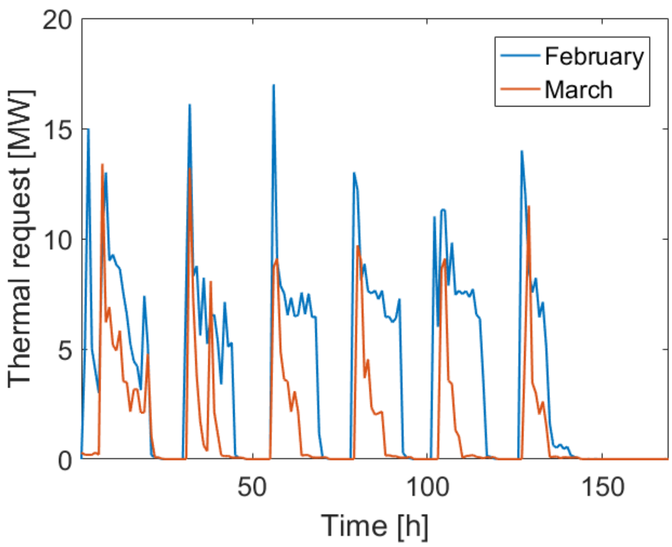


Figure 3.7: Heat profile in different months

Price of electricity and fuel

Since the plants are mainly CHP, heat and electricity production are strictly related, therefore to optimize the system it is important to known the electricity price and how it changes with time. These data are taken from GSE [36] and represents the day-ahead market. The result is shown in figure 3.8.

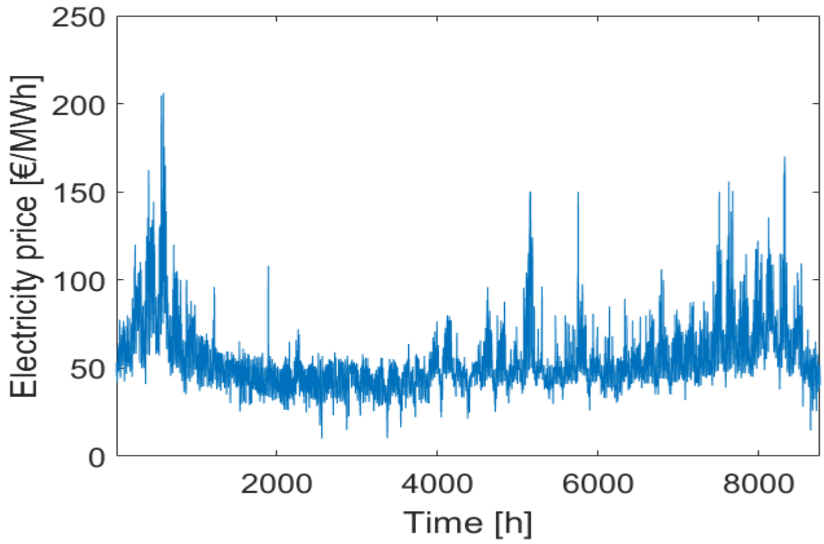


Figure 3.8: Electricity price during the year

For natural gas, that represents the main fuel for both CHP and boiler, the price has been considered time variable and its cost is taken from ARERA [4]. In particular there is a higher price in the first four months and the lowest price is in the third quarter, during summer.

CHP

The combined production of heat and power allows to lower variable costs with respect to separate production, moreover the production units analyzed use mature technology, therefore the costs associated will be relatively low. In the table 3.8 the main technologies used for combined heat and power production and their relative costs are shown.
From the table 3.8 can be seen how specific investment costs decreases as the size increases and the same for variable costs. Taking into account the gas combined cycle example, the minimum size is about 10 MW, while in the case study turbines have a nominal power of 2.6 MW. A way to take into account the size of the plant could be using the economy of scale, as suggested in [25]. The expression that relates costs and size is:

$$\frac{c_1}{c_2} = \left(\frac{p_1}{p_2}\right)^a$$

Where c and p represents the costs and sizes of the plants, while a is a proportionality factor (*often 0.6 or 0.7*). The approach followed in the thesis is to use specific and operative costs of the original plants, that have a power of around 270 MW; this because the Polytechnic represents only a single substation of the DH network and with the first assumption the specific costs would be too high for the plant to be profitable.
Moreover, looking at the table 3.8 can be seen that waste-to-energy CHP plant has the highest

Category Name	Investment cost M€/MW	Fixed O&M €/MW/y	Variable O&M €/MWh	Lifetime y
Gas turbine single cycle (0.1-5 MW)	1.65		8	10
Gas turbine single cycle (5-40 MW)	0.84	9300	3.8	25
Gas turbine single cycle (40-125 MW)	0.57	8550	3	25
Gas turbine combined cycle (10-100 MW)	0.835	12000	3.2	25
Gas turbine combined cycle (100-400 MW)	0.575	14000	1.8	25
Gas engines (1-10 MW)	1.15		9	25
Waste-to-energy CHP plant	8.5	155000	22	20
CHP Wood chips (8-10 MW)	4.85		8.3	20
CHP Wood chips (10-110 MW)	1.5	29000	3.2	30
CHP Straw (10-100 MW)	2.7	38000	6.1	25
Biomass gasifier,updraft	3.6	180000	18	20
Biogas plant (3MW)	3.4		30	20

Table 3.8: Investment, O&M cost and lifetime of different kinds of CHP

cost, several times with respect to fossil fuels plants, therefore from an economic point of view it is not feasible to substitute combined cycle CHP with this kind of plant. A more cheaper alternative could be represented by other renewable plants, as biomass plants (*wood chips or straw*) or biogas plant, that however are more expensive and bound to the presence of biomass.

Boiler

The information on the boilers are taken from [25] and re-adapted from Nielsen and Moller article [71]. The same consideration on size and prices can be applied on boilers too and can be seen that the cheapest technology is represented by electric boilers, followed by gas boiler and that biomass boiler costs up to 4 times an electric boiler, with operational costs higher for biomass. However the operational costs do not include fuel costs, therefore the cheapest technology depends from electricity prices of the country.

Category Name	Investment Cost M€/MW	Fixed O&M €/MW/y	Variable O&M €/MWh	Lifetime y
Electric boilers (1-3 MW)	0.135	1000	0.5	20
Electric boilers (3-10 MW)	0.075	1000	0.5	20
Electric boilers (10-20 MW)	0.06	1000	0.5	20
Wood chip boiler	0.21	23500		20
Straw boiler	0.26		2.8	20
Wood pellet boiler	0.17		3.1	20
Gas boiler	0.09		0.54	20

Table 3.9: Investment, O&M cost and lifetime of different kind of boilers

Storage

Storage information have been adapted to the case study from [90] and the specific investment cost has been evaluated with the size of the original system, that is around 5000 m^3, leading to an investment costs of around 150 €/m^3.

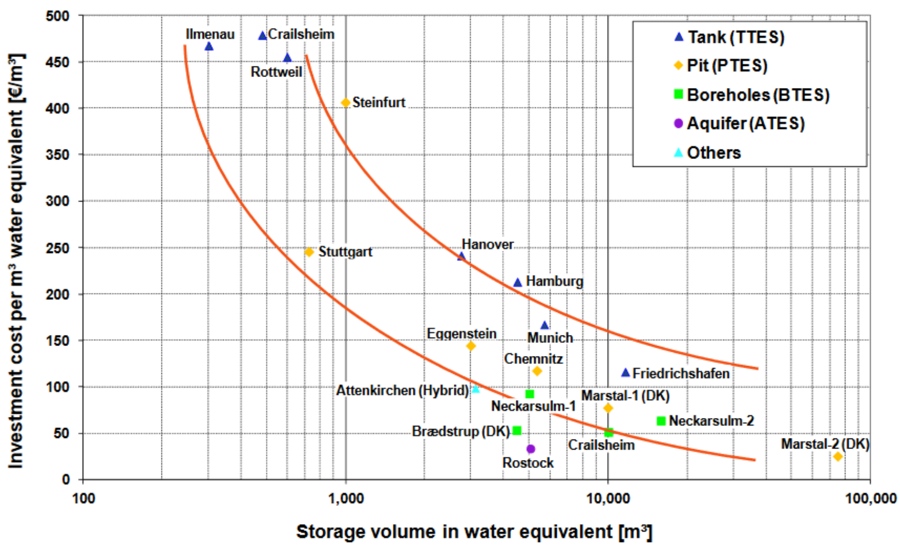


Figure 3.9: Investment cost with respect to size of the storage [90]

For the analysis it was supposed that storage does not have operational costs, even if they are driven by electrical pump to charge and discharge the hot water.

Excise & taxes

In Italy there are different taxation for the same product (natural gas) depending on its use, electricity production or heat production. Natural gas is the most used fuel for space heating and it has several separate rates, that depends on use, quantity and location.

	Usi civili Fasce di consumo annuo				Usi industriali Fasce di consumo annuo	
	$\leq$ 120 m^3	$\leq$ 480 m^3	$\leq$ 1560 m^3	$>$ 1560 m^3	$\leq$ 1.2 Mln m^3	$\geq$ 1.2 Mln m^3
Accisa c€/m^3						
Normale	4.4	17.5	17.0	18.6	1.2498	0.7499
Ex-Cassa Mezzogiorno	3.8	13.5	12.0	15	1.2498	0.7499
Addizionale regionale c€/m^3						
Piemonte	2.2000	2.5800	2.5800	2.5800	0.6249	0.5200
Veneto	0.7747	2.3240	2.5823	3.0987	0.6249	0.5165
Puglia	1.9000	3.0980	3.0980	3.0980	0.6249	0.5164
Campania	1.9000	3.1000	3.1000	3.1000	0.6249	0.5200

Table 3.10: Excise on natural gas for different quantity,location and purpose [6]

Electricity production is subject to an excise tax of 0.04493 c€/m^3, that is reduced to 30% in case of self-consumption. Analyzing the case study, it can be seen that natural gas will be subject to an excise of 0.7499 c€/m^3 plus a regional excise of 0.52 c€/m^3. Since cogeneration includes both electricity production and thermal usage of the fuel, there is a tax liability of 0.22 m^3 of natural gas for each KWh electric produced (*that represents the specific consumption of a plant with an electric efficiency of 47%*) while the remaining part of the gas is subject to heat excise.
Moreover, if electric production is at least 10% of the sum between thermal and electrical production, even the heat produced by integration boilers is subject to industrial excise duty [6].
Looking at emission taxes, even if Italy has the 5th highest tax rate on energy on an economy-wide basis [75], it does not have an explicit CO_2 tax and follows the European Trade Scheme, with a price of around 7.24 €/ton. On the other hand, in many region are present taxes on pollutant, as NO_x, that is applied on plant whose capacity is over 50 MW and that exceed emissions specified in the EU Large Combustion Plant Directive.

3.3.3 Environmental aspects

This section aims to provide information on the emission factors of pollutants for different technologies, with particular attention on the allocation factors used for cogeneration plants.

Allocation factors

From an environmental point of view the combined production of heat and power helps to reduce emissions, however, the law does not impose a method on how to allocate emissions related to heat production and those related to electricity production. Several studies have been done proposing different method for the allocation of costs and emissions in a CHP plant [22], [72]. Below are described 3 methods that have been compared for the allocation method, with pros and cons. These methods aim to define α_E and α_Q, that represents respectively the percentage of costs (*and emissions*) associated to electricity and heat production in a CP.

1. Energy methodology
   It is the simplest method and is based on the calculation of the share between heat and power. The allocation factors α_E and α_Q are defined as follows:

   $$\alpha_E = \frac{E}{E + Q}$$

   $$\alpha_Q = \frac{Q}{E + Q}$$

   Where:

   - E is the electricity produced
   - Q is the heat produced

   This method is not able to take into account the different quality of the energy flows (*exergy*) however it is interesting to notice that it is independent from external parameters that can affect the results.

2. Power bonus methodology
   This method is extended from EN 15316-4-5:2017 and it is described for the application to District Heating Systems. A similar logic can be applied to a CHP unit, by considering its primary consumption $f_{P,Q}$ defined as follows:

   $$f_{P,Q} = \frac{F * f_{P,NG,ref} - E * f_{P,E,ref}}{Q}$$

   Where:

   - F is the fuel consumption
   - $f_{P,NG,ref}$ is the primary energy factor for natural gas, equal to 1.05
   - $f_{P,E,ref}$ is the primary energy factor for electricity, equal to 2.42

Finally the allocation factors are:

$$\alpha_Q = \frac{Q * f_{P,Q}}{F * f_{P,NG,ref}} = \frac{F * f_{P,NG,ref} - E * f_{P,E,ref}}{F * f_{P,NG,ref}}$$

$$\alpha_E = 1 - \alpha_Q$$

This method is strongly affected by reference primary energy factor, that are related to the National electricity mix, the conversion efficiency of the power plants and the transmission losses of the power network.

3. Heat bonus methodology
The heat bonus methodology is strictly related to the power bonus methodology, translating the concept from the electricity production to the heat production. The allocation factors are defined as follows:

$$\alpha_E = \frac{F * f_{P,NG,ref} - Q * f_{P,Q,ref}}{F * f_{P,NG,ref}}$$

$$\alpha_Q = 1 - \alpha_E$$

Where $f_{P,Q,ref}$ is the primary energy factor supposing that the alternative production will be satisfied by distributed conventional natural gas boilers with a conventional thermal efficiency of 90% and it is equal to 1.5.

The current standard in the European Union is the power bonus method, however when the CHP has an electric efficiency higher than the national average, the allocation factor for heat is set to null; this problem has been found during the analysis, therefore it has been decided to use the heat bonus methodology.

Emission factors

For boilers the emission factor has been considered equivalent to 201.24 t/GWh [49] and it is referred to the fuel energy content, while for the CHP plants the values are shown in table 3.11, for the CO_2 it has been decided to use the same value used for the natural gas of the boiler, while for the particulates emission real data have been used.

	CO_2 emission factor t/GWh	NO_x emission factor t/GWh	CO emission factor t/GWh
Moncalieri (2GT and 3 GT)	201.24	0.074	0.052
Torino Nord	201.24	0.020	0.109

Table 3.11: Emission factors for CCGT plants [48]

3.4 Creation of the models

The data obtained from the previous section will be used to build a model with two different software, EnergyPRO and LP2, that are widely used for CHP-DH simulations. First, the software and its main features will be described highlighting the pros and cons of each one; then, the reference model will be built, the two models will be benchmarked and lastly one of the two software will be used to model base-case and alternatives.

3.4.1 EnergyPRO model

Software

Simulations have been performed using EnergyPRO 4.5, a module-base software able to model, optimize, simulate and analyze energy plants (except nuclear power plants) commercialized by EMD International A/S [24].It was initially developed for the optimization of CHP power plant [16] but with more than 50 versions released in the last 20 years it has been modified to include basically every kind of plant. It follows a deterministic approach, which is based on user-defined inputs as time series for demands, fuels, energy conversion units, taxes etc. Using time series is even possible to simulate DAH power market. In particular it is able to solve the optimal operation strategy applying a minimization of the total variable costs so that heat and power demand are met. It has been used a hourly resolution to represent the heat demand, but also shorter time steps can be used.
The main characteristic of EnergyPRO is that the optimization is not performed chronologically, but it is based on a priority order that takes into account several economic factors, as revenues from electricity sales for a CHP, taxes and incentives and constraints about the plants. The priority numbers are determined for each time step and for each production units. The optimization starts filling the hours in which the production units have the lowest priority number, consequently the optimization is performed in a non-chronological way [106]. This is possible only due to the fact that electricity prices and variable costs are assumed well known during the planning period, even if in reality this may not be completely true. Usually short-term power price and heat demand forecasts are performed to better couple production, storage and sells, making the optimization method realistic.
During the last years EnergyPRO has been used in several project that ranges from the market analysis of CHP [30] to the coupling between CHP and thermal storage [31]. Different scales can be modelled with EnergyPRO, as can be seen from the article made by Kiss [53] that modelled national analyses of Hungary to city scales, or the article made by Wang et al. [99] that compares a linear programming optimisation model (LP) with EnergyPRO and it is applied on a hybrid renewable energy systems for communities.

