POLITECNICO DI TORINO

Master Thesis

in Ingegneria Energetica e Nucleare

Master Thesis

District cooling network modelling: design and analysis for the city of Torino

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Abstract

The construction of urban district heating networks is now a widespread practice in many European areas. With the development of dedicated technologies and the growing cooling demands, the idea of district cooling networks became very attractive in the recent years. When a high thermal energy demand is requested, combined with a elevated population density, this option can be very profitable. The purpose of this Master thesis is to develop a model able to simulate the functioning of a district cooling network for the city of Torino in order to analyze different operating conditions, highlighting possible problems and improvements. Once the model has been developed, the aim is to find the optimal conditions that minimize the thermal losses, the required investment cost and the complexity of the network. To find this optimum, the system has been studied in different layouts: changing the velocity of the cold water flowing in the system, the positioning of the heat pumps that supply the cold energy, the positioning of the booster stations along the network which guarantee the minimum system pressure, load values and pipe technologies.
In particular, the created model simulates the transport network for the city of Torino based on the existing district heating grid. The map of the transport network coincides with the already existing district heating and the required thermal power is estimated starting from the heating energy demand and the climate data characterizing the entire area.
In the final chapter all the costs, advantages and weaknesses of the different cases have been presented and compared.

Keywords: district heating; district cooling; co-generation; Turin; Piedmont; feasibility study; model; optimization.

Index

Abstract **I**

List of Tables **IV**

List of Figures **VI**

List of abbreviations **VII**

1 Introduction **1**

1.1 Heating and cooling demand in Europe 1

1.2 Heating and cooling demand in Italy 2

1.3 District heating: systems overview 3

1.3.1 Network 4

1.4 District Heating and Cooling in Torino 6

1.5 District cooling 8

1.5.1 Cooling technologies 9

1.5.2 District cooling terminals 10

1.6 Cooling Energy Demand Estimation 11

1.7 Aim of the thesis 15

2 Thermal network design **16**

2.1 General model 16

2.2 Turin DC network design 19

2.3 Preliminary economic analysis 21

3 Network Optimization **23**

3.1 Velocity optimization 23

3.2 Genetic algorithm 24

3.3 Optimization of the heat pumps positions 26

3.4 Optimization of the booster pumping stations location 27

4 Results **30**

4.1 Heat pumps position optimization 30

4.1.1 Centralized Production 30

4.1.2 Distributed Production 33

4.1.3 Optimized Distributed Production 36
4.1.4 Low insulated pipes network 39
4.2 Partial Load Analysis 42
4.2.1 Partial Load Analysis in case of high insulated pipes 44
4.2.2 Partial Load Analysis in case of low insulated pipes 46
4.3 Booster pumping stations placement optimization 49
4.3.1 BPS optimal configuration high insulated pipes 50
4.4 Simulation campaign main results 56

5 Conclusions and Perspective **58**

References **61**

A Appendix **62**
A.0.1 Appendix A: Cost of the pipes 62

List of Tables

4.1 Centralized production configuration main results 30
4.2 Distributed production configuration main results 34
4.3 Optimized distributed production configuration main results 36
4.4 Simulation campaign main results 39
4.5 Well and low insulated pipes results comparison 42
4.6 Operating partial load levels 42
4.7 Pressure drop in the different configurations 50
4.8 Electrical consumption after BPS installation 50
4.9 Booster pumping stations - delivery 51
4.10 Booster pumping stations - return 51
4.11 Electrical consumption after BPS installation 54
4.12 Booster pumping stations - delivery 54
4.13 Booster pumping stations - return 54
4.14 Simulation campaign main results 57
4.15 Partial load analysis 57
4.16 Optimized BPS results 57

A.1 Pipe Price Catalogue [23] 62

List of Figures

1.1 H&C demand in 2015 (EU28) [2] 1
1.2 H&C final energy use in 2015 (EU28) [2] 2
1.3 H&C FED by sector in 2015 (EU28) [2] 2
1.4 Italy final energy use [3] 3
1.5 Typical flat energy consumption [4] 3
1.6 DHN in Italy [6] 3
1.7 DHN energy mix in Italy [6] 3
1.8 District heating and cooling [7] 4
1.9 DH pipe outline [9] 5
1.10 DH pipes example [10] 5
1.11 DH substation scheme [11] 6
1.12 300 kW DH substation [12] 6
1.13 Torino district heating grid [13] 6
1.14 European DH installations [16] 9
1.15 European DC installations[16] 9
1.16 Heat pump [17] 9
1.17 Heat pump with absorption cycle [17] 9
1.18 Fan coil of nominal cooling capacities from 0,6 to 12 kW [18] 10
1.19 Example of radiant panel under the floor [19] 11
1.20 Average monthly temperatures in Torino 2015-2019 [20] 12
1.21 Cumulative Frequency Distribution Curve 2014-2018 [21] 12
1.22 User Distribution Map [22] 13
1.23 Load Duration Curve 14

2.1 Control volume 18
2.2 Turin district heating network [22] 19
2.3 Scheme of the program procedure 20
2.4 Pipes cost [23] 22

3.1 Cost trend with thermal transmittance U=1 [$W/(m^2K)$] 23
3.2 Cost trend with thermal transmittance U = 5 [$W/(m^2K)$] 24
3.3 Genetic algorithm scheme [26] 25
3.4 Map of the barycenters 26
3.5 Available positions for heat pumps 27

3.6 Available positions for the installation of booster pumping station 28

4.1 Centralized production supply temperature map 31
4.2 CP Temperature evolution along one of the supply path 32
4.3 Centralized production return temperature map 32
4.4 CP Temperature evolution along one of the return path 33
4.5 Distributed production supply temperature map 34
4.6 DP Temperature evolution along one of the supply path 35
4.7 Distributed production return temperature evolution 35
4.8 DP Temperature evolution along one of the return path 36
4.9 Optimize HP positions delivery temperature map 37
4.10 ODP Temperature evolution along one of the supply path 37
4.11 Optimize HP positions return temperature map 38
4.12 ODP Temperature evolution along one of the return path 38
4.13 Low insulated pipes supply temperature map 40
4.14 LIDP Temperature evolution along one of the supply path 40
4.15 Low insulated pipes return temperature map 41
4.16 LIDP Temperature evolution along one of the return path 41
4.17 System load following capacity 43
4.18 Peak load replaced by storage capacity 43
4.19 Percentage heat loss at different partial loads U=1[$W/(m^2K)$] 44
4.20 50 % partial load supply temperature map 45
4.21 ODP Temperature evolution along one of the supply path 45
4.22 50 % partial load return temperature map 46
4.23 ODP Temperature evolution along one of the return path 46
4.24 50 % partial load supply temperature map - low insulated pipes 47
4.25 LIDP Temperature evolution along one of the supply path 47
4.26 50 % partial load return temperature map - low insulated pipes 48
4.27 LIDP Temperature evolution along one of the return path 48
4.28 Percentage heat loss at different partial loads U=5[$W/(m^2K)$] 49
4.29 Optimized HP position supply pressure map 51
4.30 Pressure evolution along one of the supply path 52
4.31 Optimized HP position return pressure map 52
4.32 Pressure evolution along one of the return path 53
4.33 Low insulated pipes supply pressure map 54
4.34 Pressure evolution along one of the supply paths 55
4.35 Low insulated pipes return pressure map 55
4.36 Pressure evolution along one of the return paths 56

List of abbreviations

- DH District Heating
- DC District Cooling
- DHN District Heating Network
- DCN District Cooling Network
- COP Coefficient Of Performance
- GA Genetic Algorithm
- HP Heat Pump
- SN Supply Network
- RN Return Network
- BPS Booster pumping station
- CHP Co-generation heat plant

1. Introduction

1.1 Heating and cooling demand in Europe

Improving energy efficiency is a priority of the EU's Energy Union strategy. Energy efficiency has been identified as a key element for fostering European competitiveness, for ensuring a secure energy supply and the reduction of greenhouse gas emissions.
Figure 1.1 shows that heating and cooling represent about 50% of the final energy consumed in the EU, therefore is fundamental to identify and promote potential savings in this area.
Figure 1.2 shows that 84% of heating and cooling in the EU is still generated from fossil fuels while only 16% is produced from renewable energy. In order to fulfil the EU's climate and energy goals, the heating and cooling sector must sharply reduce its energy consumption and cut its use of fossil fuels.
In February 2016, the European Commission proposed a strategy to make heating and cooling in the EU more efficient and sustainable. This strategy highlights the capacity of district energy systems to replace fossil fuels with waste heat and cold from industrial processes, waste-to-energy and renewable energy sources such as geothermal, biomass, solar thermal.
Efficient district energy systems can play a key role in the energy transition towards a low-carbon economy, acting as an evolutive backbone towards efficient local energy systems. Some European cities have already recognised the benefits of these systems and developed efficient and sustainable heating and cooling solutions, which are well functioning and result in a high-quality, efficient and low-carbon heat and cold supply to its buildings and industries. [1]

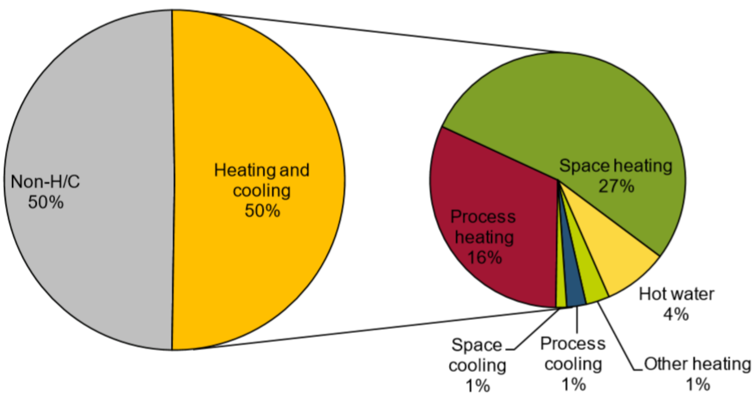

Figure 1.1: H&C demand in 2015 (EU28) [2]

In figure 1.3 the heating and cooling final energy demands by sector and end-use are reported. The residential sector has the highest H&C energy demand. Same happens for tertiary sector. Process heat accounts for about 80% of the total energy request in the industry sector. Space cooling, nowadays much more important in the tertiary sector than in the residential one, will be rising during the next years and it is fundamental to develop proper technologies capable to satisfy the demand in the highest possible efficient way. [2]

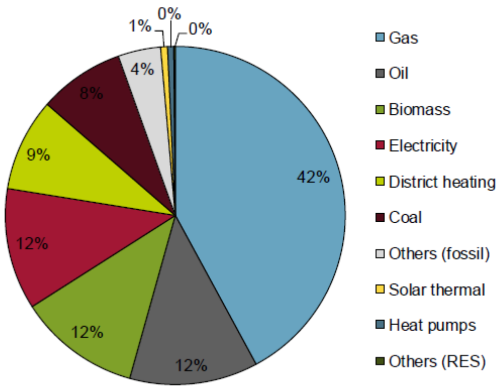

Figure 1.2: H&C final energy use in 2015 (EU28) [2]

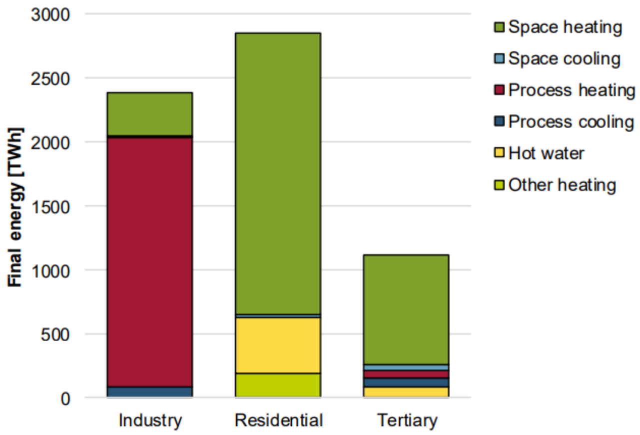

Figure 1.3: H&C FED by sector in 2015 (EU28) [2]

1.2 Heating and cooling demand in Italy

The Italian energy demand is reported in Figure 1.4.
The sector that requires more energy is the residential one, followed by industry and tertiary consistently with that is shown in Figure 1.3 which gives an average behaviour of the European Countries. Furthermore, Figure 1.5 illustrates the energy consumption in buildings during the last years.
It is possible to note the H&C demand is by far the largest, representing almost the 75 % of the total. Italian heating and cooling markets are dominated by individual solutions, mainly based on natural gas and electricity, respectively.
District heating is relatively new and in 2013 represented 5.6% of the national market share in terms of final users. Since 2000, DH has experienced an annual growth rate of about 7% in terms of heated space. DC developments are very recent, with a total installed capacity of 182 MW (2013). Italy has more than 200 DH systems, mainly located in the Northern regions, as illustrated in Figure 1.9. The 3 large cities supplied with DH, Brescia, Milano and Torino, represent 42% of the total DH supply. The highest share of total sales (67%) was also within the residential sector. [2]. Figure 1.7 illustrates the energy mix of the Italian DH systems. As displayed on the graph, the leading energy used in Italy for heating is natural gas, mainly for individual boilers. In the Alps and the Apennines mountains, biomass plants (whether used in district heating or individually) are becoming increasingly widespread. CHP plays an important role in Italy's national energy systems, with more that half of national electricity production from CHP in 2014. In addition, 67% of the district heating supply in 2014 was generated through CHP.[5]

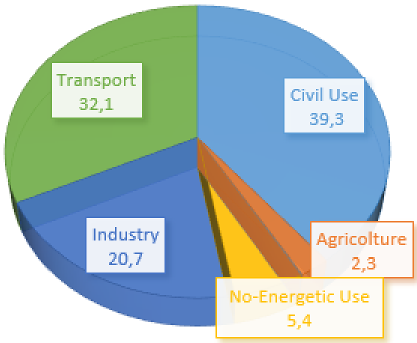

Figure 1.4: Italy final energy use [3]

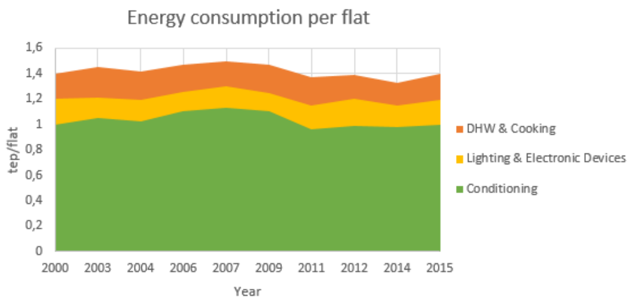

Figure 1.5: Typical flat energy consumption [4]

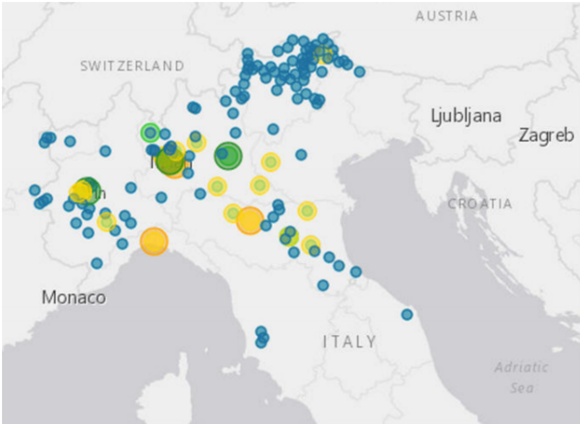

Figure 1.6: DHN in Italy [6]

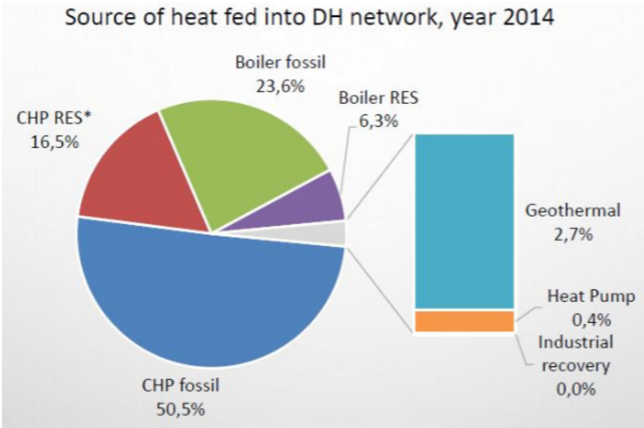

Figure 1.7: DHN energy mix in Italy [6]

1.3 District heating: systems overview

The term district heating refers to a heating system that aims to exploit a fuel resource of which the region concerned is rich (biomass or geothermal), or which is deemed convenient to buy, at that particular moment, on the market, thus reducing the waste and environmental impact and concentrating heat production in large power plants providing then heat to the surrounding areas. A large thermal plant produces heat and distributes it, in the form of hot, super-heated water, steam or diathermic liquids to a neighborhood or an entire city. The applicability of district heating on such large areas and its effectiveness makes it a real public service, which is integrated with aqueducts and electricity grids. In Figure 1.8 is reported the scheme of operation of a district heating network: the co-generation plant produces energy and heat (using different fuels), the heat is received by the primary heat transfer fluid (hot water, super-heated water, steam or diathermic liquids) which is distributed through a network of pipes to the final users; here the primary piping network meets the secondary one of the users and heat exchange takes place through the substations installed at the various buildings. The heat, transferred into the water of the secondary network pipes, can be used to heat the rooms or to produce domestic hot water; the heat transfer fluid, which has now lost its heat, returns to the district heating plant, ready to be reheated and redistributed.

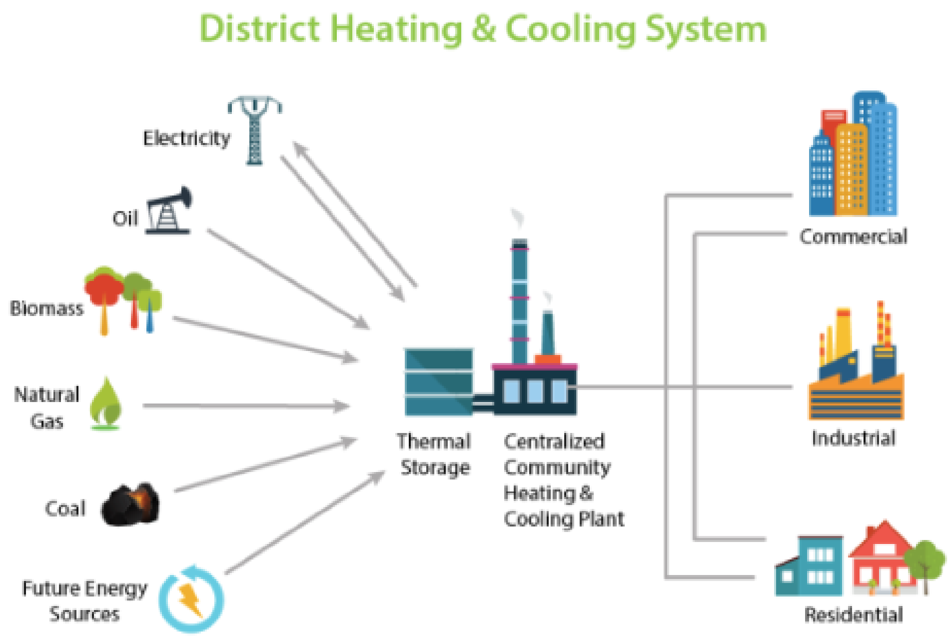

Figure 1.8: District heating and cooling [7]

Taking into account the significant lower operating costs that a thermal exchange substation requires compared to the replaced thermal plant (extreme simplicity of the plant; no need for the conductor; absence of chimney, etc.) the final cost of the heat from district heating is lower than that of any other commercial energy carrier currently available on the market. But the advantages for the user are not only economic: the absence of fuels and direct flames in rooms annexed to buildings to be heated, replaced by direct supply of hot or overheated water, make district heating an intrinsically safe and risk-free system of explosions and fires. The combustion, in fact, is carried out at the co-generation plant, located far away from the houses and in any case under the control of specialized personnel.

1.3.1 Network

The heat is carried form the production site to the users through a pipes network. This network can be tree-shaped, ring-shaped or present multiple loops. In general the complexity of the structure improves the reliability of the service but, at the same time, the cost of implementation and the complication in management increases. The characteristics of the materials currently used for the construction of the networks offer high levels of reliability. Two situations are therefore frequent: in smaller district heating systems, the network structure is generally tree-shaped, to limit construction costs; in district heating systems serving large and densely populated urban areas, the network can present one ring or (in large systems size) multiple loops; often this choice is also motivated by the needs of reliability related to the presence of several production plants [8].
Distribution network is the main element of the system, the existing networks are usually made of insulated steel pipes with welded joints made in place. Network security is guaranteed by the integration of a leak detection system that allows to establish the defective zone with a good approximation. The technological evolution of recent years has also allowed the adoption of innovative techniques that allow a significant decrease in installation costs. The distribution network consists of main and

secondary pipelines, the characteristics of these two elements are briefly described below:

- The main pipe system (transportation network) consists in a large underground net which connects the plants to the different areas using the DH service. The sizing of the primary network is of crucial importance: establishing the correct diameter of the pipes is fundamental to guarantee the correct functioning of the system (fluid speed, reduction of heat loss and prevention of pipe breakage) and to contain construction costs which increase with increasing the diameter of the tubes. In designing the primary network, the future expansion of the distribution system and the type of heat vector that will pass through it must also be taken into account.

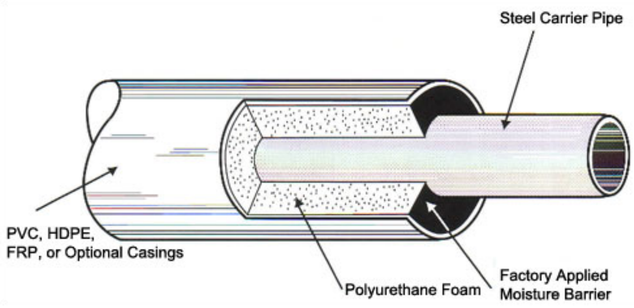

Figure 1.9: DH pipe outline [9]

Figure 1.10: DH pipes example [10]

The ground can be considered as a huge system at a constant temperature of 15°C. Without a proper distribution system, the heat loss may affect the efficiency of the system, since the fluid can be eventually sent to the users at a temperature of 135°C. Also any environmental problems due to a possible fluid leakage may occur. Advanced production technologies have been developed and, today, pre-insulated pipes made of environmentally friendly and fully recyclable grades materials can be easily found on the market. An example of the pipe structure is reported in 1.9. The cost of the network strongly depends on nature of the service (district heating or cooling), the diameter of the pipes and the characteristics of the fluid.

- The secondary pipeline (distribution network) corresponds to the connection between the main pipeline and the substation within the building. A branch leaves the main line and delivers the power to an entire neighbour or a single building. The fluid flows back to the plant after being cooled down.

- The substation replaces the building heat generator (boiler). The system of regulation of the substation allows to regulate the heat exchange between the circuit of the DH network and the building heat distribution system in order to satisfy the users demands in the best way possible.

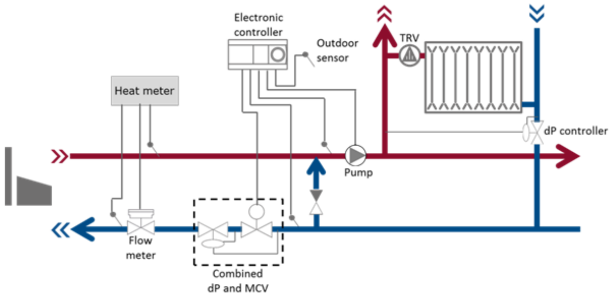

Figure 1.11: DH substation scheme [11]

Figure 1.12: 300 kW DH substation [12]

1.4 District Heating and Cooling in Torino

In the whole Province of Torino there are many district heating grids, the oldest of them was built more than 30 years ago, whereas many of them are actually working, some others are still in project. The most important part of the district heating grids is located in the city of Torino and in the surrounding municipalities, where there is the highest density of buildings and population. Also with consideration to air quality concerns, the city's been developing the largest district heating grid in Italy for two decades, connecting three thermal power plants and supporting boilers. Energy facilities are fed by natural gas.

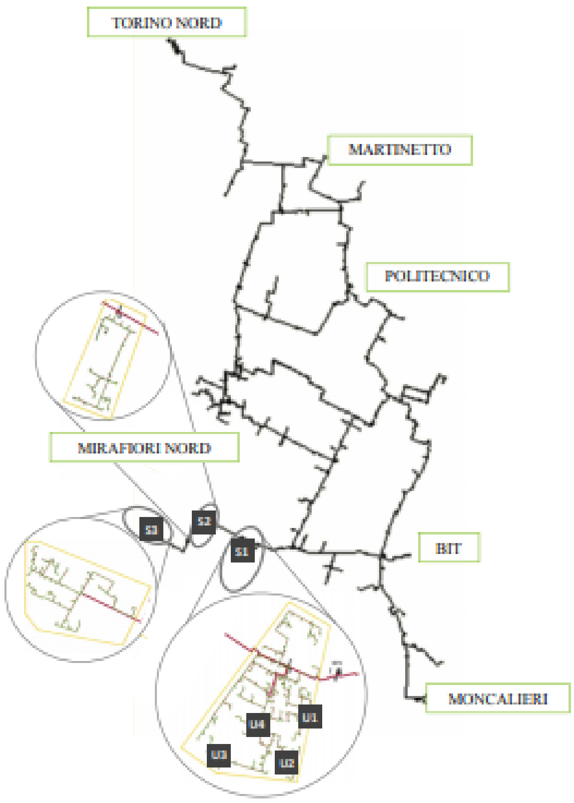

Figure 1.13: Torino district heating grid [13]

Figure 1.13 illustrates the map of the city DH network. District heating in Torino started in the quarter named “Le Vallette” in 1982, when the Municipal Electric Society AEM (actually IREN) placed a combined heat and power plant with diesel engines to increase the already existing small network, which reached in the following years the volume of 3 million of cubic meters of served buildings, i.e. about 30.000 inhabitants. Another combined heat and power plant has been installed in 1988 in Mirafiori Nord, the connected grid reached up to 2,25 million of cubic meter of buildings. Later this grid has been included in the large grid named “Torino Sud”, also owned by IREN, which has been developed gradually since 1994 reaching all the southern part of the city (27 million of cubic meters and 270.000 inhabitants), fed by the combined heat and power plant “Centrale Moncalieri” and by the backup boilers in “Centrale BIT”. Further development of “Torino Sud” network was implemented in “Torino Centro” starting from 2001 with the increase of power of the “Centrale Moncalieri”, which reached the actual configuration, and the installation of backup boilers and heat storage at “Centrale Politecnico”. The total building volume connected to the grid Torino Sud and Centro is around 36 million of cubic meters. In 2011 the old plant “Vallette” has been replaced by the new and much more powerful plant named “Torino Nord”, constitued by combined heat and power unit, backup boilers and heat storage. The new plant allows to increase the grid in the northern area of the city and to connect it with the “Torino Centro” grid.
Two storage system (at Politecnico and Torino Nord plants) allow to store night heat production, contributing up to 5% of global heat demand and shaving heat peak demand on early morning hours[14]. On 2011-2012 around 2050 GWh have been distributed, covering the demand of 550.000 inhabitants, as 50 million of cubic meters of building connected by a 515 km distribution grid. In comparison with distributed heating production and taking in account the recovery of waste heat from power station, average yearly environmental gains are estimated as follow:

- Energy saving: 280.000 toe/y ;
- CO2 emission reduction : 1.1 Mtons/y;
- NOx emission reductions : 1900 tons/y;
- SOx emission reduction : 2700 tons/Y;

The great development of Torino district heating network within a few year, which led to the city the important improvements aforementioned, and the rising cooling demand in the country suggest that the investment in a DC network would be strongly advantageous and economical profitable. A strong potential in the district cooling technologies can be easily identified. Italy, such as other European Countries, presents a Continental climate, with cold winters and hot summers. An appropriate combination between the DC system and the electricity production can lead the city to important environmental improvements and money savings.

1.5 District cooling

District cooling is the cooling equivalent of the district heating. It delivers chilled water to buildings which need cooling through a pipes network.
District cooling is still relatively little known and widespread compared to district heating but the sector is steadily growing in the past years. It is economically advantageous in high density areas, because it requires a very expensive initial investment. At the moment the users are mostly offices or factories, one of the reason for this is the lack f terminals able to use the chilled water for cooling in the residential sector.
The benefits of district cooling compared to local generation of cold are:

- Environment protection, reduction of CO_2 emission and environmental hazardous refrigerants;
- Enhanced aesthetics and an improved local environment by reducing the noise;
- Security of supply: avoid investments in summer electricity peak capacities.

The main cooling sources for district cooling are:

- Natural cooling sources from deep sea, deep lake, rivers or aquifers so called "free cooling";
- Industrial cooling sources where absorption chillers are used in combination with waste heat from industrial processes, waste incineration or co-generation production plants;
- Residual cooling from re-gassification of liquified natural gas;
- Heat pumps in combination with district heating systems
- High efficient industrial chillers are often added as a part of the production mix to secure outgoing temperatures and redundancy.[15]

The solution proposed in this study is the use of heat pumps for the production of cold energy for the district cooling network in particular absorption heat pumps in case of the centralized energy production or electrical driven heat pump for the distributed energy production.
One interesting option is to couple the district heating and cooling network taking advantage of the heat pump technology. The eventual use of both the heat and the cold production will increase significantly the system performance coefficient. Also having water at both the condenser and the evaporator means that the surface required for the heat exchange will be small (compared to heat pumps that exchange heat with air) and the use of compact heat pumps allow their allocation inside the city, the localized production will have benefits as is possible to see in the results 4.4 (mainly economic benefit due to a lower price of the pipes network).

Figure 1.14: European DH installations [16]

Figure 1.15: European DC installations[16]

1.5.1 Cooling technologies

The production of cold is an important sector in the energy production. Its demand can be easily satisfied by the use of refrigerant engines. Below two types of cycles are illustrated:

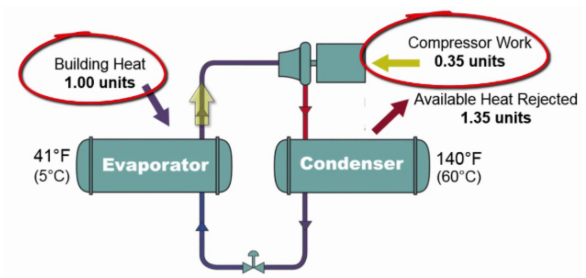

Figure 1.16: Heat pump [17]

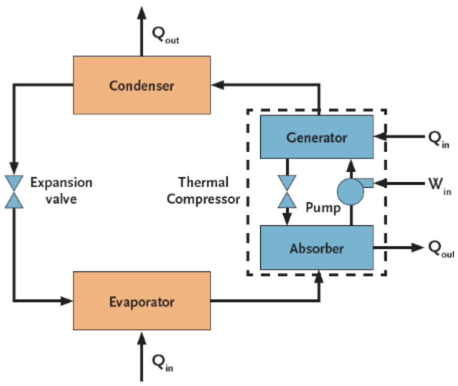

Figure 1.17: Heat pump with absorption cycle [17]

The heat pumps (Figure 1.16) are usually the first choice in this market. With an efficiency between 2.5-3, it can supply the demand absorbing relatively little quantity of electric energy. The cycle is divided in two level: high pressure and low pressure stage. The refrigerant fluid is pumped to the higher pressure passing through a compressor. The fluid releases its energy in the condenser, converted in heat flux at relatively high temperature. The expansion valve reduces the pressure of the fluid, now in the liquid phase. In the evaporator the refrigerant turns back in the vapour state: the cooling effect takes place. A reversible heat pump can provide both cooling and heating energy.
With the coupling of district heating and cooling both the heat absorbed at the evaporator and the heat released at the condenser are useful effect, meaning that the efficiency of the system will largely increase.

If there is wasted heat available is possible to use another type of cycle.
In the absorption cycle, shown in Figure 1.17, the condenser is replaced with a new component. The vapour coming out the evaporator is absorbed in a fluid solution, then pumped to the higher pressure stage. The electricity demand is way lower than the compressor one because of the phase of the refrigerant. Heating the mixture the refrigerant reaches the vapour state and can leave the liquid solution and proceed. The main advantage is the change in the resource used: the electric demand is now negligible and the only relevant expenditure is the heat request to carry out the entire process. The engine works with an efficiency of 0.7-1.
The absorption cycle can be used for the production of cold for the district cooling exploiting the heat coming from the co-generation plants (assuming the heat is not required by the district heating network).
An important task of the design is to find a proper matching of available resources and refrigerant engine. Wasted heat or exceeding electricity may be considered valid options, also accounting a policy of integration of renewable energies sources in the mix energy of the Country.

1.5.2 District cooling terminals

Once the chilled water arrives to the building, the energy from supply network to the User is exchanged in the sub-station and transferred to a second thermal vector, usually again water. The latter flows in the residential hydraulic system and reaches the cooling terminals. There are different available technologies and strategies to cool down the room depending on the building characteristics and needs. The most common solutions are:

- fan coils: terminals that supply or subtract heat from the environment thanks to forced convection. They are essentially composed by: one or two finned heat exchange batteries, one or two centrifugal or tangential fans, air filter, condensate collection and containment casing. The main factors acting in the design operations are the energy output, air flow, air outlet temperature and sound level. It is appropriate to divide the thermal power to be supplied over several fan coils to avoid not uniform internal temperatures.

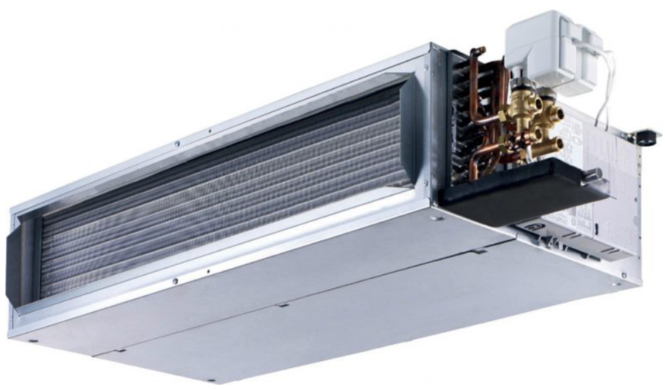

Figure 1.18: Fan coil of nominal cooling capacities from 0,6 to 12 kW [18]

- radiant walls: a piping system in plastic or copper, with inside flowing water at low temperature. The most common plant solution provides the installation of radiant tubes under the floor, but it is also possible to find them behind the lateral walls or in the ceiling. The pipes can be arranged in a spiral with the delivery pipes parallel and alternating with those of return or in a serpentine, with the tubes laid in a zig-zag pattern. There are two significant limits to consider: the restricted cooling capacity - it is not possible to excessively cool down the floor temperature without causing surface condensation phenomena - and the inability to dehumidify the room air (the control of the hygrometric conditions is possible only with the help of auxiliary dehumidifiers).

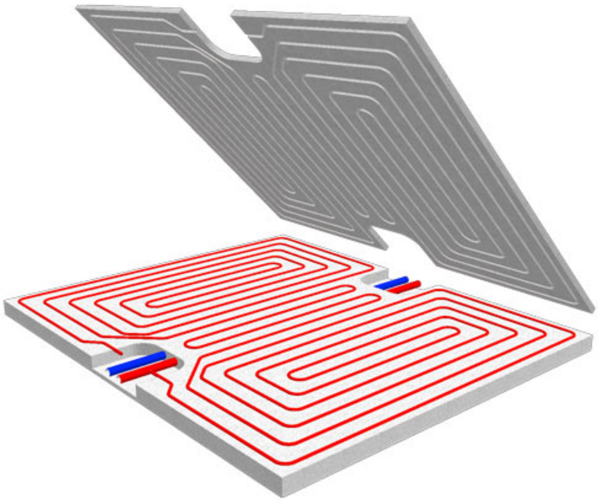

Figure 1.19: Example of radiant panel under the floor [19]

1.6 Cooling Energy Demand Estimation

One of the objective of the study is to develop a program describing the behaviour of the entire network supplying cold energy to the city of Torino.
First it is necessary to set some input parameters. The DH system delivers approximately 2050 GWh with a total installed power of 1,3 GW. To estimate correctly the cooling energy consumption during the summer season, some considerations about the city climate have to be done. To properly identify the climate of a given location, the parameter of the Degree Days is normally used. For the heating season, it's defined as the the sum, in a conventional annual period, of the positive daily differences between a base temperature, conventionally set for each country, and the average daily outdoor temperature. For the city of Torino, the hot Degree Days are approximately 2671 while the cold ones are only 133. The comparison the two values suggests the cooling demand will be much lower than the heating one.
To support this first consideration, a preliminary weather analysis has been carried out. Figure 1.20 shows the average temperature profile through the year with the amount of precipitation for each month. It is possible to note as the outdoor temperature changes widely during the year. The lowest values are registered during January, with minimum peaks under the 0°C, while the higher ones during July, with the temperature going over the 30°C.