Reference model

The starting point is the definition of the input data and the production units.
All the data needed are loaded as timeseries if they are time variable (*Heat demand, DAH*), or simply loaded as value if constant (*emission factors, taxes*).
The first obstacle trying to simulate the CHP is that the software assigns an univocal correspondence between heat and power, as shown in figure 3.10, while with the extraction of steam it can operate in a wide range. The area between the points DCBA is the actual area of operation, while the software operate on the straight line DB. To solve this problem, the first approach was using the same method used in Lewe's Master thesis [63]. In order to simulate the entire operational range of the CHP it has been decomposed in four units:

- Two purely power producing units called A and D
- One CHP unit called B
- One electrical heat pump called C

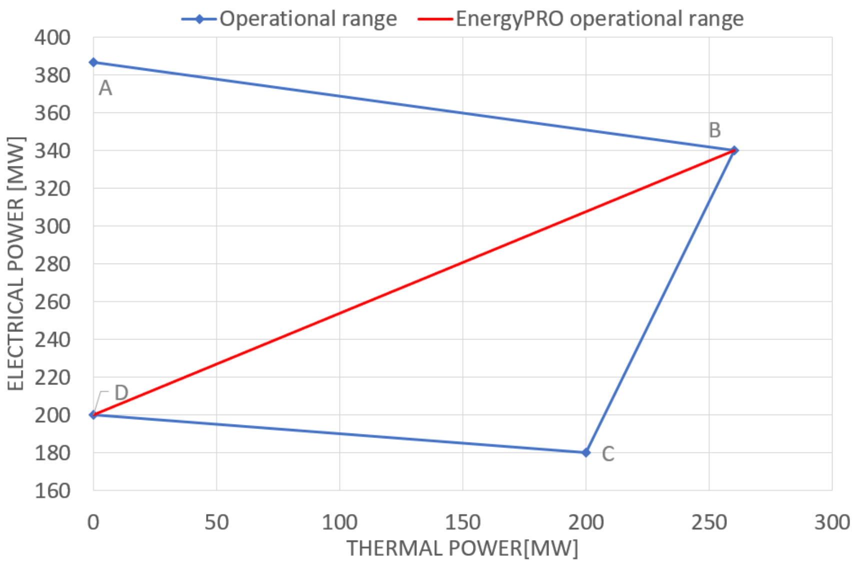


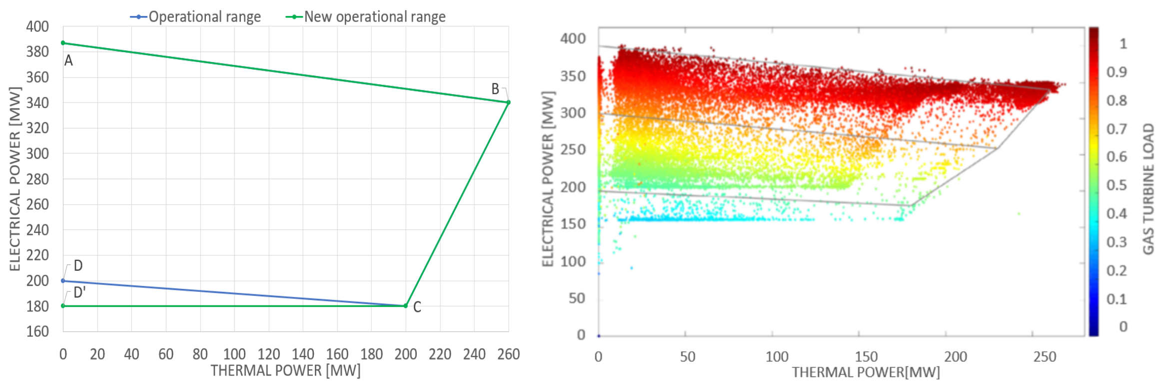
Figure 3.10: Operational range of the 2GT with EnergyPRO assumptions

The plant D produces only electricity with an efficiency of 40% [25], this aims to represent the minimum electricity efficiency of gas turbine and steam turbine at partial load. If unit D is operating, the heat pump can start, converting the amount of electrical power $P_D - P_C$ into the amount of heat Q_C. If the heat demand is higher, the CHP can start operating, producing at the same time heat and power, in particular $P_B - P_C$ and $Q_B - Q_C$. On the other hand, if it is economically feasible and the heat demand can be satisfied without the CHP plant, it can operate in a full electric mode using the two purely power units, A and D. The other unit are modelled in

order to obtain the same efficiency in point A,B and C , also partial load is allowed to cover the entire area and to not exceed the line AB a limit to the amount of fuel has been imposed.
This approach is fundamental to simulate the CHPs in this kind of situation, where heat demand does not have a constant base load (*often is 0 during the night*) and as a result, the plant was shut down due to the impossibility to reach electrical efficiency of point A. It is also possible to obtain a wide range of efficiency that the plants is able to reach, not only a linear interpolation between a maximum and minimum efficiency.
However, since the problem involves three CHP plants, the simulation lasts around two hours, whereas before it lasted only few seconds (the computer used a processor Intel(R) Core(TM) i7-4720HQ @2.6 GHz). Analyzing the software it has been discovered that the CHP is able to reproduce even a broken line, but both power and heat must be strictly increasing, therefore the system has been modified and as can be seen in figure 3.11, now the operating point are D'CBA. The main differences is the assumption that partial load is even lower with respect to the one indicated from manufacturer, but it is justified looking at functioning point from real data, shown in figure [48]. The new configuration is made up of only two components:

- A CHP with functioning range D'CB
- A purely power unit

With the same approach used by Lewe [63] the purely power unit can start only if the CHP is already operating. Instead, CHP has a minimum load, that is represented by the point D' and a maximum point, that is represented by point B. As done before, there is a maximum amount of fuel used to not exceed the line AB and the efficiency in point A,B and C is the one stated by the manufacturer.



(a) Modified operational range (b) Real operational range

Figure 3.11: Comparison between hypothesized operational range and real operational range

The resulting system can be seen in figure 3.12 where the different thermal storage and boilers have been represented with only one unit per type.

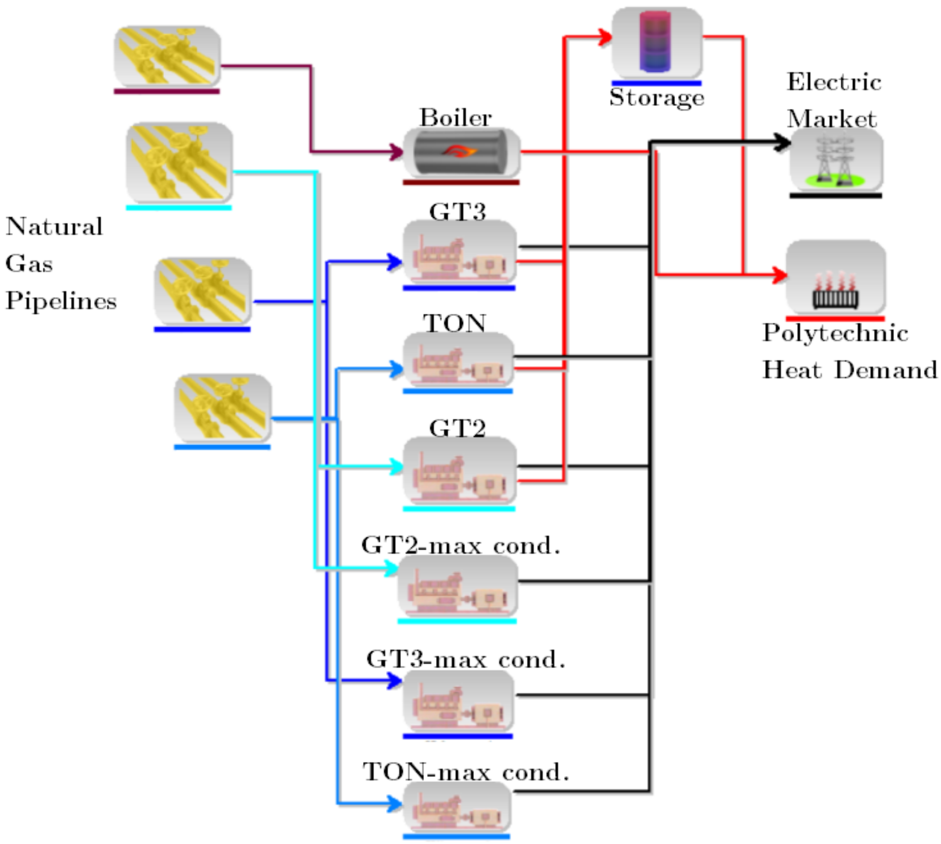


Figure 3.12: DH production units for the case study

3.4.2 LP2 model

In this section, the starting point is the analysis of a single CHP planning model, on which the entire system will be developed later.

Single CHP planning model

The characteristic operating region is assumed to be convex in terms of heat and power, and that the fuel consumption is also a convex function of the corresponding heat and power production [86]. The convexity of an operating region means that if the CHP can operate at two different points, it can also operate at any point on the line segment connecting them. Based on the convexity assumption, a CHP plant can be represented as a convex combinations of its characteristic points (p_j, q_j, f_j).

$$\begin{aligned} P &= \sum_{j \in J} p_j x_j \\ Q &= \sum_{j \in J} q_j x_j \\ F &= \sum_{j \in J} f_j x_j \\ \sum_{j \in J} x_j &= 1 \\ x_j &\geq 0, j \in J \end{aligned} \tag{3.1}$$

Where:

- P is the power production;
- Q is the heat production;
- F is the fuel consumption;
- (f_j, p_j, q_j) are the characteristic point of CHP in terms of fuel, power and heat;
- x_j is the decision variable encoding the convex combination of the operating region;
- J is the index set of characteristic points of CHP.

This assumption may seem limiting, however the operating region of many backpressure plant is convex and in more advanced CHP production technologies, such as combined gas and steam cycles the operating region may still be convex [84]. If this is not possible, the operating region can be divided into convex subregion and then encoded as a mixed integer programming model (MIP) that can be solved using branch and bound algorithm, as done by Lahdelma et al. [68].

The planning period varies from a few days in a medium-term model to one or even several years in strategic long-term model. A long-term CHP planning model can be solved by decomposing it into hourly models which are solved independently using linear programming (LP) [55], mixed integer linear programming (MILP) [85] or other fast algorithms according to the detailed problem formulation [87].

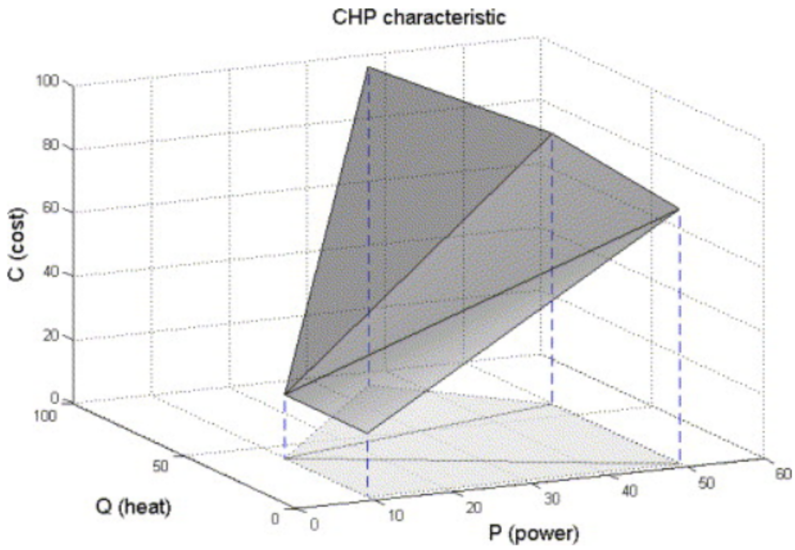


Figure 3.13: Characteristic point and feasible operating of a CHP [84]

The basic solution of the problem considering only a single CHP with heat and power demand can be written as follow:

$$min \sum_{j \in J} c_{FUEL} f_j x_j \tag{3.2}$$

Where c_{FUEL} is the cost of the fuel.

Reference model

The reference model is way more complicated, since include the presence of 3 CP, 1 HOB and a storage. The objective is to minimize the overall costs (Z) satisfying the hourly heat demand by adjusting production components. The objective function is defined as:

$$min\ Z = \sum_{t=1}^{T} \left(\sum_{j \in J_u, u \in U} c_j^t x_j^t \right) \tag{3.3}$$

Where:

- c_j is the cost function and depends on the production units;
- T is the planning period (*one year*);
- J_u is the set of extreme points of plants u;
- U is the set of all plants in the system.

For a CHP the expression is:

$$c_{CHP}^t = c_{FIXED} + f_j^t \left(c_{FUEL}^t + c_{TAX} + c_{EM} \right) + p_j^t \left(c_{OP} - c_{RHI} - c_{EL}^t \right) \tag{3.4}$$

Where:

- c_{FIXED} are fixed costs;
- c_{TAX} are the cost associated to excise and taxes;
- c_{EM} are the cost associated to emission fees;
- c_{OP} are the operational costs;
- c_{RHI} are the renewable heat incentives (*revenues*);
- c_{EL} are revenues related to the electricity sale in the spot electricity market.

It can be seen that the cost function is time dependent, since it depends from the spot electricity price and the fuel price, assumed variable in time.
For a boiler the expression can be written as:

$$c_{BOILER}^t = f_j^t \left(c_{FUEL}^t + c_{TAX} + c_{EM} + c_{OP} \right) \tag{3.5}$$

The heat demand of the system can be satisfied by the CHP or by other heat production facilities, considering the presence of the thermal energy storage.

$$\sum_{j \in J_u, u \in U} (q_j x_j)^t - q_{chr}^t + \eta_{qdis} q_{dis}^t = Q^t \tag{3.6}$$

Where:

- q_{chr}^t and q_{dis}^t are respectively the charging and discharging amounts of heat at time step t;
- η_{qdis} is the discharge efficiency;
- Q^t represents the heat demand.

Similarly to heat balance, power production is described as:

$$\sum_{j \in J_u, u \in U} (p_j x_j)^t = P^t \tag{3.7}$$

Where P^t is the amount of power that the system is able to sell to the grid.
The TES balance consider an hourly efficiency of the storage [83], and efficiency for the charging, while discharging efficiency has been considered directly in the Eq. 3.6 on heat balance. This includes the losses due to heat conduction and radiation [1].

$$S_q^t = \eta_{qs} S_q^{t-1} + \eta_{qchr} q_{chr}^t - q_{dis}^t \tag{3.8}$$

The constraints for the energy storage can be seen in Eq. 3.9 and Eq. 3.10

$$S_q^{min} \leq S_q^t \leq S_q^{max} c \tag{3.9}$$

It has been also added a maximum charge/discharge time, that resemble the concept of power ramping constraint.

$$\begin{aligned} q_{chr}^t &\leq q_{chr}^{max} \\ q_{dis}^t &\leq q_{dis}^{max} \end{aligned} \tag{3.10}$$

Where:

- S_q is the storage level;
- S_q^{max} is the maximum capacity of the storage, evaluated through EnergyPRO;
- S_q^{min} is the minimum capacity of the storage, set equal to 0;
- q_{chr}^{max} and q_{dis}^{max} are the maximum charge and discharge capacity and have been set equal to half of the total capacity.

The Eq. 3.10 states that the minimum charge/discharge time is 2 hours, or more explicitly that the maximum charged/discharged heat in an hour is half of the capacity of the storage [101].
Finally, the convexity and non-negativity constraints are expressed below:

$$\sum_{j \in J_u, u \in U^{pq}} x_j = 1 \tag{3.11}$$

$$x_j \geq 0, j \in J_u,\ u \in U^{pq} \tag{3.12}$$

$$0 \leq x_j \leq 1, j \in J_u, u \notin U^{pq} \tag{3.13}$$

Where U^{pq} is the index for CHP plants.

For a long time horizon, the model may become very large. In that case, it can be solved using special decomposition techniques, by solving hourly models separately and coordinated under top-level iteration to consider dynamic constraints . In the thesis the model has been solved using LP2, which is based on the sparse revised Simplex and the product form of inverse [55]. LP2 can run in LP or MILP mode depending on the problem formulation, but it has been decided to use the LP mode in the following case study in order to reveal more details behind the algorithm and help understand the process of making an optimal planning and operation of such CHP-DH system.

3.5 Benchmarking of the model

Since each software have different features and limitations,to compare the production system in LP2 and EnergyPRO, it has been decided to recreate a simplified model that can be handled by both software.
The simplified model:

- Not include storage losses (*since the software have two different approaches*)
- Not include limitations on maximum heat charged/discharged in a single time-step (*feature not present in EnergyPRO*)
- Allows CHP to work at any partial load

Results

The comparison between the two models shows the same objective function (*table 3.12*). Moreover, to get additional information, two error indicators have been analyzed:

- Mean error (ME): $\frac{\sum_{t=1}^{T} y_t - x_t}{T}$
- Mean absolute error (MAE): $\frac{\sum_{t=1}^{T} |y_t - x_t|}{T}$

Where T=8760 and y_t and x_t represent the production of heat for the two models in each time-step. Since the mean error is subject to compensation between positive and negative values, it is not able to prove the goodness of a measure and it is often coupled with the mean absolute error, which is not subject to compensation.
Looking at the table 3.12 can be seen that ME is ≈ 0 and MAE is slightly higher than 0, highlighting the similarity between the two models, with the possible presence of compensating errors.

	LP2	EnergyPRO
Objective Function	226328	226327
ME	$6.8\ 10^{-6}$	
MAE	0.03	

Table 3.12: Comparison of LP2 and EnergyPRO results

In table 3.13 the share of different plants in the two models is shown and can be seen that it is almost the same, with some differences in the use of the 3 CHP, but with the same value for the HOB.
In figure 3.14, 3.15, 3.16 electricity production, heat production and storage content of the two models are compared. Most of the time the two trends overlap and there is a slight difference only in some time steps due to a different use of storage (*ex: around hour 85*), that however not

	LP2	EnergyPRO
GT2	37.99	37.90
GT3	49.05	49.20
TON	12.47	12.41
HOB	0.49	0.49

Table 3.13: Comparison of the annual heat production share for LP2 and EnergyPRO

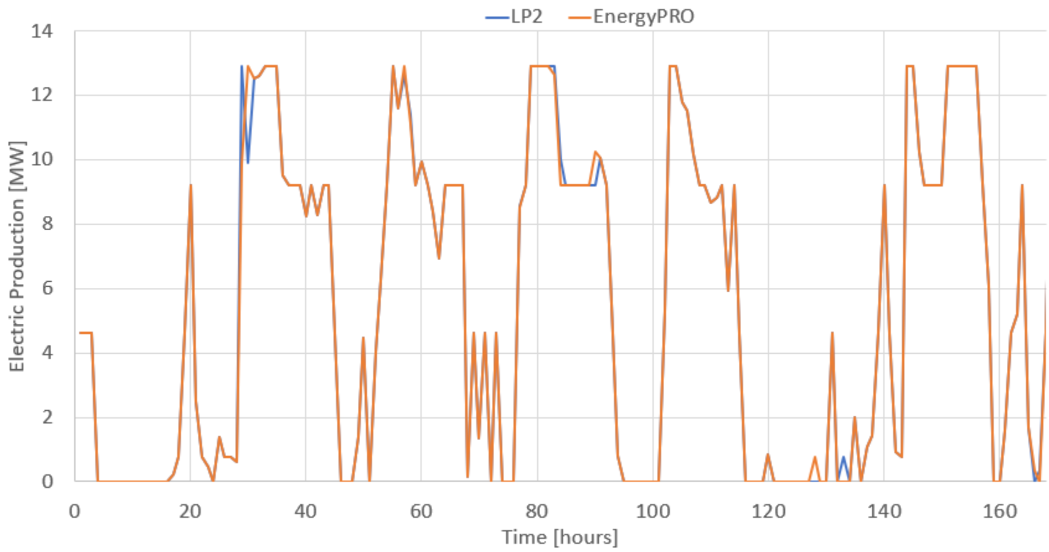


Figure 3.14: Comparison of electricity production for LP2 and EnergyPRO

affect objective function. The three figure are closely linked since electricity and heat production are strictly connected in a CHP and storage content is related to the heat production. The two software have been already compared in[1],[99] and used in real cases [63], but there is no obvious advantage between the two. EnergyPRO has a Graphical User Interface (GUI),which appears to be more user-friendly, while LP2 use a Command-Line Interface (CLI), that for large system may become complex, however, differently from EnergyPRO, it allows modification of all parameters. It has been decided to use LP2 for its flexibility, since EnergyPRO is not able to represent a maximum charge/discharge constraint on the storage, component that will be fundamental with the introduction of renewable.