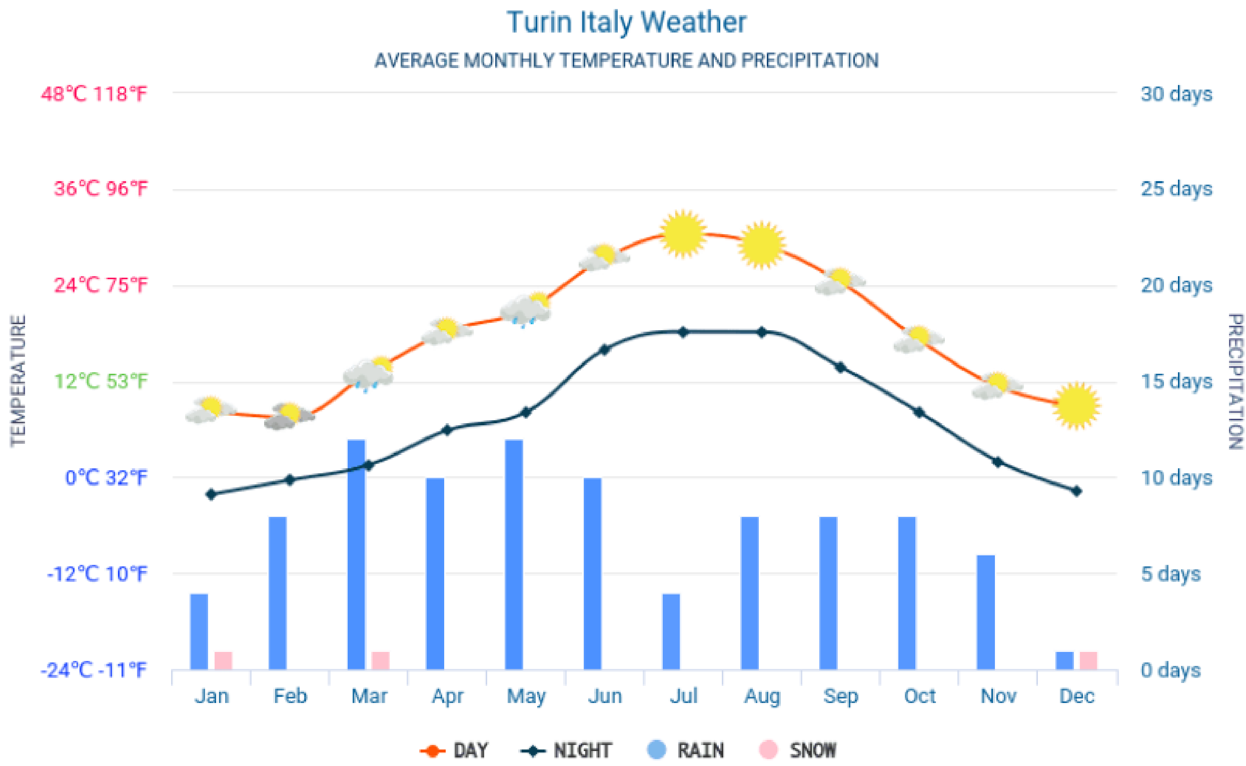

Figure 1.20: Average monthly temperatures in Torino 2015-2019 [20]

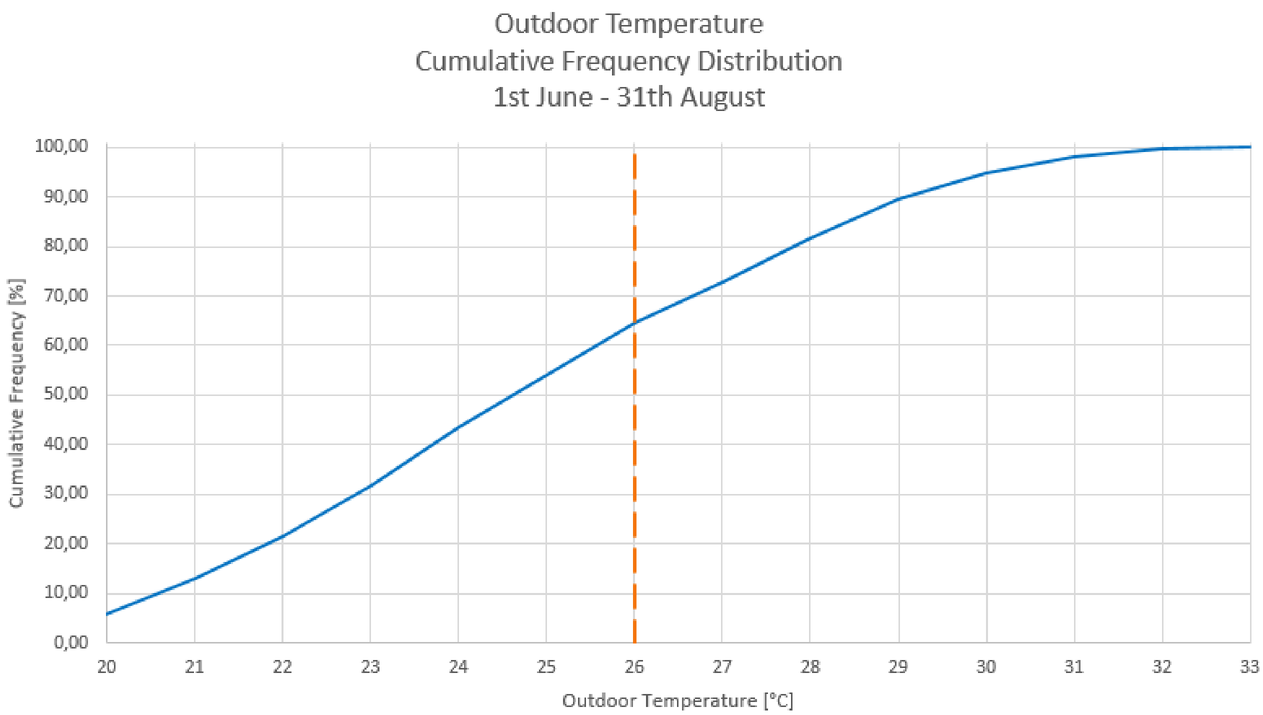

Figure 1.21: Cumulative Frequency Distribution Curve 2014-2018 [21]

Figure 1.21 represents the Cumulative Frequency distribution Curve of the temperature during the three summer months (i.e. 1th June - 31th August), not the whole 24h day has been considered for the data collection but just the period going from 5 a.m. to 23 a.m. The weather data are reported as hourly averages and they have been collected from one representative weather station over a total period of 5 years (2014-2018), thus constituting a reliable and statistically significant data-set. [21]

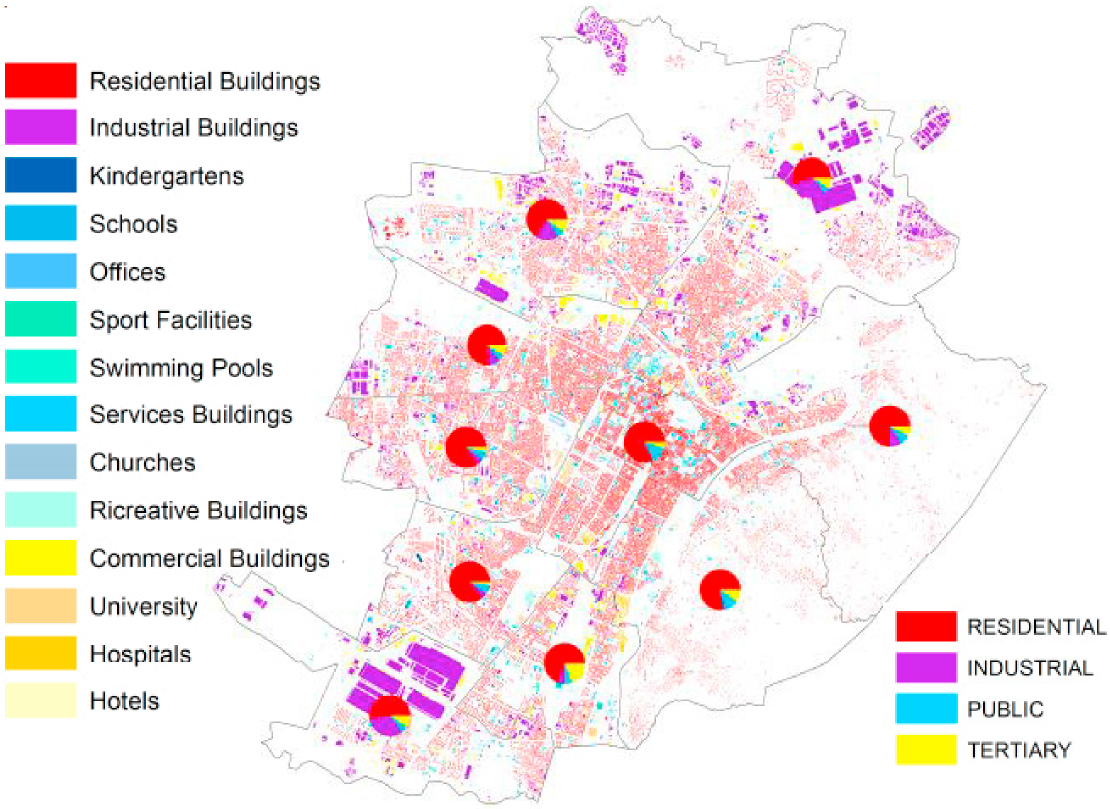

Figure 1.22: User Distribution Map [22]

The Cumulative Frequency Distribution is used to estimate the operating hours of the system. The ones requiring a cooling intervention, i.e. the outdoor temperature overcomes the value of 26 °C, are approximately 403 hours over a period of 90 days. This means 35% of the hours considered, equivalent to around 5 hours per day.

Once the climate has been analyzed, there is another aspect it is important to discuss: the User Side. Figure 1.22 shows the distribution of consumers typology in some macro-areas of the city for the district heating network. The Users are divided in four sectors: residential, industrial, public and tertiary. Figure 1.1 and 1.3 showed in the chapter 1.1 how energy consumption is strictly related to the consumer type.

It is possible to forecast and set the parameter representing the cooling energy consumption for the city of Torino. The starting value of the heating energy delivered is 2050 GWh, since most of the Users are in the residential sector the total cooling energy demand is expected to be around one 27^th of the total heating demand as Figure 1.1 suggests. The resulting cooling energy the DC network will be supplying during the year is then fixed at 75 GWh. It is now hypothesised that the system will work when the outside temperature overcomes the 26 °C and will require the maximum power when the latter rises over the 30 °C, ensuring a 6°C difference between the external and the internal temperature. The calculation of the system nominal power follows below. The hours the system will at the different allowed power levels, i.e. at the different outdoor temperatures, are obtained from the

Cumulative Frequency Distribution Curve. The only unknown is the nominal power of the system. The reverse equation gives 220 MW as value for the system installed power. To understand better how the system will work and in which condition the load duration curve has been extrapolated from the cumulative frequency distribution curve and it is shown in Figure 1.23. The black curve is a rough representation of the cooling power demand and it displays how many hours the system will supply a certain power. The blue one is simply the results of the data fitting operation and it is expressed by a polynomial equation of the 5th order. Both maximum power level and total working hours, respectively 220 MW and 403 hours,are pointed out on the graph.

$$E_{cooling} = P_N \sum(p_i \cdot h_i) \tag{1.1}$$

$$p_i = \frac{P_i}{P_N} \alpha \frac{\Delta T_i}{\Delta T_N} \tag{1.2}$$

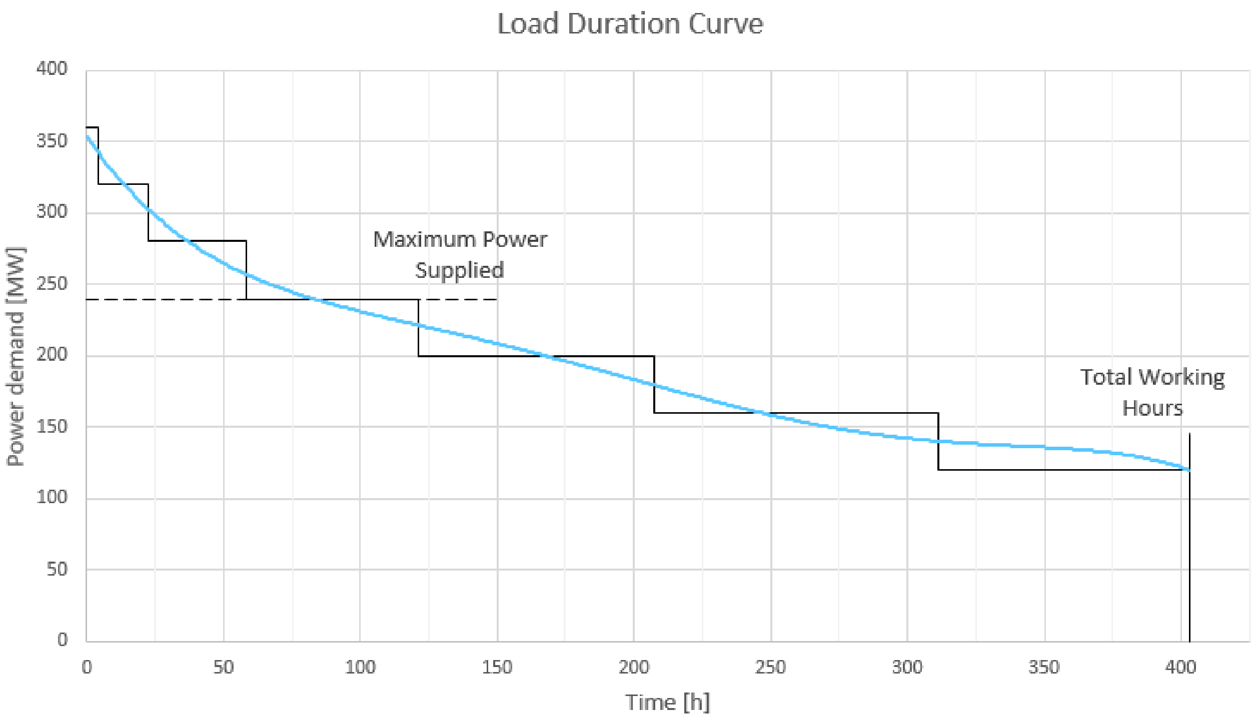

Figure 1.23: Load Duration Curve

1.7 Aim of the thesis

The purpose of this thesis is to develop a model able to simulate the operation of a district cooling network in order to analyze different operating conditions, highlighting possible problems and improvements. The model, developed for the steady state conditions, will be able to evaluate the pressure and temperature of every node composing the thermal network, the heat losses, the pumping power required and the cost of the network. Once the model is developed the aim is to find the best positions for the heat pumps and for the booster stations to be installed in order to minimize the cost and the losses.

The choice of the distributed production should allow a lower maximum diameter of the pipes and lower cost of the network compared to the centralized production. Furthermore the use of a new kind of pipe with less insulation compared to the usual type employed for the district heating is also tested in order to understand if they would be convenient, the reduced cost for this kind of duct is at the price of higher heat losses.

It is important to note that the main focus of the study will be the network while the users side and the supply side are studied at a more superficial level.

2. Thermal network design

2.1 General model

A model of the system is required to size correctly the system and to test different working conditions in order to highlight possible improvements or issues.
There are two possible approaches used for modelling: black-box or physical approaches. The physical approaches use mathematical methods for computing mass flow and temperature in the network while in the black box approaches, the non-linearity that characterize the DCN fluid-dynamic problem is overcome using standard transfer functions or neural networks.
The model proposed in this study use a physical approach: the topological description of the network is required (pipe lengths, diameters, connections, friction factors), which is usually based on a graph representation of the network.
The model used for solve the fluid dynamic and thermal problem of the network is based on the conservation equations: continuity, momentum and energy. In the graph approach each pipe is considered as a branch delimited by two nodes: the inlet node and outlet node, based on a reference direction (velocity is positive when the fluid is flowing in the same direction as the reference direction and negative when flowing in the opposite direction). The incidence matrix, A, is created to express the connections between nodes and branches. Every row in the incidence matrix represent a node and every column a branch. The general element $A_{i,j}$ (row i and column j) is equal to 1 if the branch j enters the node i, -1 if the branch j comes out of the node i and 0 otherwise.
First the mass conservation equation is applied. The mass entering a node must come out of it:

$$\sum G_{in} - \sum G_{out} = \sum G_{ext} \tag{2.1}$$

For the calculations the unsteady term is neglected and the density of the fluid is considered constant. The first term is the sum of the mass flows entering the node for the branches, the second is the sum of the mass flows getting out of the node from the branches and the last term is the mass flow extracted (or injected if is negative) directly from the node. This conservation is valid for all the nodes in the network.
The mass balance for the whole network can be written using matrix formulation:

$$\mathbf{A}G + G_{ext} = 0 \tag{2.2}$$

A is the incidence matrix (size $i \cdot j$), G is the vector of the mass flows in all the branches ($j \cdot 1$) and G_{ext} is the vector of the mass flows exiting or entering the nodes outwards. The vector G_{ext} is

different from zero in case of open network; for the analysis it is first considered the supply network only and then the return network only, the terms of G_{ext} are going to be positive when there is an injection in the network and negative where there is an extraction from the network.
The momentum equation is used to identified the pressure losses in the branches. The pressure drop in a branch is the sum of the distributed and the localized pressure losses minus the term τ which represents the pressure rise due to a pump that might be located in the branch.

$$(p_{in} - p_{out}) = \frac{1}{2}\frac{L}{D}f\frac{G|G|}{\rho S^2} + \frac{1}{2}\beta\frac{G|G|}{\rho S^2} - \tau \tag{2.3}$$

Knowing the pressure losses in every branch is possible to calculate the pressure in every node imposing a known pressure in one node.

$$\mathbf{A}^T P = \Delta P \tag{2.4}$$

$$KP = Pimp \tag{2.5}$$

A is a matrix with i row and j column, with j=$i-1$ since it represent a tree-shaped network.
The pressure in one node k is imposed adding one row K to the matrix A^T with all terms equal to zero except for the term in the k column which will be equal to 1 while one term corresponding to the imposed pressure is added at the end of vector of known terms ΔP. First it is imposed one pressure in the supply network (we imposed the pressure in the node with the maximum pressure which will be one node with the presence of the heat pump) and the pressure in every node of the supply network is calculated; for the return network the pressure imposed will be at the node with the lowest pressure in the supply network and it will be equal to the supply pressure minus the pressure drop in the distribution network.
Once all the pressures are evaluated it is possible to calculate the pumping power required for the operation of the network. In every position with the presence of one pump the pumping power required will be equal to the mass flow divided by the density of the water multiplied by the pressure increment required.

$$W = \frac{G \cdot \Delta P}{\rho} \tag{2.6}$$

Dividing the pumping power times the efficiency of the pump it is evaluated the electrical power required.

$$W_{el} = \frac{W}{\rho_{el}} \tag{2.7}$$

Finally the energy conservation equation is applied at all nodes of the network. The control volume considered for the analysis of every node includes the junction, node and half of each duct entering or exiting the junction, as shown in Figure 2.1.
Adiabatic and perfect mixing is assumed, each node can be described by a single temperature (the water exiting the node at the temperature of the node, and this temperature is also used to calculate the heat dispersion), for this reason in of case large temperature decrease between consecutive nodes a better approximation of heat losses can be obtained using additional nodes, which have a numerical role only. The density of the water is assumed constant, so there are not comprehensibility effects,

and the viscous term is neglected. For every node it is possible to write the conservation equation.

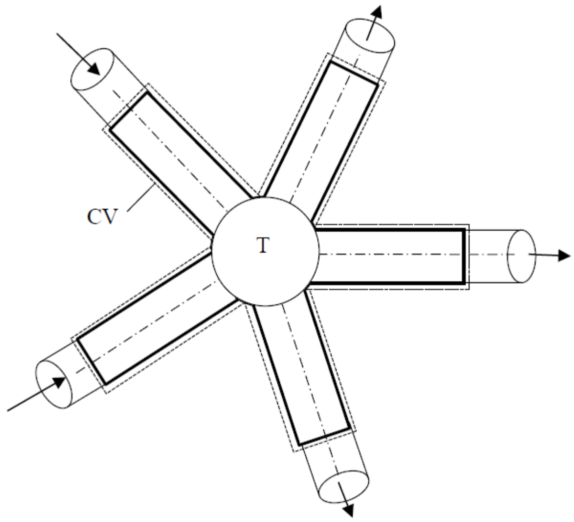

Figure 2.1: Control volume

$$\rho c\frac{\delta T}{\delta t} + \rho cv\Delta T = \Delta k\Delta T + \phi \tag{2.8}$$

The first term is the transient term, the second term takes into account the energy of the mass flow in every branches connected to the node, the third is the conductive term and the last one is the heat source or heat sink. Neglecting the conduction in the water and developing everything to one single dimension we obtain:

$$\frac{\delta(\rho cT)}{\delta t} + \frac{\delta(\rho cvT)}{\delta x} = \phi \tag{2.9}$$

The first term is neglected because the aiming of this study is to resolve the steady state. The heat source is the heat coming from the environment for conduction through the duct (the water flowing in the pipes is at a lower temperature than the ground temperature). It is possible now to express the equation in integral form:

$$\sum GcT = U(T - T_{env}) \tag{2.10}$$

The right-hand side term represents the heat exchanged with the environment (in our case this term will be negative, meaning that the heat is coming from the environment to the system) and the term before the equal is the summation of the heat entering (positive) or exiting (negative) the node from the branches. The mass flow entering the node i coming from the node j will be at the temperature j while the water exiting the node i will be at the temperature i, this will also be the temperature used in order to calculate the heat coming to the node i from the environment.
This equation can be now expressed for every node in a matrix formulation:

$$\mathbf{K}T = g \tag{2.11}$$

Where K is the stiffness matrix, which contains the coefficients of the term linear dependent on temperature, T is the vector of the temperatures in every node and g includes the known terms.

Knowing all the mass flow entering or exiting the nodes (through branches, vector G or directly, vector G_{ext}), the thermal transmittance of every node (which depends on the area of every node), the temperature of the ground and the temperature of water injected in the network it is possible to evaluate the stiffness matrix and the vector of known terms. Solving the system we obtain the vector of temperatures.

2.2 Turin DC network design

The whole study is done on the transportation network used for the district heating in the city of Turin, which is the largest network in Italy and one of the largest in Europe. The installation of the network for district cooling is supposed to be parallel to the one for the heating; the heat pumps used for the cold production can also be used for the heating with a double gain. Barycentres are the nodes where the distribution networks are connected to the transportation network, the distribution networks are not analyzed, it is assumed constant temperature for the supply and for the return and the pressure drop in every distribution network is supposed to be equal to 2 bar. In the transportation network there are multiple loops, to simplify the network and reduce the calculation time required these loops are opened creating a tree-shaped network.

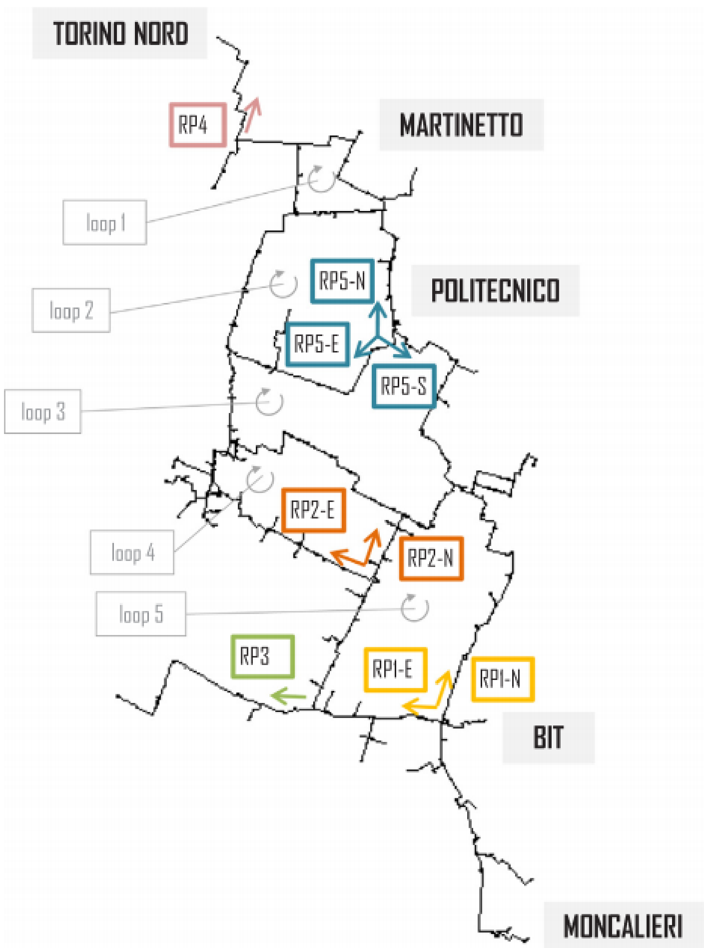

Figure 2.2: Turin district heating network [22]

The final network presents 696 nodes and 695 branches. The barycenters are 182. The total length of the network is 67.3 km. The nominal temperatures of the supply network and the return network are respectively 7°C and 12 °C, the heat pumps inject water in the supply network at 7°C while the water coming from the users is injected in the return network at 12°C. In order to obtain the vector G_{ext} from the vector of the cold needs in every barycenter, the temperature difference between the supply network and the return network at the user nodes is required (it will be the difference of temperature through the sides of the heat exchanger), the temperature of heat exchanger outlet is fixed at 12°C while the input temperature depends on how much the water is heated coming from the heat pumps to the nodes. For the first calculation the temperature difference is assumed equal to 5°C, the system is solved and for every node the temperature is evaluated, a new G_{ext} is calculated with the new difference of temperature calculated knowing the temperature of every node, we iterate this process until reaching the convergence.

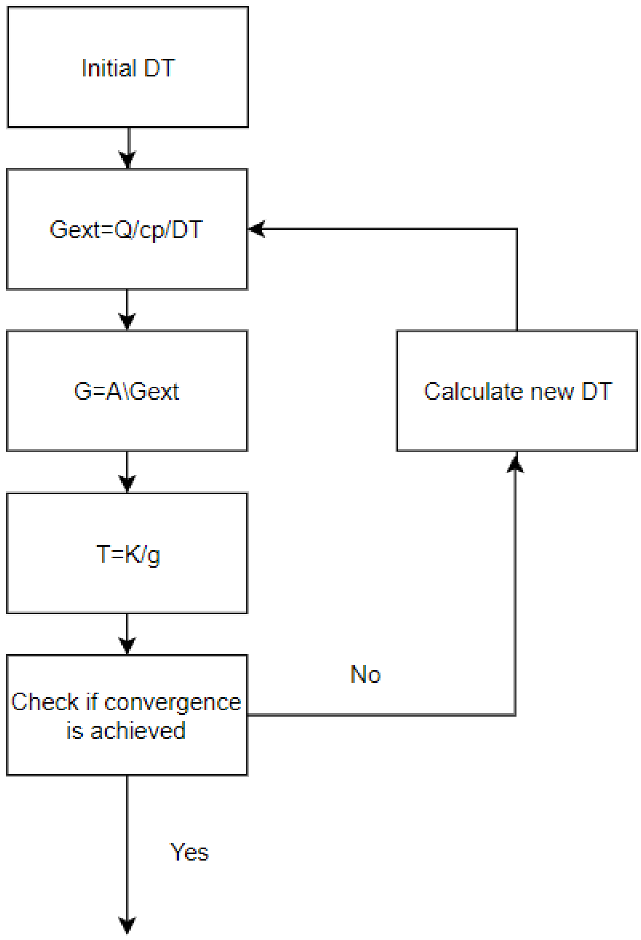

Figure 2.3: Scheme of the program procedure

The mass flow in every branch is evaluated and the required diameter is calculated with a supposed velocity (the velocity of the fluid in the distribution network may vary from 1 to 4 m/s, it will be used the velocity that optimize the investment cost), the commercial diameter immediately over the required diameter is chosen.

It is then evaluated the pressure for every node of the supply network imposing a pressure in one of the heat pump location (the maximum pressure tolerated by the pipes is 17 bar, for safety reason the maximum pressure in the system is choose to be equal to 16 bar), knowing the supply pressures and the pressure drop in the distribution networks the most limiting pressure (every users node in the return network must be at a pressure equal or lower to his supply pressure minus the pressure drop in the distribution network) is imposed at one barycenter for the return network and the pressure is then calculated for every other node. If required, booster pumping stations are placed along the network in order to maintain a minimum pressure equal to 1 bar.
The thermal problem is then resolved for the supply and for the return networks and the two temperatures of every node are calculated.
The total cooling power required is calculated knowing the return temperature at the heat pumps positions and the mass flow required from every heat pump, this power minus the sum of the power required from every users give the losses through the network.

2.3 Preliminary economic analysis

In the next chapter the economic optimization of the network will be carried out. It is necessary to estimate the prices of the various components of the system such as pipes, joints or special elements and the cost of the electricity used by the pumps during the life time of the plant. The cost of the heat pumps is not taken into account because, since a fixed number of heat pump with the same nominal power is used, their cost will stay the same in every configuration. The expense for the electricity consumed by the heat pumps can be quickly estimated assuming a COP equal to 2,5.
The expenditure for the pipes is usually the most important component of the total cost and will depend on many factors: diameters and length of the tubes, operating pressure, characteristics of the fluid, insulation layer thickness. Since the used fluid is water and the operating pressure is similar in DH and DC grids, it is possible to use the same ducts utilized in the Torino district heating network. The price of these pipelines is shown in the Appendix A.0.1.
However the insulation provided for the DHN is not necessary in the case of a DC network because the temperature difference between the operating fluid and the ground is only few degrees Celsius. For this reason it would be possible to use less insulated pipes with a lower cost.
The figure 2.4 represents the cost per meter of high and low insulated pipes in function of the different diameters size. Special components (curve, branches splitting or valves) and trenches excavation expenses are hypothesized to be the 50% of the total cost of the grid. The price for the low insulated pipes is estimated calculating the cost of the insulation in the case of high insulated pipes (U=1$W/(m^2K)$) and the thickness of the insulation necessary to reach a thermal transmittance equal to 5 $W/(m^2K)$.
To evaluate the cost of the electricity consumed it is necessary first to estimate the plant operating hours. In the section 1.6 the power demand was related to the outdoor temperature and the power curve for one year of operation was traced. For each of the four power levels the simulation is performed and the power absorbed by each pump is calculated. Knowing the fraction of time spent at each power load, the energy consumption in one year is finally determined.
This annual expense has to be summed up along the whole life period of the system, fixed at 30 years.

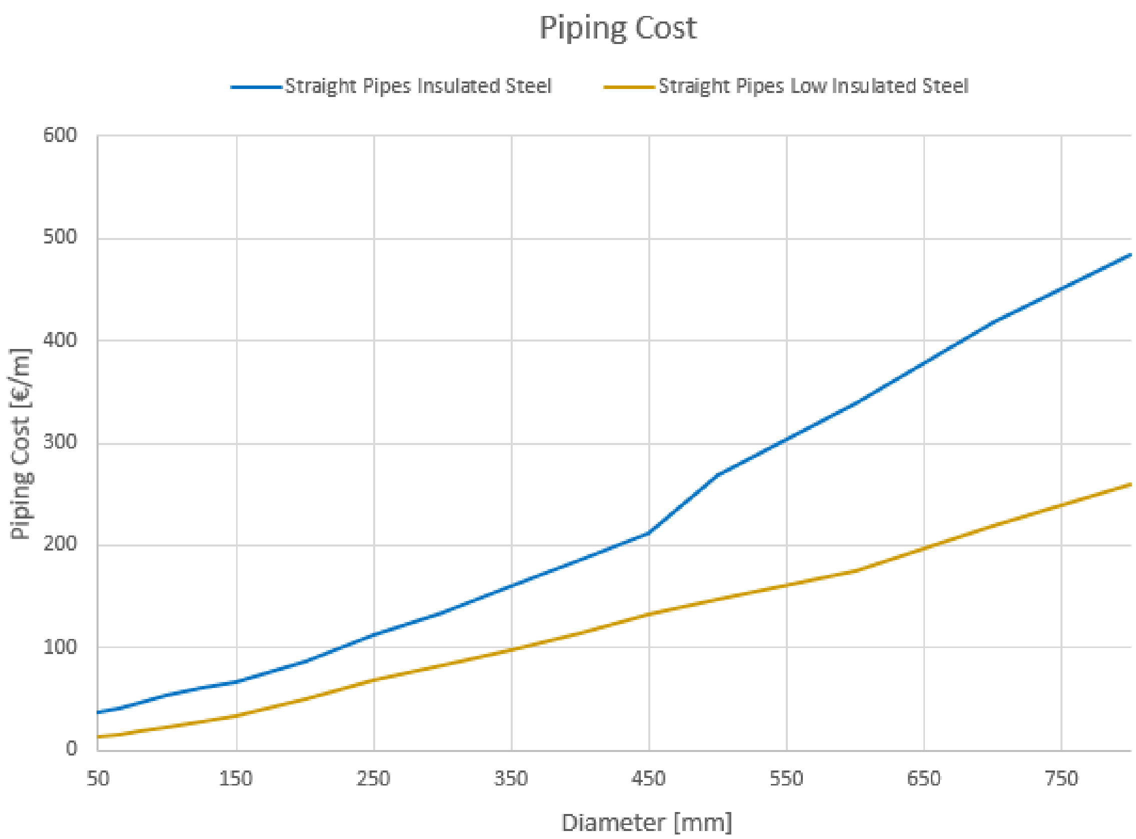

Figure 2.4: Pipes cost [23]

In order to compare this sum to the initial economic investment, such as pipes, it is needed to discount its value according to the equation 2.13 where sc is equal to the specif cost of electrical energy $(Euro/KWh)$ [24], int is the discount rate - fixed for this analysis at 5% and t is the number of years the plant is supposed to operate.

$$Energy_{year} = \sum P_i \cdot hours_i \tag{2.12}$$

$$Electricitycost_{tot} = \sum_{k=1}^{t} Energy_{year} \cdot sc \cdot \frac{1}{(1+i)^k} \tag{2.13}$$

3. Network Optimization

3.1 Velocity optimization

The choice of the water velocity in the pipes has a great influence in both the grid cost and the power required by the pumps. Also the thermal dispersion are strongly dependent on this variable. Higher velocities lead to lower diameter of the pipes and a lower cost of the network but bigger pumps are required and the electrical energy consumption increases. It is needed to find a proper compromise. The variable to minimize will be the total cost of the plant and it includes: cost of the pipes and cost of the electricity consumed by the pumps during the the system entire life time. The typical value for the velocity in the modern district heating systems is between 2 and 4 m/s. The velocity field explored goes from 1 m/s to 5 m/s. For each velocity, the heat pumps positions that minimize the total cost were found and the total cost was calculated. The results are shown in Figure 3.1 and 3.2. The network operation is studied with two types of pipes: the one used for district heating with a high insulated layer and therefore a higher price and less insulated pipes with a lower cost.