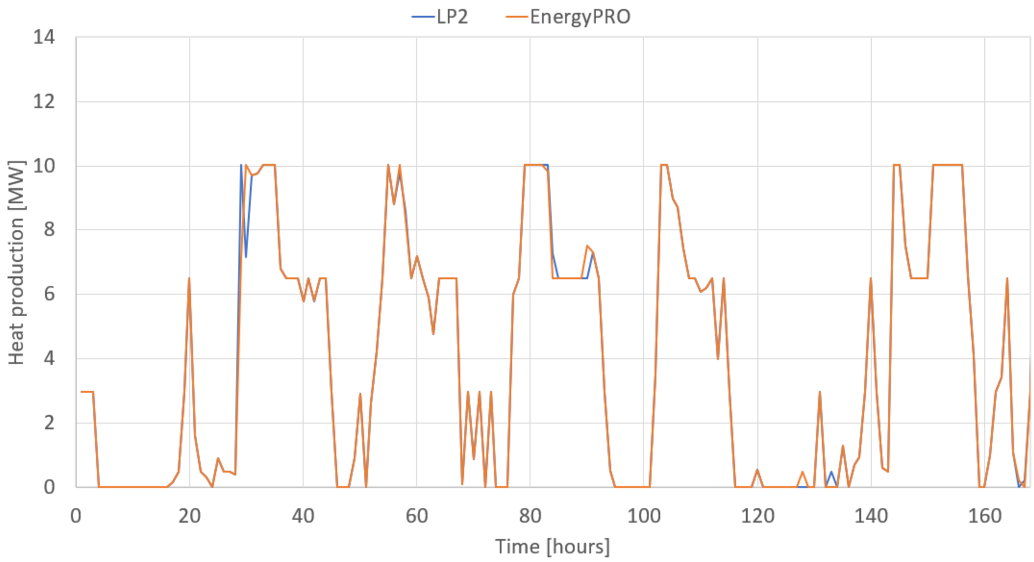


Figure 3.15: Comparison of heat production for LP2 and EnergyPRO

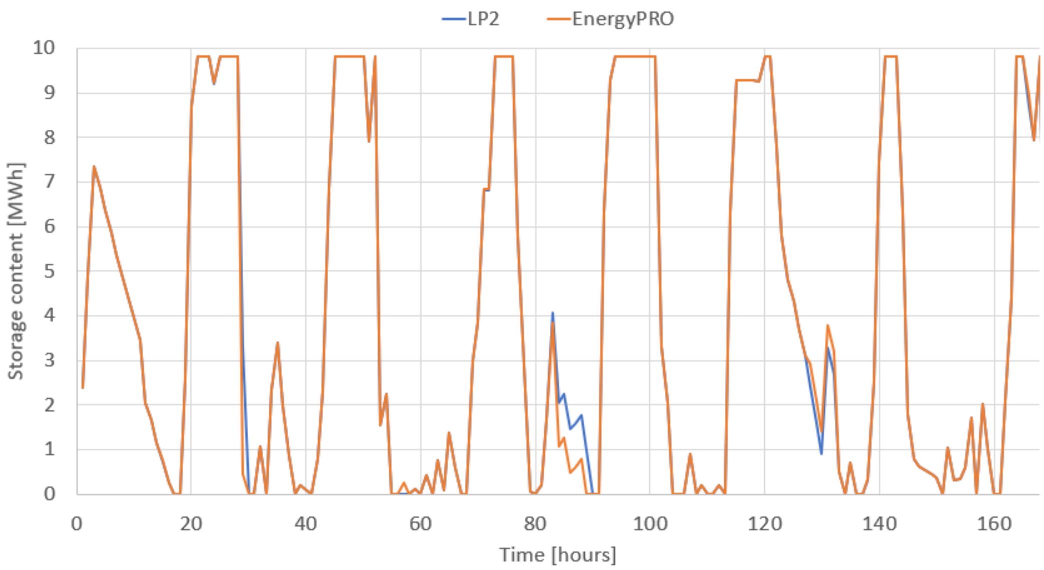


Figure 3.16: Comparison of storage content for LP2 and EnergyPRO

Chapter 4

Scenario Design

The chapter aims to complete stage 1 of the proposed methodology, identifying the set of criteria used in the next part of the analysis and possible alternatives, modelling, optimizing and evaluating outputs for the multi-criteria decision analysis.
The selection of criteria itself may influence the results of the analysis, therefore it should be carefully performed, as suggested by [50]. Also, since criteria should be measurable, knowing them in advance may be helpful while modelling the alternatives.
To create the set of alternatives several technologies have been surveyed during the first part of the work, however not every alternative was feasible applied to the case study. Unfeasible alternatives included carbon-capture and storage (*since it does not add any capacity or flexibility to the actual system*). Also geothermal plants, surplus heat from industries and heat from the incineration of municipal solid waste, were not considered because these technologies are not available in the case study. The alternative chosen are summarized in table 4.1 and includes the most promising technologies that can be used in Piedmont.

Alternative	Description
BC	Base case
BCS	Base case with increase of storage
SH	SH plant without heat storage
SHS	SH plant with heat storage
SHSS	SH plant with seasonal storage
GSH	GSH without storage
GSHS	GSH with storage
BB	Biomass boiler
EB	Electrical boiler

Table 4.1: Set of alternative scenario

For each scenario first the technology will be briefly described, then its current use, with economic data and incentives will be discussed and after that, the sizing of the plant will be carried out.

4.1 Criteria selection

Criteria have been chosen trying to satisfy the requirement described by [50]:

- Completeness: the criteria ensemble should reflect the features and performances of the whole energy system.
- Operationality: all the important points of view of the problem are covered.
- Non-redundancy: two or more criteria should not measure the same thing.
- Minimality: the dimension of the problem should be kept to a minimum.

The criteria selection is performed trying to properly represents the case study and highlight possible changes resulting from the introduction of new technologies.
Criteria can be divided as follows:

- Economic: in the analysis two economy-related criteria have been considered, the investment cost and the operational cost.
- Environmental: the criteria included in the analysis are CO_2 and pollutants emissions, that varies with the technology used.
- Technical: from the technical point of view it has been considered important to increase production capacity to replace heat-only boilers for peak heat demand. However, the introduction of new capacity should not be used only to cover peak demand, but should increase the flexibility of the system. Flexibility measures how energy production can be started, adjusted and operated on partial load to match the demand in different situations.

Criteria	Description
Cost	
C1 Investment cost	Cost of initial investment for the alternative
C2 Operational cost	Cost of the production system for fuel, electricity and maintenance
Environment	
E1 CO_2 emissions	The total CO2 emission of the production system
E2 Pollutants emissions	Other emissions caused by the technology
Technical	
T1 Flexibility	Fast-response adjustment of production volume

Table 4.2: Criteria chosen to evaluate carbon-neutral heat-only production technologies for the case study

The criteria chosen for the analysis are summarized in table 4.2. Usually, after the analysis of the criteria, there is the criteria weighting, where weights are assigned to the criteria to indicate their

relative importance. As a result, different weights will influence the results of the analysis, therefore it is necessary to obtain rational and consistent value for different weights, able to represent DM preferences.
Since assigning a unique value to weights could lead to incorrect results, it has been decided to use Stochastic Multiobjective Acceptability Analysis (SMAA), able to handle these kind of uncertainties and described in the next chapter.

In the next sections, the set of alternatives will be intensively modelled and described.

4.2 Base case

The reference model is based on the Turin production unit, intensively described in the section 3.2 and adapted with the input data described in section 3.3 to recreate a case study based on Polytechnic heat demand.
Using the LP2 software the system has been modelled as described in the previous section, simulating the CHP as a convex combination of its characteristic points (*Eq.3.1*) and then applying constraints with the system of equation 3.3-3.13 for the entire planning period.
Analyzing the table 4.3, in which the main outputs are shown, can be seen that the base case has a much higher operational cost than the test case, this because the previous model was able to work at any partial load. However, from an economical and environmental point of view this is not acceptable, since at partial load the efficiency decreases and emissions increase, therefore, according to the operating range described in section 3.2, the CHP are not allowed to work under 45% of maximum load. To calculate the emissions, the allocation factors have been evaluated through the heat bonus methodology, as stated in section 3.3.
In table 4.4 the heat share for different plants is shown and can be seen the marginal role of the heat-only-boiler, that produce less than 1%. The purpose of the alternative proposed is to limit even more the production of heat with boilers, taking advantage from storage and renewable.

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
Base case	0	360000	3800	2.41

Table 4.3: Main outputs of the model for the base case

	Share
GT2	31.62
GT3	10.84
TON	56.70
HOB	0.84

Table 4.4: Heat production share for the base case

Last, in figure 4.1 the cumulative for the optimized base case is shown and can be seen how storage helps to increases the capacity factor of the CHP and fill the gap between the maximum value of heat demand (*18.9 MW*) and the maximum value of heat production(*14.2 MW*).

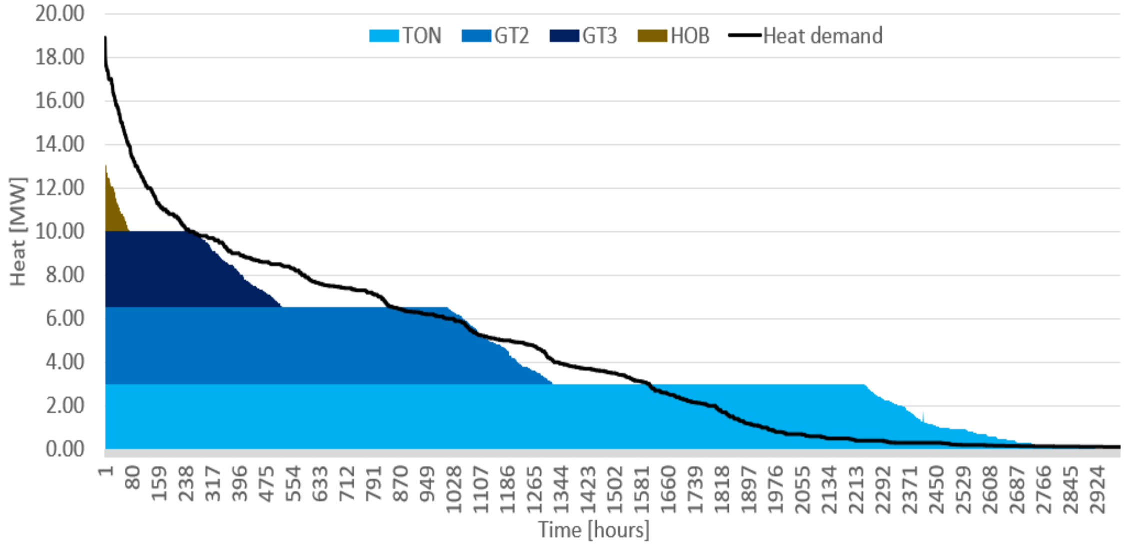


Figure 4.1: Cumulative of the base case

4.3 Base case with increase of storage

The first attempt to modify the system has been done increasing the storage volume. Storage technology and the advantages of the storage coupled with CP have been already described in section 3.2 and the investment cost has been evaluated based on the assumption done in chapter , using as reference price 150 €/m^3. The analysis on the storage size focuses on the minimization of the objective function, however it does not only consider the operational benefit, but includes also the investment cost and the depreciation.
This is done using the following expression:

$$AP = \frac{r * INV}{1 - (1 + r)^{-y}} \tag{4.1}$$

Where:

- r is the interest rate (5%)
- y is the number of year (20 y)
- INV is the initial investment cost
- AP is the annual rate including interest rate

The result of the sensitivity analysis on the storage is shown in figure 4.2 and can be seen that without considering the investment cost there is an asymptotic trend that lead to a trivial solution, while including it there is a clear optimum, around 50 MWh of heat stored. The main assumption is that storage can be loaded from all facilities, while in practice this will introduce further distance-dependent losses, that may be considered in further studies.

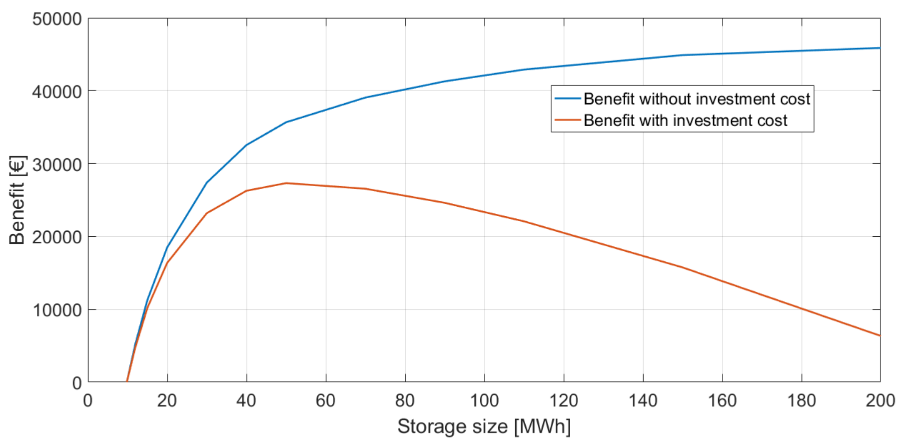


Figure 4.2: Benefit as function of storage size with and without including investment cost

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
Base case	100000	344000	4000	2.53

Table 4.5: Main outputs of the model for BCS scenario

	Share
GT2	27.91
GT3	1.87
TON	70.22
HOB	0

Table 4.6: Heat production share for BCS scenario

The main result is that the new production assets does not use HOB, as can be seen in table 4.6, but maximizes the heat production from CHP, reducing peak to about half (*fig. 4.3*). Table 4.5 shows that the increase of storage size helps to reduce operational costs of the system, but,on the other hand, storage increases emissions, because part of the stored heat will be dispersed with the consequent necessity of additional heat. Moreover, from figure 4.3 can be seen that the heat production share of GT3 is very low (*around 2%*), losing its potential to produce both heat and power. This can be seen as a drawback or as an opportunity for the expansion of the network, that would be able to satisfy a higher demand reusing GT3 in cogeneration mode.

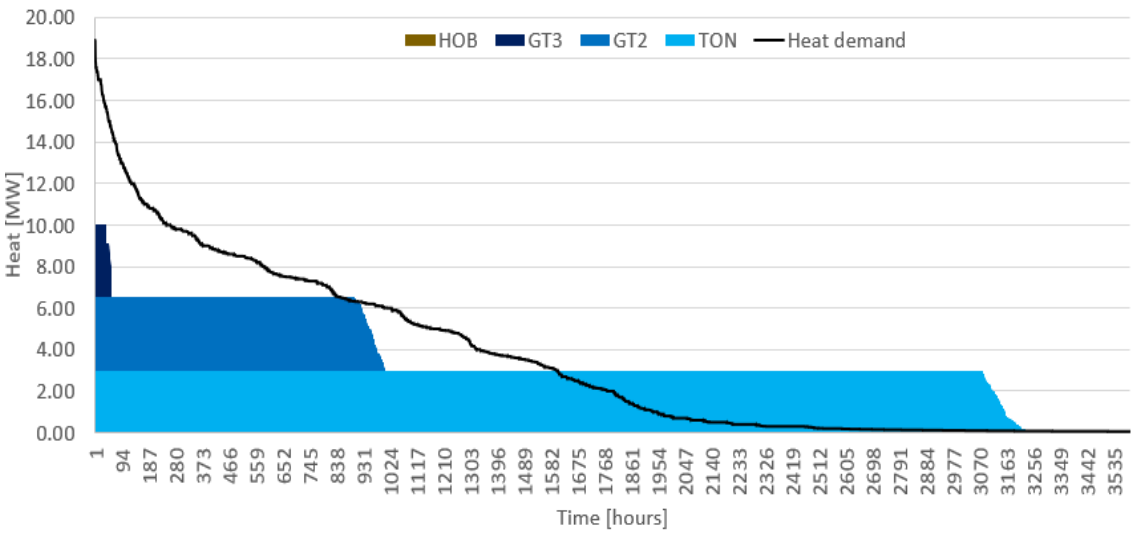


Figure 4.3: Cumulative for BCS

4.4 Solar heat plant

A solar heat plant consists of a field of solar collectors, pumps and pipes to transfer the collected heat to the DH system. So far, 300 plants above 350 kW$_{th}$ of capacity have been put into operation in Europe, in particular the market has experienced a boom in Denmark and sound growth in several other places, such as Austria, Germany and Sweden [91].