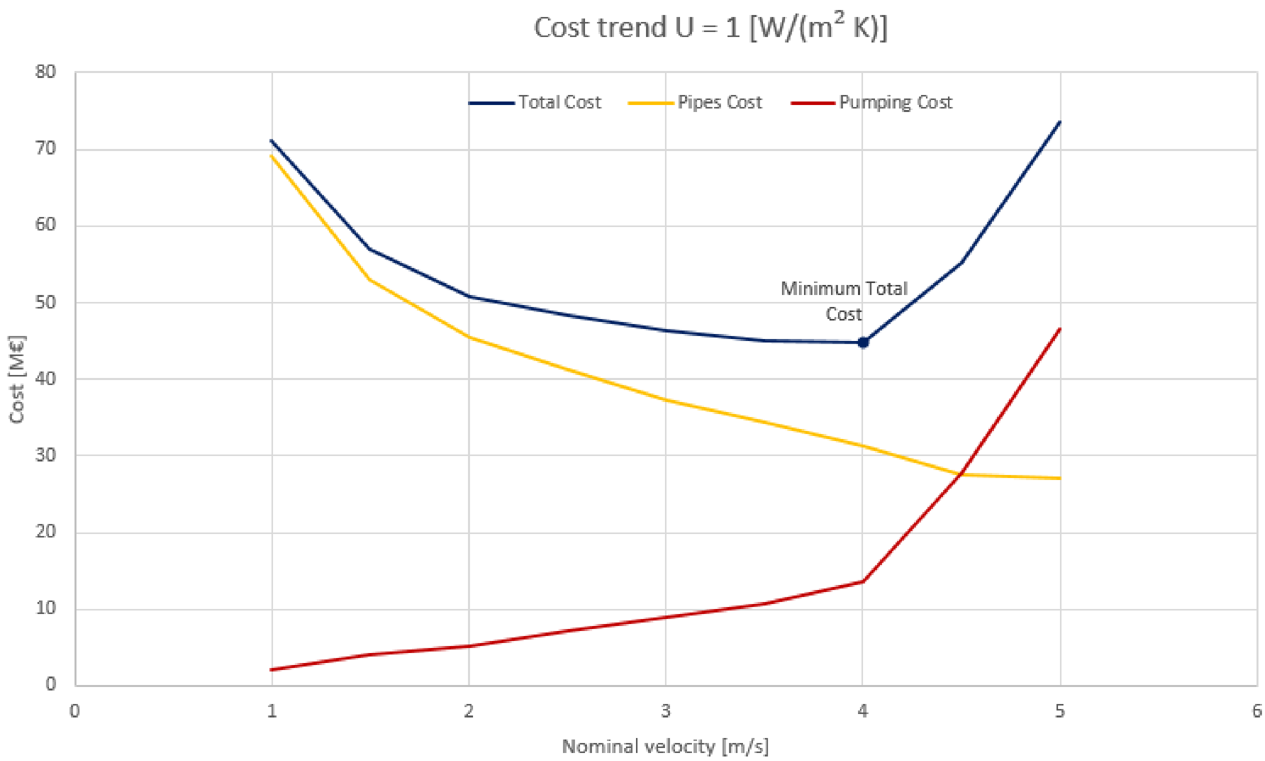

Figure 3.1: Cost trend with thermal transmittance U=1 $[W/(m^2K)]$

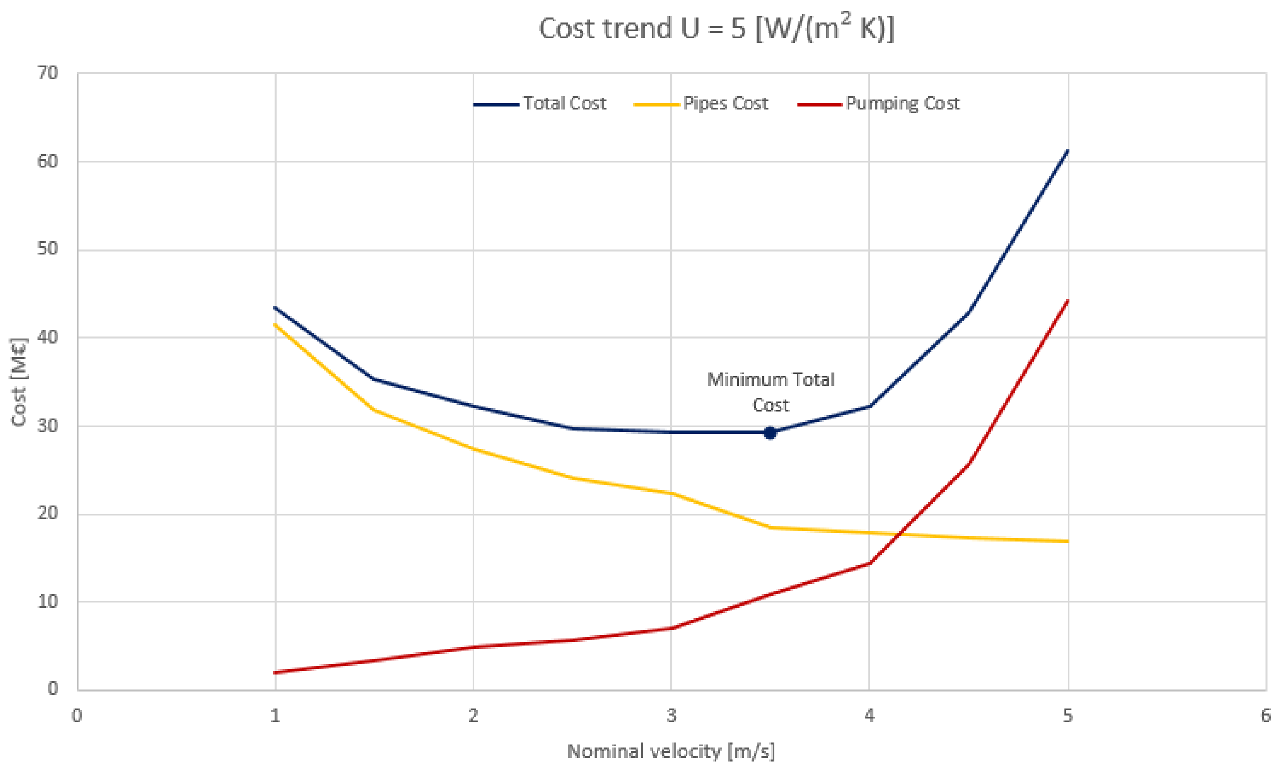

Figure 3.2: Cost trend with thermal transmittance U = 5 $[W/(m^2K)]$

In the first case, the value of heat transmittance is 1 $W/(m^2K)$. Because of the high pipe cost, the electricity expense becomes important only with high velocity values. For this reason the total minimum, i.e. the optimal velocity value, is displaced to higher velocity values. The data elaboration gives back as the optimal value of the fluid velocity 4 m/s thus the same of many existing district heating systems.
In Figure 3.2 the use of less insulated pipes (thermal transmittance 5 $W/(m^2K)$) changes the simulation outcome. Because of the thinner insulation layer, the pipes cost decreases and gets closer to the electricity cost. Being the electrical expense important also for lower velocities, the global minimum moves to the left side of the graph and 3.5 m/s is identified as the optimal nominal velocity.

3.2 Genetic algorithm

To carry out the optimization operations the genetic algorithm, available on MatLab, is used. Calling that particular function, the program returns the local minimum of a given function.
Genetic Algorithms (GA) are complex adaptive procedures aimed at solving research and optimization problems, conceptually based on the principles that regulate the natural evolution of species. [25]. The idea behind the GA is to select the best solutions and to recombine them together in such a way the evolution towards an optimum point is favored. Five phases are considered in a genetic algorithm:

- Initial population;
- Fitness function;

- Selection;
- Crossover;
- Mutation.

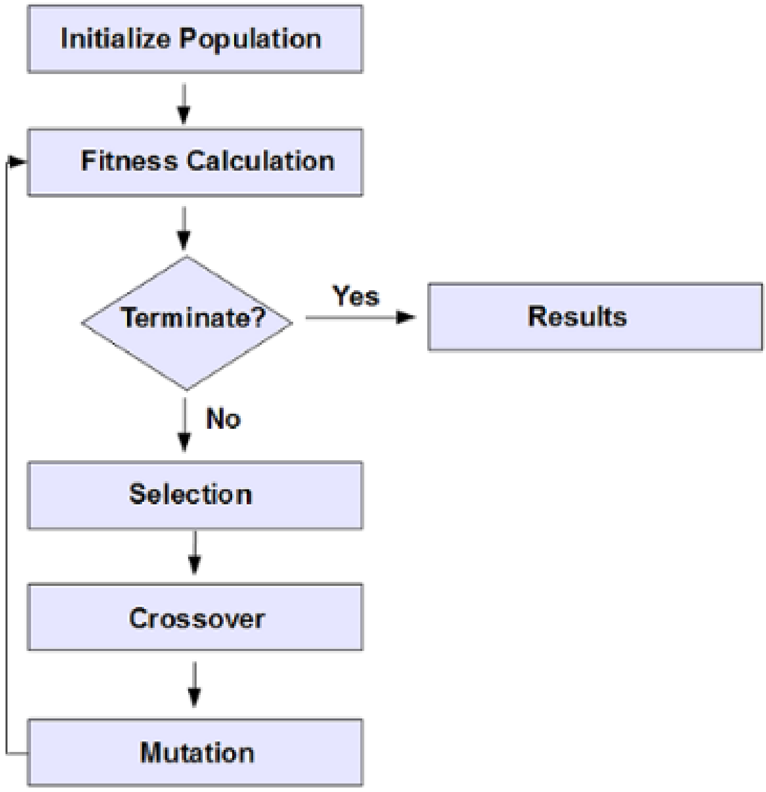

Figure 3.3: Genetic algorithm scheme [26]

The procedure is quite simple and iterative: first an initial set of possible solutions is set, even randomly. Each solution is evaluated and characterized with an indicator of quality, or fitness. A new solution group is defined by modifying appropriately the previous higher quality solutions. After a number "n" of attempts, if the number of established iterations has been reached or the quality of the best solution available is acceptable the process can be considered successfully finished, otherwise new generations are requested. For the creation of new individuals, two operations inspired by biological evolutionist theory can be used: the crossover and mutation.
First a selection process occurs. The selection of an individual depends on his fitness value (i.e. how much the individual is "good" to solve the problem): a value higher of fitness corresponds to a greater chance of being chosen as a parent to create the new generation. One of the most used criteria consists into attribute the probability of choice proportionally to fitness. Thanks to the mechanism of selection, only the best individuals have the opportunity to reproduce and then transmit their genomes to the next generations.
Once identified a pair of parents with the mechanism of selection, their genomes can be modified by each of the two operations, with probability respectively called crossover rate and mutation rate. There are different kinds of crossover here just mentioned: one point crossover, standard crossover, order crossover. [25]

3.3 Optimization of the heat pumps positions

The optimization of the cost of the network is performed looking for the best positions for the heat pumps to be installed. Once the cooling demand is estimated, the number of heat pumps needed to cover the power demand and the heat losses through the network (almost negligible compared to the demand itself, since the temperature of the water is close to the temperature of the ground and the pipes are very well insulated) can be calculated.
The size of the single heat pump is chose to be equal to 20 MW because the price does not scale linearly with the size and a bigger heat pump will be always more convenient than 2 smaller heat pumps, 20 MW is one of the biggest size for the heat pumps available on the market. [27].
Figure 3.4 highlights the areas and the nodes where the cooling water has to be delivered while 30 possible locations for the heat pumps installation are selected between the remaining nodes as reported in Figure 3.5. For space reasons it is possible to install in each possible location a maximum number of 3 heat pumps for a maximum installed power per site of 60 MW. The optimization process returns the positions of the heat pumps that minimize the total cost of the plant.

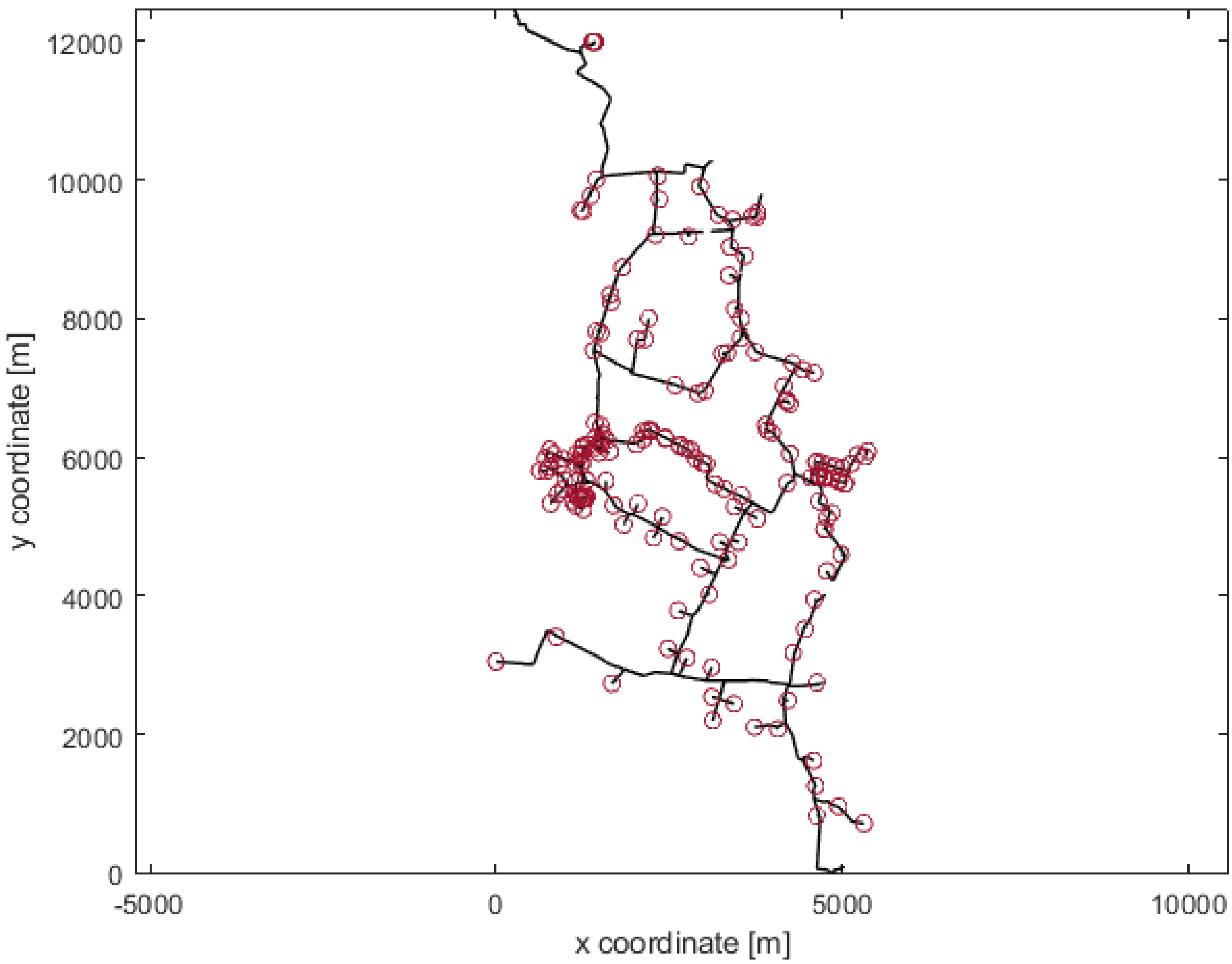

Figure 3.4: Map of the barycenters

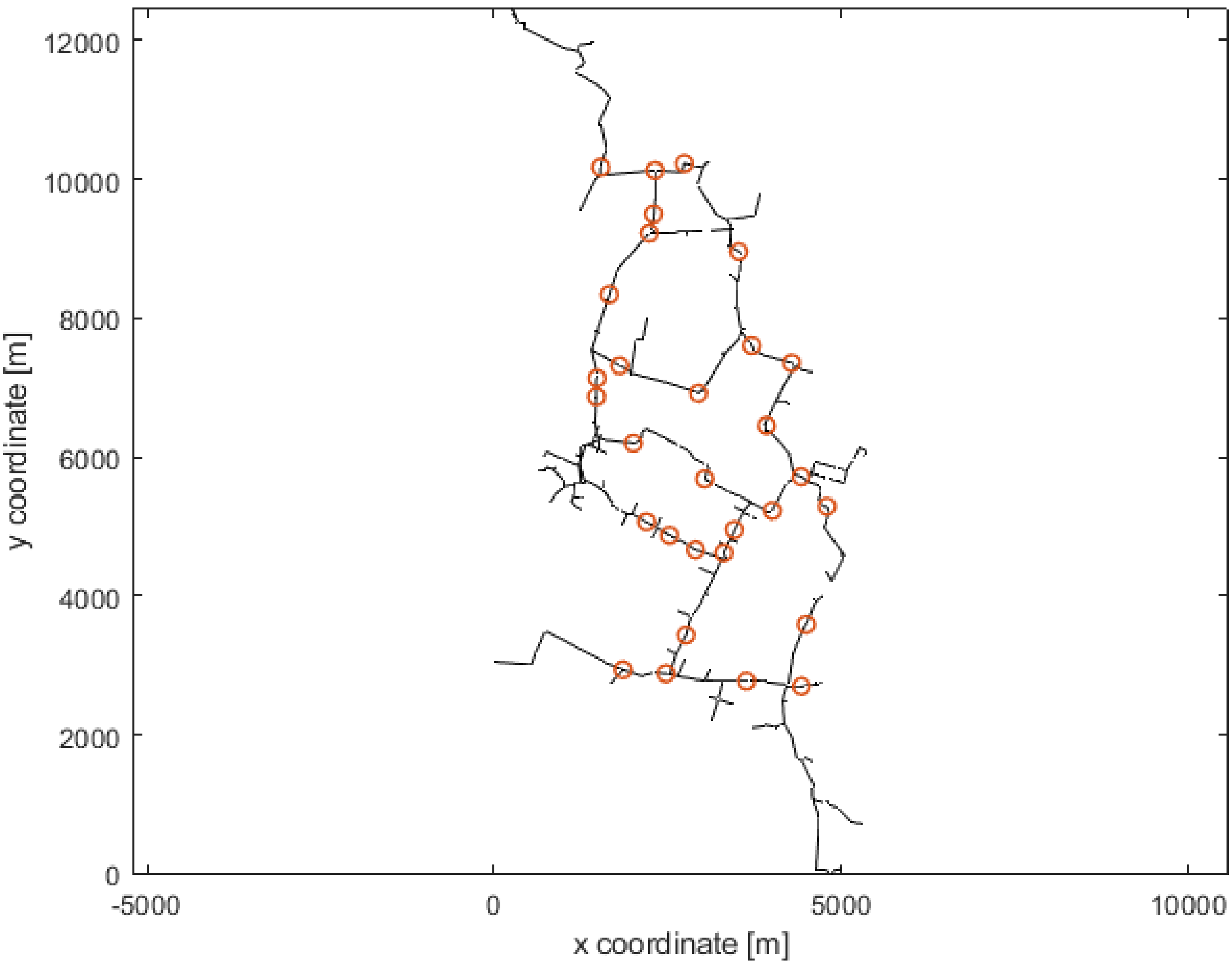

Figure 3.5: Available positions for heat pumps

3.4 Optimization of the booster pumping stations location

The pressure in the network has always to be between a maximum value, which depends on the pressure that the pipes can stand, and a minimum value. In the case of the analyzed network the maximum value for the pressure in the system is chosen to be 16 bar and the minimum value 1,5 bar, the pressure can not be lower than the atmospheric pressure in order to avoid air infiltration.
Another constraint the solved system has to respect is that the pressure of the returning water in every node connected with the users must be at least 2 bar lower than its pressure in the supply network due to the pressure drop in the distribution network. Once the pressure is fixed in one single barycenter, all the other pressure are evaluated solving the equations 2.4 and 2.5 represented in chapter 2.1. Throttling valves able to provide the required pressure drops in order to maintain the stability of the system are inserted.
For certain configurations the total pressure drop in the pipes requires the insertion of booster pumping stations along the branches in order to have the lower pressure level above the minimum set value.
The installation of booster pumping stations along the lines implies also a lower pumping power required at the heat pump positions since the pressure difference between return and supply at these points will be lower compared to the case without any pumping in the branches.