The solar heat plant production strongly depends on several factors, as solar radiation G and external temperature (*that affects efficiency*). Moreover, solar radiation is in general made up of two components, a direct radiation G$_b$, that is the solar radiation received from the sun without having been scattered by the atmosphere, and diffuse radiation G$_d$, that is the radiation scattered by the atmosphere, characterized by a different direction. The total horizontal irradiance will be given by the sum of direct (*beam*) and diffuse components:

$$G = G_b + G_d \tag{4.2}$$

To maximize the total irradiance a surface can be tilted or oriented towards different cardinal point to obtain a different production, shifted towards seasons or specific hours of the day. To optimize the system two concept will be used:

- Tilt angle (β): is the angle at which a solar thermal panel is set to face the sun relative to a horizontal position
- Azimuth angle (γ): is the angle that defines the Sun's relative direction along the local horizon

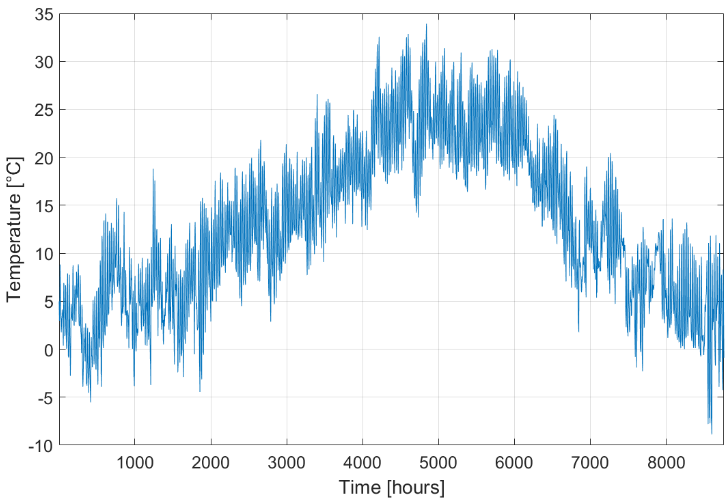


Figure 4.4: Temperature during the year

The analysis of the demand, described in section 3.3, shows that there is a peak during the early morning and that the heat demand is relevant from September to March. In general, the hardest

goal of a renewable system is to match demand and production and an initial attempt has been done changing both β and γ.
The optimization consists in an iterative process that changes both β and γ, trying to maximize matched production between the demand and the solar irradiance, provided by [81]. The analysis lead to the following results: $\beta = 60$ °and $\gamma = -15$ °.
The drawback of this choice is that the solar field needs more space in order to avoid mutual shading, especially during the morning when the sun is lower. The data concerning solar irradiance have been taken from PVGIS [81], where also temperature has been taken, in order to evaluate the collector efficiency. As said before, the efficiency ratio η_{SH} of the solar collectors is a time-dependent factor, because it depends heavily on the solar irradiation, the outdoor temperature and the operating temperature of the collector. The last one is the average between the inlet and the outlet temperature of the solar collectors and varies with the kind of connection and how it is operated with the DH system.
A way to reduce the losses is to reduce the temperature difference between the outlet and inlet and the ambient temperature; this can be done assuming a RR-assisted connection, where SH is used to heat up part of the DH water in the return pipe. The RR-assisted connection is used mostly in northern country due to the low external temperature and the small sun radiation, however since CHP represents the main production unit it seems reasonable to use this kind of connection also in the case-study.

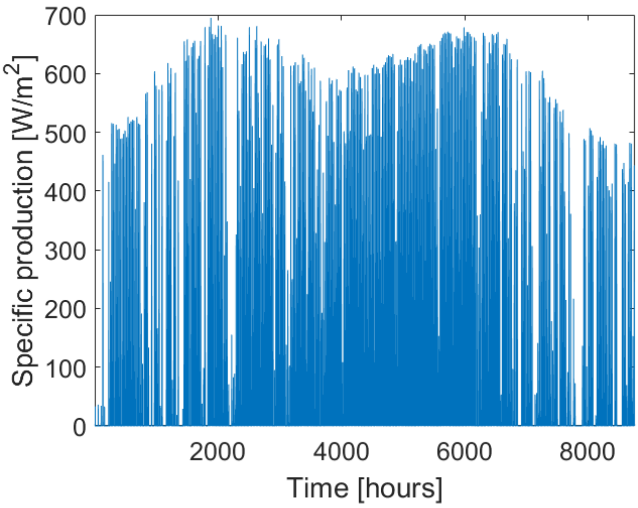


Figure 4.5: Solar production with optimal β and γ

The efficiency ratio can finally be written as:

$$\eta_{SH} = \eta_0 - \frac{\alpha_1 \Delta T}{G} - \frac{\alpha_2 \Delta T^2}{G} \tag{4.3}$$

And the production can be written as:

$$Q_{SH} = \eta_{SH} * G * A = q * A \tag{4.4}$$

Where:

- η_0 is the zero loss collector efficiency;
- α_1 the first order coefficient;
- α_2 the second order coefficient;
- $\Delta T = \frac{T_{in}+T_{out}}{2} - T_{amb}$;
- A is the area of the field.

In figures 4.4 and 4.5 are respectively shown the temperature during the year and the specific production. It is important to underline that even if the goal is matching production and demand, this has certain limits. In fact, due to the higher irradiance the maximum production will be shifted towards autumn/spring, where the temperature difference is not so high.

Economic data

Following the example of the first solar district heating plant in Italy (*located in Varese*) [92] it has been decided to adopt the same flat plate solar collectors, HT-HEATBoost35/10 with a gross surface area of 13.6 m^2 with a panel area of around 1000 m^2. The flat plate solar collectors are certified with EN12975 or EN12976 and have the Solar Keymark, that grants the access to the incentives.

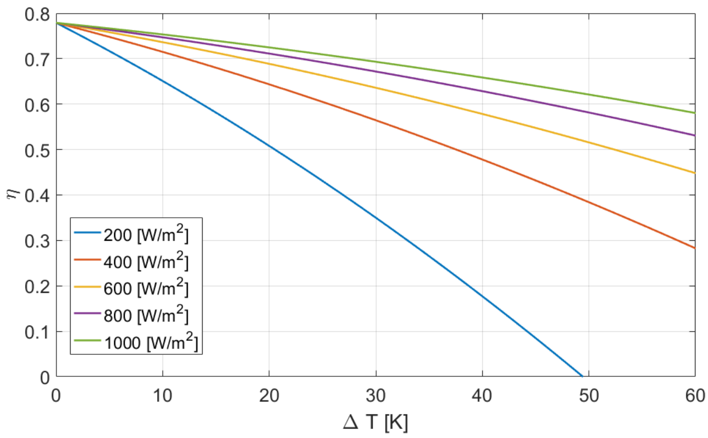


Figure 4.6: Solar efficiency of HT-HEATBoosts35/10 as function of temperature difference and radiation intensity

Concerning investment and operational costs, it has been decided to use the same costs of the Varese plant. The investment cost is equal to 424 €/m^2 while the operational cost,that includes pumps, control system and maintenance is around 2 €/MWh.

Incentives

For the possible incentives it has been analyzed the Conto Termico 2.0 [35], that is the national subsidy scheme for energy efficiency and small renewable heat plants. The type of incentive is a rebate, that means that is not evaluated on the investment cost but from an expected performance level, therefore it is typical of that specific technology. The incentives depends also on the purpose of the plant (*solar cooling, hot domestic water, space heating*) and are evaluated yearly and paid in 2 annual installments if the installed surface is smaller than 50 m^2 or 5 annual installments for surface greater than $50m^2$. The yearly installments is evaluated as follow:

$$I_a = c_{ISH} * S_l * Q_u \tag{4.5}$$

Where:

- c_{ISH} €/KWh is a parameter related to the size of the system and its application
- $Q_u = \frac{Q_L}{A_G}$ where Q_L is the annual collector yield reported on the Solar Keymark certificate for Wurzburg at a temperature depending on the system application and A_G is the gross area of the collector
- S_l is the system size

Must be specified that the incentives for solar heating are financed up to a maximum of 2500 m^2 of gross collector area and up to 65% of the investment cost. If the incentive is higher than the threshold is automatically lowered to cover the 65% of the total system cost. The incentives for the case study amounts to 236550 € (*55% of the total cost*).

4.4.1 SH without storage

The simulations have been performed considering 1000 m^2 of panels area (*73 panels*), where the efficiency and the production are evaluated according to equations 4.3 and 4.4 and the orientation of the panels has been described in the previous section.
The first simulation is performed not considering thermal storage for the solar heat plant, rejecting the heat that does not match the demand. The main assumption done is that the heat rejection does not have additional cost. Figure 4.7 shows that during the summer the majority of heat is rejected, and in some days in autumn and spring the production is greater than the demand, highlighting the possible benefit of the storage introduction.
In fact, during the entire heating season around 300 MWh are produced, however, this quantity does not represent even half of total production (*895 MWh*). To model the solar plant without a storage, two equations have been added to the initial model, to evaluate respectively the production and the cost associated to the solar heat plant.

$$x_{SH} = G^t \eta^t_{SH} A_{SH} \tag{4.6}$$

$$c^t_{SH} = c_{OP} x_{SH} \tag{4.7}$$

Where x_{SH} is a variable that encode the solar production, function of the irradiance, the efficiency and the total area of the plant. While c_{SH} represents the cost, where c_{OP} are the operating cost of the plant.

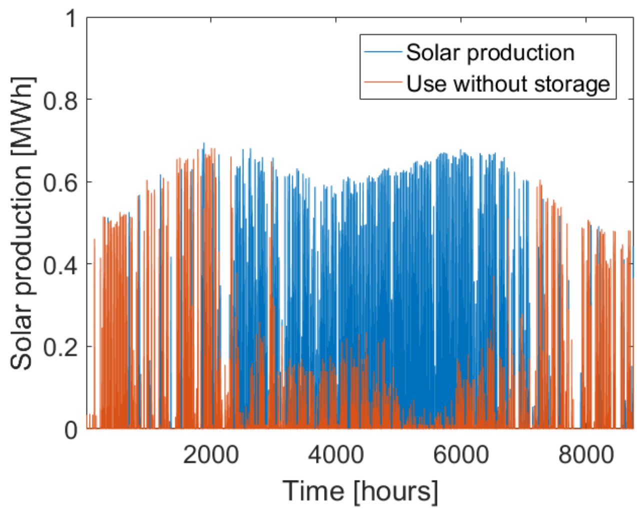


Figure 4.7: Comparison between solar production and use without storage

Analyzing table 4.7 can be seen that despite the initial investment, the operational cost is only slightly reduced, but there is a clear reduction in CO_2 and pollutants emissions.

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
SH	190000	359000	3720	2.36

Table 4.7: Main outputs of the model for SH case

	Share
GT2	31.62
GT3	10.84
TON	56.7
HOB	0.77
SH	2.30

Table 4.8: Heat production share for SH case

Table 4.8 shows that solar production has been prioritized over CHP production, due to the fact that the share of heat-only boiler is only slightly reduced. Two different approach have been applied trying to match production and demand, reducing the role of the HOB.
The first one is an increase of storage size similarly to the previous case, that aims to store solar heat, while the second alternative will concern the use of a seasonal storage, that in principle should be able to store the entire amount of solar heat produced.

4.4.2 SH with storage

As done for the base case, a sensitivity analysis on storage size has been performed. Figure 4.8 shows that storage size is the same of the previous case. This can be explained looking at the share of different technologies, where almost all the heat is produced by CHP, therefore applying a weighted average between the optimum for the solar heat plant and the one for CHP, the result will be shifted towards CHP optimal size.

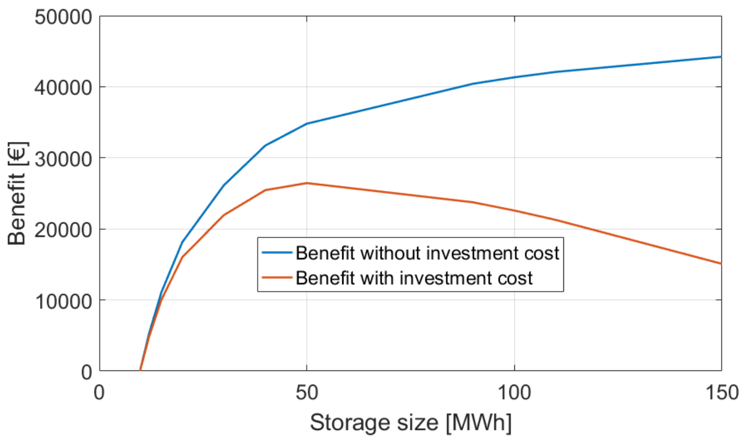


Figure 4.8: Benefit as function of storage size in the solar heat plant scenario

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
SHS	290000	332000	3700	2.35

Table 4.9: Main outputs of the model for SHS case

	Share
GT2	27.41
GT3	1.71
TON	67.90
HOB	0
SH	2.98

Table 4.10: Heat production share for SHS case

Table 4.9 shows that the coupling between storage and solar plant lead to a decrease of operational cost, maintaining the benefit from the reduction of CO_2 and pollutants. As shown by table 4.8, HOB are no more used and solar heat is able to satisfy around 3% of the heat demand, with the main disadvantage of using the GT3 in cogeneration mode only few hours.

4.4.3 SH with seasonal storage

The third scenario considered for SH includes a seasonal storage, that represent the best solution to store solar heat, however it is subject to a lot of losses and uncertainties. In particular, the performances of a seasonal storage are quite low if compared to short-term storage, and a seasonal sensible heat usually can reach 81% of efficiency [39]; therefore the model has been changed according to the reference. From the analysis of the heat production in figure 4.7 and from a sensitivity analysis of storage' size it has been decided to use a value of 150 MWh. With respect to the first case this represents another 4% of renewable capacity added to the system, however, the main drawback of seasonal storage is that although small, losses that involves long time of period are present,therefore part of the renewable heat will be lost.

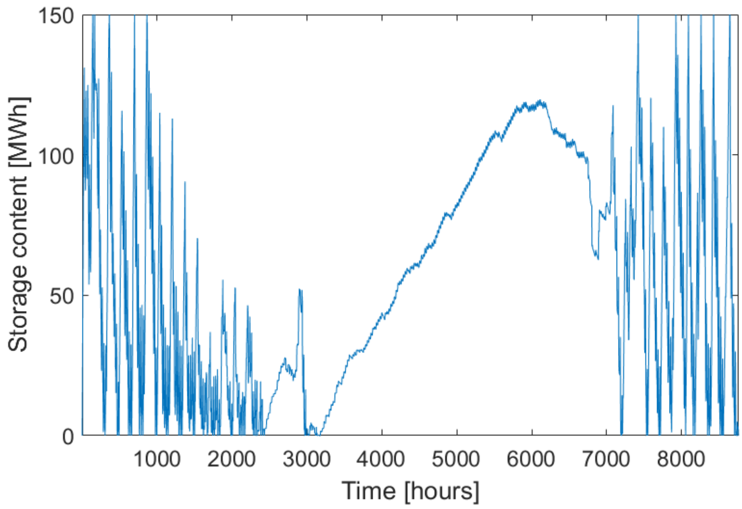


Figure 4.9: Storage content in solar thermal case with seasonal storage

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
SHSS	550000	323000	3900	2.46

Table 4.11: Main outputs of the model for SHSS case

From table 4.11 can be seen that the introduction of seasonal storage coupled with solar thermal led to a decrease of operational cost, while the advantage of the solar plant vanishes in terms of emissions of CO_2 and pollutants. Looking at figure 4.9 can be seen that storage content constantly increases after 2500 h and reaches its maximum around 6000 hours, when the heat content is used to satisfy the demand and refills is made up with CHP plants.

	Share
GT2	23.12
GT3	0.44
TON	70.17
HOB	0
SH	6.26

Table 4.12: Heat production share for SHSS case

4.5 Ground source heat pump

Ground source or geothermal heat pumps (GSHP) are a highly efficient technology to produce heating and cooling for space heating in both small-scale and large-scale applications and they are increasingly affirming technologies [65].The operation of heat pump employ the same technology as refrigerators, upgrading the heat from a low-temperature level to a high-temperature level using external energy sources (*electricity or high-temperature heat*).

There are mainly 2 kind of heat pumps:

1. Compression heat pumps: in which the energy source used to upgrade the heat is electricity. They have a high COP (*coefficient of performance*) and high operational cost, often related to the electricity price.

2. Absorption heat pumps: in which the energy source used to upgrade the heat is high temperature heat (*steam, waste heat*). For absorption heat pumps, COP is not affected by temperature levels, therefore they have a more constant efficiency with respect to compression heat pumps.

The main difference is related to investment and operational costs that, for mechanical heat pumps, are greater; but, on the other hand, also COP is higher.
It has been decided to focus the attention on the compression heat pumps, since absorption heat pumps requires an external source of heat not always available without using fossil fuels and a lower COP. Moreover, compression heat pumps are often adopted with district heating systems in North America and parts of Europe [76]. In particular, in Denmark, the application of large heat pumps in district heating system is expected to influence the development of the heat pumps globally, both the technology itself and the applications [25].
According to HRE large-scale heat pump are expected to become more important on a European level [20], highlighting the possibility to supply 30% of the total DH production by 2050. The importance of large-scale electric heat pumps in DH system has been already analyzed in several reports [17],[18], however there is still not an explicit formula for practical COP. A survey on heat pumps in [20] shows that the highest COP actually achieved is 6.5 and that the average COP is slightly higher than the one achieved in small heat pumps.

Starting from the formula of theoretical COP:

$$COP = \frac{Q}{W} = \frac{T_H}{T_H - T_C} \tag{4.8}$$

Where:

- T_H= higher temperature (K)

- T_C= lower temperature (K)

The practical COP will mainly depend on:

- Maximum temperature: from the formula 4.8 can be seen that T_H is present in both numerator and denominator, therefore maximum temperature will strongly influences the COP. The output temperatures are classified as follows:
  - $<$ 70 °C: achieved in the advanced low temperature DH.
  - 71-80 °C: that is the most common range of temperature found in the survey
  - $>$ 80 °C: that have the highest ΔT
- Temperature boost (ΔT) : there is a linear relation and in general lower the temperature boost higher the COP.
- Quality of the heat pump: that influences thermal and hydraulic losses.

Output temperature ranges (°C)	$<$ 70	71-80	$>$ 80
Units	19	57	34
Capacity (MW)	40	725	425
Average COP	4.5	3.6	3.7

Table 4.13: Average characteristics of heat pumps as function of temperature range

Table 4.13 shows that there are few heat pumps that operates at lower temperature and achieve high COP. In fact, the most common range is 71-80 °C, with a COP of 3.6, that is the lowest average COP. This because these heat range was achieved in the 1980s in Sweden while high temperature heat pumps represent some of the most optimized heat pumps.

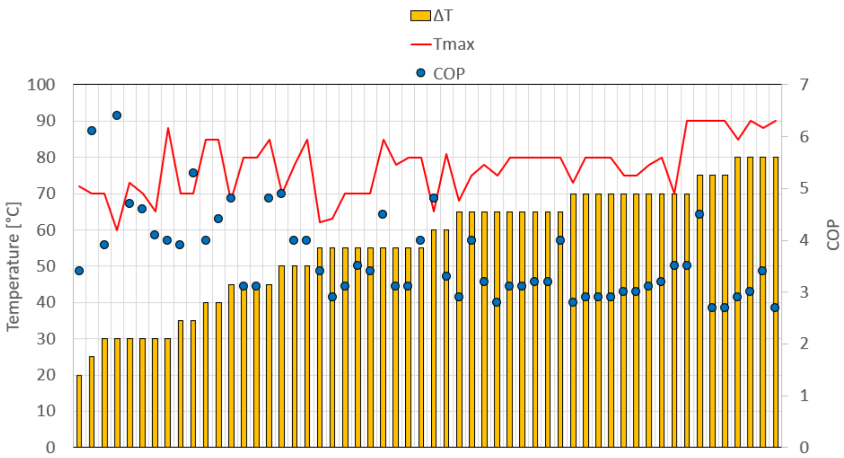


Figure 4.10: COP as function of ΔT and T_{max} [20], as the ΔT increases the COP decreases

Figure 4.10 analyze the relation between COP,ΔT and T_{max} highlighting how higher COP are achieved using low ΔT and low operating temperature. This may seem in contrast with the purpose of DH that employs high temperature, however if heat pumps are coupled with CHP or boilers, they can be used to upgrade heat in the return line, as previously seen for solar, with a RR-assisted connection. Moreover, new generation of DH aims to reduce the operating temperature under 70 °C.

Economic data

For the analysis it has been considered a mechanical compression heat pumps system, with a COP of 4.5 assumed constant over the year. Since GSH has high investment cost compared to operating costs, it should operate with a high capacity factor and to achieve this, the GSH capacity is dimensioned on the base load (0.15 MW).
According to [25] the investment cost needed for heat pumps is 0.7 M€/MW while the operational and maintenance costs (*that does not include electricity*) are 2 €/MWh. The electricity price will be taken from the spot electricity market previously analyzed.

Incentives

In Conto Termico 2.0 is stated that incentives for heat pumps are provided to private and public administration only for replacements interventions of standard heating system, as boilers and for hybrid system that aims to maintain boilers as back-up, they must be condensing boiler. In this case, there is the construction of a new plant, that however aims to partially replace the heat only boilers.

Another subsidies mechanism is represented by "Certificati bianchi" [34] or "Titoli di Efficienza Energetica" (TEE), that are negotiable securities that certify the energy savings achieved in the final uses of energy, implementing measures to increase energy efficiency. However they are given to absorption heat pumps for space heating and electrical heat pumps for hot tap water, therefore there is no possibility to access incentives for this specific purpose neither with Conto Termico 2.0 or TEE.

4.5.1 GSH without storage

The first case analyzed not consider thermal storage for GSH and, since in principle GSH are able to work all year around, a large part of the heat produced will be rejected.
To take advantage of the high capacity factor of the heat pump, the plant has been dimensioned on a lower load (0.15 MW).This solution is able to produce 1314 MWh, however without the matching between production and demand the actual production will be around 528 MWh (*40% of the total one*).
In addition, it is known that mechanical heat pump uses electricity to upgrade the heat, and in some situation this may lead to very high cost of heat, even with a good COP. As said before, the main hypothesis is that the heat pump has a constant COP over the year equal to 4.5, due to the lack of information regarding the exact temperature of the DH system. To model the production and evaluate the cost two equations have been added to the base case model to model production and expenditure.

$$0 \leq x_{GSH} \leq x_{GSH}^{MAX} \tag{4.9}$$

$$c_{GSH}^{t} = x_{GSH} \left(\frac{c_P^t}{COP} + c_{OP} \right) \tag{4.10}$$

Where x_{GSH}^{t} represents the production of the heat pump, between 0 and its maximum capacity, while the second equation evaluates the costs of the heat pump, depending on the electricity price c_P^t, the COP and other operational costs c_{OP}.
Moreover, it has been decided to limit the functioning of the heat pumps only when the cost of electricity divided by the COP is smaller than the cost of gas used to run the HOB.

$$\frac{c_{EL}^t}{COP} \leq c_{FUEL}^t \tag{4.11}$$

Looking at the electricity price in 3.8 can be seen that this happens mostly during the winter, and even if it seems a boundary too strong, the result is a reduction of capacity around 10% without the storage.
Figure 4.11 highlight the difference between the total production and the production actually used without the storage and can be seen that with this limitation, the GSH plant run at partial loads almost half of the time with frequent shut down and start up, that may influence the COP.

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
GSH	110000	364000	3680	2.33

Table 4.14: Main outputs of the model for GSH case

Table 4.15 shows that the operational cost increases, due to the high costs of electricity. On the other hand, there is a great reduction of both CO_2 and Pollutants, slightly higher to the SH case

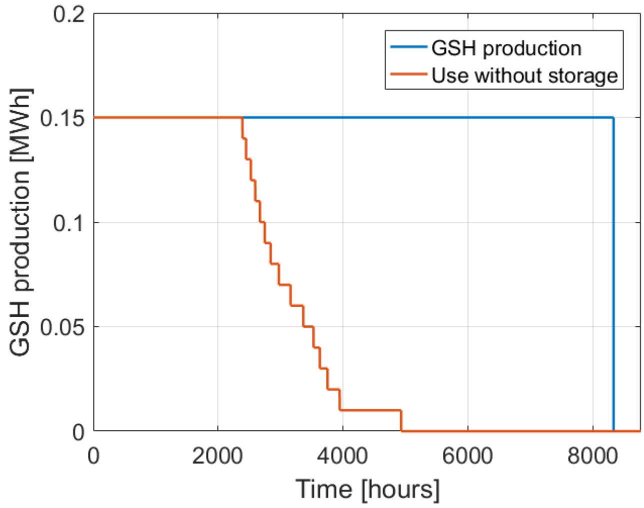


Figure 4.11: Comparison between GSH production and use without storage

	Share
GT2	30.80
GT3	10.20
TON	54.24
HOB	0.74
GSH	4.02

Table 4.15: Heat production share for GSH case

because the heat produced by GSH plant has an emission factor equal to the electricity production divided by the COP. As can be seen in table 4.15 the share of heat produced is almost the same of SH case, therefore as done for the solar case, a second simulation involving an increase of storage size will be considered.

4.5.2 GSH with storage

As done for the other technologies, a sensitivity analysis on storage size has been performed following the assumption of the other cases, i.e. that storage can be loaded by all facilities.

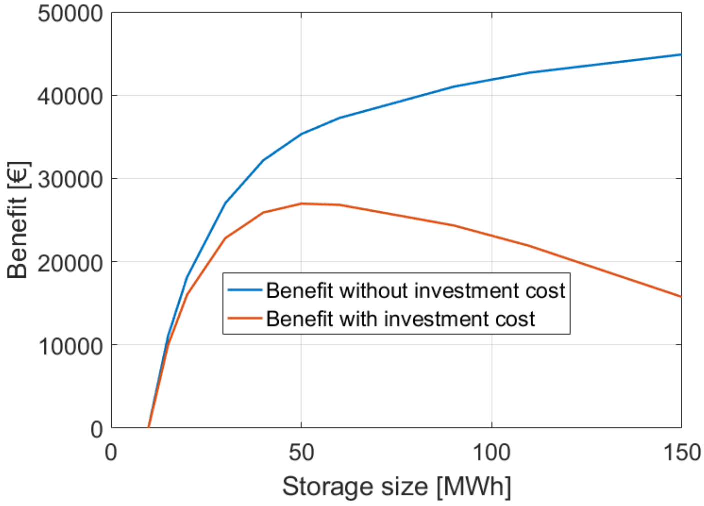


Figure 4.12: Benefit as function of storage size in the Ground source heat pumps scenario

As expected, from figure 4.12 can be seen that optimal size is again 50 MWh, due to the fact that the largest amount of heat is still produced by CHP (90%), therefore the optimum is a weighted average between the CHP optimum and the GSH optimum.
The use of storage is different from solar case, since GSH works constantly during days and nights and during the year, however the operational cost is way higher than the previous case, because now GSH operates almost all year with a consequent expenditure for the electricity.

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
GSHS	210000	345000	3830	2.42

Table 4.16: Main outputs of the model for GSH case

	Share
GT2	25.51
GT3	1.50
TON	63.89
HOB	0
GSH	9.10

Table 4.17: Heat production share for GSHS case

Looking at operational cost in table 4.16 and comparing it with 4.9 can be seen that with the introduction of storage the difference between the operational costs increases, leading to a difference of around 4% between the two cases. On the other hand, emissions continue to decrease, because storage is mainly loaded by GSH constantly during the year. Moreover, looking at table 4.17 can be seen that the share of GSH is around 10%, way higher than SHS case.

In the last two scenarios the role of the boiler will be analyzed, trying to replace the actual boiler with biomass or electric boiler, with the main assumption that electricity is obtained from renewable sources. The following scenario will study the use of biomass boiler.

4.6 Biomass

Combustion of biomass is the oldest known energy source on earth. According to directive 2009/28/EC biomass is defined as "the biodegradable fraction of products, waste and residues from biological origin from agriculture (*including vegetal and animal substances*), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste" [27].

In recent years, the development of technologies and the rising costs of fossil fuels have made biomass combustion economically convenient in certain region. In many northern region biomasses is widely used in both residential sector (*biomass boiler*) and industrial sector (*CHP*), for example in Finland according to [28], [93] around 30% of the heat produced came from biomass (*wood, industrial wood residue or other biomass*). Moreover, heat production from biomass combustion is considered carbon-neutral, because emissions caused by the combustion are offset by CO_2 absorbed during tree growth.

Biomass products for combustion can be divided in:

- Wood chips and pellets: that are the least processed forest industry by-products. They can be burned in fluidized bed boiler, bubbling fluidized bed boiler, or grate boiler.
- Biogas: that can be produced from the processing of biomass to obtain a more easily combustible fuels that could be used in gas boilers. This can be done through a thermal gasification process, that however requires specific component.
- Bio-liquid: represents an alternative to biogas and it is obtained from a biomass-to-liquid process, that however is mainly used for other purposes and allows the use of biomass in oil plant without modification of the system.

Economic and environmental data

The scenario will consider the substitution of the gas boiler with grate boiler fed by wood chips. The capacity of the biomass boiler will be 5 MW and looking at table 3.9 can be seen that a wood chip boiler has an investment cost of around 210000 €/MW and, according to [32], the price of wood chip has been chosen equal to 20.5 €/MWh.

From an environmental point of view, even if the combustion of biomass is carbon-neutral, presents several drawbacks. In fact, according to [29] the emission factor for CO is around 1.8 $\frac{t}{GWh}$, while the emission factor of NO_x is 0.54 $\frac{t}{GWh}$, more than 10 times the one of gas turbine.

Incentives

For the evaluation of the incentives it has been used Conto Termico 2.0 [35], as previously done for solar thermal. In order to access incentives boiler with capacity greater than 500 KW must have

an efficiency higher than 89%.
The incentives for biomass boiler can be evaluated as follows:

$$I_{bio} = P_n * h_r * C_i * C_e * y \tag{4.12}$$

Where:

- C_i is the coefficient of valorization of the thermal energy produced expressed in €/KWh$_t$
- C_e is is the premium coefficient referred to dust
- h_r is the coefficient of use, defined according to the climatic zone in hours
- P_n is the nominal power of the biomass boiler
- y is the number of years of the incentives, 2 for $P_n < 35kW$ and 5 for $P_n > 35kW$

The total amount of incentives is 765000 €, compared to an initial investment of 1.155 M€, however since the incentives can cover up to 65% of the total investment cost, the final subsidy used will be 750750 €.

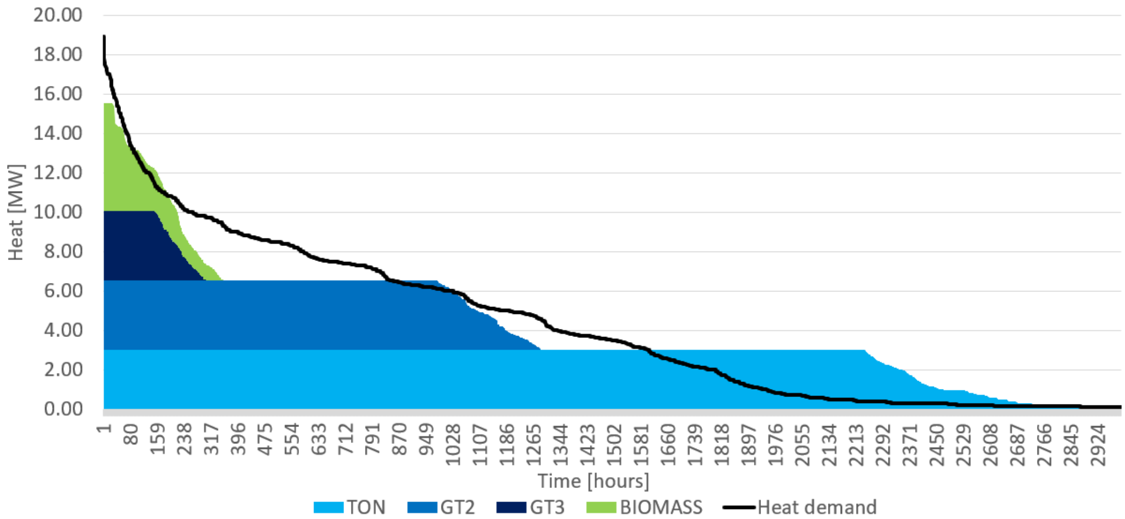


Figure 4.13: Cumulative in the biomass boiler scenario

To model the biomass boiler, the equations of the natural gas boiler have been modified.

$$0 \leq x_{BIO} \leq x_{BIO}^{max} \tag{4.13}$$

$$c_{BIO}^{t} = \frac{c_{WOOD} x_{BIO}}{\eta_{BIO}} \tag{4.14}$$

As previously done for the natural gas boiler, the first equation limit the production to the maximum capacity of the biomass boiler, while the second equation evaluates the costs associated to the biomass boiler, where the fuel is the wood chip.

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
BB	400000	355000	3520	4.29

Table 4.18: Main outputs of the model for BB case

	Share
GT2	30.73
GT3	5.81
TON	56.75
HOB	0
BB	6.71

Table 4.19: Heat production share for BB case

Figure 4.13 shows the different composition of the cumulative, due to the higher use of biomass boiler with respect to normal boiler, in particular there is the overlapping between Biomass Boiler and GT3 CHP, highlighting that in some period the heat production from biomass boiler may be more convenient than CHP production. Looking at table 4.19 can be seen how the share of boiler is comparable with the share of GT3. Moreover, table 4.18 shows the main outputs of the simulations, pointing out the reduction in CO_2 emission, with an increase in pollutants of 85%.

4.7 Electric boiler

Economic data and incentives

For the last scenario, the boilers are replaced with electric boilers, with the hypothesis that that the energy used to run the boiler came from renewable.
Electric boilers are a well-known technology that uses a resistance to boil water,the main feature is the simplicity of the system, with the disadvantage of having a high operational cost. In fact it is already known that this scenario will be the most expensive one, because it will use electricity as a fuel. In some cases, if there is a surplus of electricity production, this kind of boilers can be used at almost zero price.
The investment cost considered for the electric boilers is 0.075 M€/MW, according to reference [25] with a variable operational cost of 0.5 €/MWh (*excluding the electricity price, taken from the market previously described*).
As done for the biomass boiler, the size of the electric boiler is 5 MW, with an efficiency of 100% and the boiler is modelled with two equations:

$$0 \leq x_{EB} \leq x_{EB}^{max} \tag{4.15}$$

$$c_{EB}^{t} = x_{EB} \left(\frac{c_P^t}{\eta_{EB}} + c_{OP} \right) \tag{4.16}$$

The main difference with respect to the previous case is that there are no incentives available for the electric boiler, therefore the investment cost will be the same, even if the fuel is more expensive. As a consequence, the electric boiler will be used only to cover peak demand, as previously done with the natural gas boiler.