The total power required for the pumping operations is the sum of two contributions: the first one is request to re-insert the water coming from the return path at low pressure into the high pressure supply network after it has been cooled down while the second is the power required from the booster pumping stations along the network. In order to minimize its value, 30 possible branches in the supply path and 30 in the return one are chosen as possible places where to host a booster pumping station. The choice of these locations was done knowing the areas were the biggest pressure drop happened. In Figure 3.6 the available positions are shown; as already stated the restoration of the pressure takes place in the branches while in the figure the circles represent one of the two nodes delimiting the branch. These branches are available for booster pumping stations on the supply and on the return network, for a total of 60 possible pumps. The optimization of the total pumping power

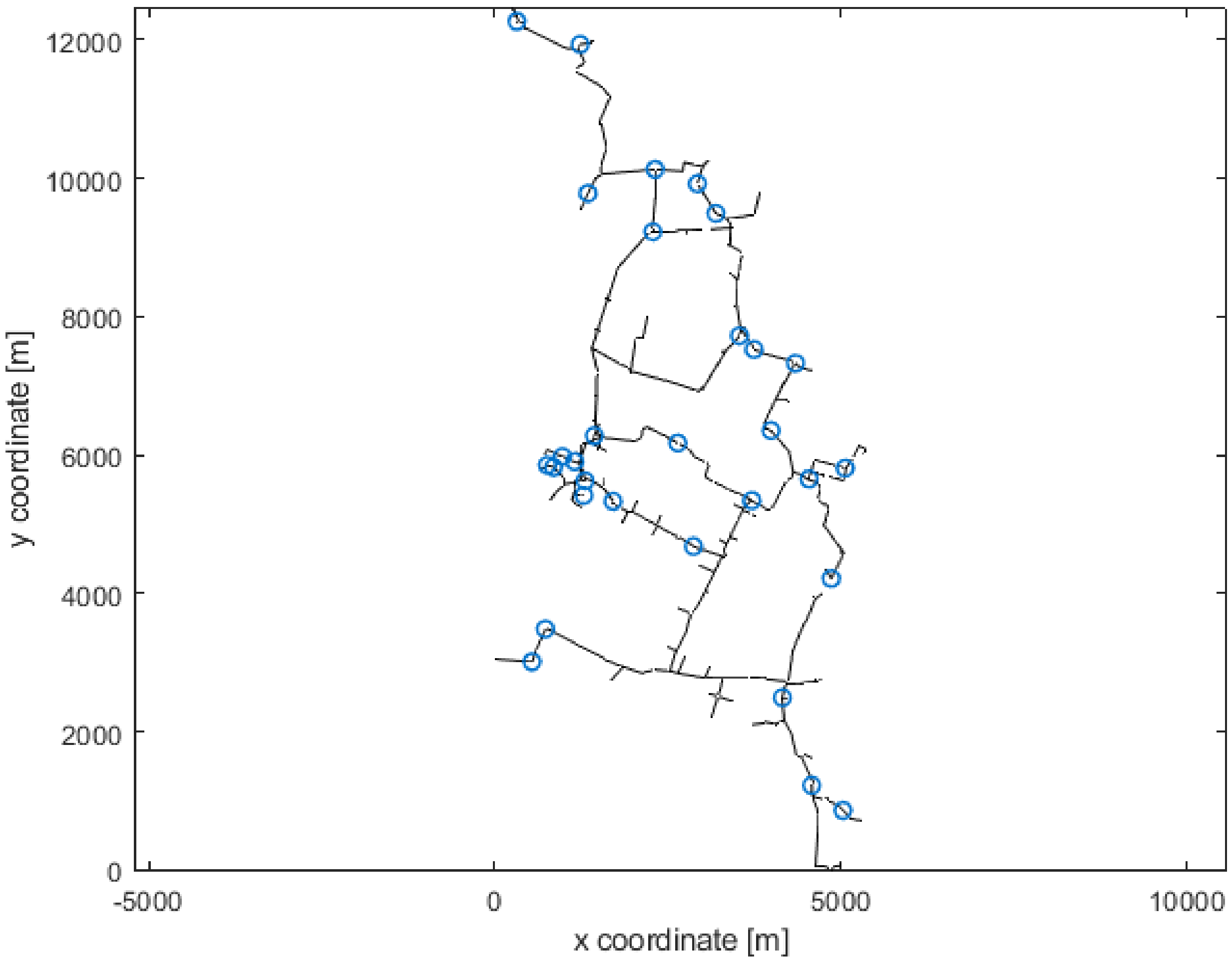

Figure 3.6: Available positions for the installation of booster pumping station

required is carried out using the genetic algorithm on MatLab; the configurations that do not respect the three limitations (minimum and maximum pressure and pressure of the barycenters in the return network lower than their pressure in the supply minus the pressure drop in the distribution network) are excluded setting a big penalty every time one of these restrictions are not satisfied.
A higher number of booster pumping station can lead to lower total power required but it will also increase the complexity of the network, with more components that requires maintenance and can fail. For this reason it is important to limit the number of stations along the network. In order to reach

this purpose a premium proportional to the number of empty positions between the 60 available ones is set in the program.

4. Results

In the following paragraph the main results are presented. As anticipated, the variables that affect the most the cost and the efficiency of the system are the water velocity, the position of the heat pumps and of the booster pumping stations and the type of pipes used.
Exploring different configurations, the study purpose is to find a system layout able to minimize the initial investment cost. Because the problem does not refer to a single year but to the entire project lifetime, it is request to compare costs that are incurred at the beginning with others that are spread along the entire life of the plant, in particular the pipes cost and electrical consumption of the pumps. The first one can be considered the effective initial investment cost while the second one intervenes throughout the entire period. For this reason, it was chosen to actualize all the expenses following a few economical principles expressed in chapter 2.3.

4.1 Heat pumps position optimization

4.1.1 Centralized Production

The centralized production of the cold energy was the first configuration studied. The concept is the same of a classical district heating system: the energy is produced in two big power plants and the cold water sent to the users through an underground grid. Then a parallel net receives the hot flow from the users and brings it back to the facilities. The cold water could be produced using absorption heat pumps, taking advantage of the waste heat coming out from the power plants.
The temperature of the ground can be assumed as a constant during the whole year and its value is around 15 °C. Since the water is injected at 7 °C and returns at 12 °C , a heat exchange takes place increasing the fluid temperature. Control this phenomenon and forecast its effects is essential to minimize the amount of energy inputs. A code has been developed to simulate the temperature evolution of the fluid along the whole circuit.
In Table 4.1 the main results are reported. The heat loss amounts to 1,2 MW, i.e to the 0,5% of the total power.

Maximum Diameter [m]	Average Diameter [m]	Heat Loss[MW]	Pipe Cost [M€]	Pumping Cost[M€]	Total Cost [M€]
1,5	0,512	1,2	66,1	21,6	87,7

Table 4.1: Centralized production configuration main results

The results obtained are shown in Figure 4.9 and 4.10, the thickness of the branches scales with the mass flow while their color represent the temperature. Because of the small temperature difference, the heat flux exchanged does not affect significantly the system performance. Also the simulation is run with a very low value of the thermal transmittance with the direct effect of reducing the heat loss to a few percentage points.

In Figure 4.9 and 4.10 is possible to note how the entity of the temperature increment is only of few centesimal points. The temperature increases less in the return network because the temperature difference between the water and the ground is lower and because there are many injection nodes (182 barycenters) and the more warm water coming from the farthest users is often mixed with colder water coming from the closer users.

To have a centralized production system means the energy is put into the grid in a few points, the mass flow rate injected and extracted in these points is much higher than the one needed in a distributed production system. The direct consequence is to increase the pipes diameter with a consequent great rise in the cost of materials and installation. The cost of the pipes does not increase linearly with the diameter and beyond certain diameters there are not commercial pipes available, the cost will rise even more as they should be made specifically for this application.

Figure 4.1: Centralized production supply temperature map

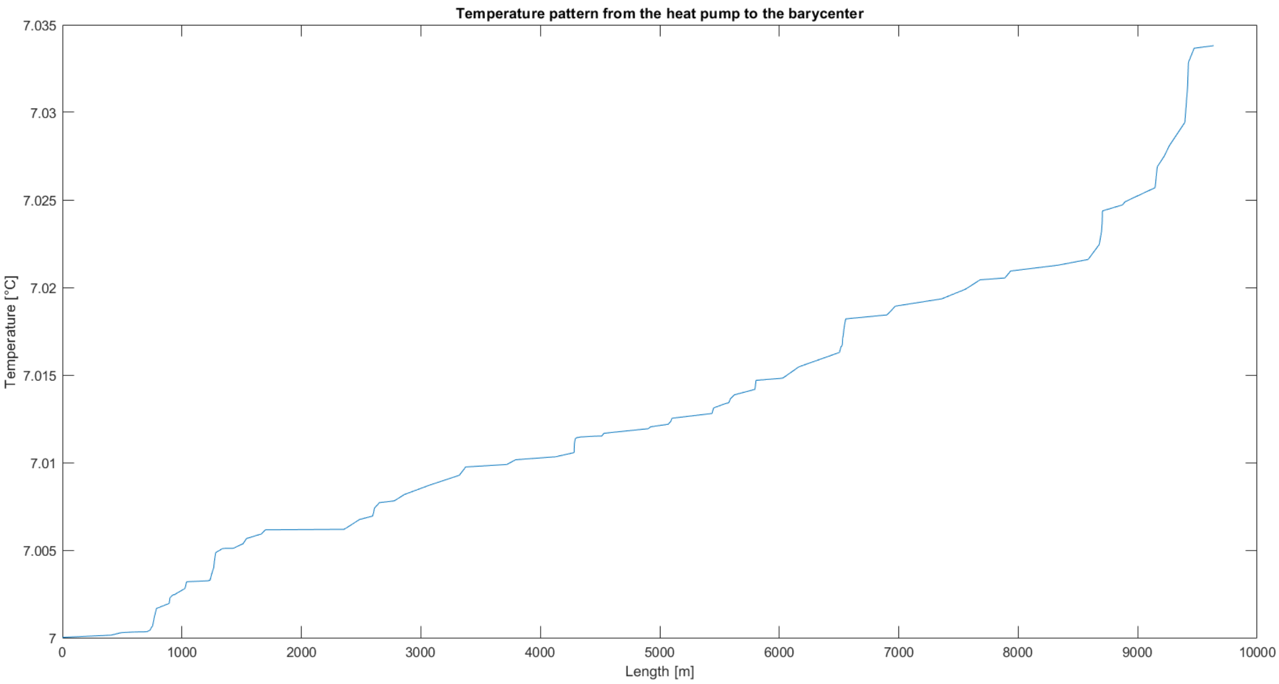

Figure 4.2: CP Temperature evolution along one of the supply path

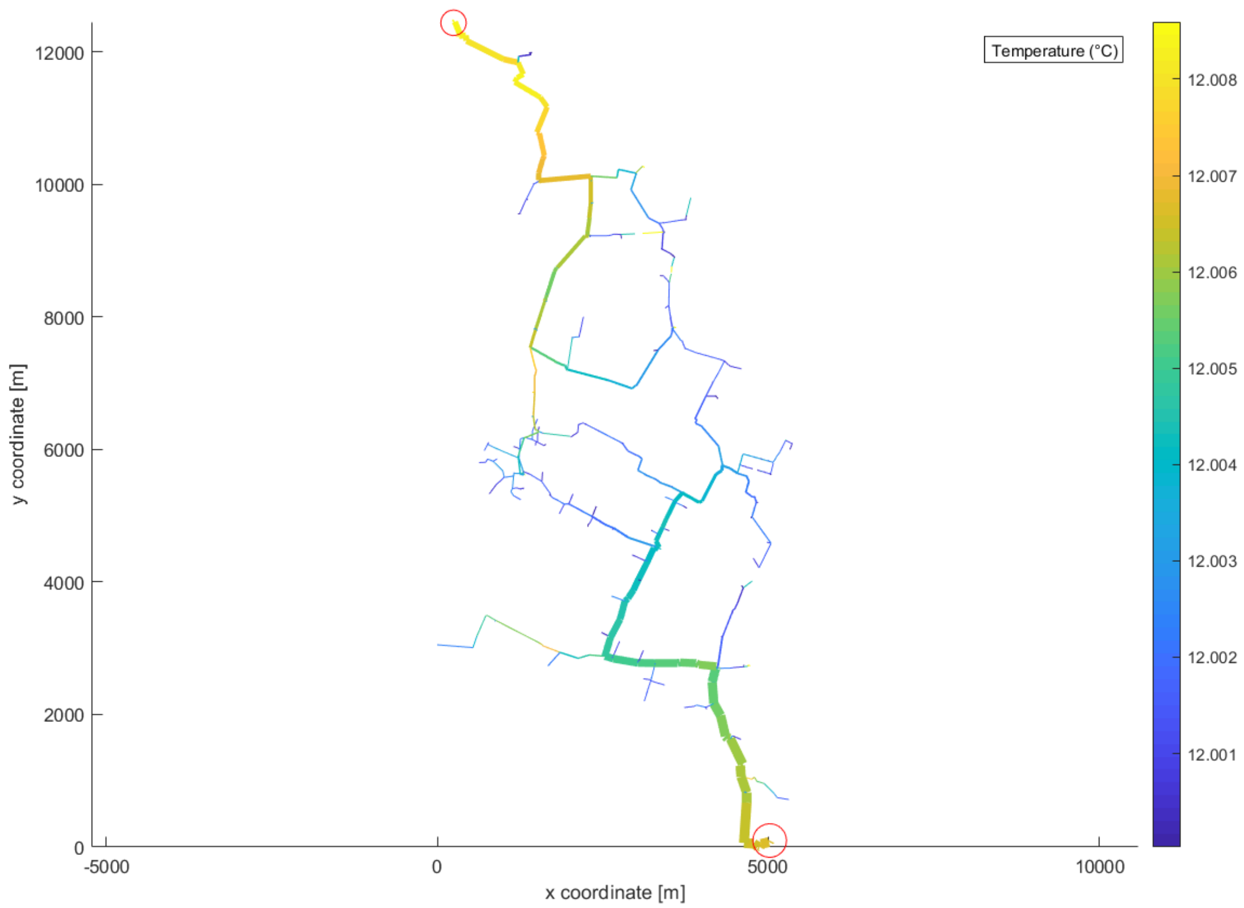

Figure 4.3: Centralized production return temperature map

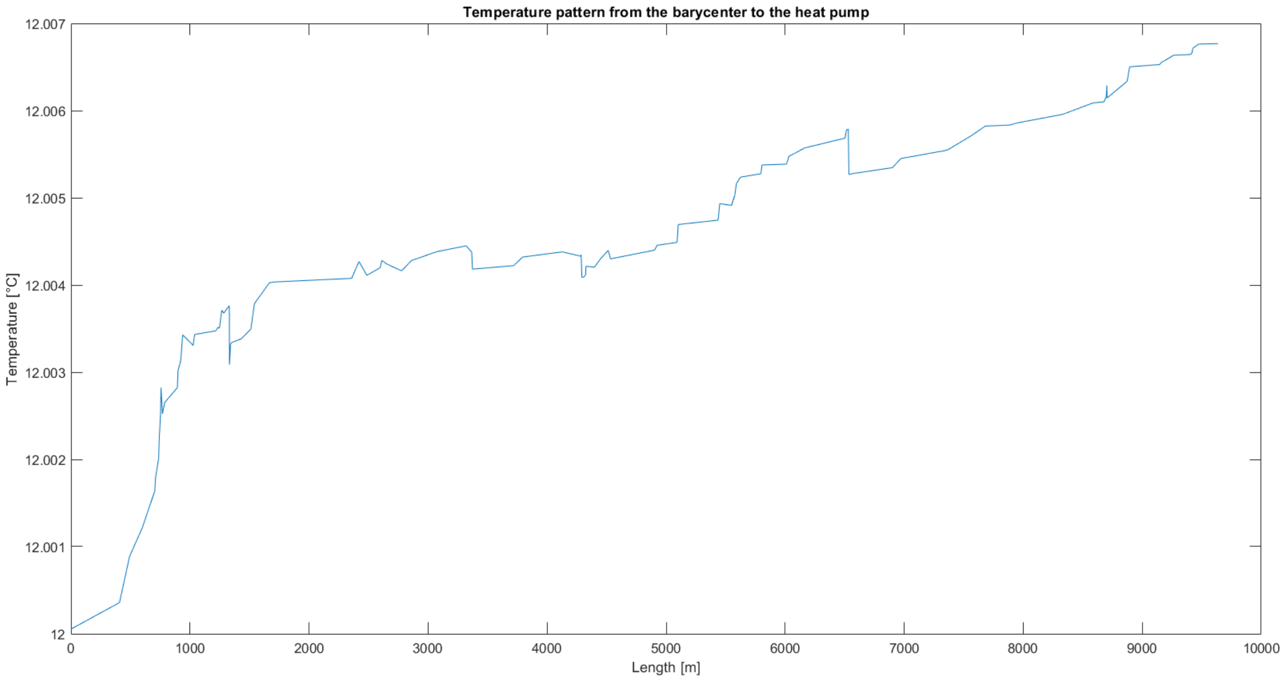

Figure 4.4: CP Temperature evolution along one of the return path

The figures 4.2 and 4.4 represent the temperature evolution in the supply network and in the return network for the farthest barycenter from the power plants. The fluid has to travel almost 10 kilometers with consequent greater increase in temperature respect to other configuration with closer production sites (i.e. optimal distributed production) this leads also to higher heat losses. The supply temperature, figure 4.2, steadily increases along the network while the return temperature (figure 4.4 sometimes decreases because the flow coming from the more distant users it is mixed with colder water coming from closer users.

4.1.2 Distributed Production

Once the centralized system was analyzed, the distributed energy production was studied. After a study of the user side, a set of 30 possible positions was selected to allocate the 11 heat pumps required to satisfy the cooling demand as explained in 3.3.
In this case, each site will host a single heat pump except for one position in the bottom part of the map, where 2 machines were inserted.
In Figure 4.19 and 4.28 is possible to observe the simulation results. The heat pump positions are identified with red points while the flow rate intensity is represented by the thickness of the lines on the map. Also, the fluid temperature evolution along the longest path is illustrated for both supply and return in Figures 4.6 and 4.8, the path is way shorter than the one for the case with centralized production.
In table 4.2 the characterizing variables are reported. Because of the distributed strategy for the energy production, the heat loss is halved, despite the highest maximum temperature reached in the supply and return network (those temperature are reached only in few particular points). The maximum dimension of the pipes is reduced because the cooling demand is supplied from different stations with benefits for the mass flow rate that decreases. On the economical side, to decentralize the production

of the energy allows significant savings: although the pumping cost is increased, the benefit coming from the reduction of the pipe cost has a strong impact on the final total cost, reducing of almost the half - exactly 45% - the initial investment cost. However, this positioning of the heat pumps cannot be considered the optimal, the low average diameter of the pipes causes high pressure drops leading to an high electrical consumption in the booster pumping stations during the life time of the plant.
There is still a huge field of possible combinations to be analyzed with the opportunity to reach a global minimum able to reduce as much as possible the grid final cost.