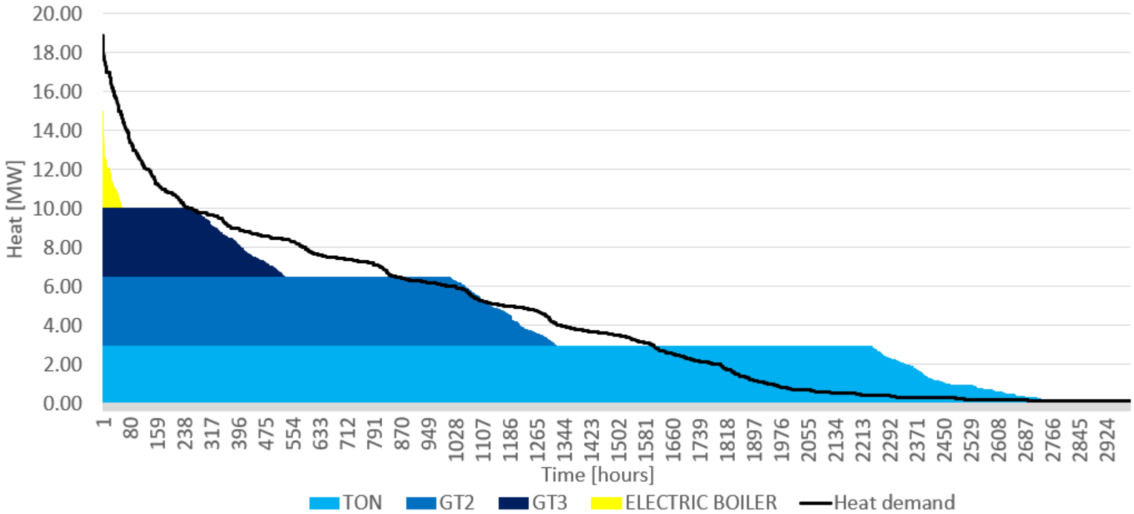


Figure 4.14: Cumulative in the electric boiler scenario

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]
EB	410000	363000	3770	2.39

Table 4.20: Main outputs of the model for EB case

	Share
GT2	31.62
GT3	10.96
TON	56.68
HOB	0
EB	0.74

Table 4.21: Heat production share for EB case

Figure 4.14 shows the cumulative for the EB scenario. The main comment concerns the clear resemblance between the BC and EB cumulative. In fact, as already said, the electric boiler is the source with the highest cost, therefore it is used only in situation in which the CHP are not able to satisfy the heat demand. Table 4.20 confirm that the EB scenario is the most expensive, with only a partial reduction of emissions, due to the marginal role of the electric boiler.

Chapter 5

SMAA

After the description and the optimization of each scenario, a multiple-criteria decision analysis will be performed to select the best (*or bests*) alternative between the one proposed. This chapter will provide an overview on Multiple-criteria decision analysis (MCDA) methods, explaining the main procedure of MCDA methods, followed by a detailed description of the SMAA, the MCDA chosen for the stage 2 of the methodology.

5.1 MCDA

"Multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) is a sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision making" [105].

In our routine, this kind of analysis is performed only with intuition. For example, when buying a car costs and performance can be compared, since they are easily measurable criteria, or the beauty of the car itself can also be considered, a subjective and hard to measure criteria. Very often there is not a single better alternative, because it depends from the decision maker preferences, however when the stakes are high, it is fundamental to analyze the alternatives from more than one perspective.

Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for sustainable energy, with particular emphasis on power system, applied on large scale power systems [69],[70],[89], community level power solutions [10],[82] or site selection for several technologies, including hydropower plant [77], solar power plant [8], wind power plant [94] or ORC plant [51]. Also in the heating sector several MCDA have been performed, including both community level [33], [54], [100] and building level [12].

According to [102] "the rational decision-making (DM) in energy supply system options, planning, management and economy is helpful to the sustainable development", however, due to the multi-dimensionality of the sustainability (*shown in figure 5.1*), decision makers may find many

difficulties.
MCDA provides a method to eliminate the difficulty to handle conflicting criteria, high uncertainty and different forms of data and information.

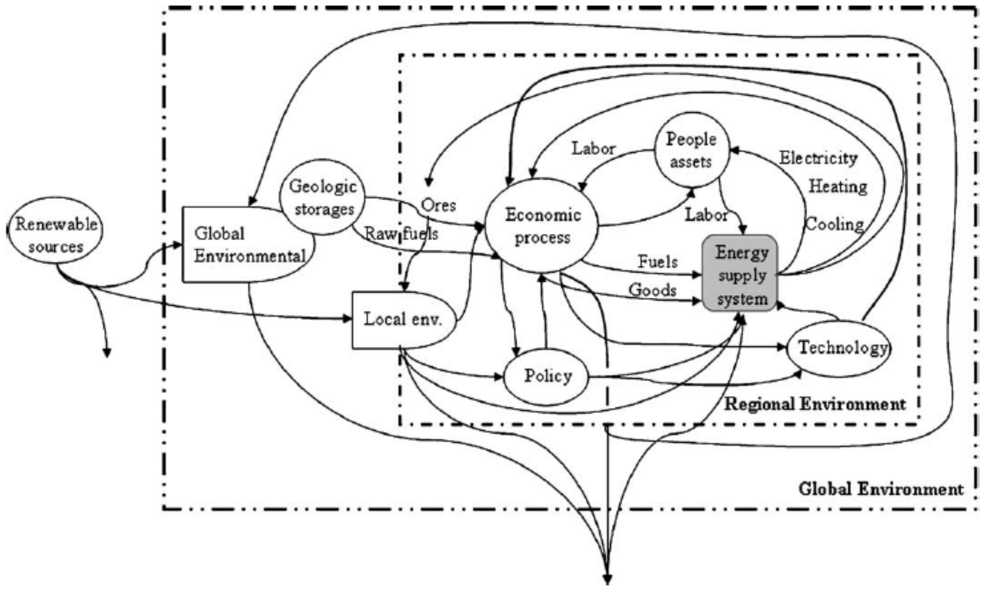


Figure 5.1: Interactions in an energy system [102]

In the renewable energy field, several methods are used to handle multi-criteria decision problems; the most common are:

- Weighted sum methods (WSM)
- Unique synthesizing criteria methods
  - Analytical Hierarchy Process (AHP)
  - Technique of Order Preference Similarity to the Ideal Solution (TOPSIS)
  - Multi-attribute value theory (MAVT) (*in which is included SMAA*)
  - Grey relation method
  - MCDA combined fuzzy methodology
- Outranking Methods
  - Elimination et choice translating reality (ELECTRE)
  - Preference ranking organization method for enrichment evaluation (PROMETHEE)

In a general way, MCDA involves m alternatives evaluated on n criteria with different weights w, and the formulation of the problem involves four main stages:

1. Alternatives' formulation and criteria selection
2. Criteria weighting
3. Evaluation
4. Final treatment and aggregation (*depending on the problem*)

The alternatives' formulation and criteria selection are strongly dependent on the decision makers, and they have been analyzed in chapter 4. There are several methods to evaluate the weights of different criteria, however this procedure can be complicated and lead to wrong solution if the decision makers are not sure about the weights used. To overcome this problem, it has been decided to use stochastic multicriteria acceptability analysis (SMAA), that explores the weight space describing how different weights can lead to different best alternatives, therefore with SMAA criteria weighting and evaluation of alternatives are carried out simultaneously.
In the following sections, several SMAA methods are shortly presented and a detailed description of SMAA-2 is provided.

5.2 SMAA methods

There are several MCDA methods that apply different approaches to tackle the difficulties encountered in many real-life problems, as: uncertainties in measures, partially missing information or uncertainties in weight preferences. The Stochastic multicriteria acceptability analysis (SMAA) method, introduced by Lahdelma et al. [58], is based on exploring the weight space to describe the preferences that would make each alternative the most preferred one (*or that would give a certain rank for a specific alternative in SMAA-2*).
Related ideas have also been presented by [9] and [23], however earlier paper discussed a general n-dimensional framework, but the computational formulae were developed only for the 3-dimensional case. SMAA extended the methodology considering the criterion values as n-dimensional stochastic probability distributions, while the weight space analysis is performed based on an additive utility or value function. Moreover, SMAA-2 [56] extended the analysis to a general utility or value function, including preference information and considering holistically all ranks, while SMAA-O aims to extend SMAA-2 for treating mixed ordinal and cardinal criteria in a comparable manner [59]. There are also extension of SMAA based on data envelopment analysis (SMAA-D) [57] and prospect theory (SMAA-P).
SMAA has also been modified to include different selection methods, as outranking methods or achievement functions methods. SMAA-TRI can use ELECTRE-type procedure, instead of the utility function and can be useful if the goal is sorting the alternative and not ranking them.
Another extension of the SMAA can be used for cases in which information on weights absent. In Ref-SMAA [60] decision makers can specify a preference value for each criterion, therefore the attention will be shifted from the weights to the value of each criteria.
A survey on SMAA methods have also been presented by [95] and, depending on the purpose of the analysis, a decision-tree to select the best SMAA method is proposed in figure 5.2.

In the next section SMAA-2 will be intensively described and in the next chapter it will be used to perform the simulations and assess the best alternatives.

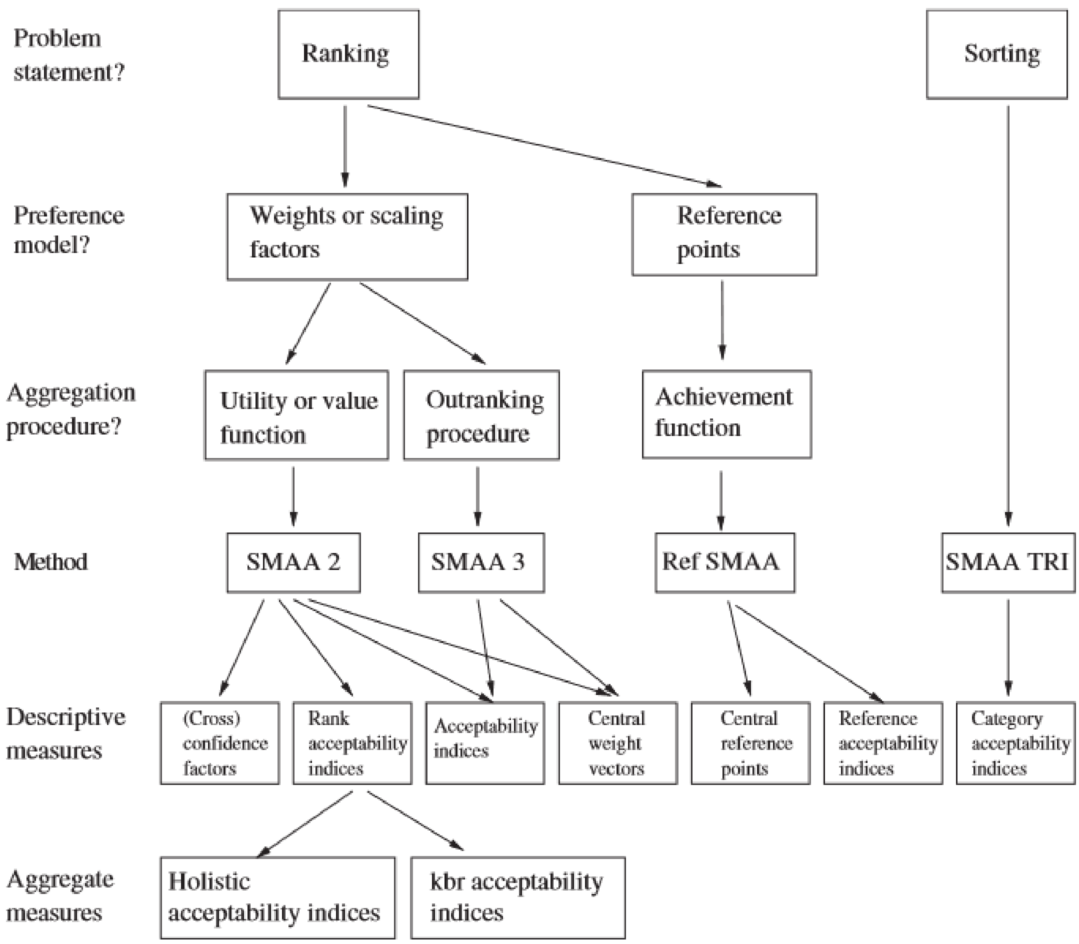


Figure 5.2: Decision-tree to choose the SMAA variant [95]

5.3 SMAA-2

The SMAA-2 has been developed for discrete stochastic multicriteria decision making problems with multiple DMs. The decision problem is represented as a set of m alternatives $\{x_1, x_2, ;x_m\}$ to be evaluated in terms of n criteria. The DMs' preference structure is represented by a real-valued utility or value function $u(x_i,\mathbf{w})$, that maps the different alternatives to real values by using a weight vector $\mathbf{w}$. SMAA-2 has been developed for situations where neither criteria measurements nor weights are precisely known, as in the case study, where there are no preference information about the weights and criteria measurements are influenced by many factors (*electricity and fuel price, heat demand*). Uncertain or imprecise criteria are represented by a matrix of stochastic variables ξ_{ij} with joint probability density function $f(\xi)$ in the space $\mathrm{X} \subseteq R^{mxn}$. The DMs' preferences about the weight can be represented by suitable weight distribution with joint probability density function $f(\mathbf{w})$ in the feasible weight space W.
For example, the DM can:

- Specify precise weights
- Use weight intervals
- Use intervals for weight ratios
- Use arbitrary linear or non-linear constraints for weights

Total lack of preference information is represented by a uniform weight distribution in W.

$$f(\mathbf{w}) = \frac{1}{vol(\mathrm{W})} \tag{5.1}$$

The weights are, typically, non-negative and normalized and the feasible weight space is defined as follows:

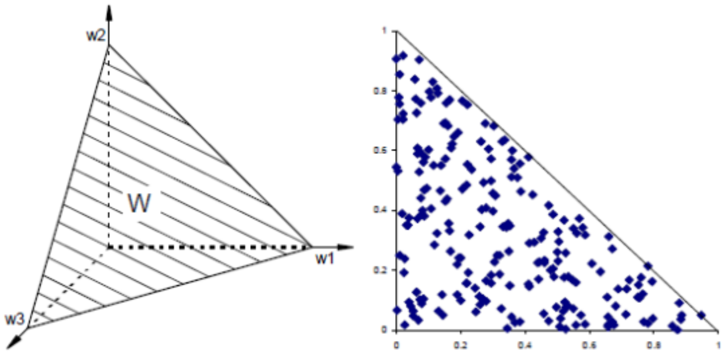
$$\mathrm{W} = \{\mathbf{w} \in R^n \mid \mathbf{w} \geq 0 \text{ and} \sum_{j=1}^{n} w_j = 1\} \tag{5.2}$$

Figure 5.3a shows the feasible space domain in the 3-dimensional case, while figure 5.3b shows the uniform distribution in the 3-dimensional case projected on a plane.
The value function is then used to map the stochastic criteria and weight distbutions into value distibutions $u(\xi_i, \mathbf{W})$. Based on this, the rank of each alternative is defined thanks to a ranking function:

$$\mathrm{rank}(i, \xi, \mathbf{w}) = 1 + \sum_{k=1}^{m} \rho(u(\xi_k, \mathbf{w}) > u(\xi_i, \mathbf{w})) \tag{5.3}$$

Where:

- 1 is the first rank
- m is the worst rank



(a) Feasible weight space in the 3-criterion case

(b) Sampling uniformly distributed weights in the 3-criterion case projected on the (w_1, w_2) plane

Figure 5.3: Feasible weight space and sampling distribution

- ρ(true)=1
- ρ(false)=0

SMAA-2 does not require a cardinal utility function and is based on analysing the stochastic sets of favourable rank weights:

$$\mathrm{W}_i^r(\xi) = \{\mathbf{w} \in \mathrm{W} \mid \mathrm{rank}(i, \xi, \mathbf{w}) = r\} \tag{5.4}$$

Any weight $\mathbf{w}\ in \mathrm{W}_i^r(\xi)$ results in such values for different alternatives, that alternative x_i obtains rank r.

The first descriptive measure of SMAA-2 is the *rank acceptability index* b_i^r, which measured the variety of different preferences that allows alternative x_i to obtain rank r. It is the share of all feasible weights that make the alternative acceptable for a particular rank, and it is usually expressed in percent. b_i^r is computed numerically as a multidimensional integral over the criteria distribution and the favourable rank weights as follows:

$$b_i^r = \int_{\mathrm{X}} f(\xi) \int_{\mathrm{W}_i^r(\xi)} f(\mathbf{w}) d\mathbf{w} d\xi \tag{5.5}$$

The most acceptable alternatives are those with high acceptabilities for the best ranks. Evidently, the rank acceptability indices are in the range [0,1] where 0 indicates that the alternative will never obtain a given rank and 1 indicates that it will obtain the given rank always with any choice of weights. The first rank acceptability index is called the *acceptability index* a_i and it is particularly interesting because it is able to discern between efficient and inefficient alternatives. In fact, $a_i > 0$ classify alternatives into efficient ones, while $a_i = 0$ or $a_i \approx 0$ represents an inefficient or weakly efficient alternative. Moreover, also measures the strength of the efficiency considering the uncertainty in criteria and DMs' preferences.

For comparing how different sets of weights support each rank for each alternative, graphical examination of the rank acceptability indices can be used. Alternatives with high acceptabilities for the best ranks are taken as candidates for the most acceptable solution. On the other hand, alternatives with large acceptabilities for the worst ranks should be avoided when searching for compromises - even if they would have high acceptabilities also for fair ranks.

The *holistic acceptability index* can be computed for each alternative as a weighted sum of the rank acceptabilities:

$$a_i^h = \sum_{r=1}^{m} \alpha_r b_i^r \tag{5.6}$$

Where α represents meta-weights ($1 = \alpha_1 \geq \alpha_2 \geq \ldots \alpha_m \geq 0$) to emphasize the best ranks.The holistic acceptability index is thus in the interval [0,1] and aims to measure the overall acceptability of the alternatives and of course the choice of the meta-weight will slightly influence the holistic acceptability index. Different ways to choose meta-weights are discussed in [56].The holistic acceptability indices have an important practical use: sorting the alternatives by their holistic acceptability index brings similar alternatives close to each other and makes the rank acceptability index graph and table much more descriptive.