Maximum Diameter [m]	Average Diameter [m]	Heat Loss[MW]	Pipe Cost [M€]	Pumping Cost[M€]	Total Cost [M€]
0,8	0,275	0,6	26,6	21,5	48,1

Table 4.2: Distributed production configuration main results

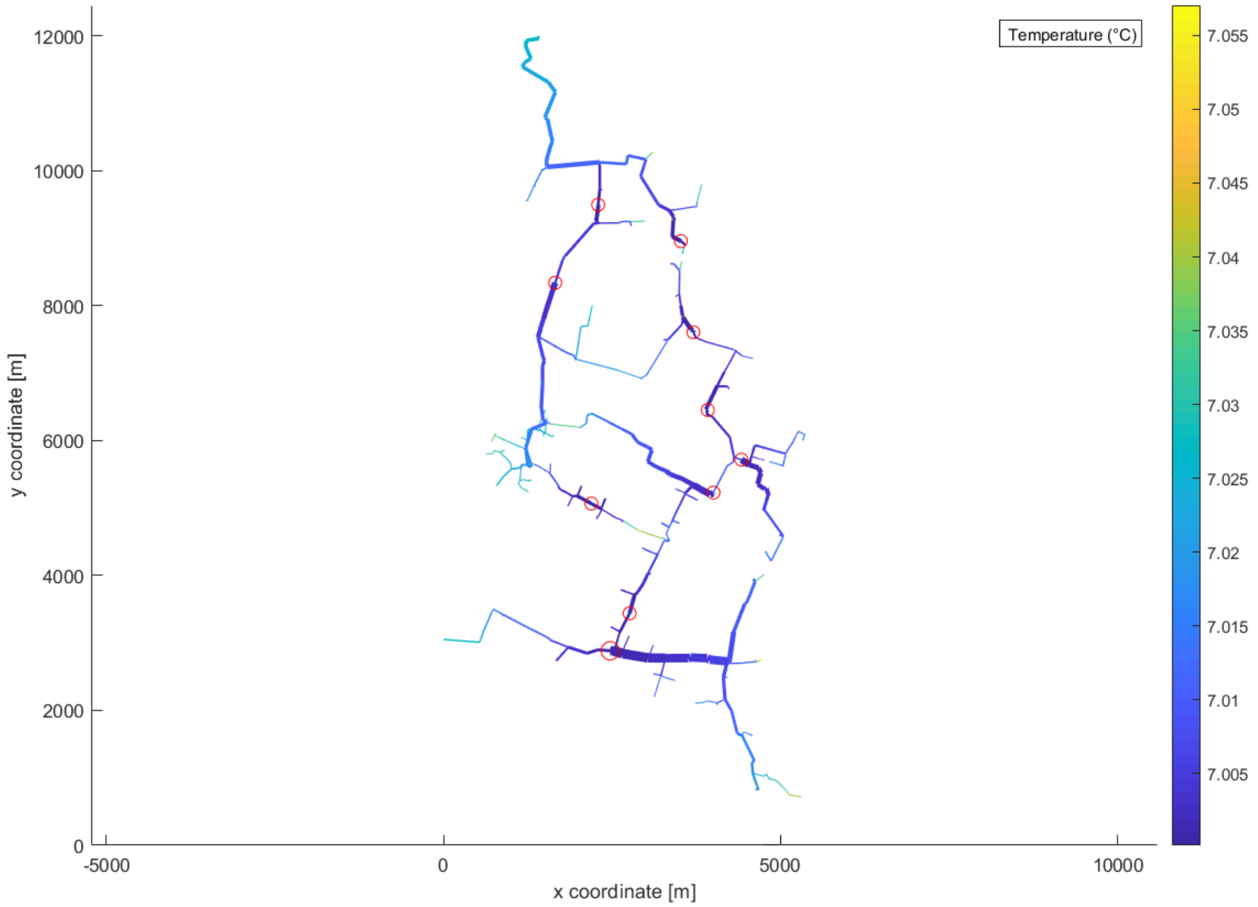

Figure 4.5: Distributed production supply temperature map

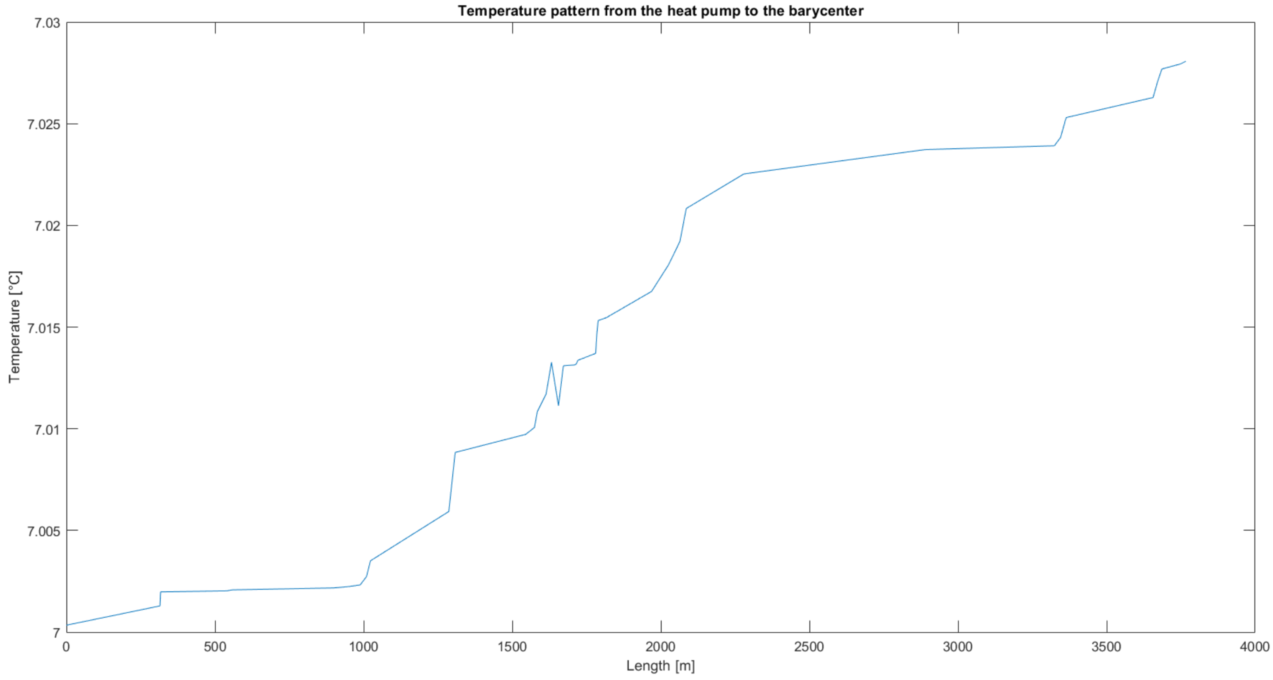

Figure 4.6: DP Temperature evolution along one of the supply path

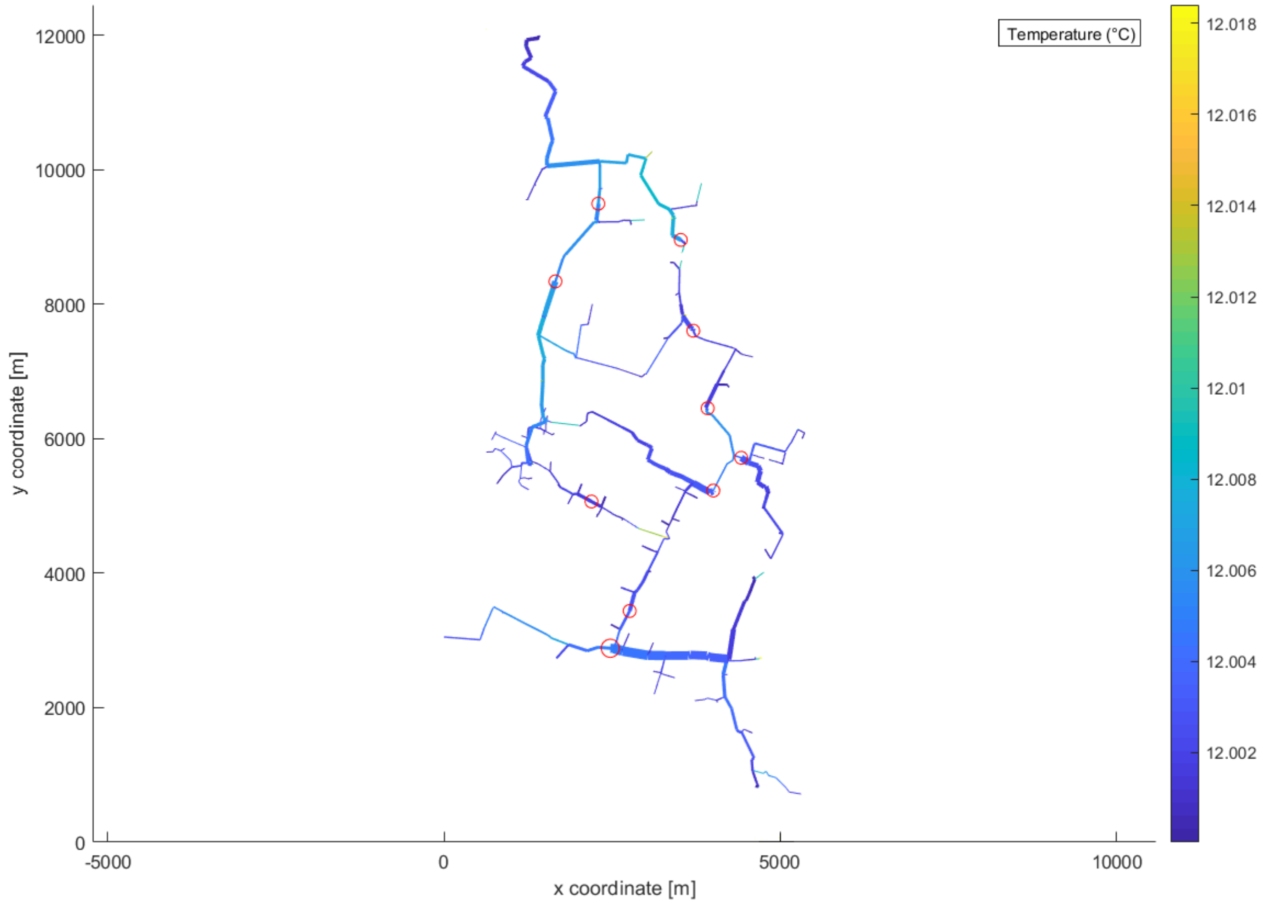

Figure 4.7: Distributed production return temperature evolution

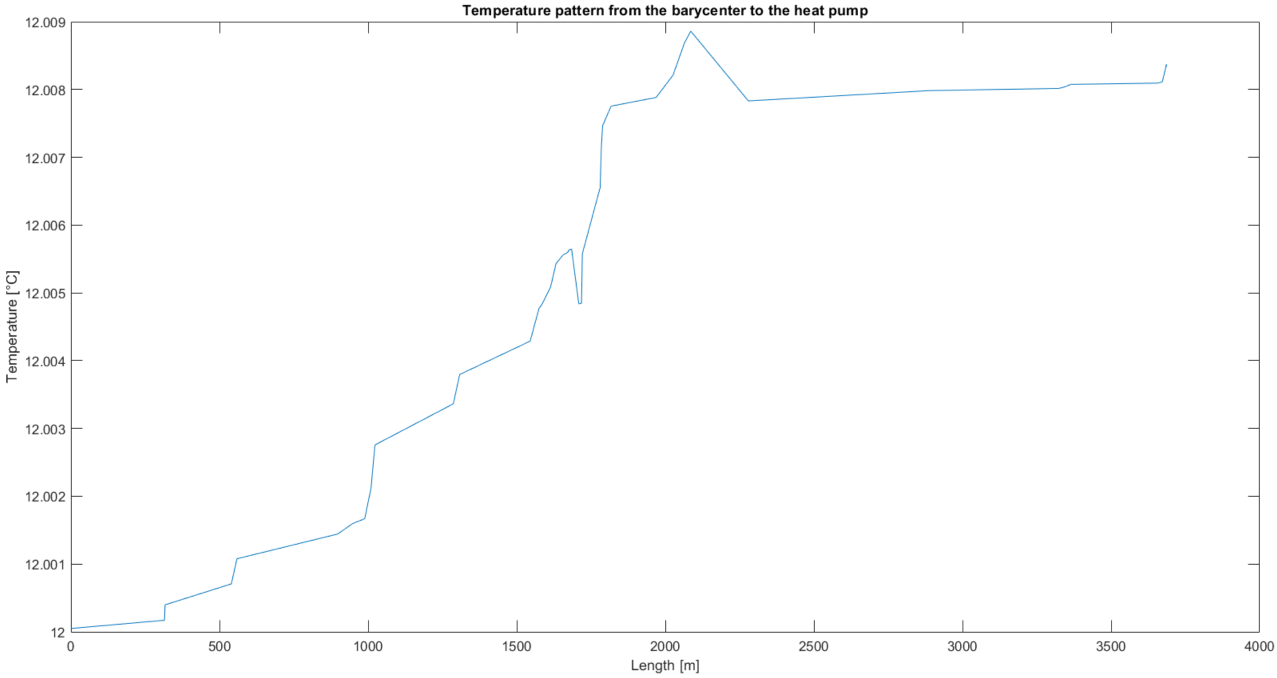

Figure 4.8: DP Temperature evolution along one of the return path

4.1.3 Optimized Distributed Production

As explained in the chapter 3.3 a program which find the location of the heat pumps able to minimize the cost of the pipes and the cost of the electricity consumed was developed. The optimization algorithm found a solution that is quite different from the previous one. Only 7 positions over 30 were selected. Two sites will host 2 heat pumps for a total installed power of approximately 40 MW, 3 engines will be allocate in another site each with a power of 20 MW each while the remaining 4 will be lodged in a equal number of places.

The results of the optimization are reported in Table 4.3. The heat loss is almost the same of the previous configuration. But the other parameters are different: the cost of the pipes is a bit higher because of bigger average diameter in the network, however this allow lower pressure losses in the system and much lower cost for electricity consumed by the pumps during the lifetime of the plant. This leads to a lower total cost.

It is possible to state that, of the three configurations studied, this seems to be by far the best matching solution.

Maximum Diameter [m]	Average Diameter [m]	Heat Loss[MW]	Pipe Cost [M€]	Pumping Cost[M€]	Total Cost [M€]
1,0	0,313	0.7	31,3	13,5	44,8

Table 4.3: Optimized distributed production configuration main results

In the Figure 4.9 and 4.10 the map of the network is shown for the supply and for the return.