The *central weight vector* $\mathbf{w}_i^c$ is the expected centre of gravity (centroid) of the favourable first rank weights of an alternative. $\mathbf{w}_i^c$ is computed numerically as a multidimensional integral over the criteria distributions and the favourable first rank weights:

$$\mathbf{w}_i^c = \int_{\mathrm{X}} f(\xi) \int_{W_i^1(\xi)} f(\mathbf{w}) \mathbf{w} d\mathbf{w} d\xi / a_i \tag{5.7}$$

The central weight vector represents the preferences of a ‘hypothetical DM supporting this alternative. Of course, the actual preferences of the DMs may be more or less incompatible with the central weight vectors. Still, presenting the central weights of different alternatives to the DMs may help them to understand how different weights correspond to different choices with the assumed preference model, or can even help the DMs to express their preferences in terms of weights.

The *confidence factor* p_i^c is the probability for an alternative to obtain the first rank when the central weight vector is chosen. The confidence factor is computed as a multidimensional integral over the criteria distributions:

$$p_i^c = \int_{\xi \in \mathrm{X}: \mathbf{w}_i^c \in \mathrm{W}_i^1(\xi)} f(\xi) d\xi \tag{5.8}$$

Confidence factors can similarly be calculated for any given weight vectors. The confidence factors measure whether the criteria data are accurate enough to discern the efficient alternatives, it can also be used together with the acceptability index for eliminating weakly efficient alternatives.

In this kind of methods, specific attention must be put into the evaluation of uncertainties and dependencies among alternatives and criteria. In many real-life problems, uncertainties may be dependent. This occurs, for example, in the Italian electricity market, when evaluating different alternatives for buying and selling electricity, where the market is influenced also by the natural gas price. In Europe in fact, there is an increase in demand from gas-fired power, due to the shift from coal to gas [2].
Since treating the uncertainties as independent could give the false interpretation than sometimes the CHP in an alternative is much cheaper than the same CHP in another alternative, a specific analysis must be carried out.
In the next section a way to handle criteria uncertainties in SMAA, based on [62] and [61], is presented.

5.4 Handling criteria uncertainties and dependencies

The main problem while treating dependency information is the difficulty to represent dependencies compactly. In the general case, this requires the representation of the joint density function $f(x_{11}, \ldots, x_{mn})$ with $m \cdot n$ variables. In practice, it is convenient assume some parametric function type. The multivariate Gaussian distribution is particularly suitable, since it is theoretically well understood and approximates well many real-life phenomena. According to probability, phenomena influenced by many small uncertainties tend to follow a normal distribution.
In the next part will be briefly presented some properties of the multivariate Gaussian distribution, that can be found in [5].

The multivariate Gaussian distribution between a vector of stochastic variables $[\lambda_1, \ldots, \lambda_L]^\perp$ is defined as:

$$f(\lambda_1, \ldots, \lambda_L) = \frac{1}{\sqrt{(2\pi)^L \det(\boldsymbol{\Lambda})}} e^{-\frac{1}{2}(\boldsymbol{\lambda}-\overline{\boldsymbol{\lambda}})^\perp \boldsymbol{\Lambda}^{-1}(\boldsymbol{\lambda}-\overline{\boldsymbol{\lambda}})} \tag{5.9}$$

Where $\overline{\lambda}$ is the vector of expected values of the stochastic variables and $\boldsymbol{\Lambda}$ is the $L \times L$ covariance matrix.
Where the covariance is defined as follow:

$$\text{cov}(\lambda_j, \lambda_k) = E((\lambda_j - \overline{\lambda_j})(\lambda_k - \overline{\lambda_k})) \tag{5.10}$$

The covariance matrix has several properties:

- Is symmetric
- Is positive semi-definite
- The diagonal contains the variances σ^2 of the variables

Thanks to the symmetry, $\boldsymbol{\Lambda}$ contains only $(L^2 + L)/2$ unique values, providing a compact representation of both uncertainty and dependency information. However, since the measurement units of the covariance and variance are products of the units of two variables, it is no easy to interpret the numerical values of the covariance matrix, therefore it can be more convenient to express uncertainty and dependencies in terms of a vector of standard deviations $\boldsymbol{\sigma}$ and as an $L \times L$ correlation matrix ρ. The correlation matrix can be derived from the covariance matrix as follows:

$$\rho_{jk} = \frac{\text{cov}(\lambda_j, \lambda_k)}{\sigma(\lambda_j)\sigma(\lambda_k)} \tag{5.11}$$

The standard deviations are easy to interpret and understand, because their measurement units match those of the stochastic variables. Moreover, the correlation coefficients are easy to interpret, because they are dimensionless quantities between -1 and 1 that measures how well a linear model explain the dependency of the variables. In particular, ± 1 indicate perfect correlation (*positive* *or negative*), while 0 indicates that there is no linear dependence between the variables. Since correlation matrix is symmetric with units on the diagonal, the $\boldsymbol{\sigma} - \boldsymbol{\rho}$ representation is equally compact as the covariance matrix. This representation is also convenient because it separates the uncertainty information, contained in the $\boldsymbol{\sigma}$ vector, from the dependency information, contained in the correlation matrix $\boldsymbol{\rho}$.

Chapter 6

SMAA simulations

In this chapter SMAA will be used to point out the best alternatives in three cases, considering specific analysis for uncertainties,dependencies and preference information, highlighting the iterative nature of the decision making process. The three cases will consider:

1. Independent variable without preference information
2. Multivariate Gaussian distribution without preference information
3. Multivariate Gaussian distribution with preference information

6.1 Independent variable without preference information

The first simulation was performed without preference information or any precise information about uncertainties, supposing a ± 10% and a normal distribution for every parameter. Flexibility was treated as an ordinal criteria, no subject to uncertainty, where values were assigned from 1 (*best*) to 9 (*worst*).

6.1.1 Results case 1

The following subsection presents and analyzes the results of a SMAA simulation based on criteria measurements and uncertainties from table 6.1. Figure 6.1 shows the rank acceptability indices for the alternatives. As said in the previous chapter, the rank acceptability indices describe the probability of each alternative to obtain a certain rank. Therefore, the most significant results are provided by the first and the last ranks, to identify respectively best and worst solutions.

Table 6.2 summarizes the results of the simulation, providing the holistic acceptability index, the confidence factor,the percentage for each alternative to obtain a certain rank and the central

	Investment cost [€]	Operational cost [€/y]	CO_2 [t/y]	Pollutants [t/y]	Flexibility
BC (A1)	0	360000	3800	2.41	9
BCS (A2)	100000	344000	4000	2.53	4
SH (A3)	190000	359000	3720	2.36	6
SHS (A4)	290000	332000	3700	2.35	3
SHSS (A5)	550000	323000	3900	2.46	1
GSH (A6)	110000	364000	3680	2.33	5
GSHS (A7)	210000	345000	3830	2.42	2
BB (A8)	400000	355000	3520	4.29	7
EB (A9)	410000	363000	3770	2.39	8
Uncertainties	± 10%	± 10%	± 10%	± 10%	

Table 6.1: Input data and relative uncertainties for SMAA simulations without preference information or dependencies information

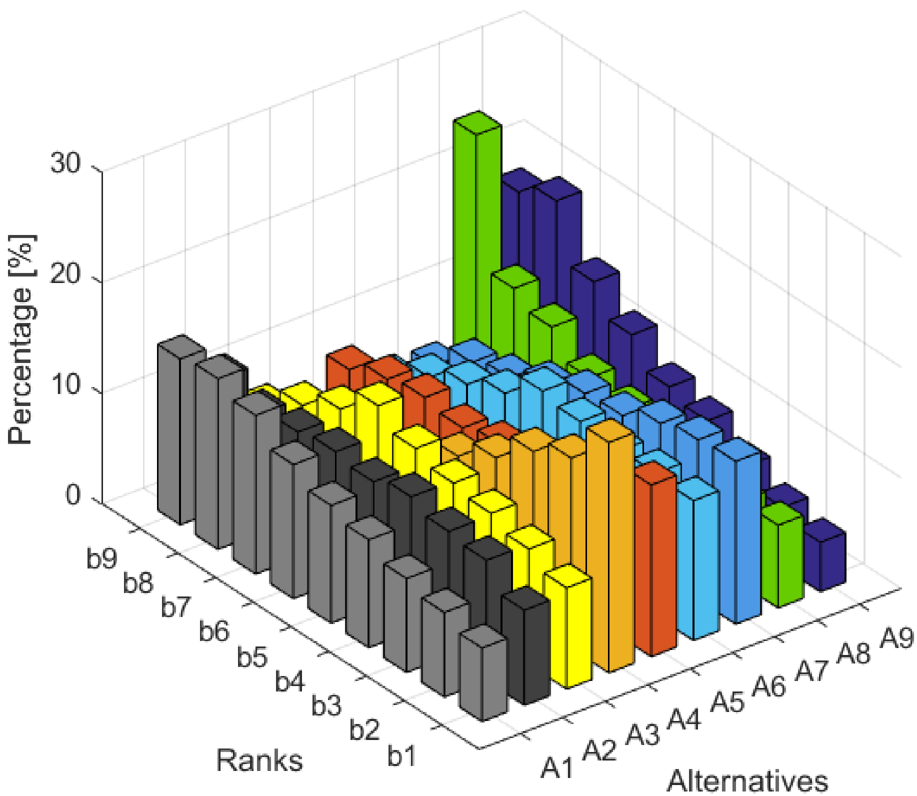


Figure 6.1: Rank acceptability indices of alternatives without preference information or dependencies information (%)

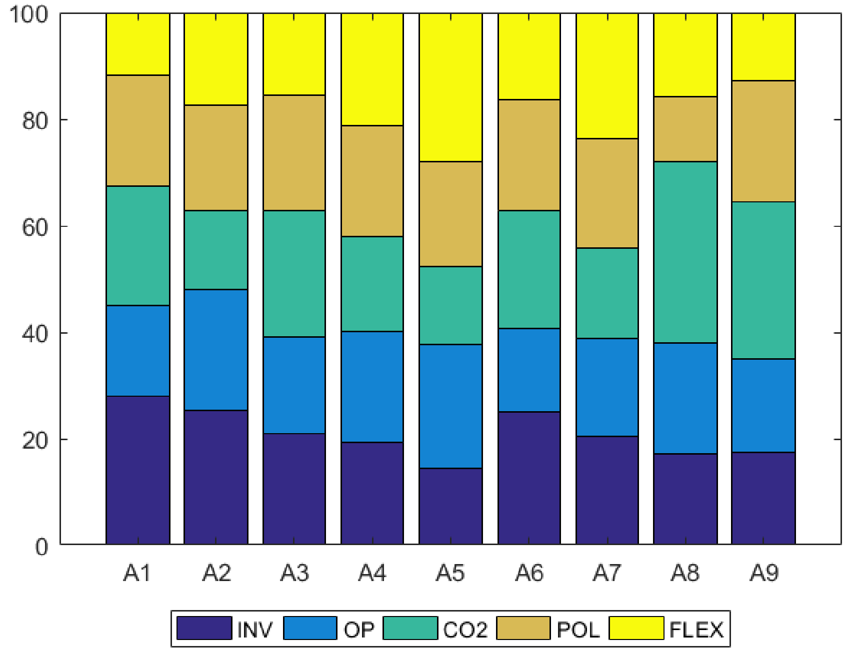


Figure 6.2: Central weights of alternatives without preference information or dependencies information (%)

weights of each alternative.
From figure 6.1 can be seen that the alternative with the highest acceptability index for the first rank is the solar heat with storage (21%), followed by the seasonal storage and the ground source heat pump with storage. On the other hand, biomass and electric boiler alternative have the highest probability to be the worst alternative. Looking at the holistic acceptability indices, can be seen how the situation is similar, but not the same. In fact, the first alternative remains the solar heat with storage, followed now by the ground source heat pump with storage.
Moreover, the confidence factor of the alternatives never exceed 25%, highlighting that there is not a clear optimal solution. It was therefore decided to analyze the cases with dependencies and preference information.

Alt	a^h	p^c	b^1	b^2	b^3	b^4	b^5	b^6	b^7	b^8	b^9	INV	OP	CO_2	POL	FL
BC	25	9	7	8	8	10	11	12	14	15	15	28	17	22	21	12
BCS	31	9	9	11	11	12	11	12	11	11	12	25	23	15	20	17
SH	32	12	9	10	11	12	13	15	12	10	8	21	18	24	22	16
SHS	48	24	21	17	16	13	11	8	6	5	3	19	21	18	21	21
SHSS	39	20	16	14	12	11	10	10	10	9	8	15	23	14	20	28
GSH	37	17	13	13	13	13	14	11	10	7	6	25	16	22	21	16
GSHS	40	15	15	14	14	12	12	11	9	7	6	20	18	17	20	24
BIO	24	15	7	7	8	8	9	10	12	14	25	17	21	34	12	16
EB	20	7	4	5	7	9	10	12	15	20	18	17	18	29	23	13

Table 6.2: Results using independent distribution and no preference information: holistic acceptability index, confidence factor, rank acceptability indices (b^r) and central weights (%)

6.2 The role of the uncertainties and dependencies

As stated in chapter 5, to perform the SMAA simulations not only a deterministic value is needed, but also uncertainties associated to that value can contribute to modify the results of the analysis. Usually ordinal criteria are not affected by uncertainties, while for certain criteria a reasonable uncertainties can be assumed without making mistakes. However, for criteria that involves complex system a specific analysis must be carried out.
In the thesis the uncertainties related to different criteria were treated as follows:

- Investment cost: an uncertainty of ± 10% was assumed.
- Operational cost and CO_2 emissions: a specific analysis was carried out to evaluate the robustness of the model.
- Pollutants emissions: since the pollutant emissions strongly depend on start up and partial load functioning, it was preferred to assign an uncertainties of ± 10% due to the absence of information.
- Flexibility: due to the nature of the criteria it is not affected by uncertainties, therefore it was considered with a fixed order.

To assess the uncertainties related to operational cost it was decided to perform a sensitivity analysis on two of the most relevant factor that influences expenditure and revenues of the system: fuel and electricity price. In particular, electricity and gas price trends in the previous years were analyzed,identifying a possible range of variation. First, only one of the two parameter was changed, highlighting a linear dependence with both variables, then a change in both parameter was considered. These simulations were used to recreate the Multivariate Gaussian Distribution, already discussed in the previous chapter.
To recreate the distribution, a correlation matrix and a standard deviation vector for each parameter considered were used. The resulting standard deviation vectors are displayed in table 6.3.

	BC	BCS	SH	SHS	SHSS	GSH	GSHS	BIO	EB
OP	13000	17000	15000	17000	18500	13000	16000	15500	13500
CO_2	0.00	0.01	0.40	0.03	15.09	0.14	0.33	73.77	0.02

Table 6.3: Standard deviation vector for operational cost and CO_2 emissions

The main comment related to the simulations is that, as can be seen, the standard deviation of CO_2 emissions is small compared to the mean value except for two alternatives: the seasonal storage and the biomass boiler. This result was expected, since the merit order of the production system is only slightly related to the gas and electricity price. In the seasonal storage case, where the production system can be adjusted more than the other alternatives, a variation of gas or

electricity price can also influence the production system, that can store or directly use the heat. For the biomass case, the gas and electricity price is compared to biomass price, therefore the production system can have significant changes.
Table 6.3 shows also the standard deviation of the operational cost, that is much higher with respect to the CO_2 variation, but whose values change more uniformly. As already commented for the CO_2 emissions, the main driver is the heat demand, whose variation is beyond the scope of the thesis.
Since SMAA perform several simulations based on the mean value and uncertainties associated to a specific criteria, it is important to relate the alternative to a certain scenario (*e.g. increase of electricity price*). In fact,starting from the mean value, the first alternative could use a positive variation $+\sigma$, while the second alternative a negative one $-\sigma$. This could lead to completely wrong results, since as explained before, the alternatives are related to the same production system (*CHP cover more than 90%*). To solve this problem, a correlation matrix, displayed in table 6.4 was used to recreate the Multivariate Gaussian Distribution. The matrix shows a perfect positive correlation between the operational cost of the alternatives, while a slight negative correlation is assessed between operational cost and emissions. Lastly, the correlation between emissions of the alternatives is negligible.

Table 6.4: Correlation matrix (ρ) for uncertainty dependencies of criteria measurements (%)

	$A1_c$	$A2_c$	$A3_c$	$A4_c$	$A5_c$	$A6_c$	$A7_c$	$A8_c$	$A9_c$	$A1_e$	$A2_e$	$A3_e$	$A4_e$	$A5_e$	$A6_e$	$A7_e$	$A8_e$	$A9_e$
$A1_c$	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$A2_c$	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$A3_c$	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$A4_c$	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$A5_c$	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0
$A6_c$	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0
$A7_c$	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0
$A8_c$	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0
$A9_c$	98	98	99	98	98	98	98	98	100	0	0	0	0	0	0	0	0	0
$A1_e$	59	59	53	59	60	59	59	58	40	100	0	0	0	0	0	0	0	0
$A2_e$	-17	-17	-25	-17	-17	-17	-17	-19	-38	69	100	0	0	0	0	0	0	0
$A3_e$	-39	-39	-46	-39	-39	-39	-39	-40	-58	51	97	100	0	0	0	0	0	0
$A4_e$	-80	-80	-75	-80	-81	-80	-80	-80	-65	-96	-45	-24	100	0	0	0	0	0
$A5_e$	-10	-10	-17	-9	-9	-10	-10	-11	-31	75	100	95	-52	100	0	0	0	0
$A6_e$	-36	-36	-29	-36	-37	-36	-36	-35	-15	-97	-86	-72	85	-89	100	0	0	0
$A7_e$	-99	-99	-98	-99	-99	-99	-99	-99	-94	-70	3	26	88	-5	49	100	0	0
$A8_e$	100	100	100	100	100	100	100	100	98	57	-20	-41	-79	-12	-34	-99	100	0
$A9_e$	0	0	8	0	0	0	0	1	22	-81	-98	-92	60	-100	93	14	2	100

6.2.1 Results case 2

The following subsection presents and analyzes the results of a SMAA simulation based on criteria measurements provided by previous simulation, while the uncertainties and dependencies used have been taken from table 6.3 and 6.4. Figure 6.3 shows the rank acceptability indices for the alternatives. With respect to the previous case, the output of this simulation are more clear and can be seen a clear predominance of solar combined with storage, followed by biomass.

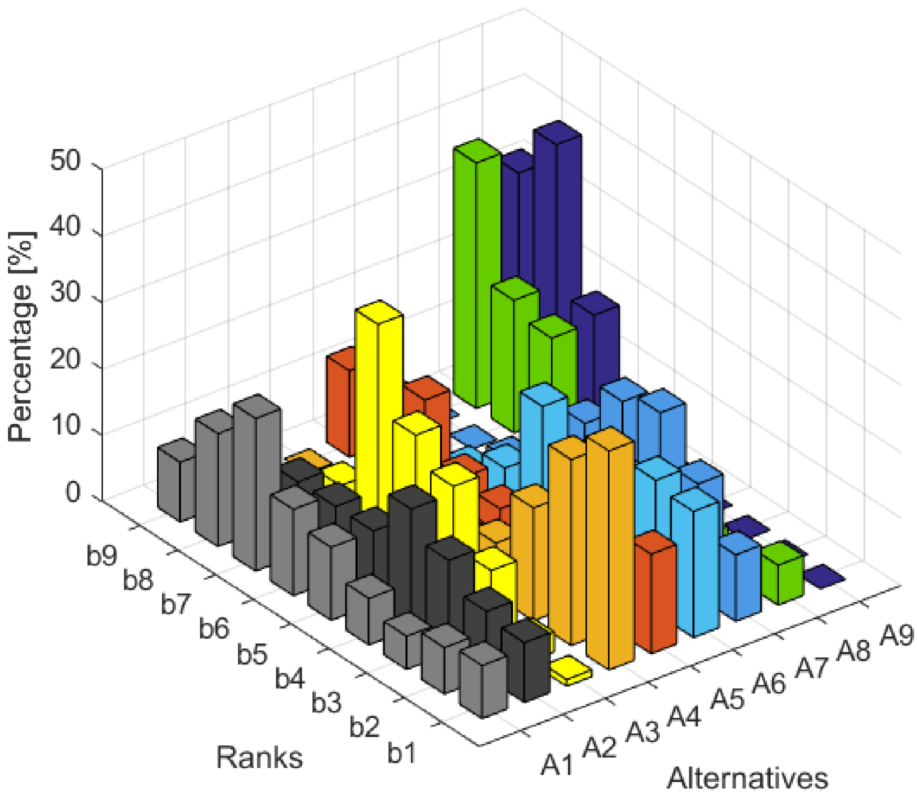


Figure 6.3: Rank acceptability indices of alternatives with dependencies information without preference information (%)

Table 6.5 summarizes the results of the simulation as done in the previous case. From figure 6.3 can be seen that the alternative with the highest acceptability index for the first rank is again the solar heat with storage (32%), followed by the ground source heat pump and the seasonal storage. The main difference with respect to the previous simulation is that the solar heat has a higher probability to be the best choice, but after the solar heat, the ground source heat pump increased its acceptability. Looking at the holistic acceptability indices,can be seen how ground source heat

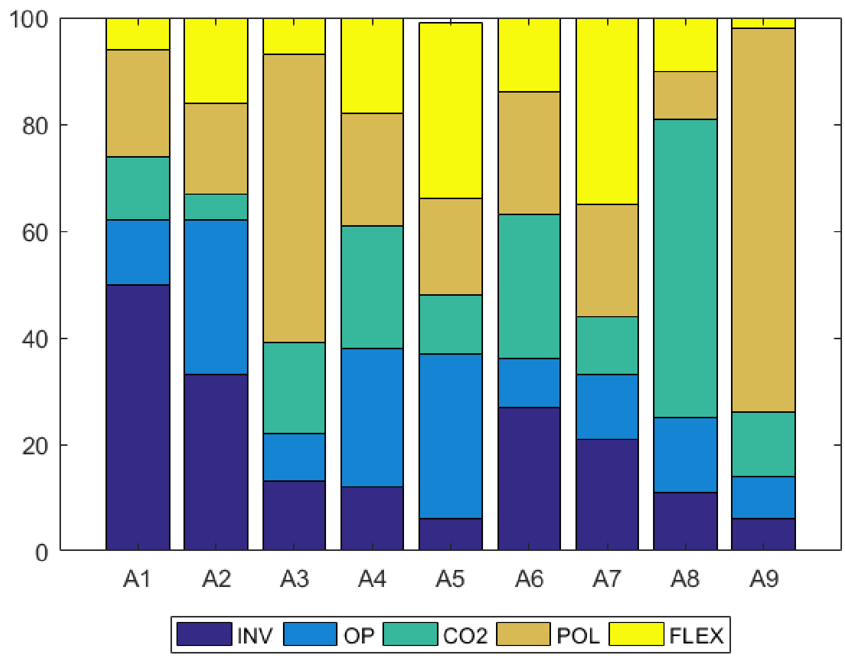


Figure 6.4: Central weights of alternatives with dependencies information without preference information (%)

Alt	a^h	p^c	b^1	b^2	b^3	b^4	b^5	b^6	b^7	b^8	b^9	INV	OP	CO_2	POL	FL
BC	25	90	8	7	5	7	11	13	23	17	9	50	12	12	20	7
BCS	33	82	9	10	14	18	11	11	11	8	9	33	29	5	17	17
SH	25	11	1	3	10	19	23	36	8	1	0	13	9	17	54	7
SHS	63	92	33	28	17	8	6	7	0	0	0	12	26	23	21	18
SHSS	33	66	15	11	9	8	7	8	16	13	13	6	31	11	18	33
GSH	50	86	19	20	17	15	20	7	3	0	0	27	9	27	23	14
GSHS	44	58	10	17	24	22	15	9	2	0	0	21	12	11	21	36
BIO	15	63	6	3	3	3	5	5	18	20	37	11	14	56	9	11
EB	5	3	0	0	0	0	2	4	19	41	33	6	8	12	72	4

Table 6.5: Results using Multivariate Gaussian distribution and no preference information: holistic acceptability index, confidence factor, rank acceptability indices (b^r) and central weights (%)

pump coupled with storage and seasonal storage represents the second alternative. Lastly, the confidence factor of the solar combined with storage reaches value of almost 90%, highlighting how the information gathered during the simulations increased the confidence factor of the choice.

Looking at figure 6.4 can be seen that:

- Alternative 1 is characterized by the highest weight of investment cost

- Alternative 5 is characterized by the highest weight of operational cost
- Alternative 8 is characterized by the highest weight of CO_2 emissions
- Alternative 9 is characterized by the highest weight of Pollutants emissions

Even if these analysis are quite clear and point out pros and cons of every alternative, a further analysis including information provided by the decision maker is necessary, to assess which of the previous alternative is the most preferred in the case study.

6.3 Preference information

A group of energy experts from Politecnico di Torino participated in the process. The experts were chosen among Polito's professors; therefore, they hold at least a Master's level academic degree and a Phd in the field of energy, with working experience from 5 years to over 15 years in the energy field. To provide a broad set of points of view to the decision process, the experts were chosen from different sectors, involving knowledge of DH production and distribution, new energy production development, optimization of energy systems and multicriteria decision making. The experts provided information independently and anonymously, to avoid unbiased opinions.
Each expert was asked to assess the importance of the criteria ordering it from the most to the least important. If the experts could not provide a certain preference, they could insert a question mark, denoting unspecified preference order. Table 6.6 shows the order of preference for criteria by the experts.

1	C1	>	C2	>	E1	>	T1	>	E2
2	C2	?	C1	>	E1	>	T1	>	E2
3	C1	>	C2	>	T1	>	E1	>	E2
4	C1	>	C2	?	T1	>	E1	>	E2

Table 6.6: Order of preference for criteria given by experts

As can be seen, there is a clear preference for the investment cost, followed by the operational cost, while flexibility and CO_2 emissions are considered least important than the two economical criteria but there is not a single preference from the experts. The least important criteria is the pollutants emissions, that is already regulated by environmental law and respected by all scenarios.

6.3.1 Results case 3

The following subsection presents and analyzes the results of a SMAA simulation based on criteria measurements provided by previous simulation, uncertainties and dependencies taken from table 6.3 and 6.4 and preference information taken from 6.6. Figure 6.5 shows the rank acceptability indices for the alternatives. Can be seen how including preference information drastically changes the output of the analysis. The best solution is still the solar heat with storage, followed now by the increase of storage alternative. The other alternative are clearly outranked from these two, that obtains respectively 50 and 26% of the preferences.

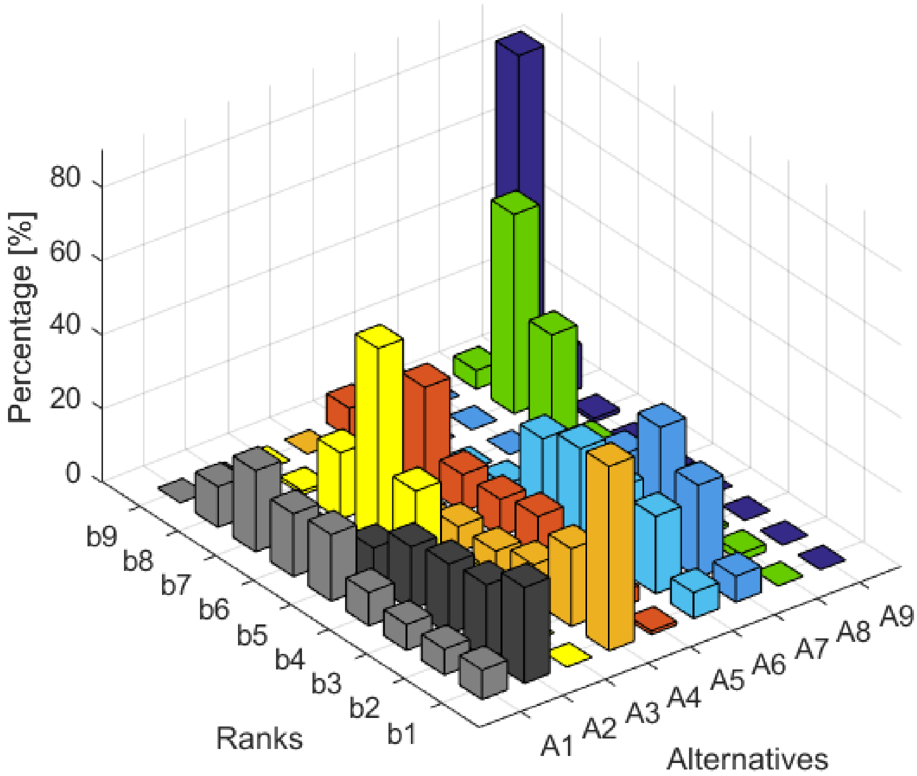


Figure 6.5: Rank acceptability indices of alternatives with dependencies and preference information (%)

Table 6.7 summarizes the results of the simulation as done in the previous cases. Looking at the table can be seen how the solar heat alternative and the electric boiler alternative are considered inefficient, meaning that does not exist a single weight combination that favours these alternative, therefore the central weights are written as a 0 vectors. On the other hand, thanks to the preference

Alt	a^h	p^c	b^1	b^2	b^3	b^4	b^5	b^6	b^7	b^8	b^9	INV	OP	CO_2	POL	FL
BC	28	96	8	7	7	9	18	17	22	11	0	68	16	9	2	5
BCS	56	93	26	20	19	17	10	5	3	1	0	52	28	6	3	11
SH	18	0	0	0	1	6	21	53	18	1	0	0	0	0	0	0
SHS	73	94	50	21	10	7	7	4	0	0	0	38	27	16	5	14
SHSS	18	6	1	4	6	12	10	10	27	21	8	34	28	12	5	21
GSH	44	55	7	21	22	26	22	3	0	0	0	52	19	15	5	10
GSHS	48	24	7	25	34	20	11	3	0	0	0	43	24	11	5	18
BIO	9	9	0	2	1	2	2	5	28	54	5	38	29	26	2	6
EB	1	0	0	0	0	0	0	0	1	12	86	0	0	0	0	0

Table 6.7: Results using Multivariate Gaussian distribution and preference information: holistic acceptability index, confidence factor, rank acceptability indices (b^r) and central weights (%)

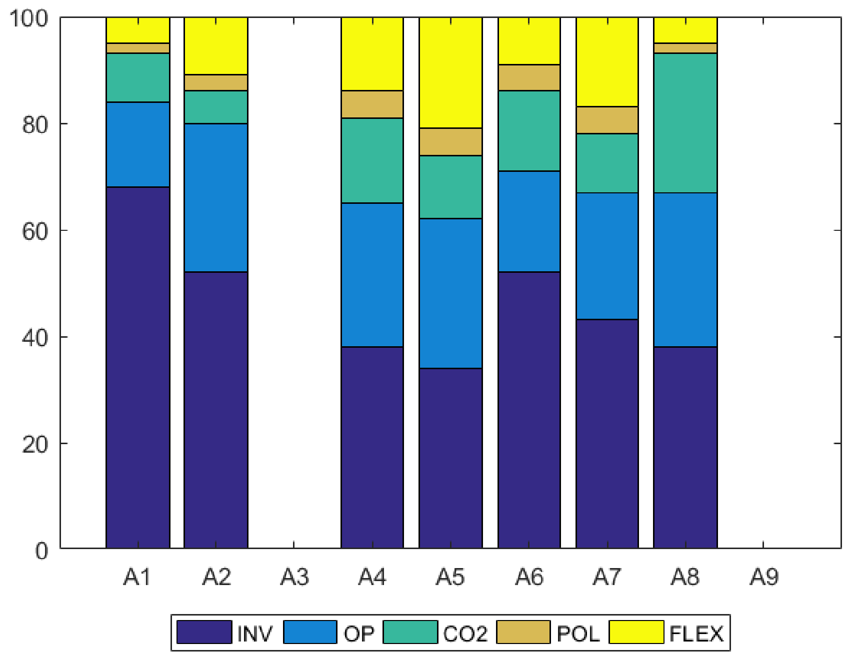


Figure 6.6: Central weights of alternatives with dependencies and preference information (%)

information, the confidence factors for the preferred alternatives almost reach 100%, highlighting how it is important in these kind of analysis to include preference information to strengthen the results. Also looking at the holistic acceptability indices, can be seen how the solar heat is the most preferred alternatives, but followed by the increase of storage and the ground source heat pump with storage, that represents a good compromise between the alternatives.
Analyzing figure 6.6 can be seen that:

- Alternative 3 and 9 are nomore considered in the analysis

- Alternative 1 and 2 are characterized by the highest weight of investment cost, limiting the importance of operational cost and flexibility
- Alternative 4 and 5 are characterized by a more homogeneous distribution of the weights, according to the preference information provided by the DMs

Chapter 7

Conclusion

The aim of the work was to create a methodology for supporting decision making in the energy field. In particular, the analysis focused the attention on cases in which criteria measurements can be uncertain or dependent between each other. The process can be divided in 2 stages: the first one aims to simulate the energy system (and consequently the alternative proposed for the decision making), while the second one use information provided by the first stage to perform a Monte Carlo simulation to select the best alternative, considering uncertainties, preference information and dependencies.

The methodology was applied to a case-study created starting from data provided by the LivingLAB. These data includes thermal load of Politecnico di Torino, a university that uses DH to satisfy its heat demand, with the aim to replace gas boiler with more sustainable technologies. After a brief survey on DH, the actual production system and the data were studied to create the model, that was modelled with LP2 software and benchmarked using EnergyPRO. The comparison highlighted the higher ability of LP2 software to simulates more precisely the actual production system, therefore it was used to evaluate the alternatives.

Then, several alternatives were considered to replace gas boiler, including the most promising technologies coupled with DH in Europe. Before modelling every alternative, a quick introduction of each technology was provided, including every relevant information regarding the assumption made. Every alternative was then optimized according to specific criteria, trying to minimize the operational cost of the system.

Lastly, the thesis analyzed the alternatives with a MCDM tools (SMAA), able to consider uncertainties, dependencies and preference information. To highlight the importance of these kind of information, SMAA was repeated three times, including at each simulations a higher level of detail. These process helps to understand how the best alternative can change depending on data availability and helps to strengthen the results, highlighting the iterative nature of the decision making process.

Results underline that the first simulation was not able to identify a clear solution, while with more information several feasible solutions were identified. Lastly, considering preference information of decision makers the best solution was pointed out.

Analyzing in detail the last simulation, to replace gas boiler, solar heat plant coupled with an increase of storage was identified as the best solution, covering more than 50% of first acceptability index and 73% of holistic acceptability index. On the other hand, solar heat was identified as inefficient solution, highlighting the fundamental role of storage to match renewable energy and demand. Moreover, electric boiler (A9) was ranked last, due to its both high operational and investment cost.

Future works may consider the application to the entire city using data provided by IREN company, or the extension of the methodology to a “multi-optimization and multicriteria evaluation of alternatives”, following the same iterative process, but based on DMs’ preferences changing the objective functions.

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