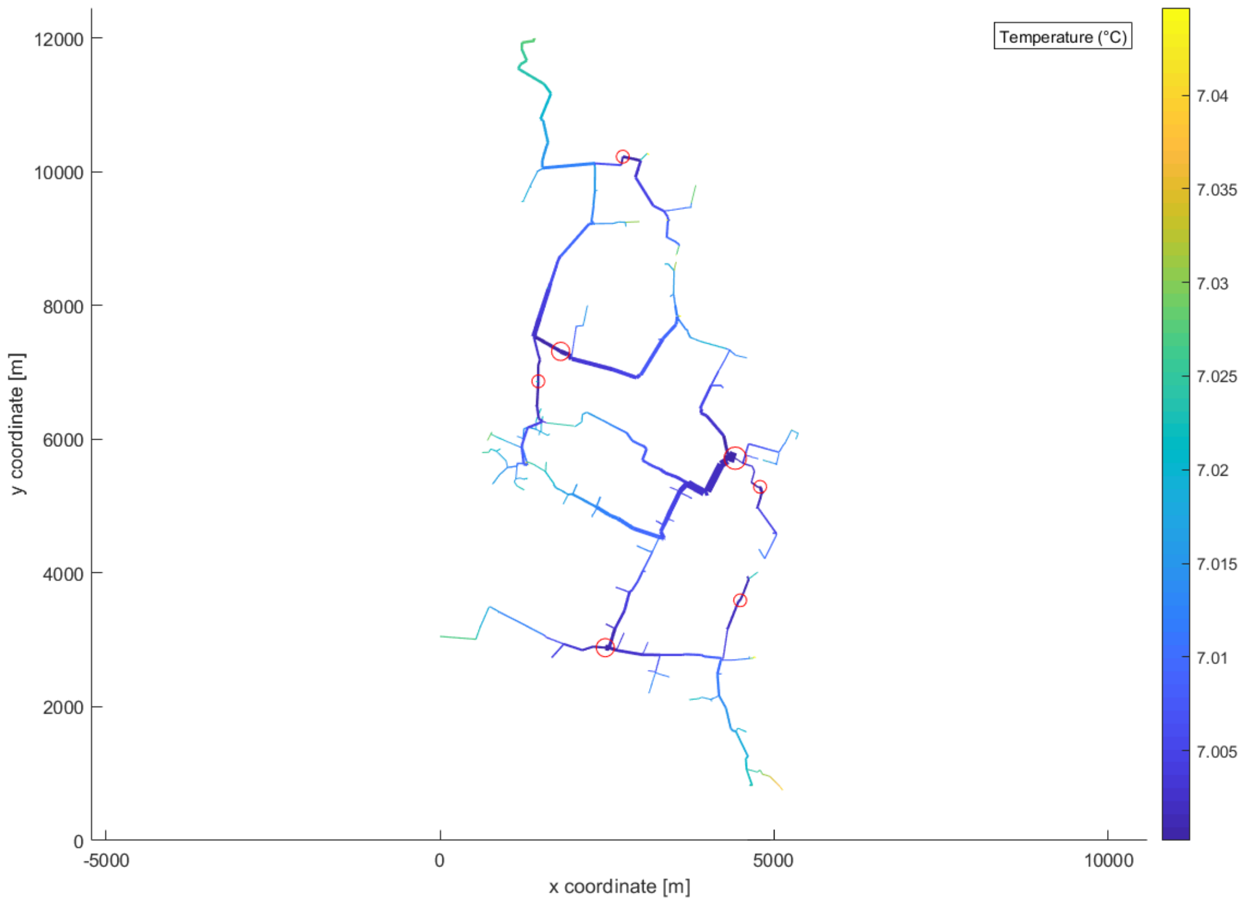

Figure 4.9: Optimize HP positions delivery temperature map

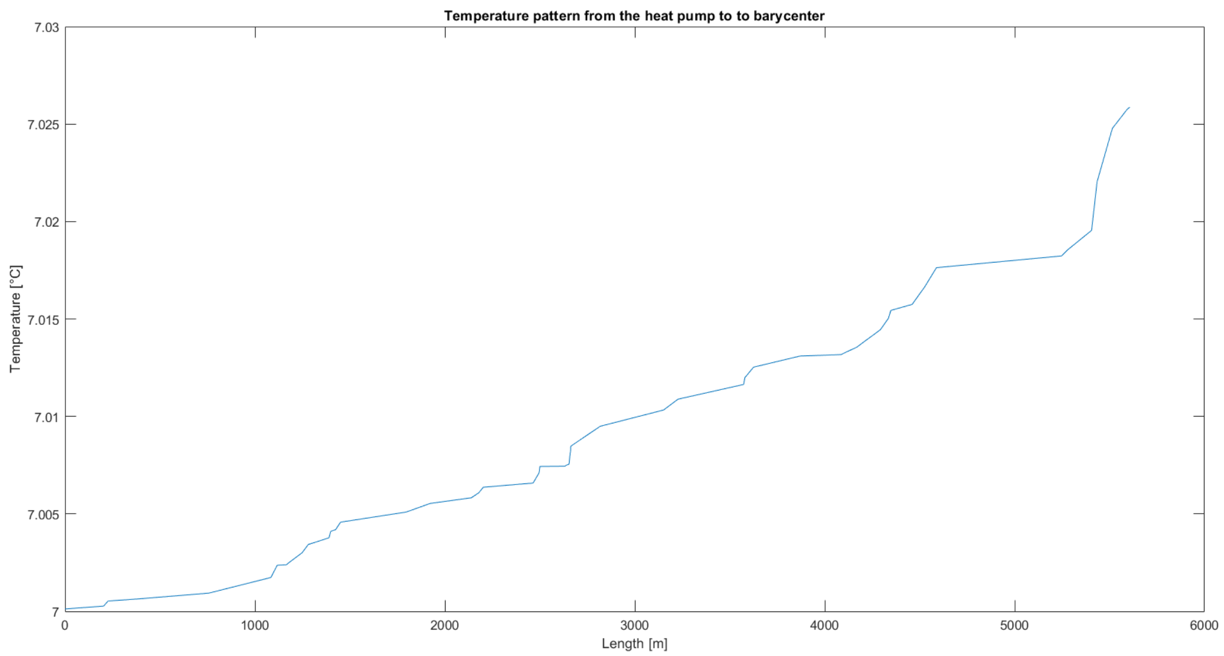

Figure 4.10: ODP Temperature evolution along one of the supply path

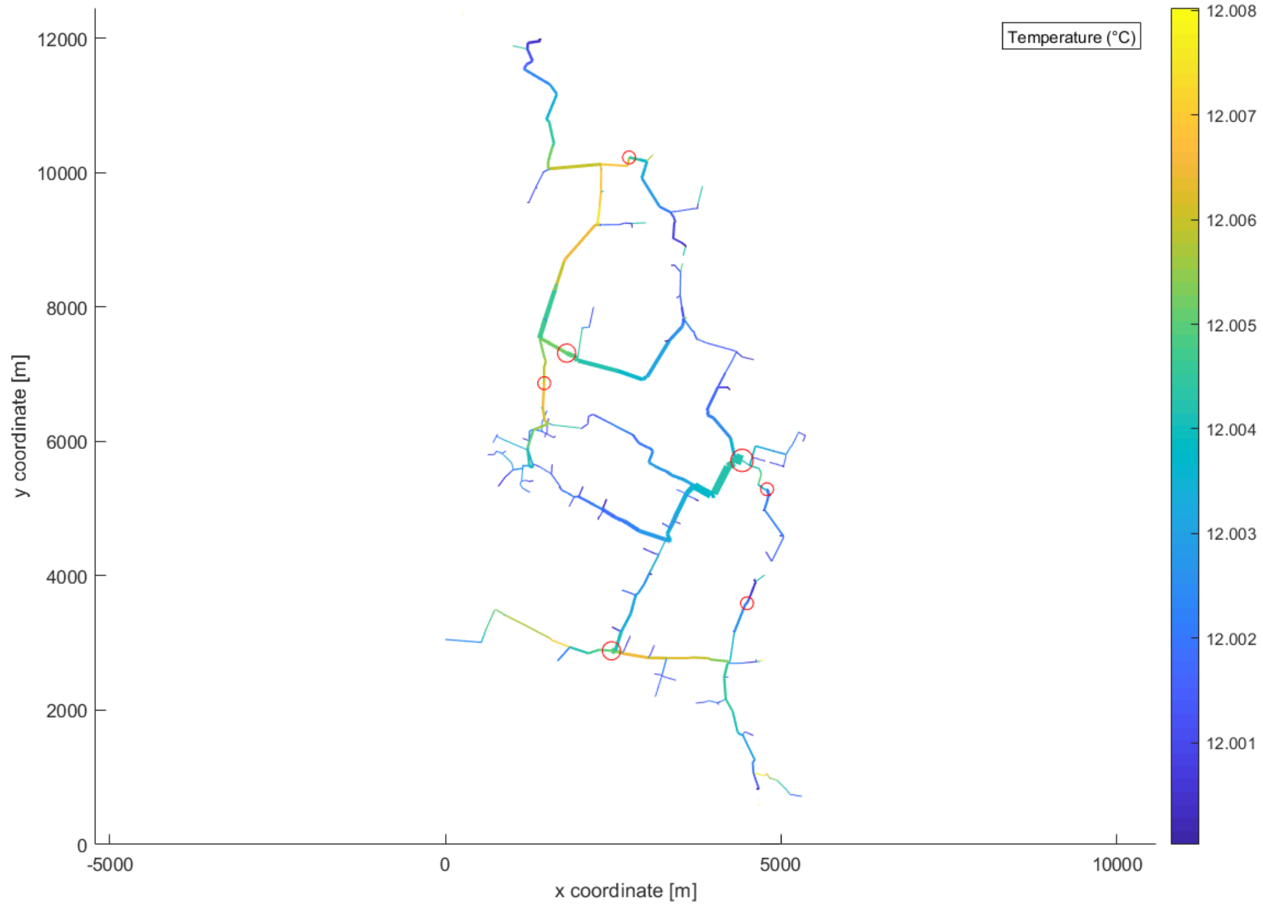

Figure 4.11: Optimize HP positions return temperature map

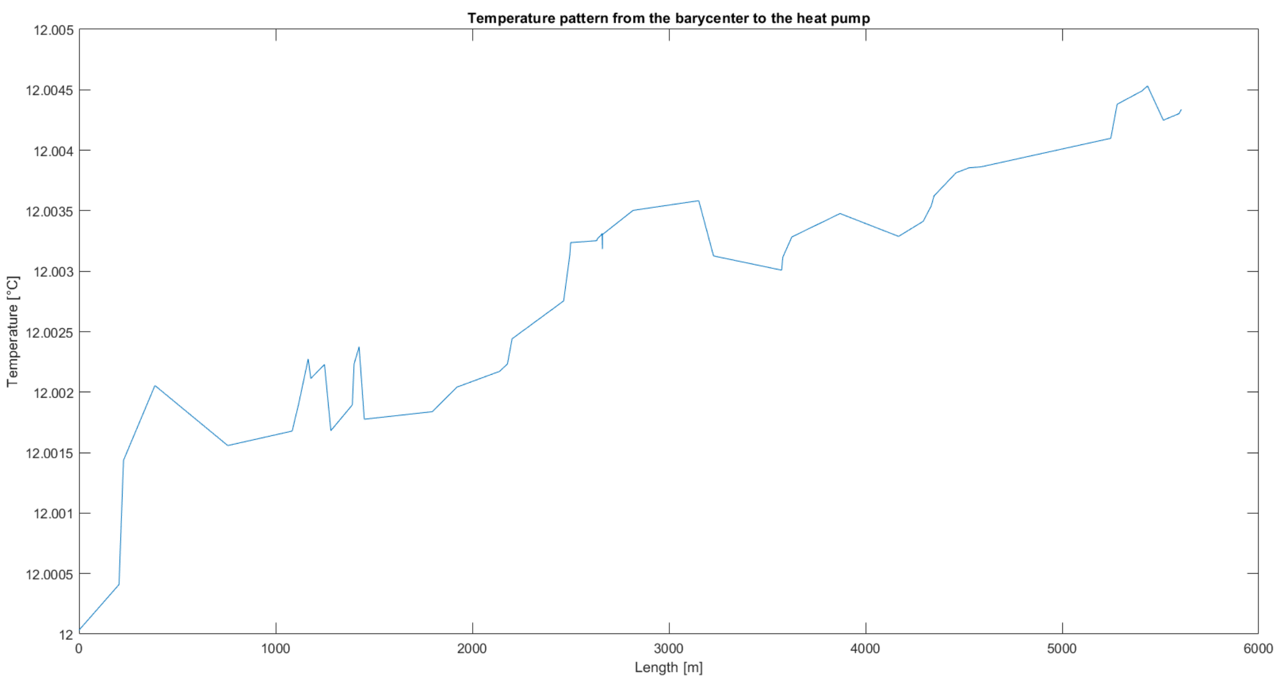

Figure 4.12: ODP Temperature evolution along one of the return path

The data coming from the different models are compared in Table 4.4 below. There is a significant reduction respect the centralized production case. In fact the reduction of the final cost is close to the 50% with a significant reduction of the components size.
Between the two distributed production configurations the main difference is the cost of electricity required by the pumps: while the first configuration as a lower pipes cost it is disadvantageous for its high pressure drops.

Configuration	Maximum Diameter [m]	Heat Loss[MW]	Pipe Cost [M€]	Pumping Cost[M€]	Total Cost [M€]
Centralized Production	1,5	1,2	66,1	21,6	87,7
Distributed Production	0,8	0,6	26,6	21,5	48,1
Optimal Configuration	1,0	0,7	31,3	13,5	44,8

Table 4.4: Simulation campaign main results

4.1.4 Low insulated pipes network

The configurations studied until this moment have been characterized by a low value of the heat loss, below the percentage point. The reason is easy to identify: the pipes adopted for the simulation have a very low value of the thermal transmittance, precisely 1 $W/(m^2K)$. This coefficient represents a very high insulation capacity. This kind of pipes are used in district heating networks where the temperature can overcome the 100°C, to minimize the thermal dispersion the system is request to have an excellent insulation attitude. This study is referred to a district cooling grid with temperatures way lower than the DH ones. In fact the project values for the variables are 7°C and 12°C. Such a high insulation capacity is not essential for the district cooling network since the maximum temperature different between the cold fluid and the ground is only 8°C. The use of pipes with a value of the thermal transmittance equal to $5W/(m^2K)$ could represent a notable chance to reduce the initial investment cost (see 2.3) and a better way to use the available materials.
In this chapter, the idea to use lower insulated pipes is developed and compared to the other simulation results, a study aimed at choosing the new ideal nominal velocity is first performed, since the cost of the pipes goes down the cost of the electricity consumed by the pumps is more important, therefor the new nominal velocity is lower than the former one (chapter 3.1).
Figures 4.14 and 4.16 report the system final configuration with the heat pumps allocated in their optimal positions. The water rise in temperature is still contained but, contrarily to the previous cases, begins to be more significant. The temperature increment is now of few decimal points for the delivery side. The percentage heat loss is now around 1,7%. The slightly higher total mass flow in the system and the lower velocity of the water cause the average diameter to increase.

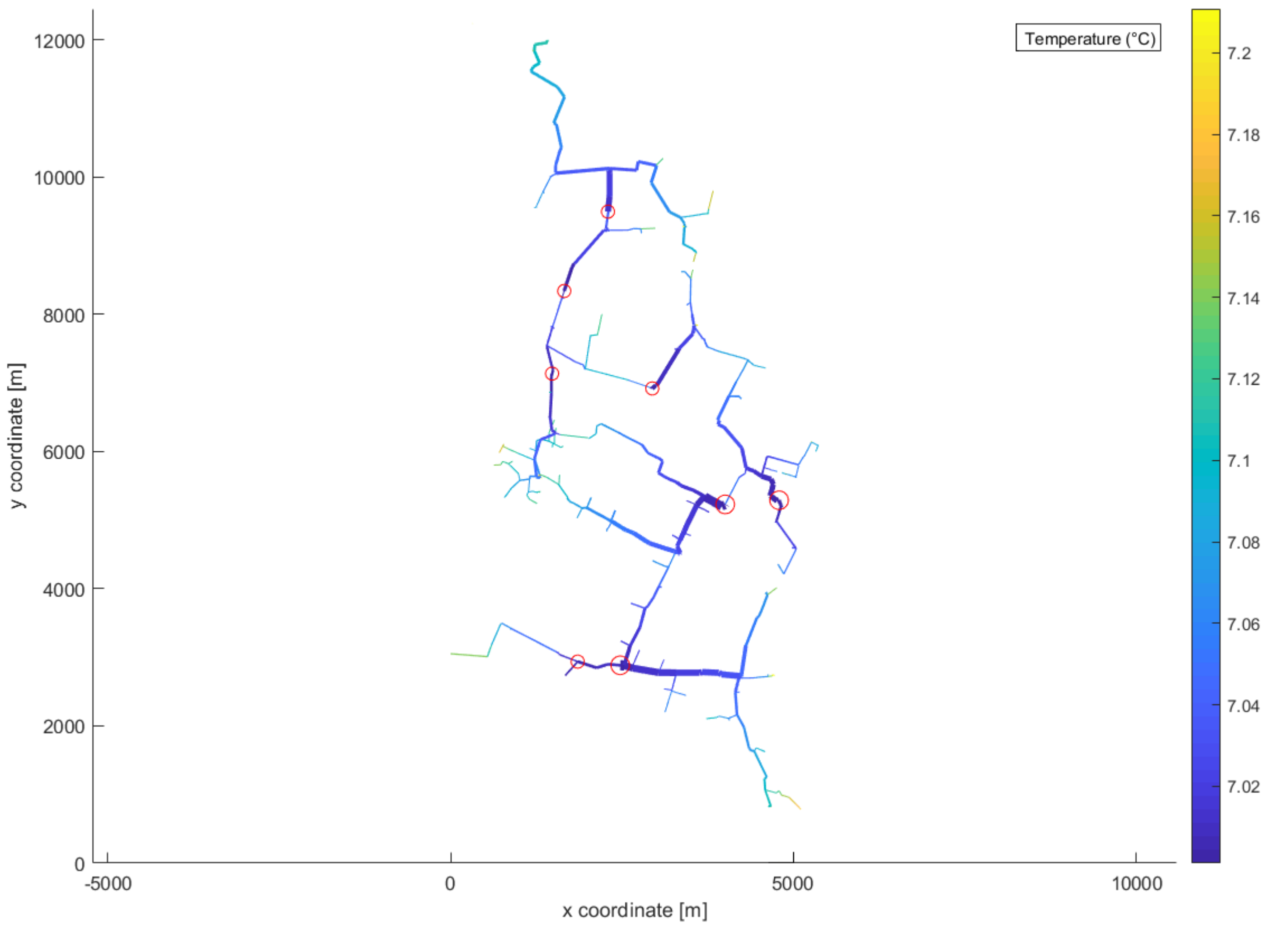

Figure 4.13: Low insulated pipes supply temperature map

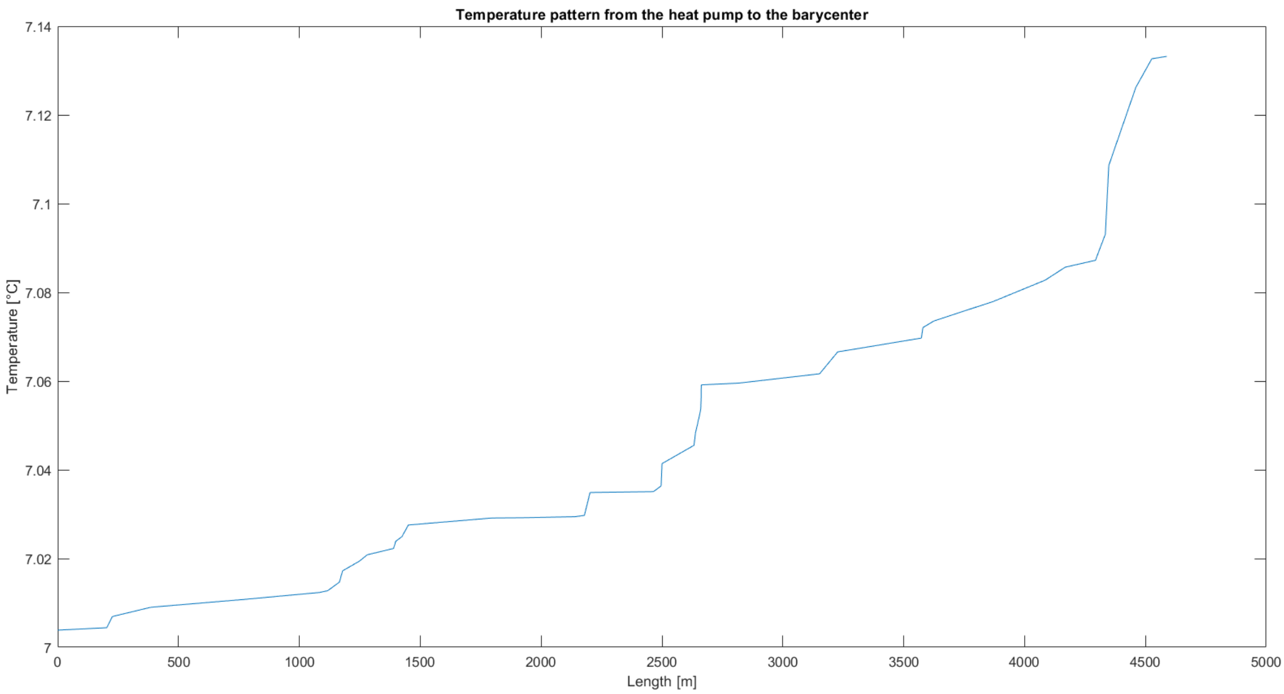

Figure 4.14: LIDP Temperature evolution along one of the supply path

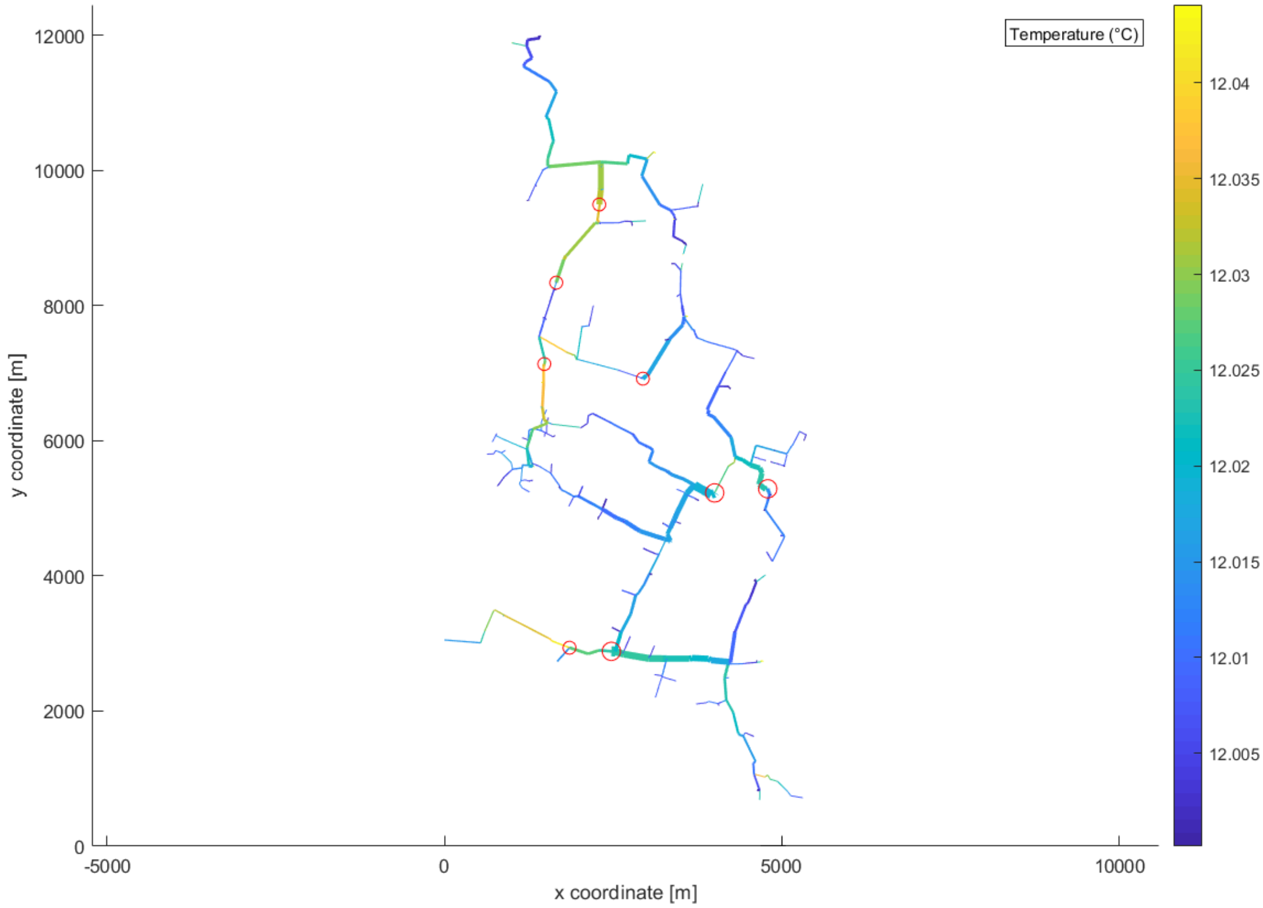

Figure 4.15: Low insulated pipes return temperature map

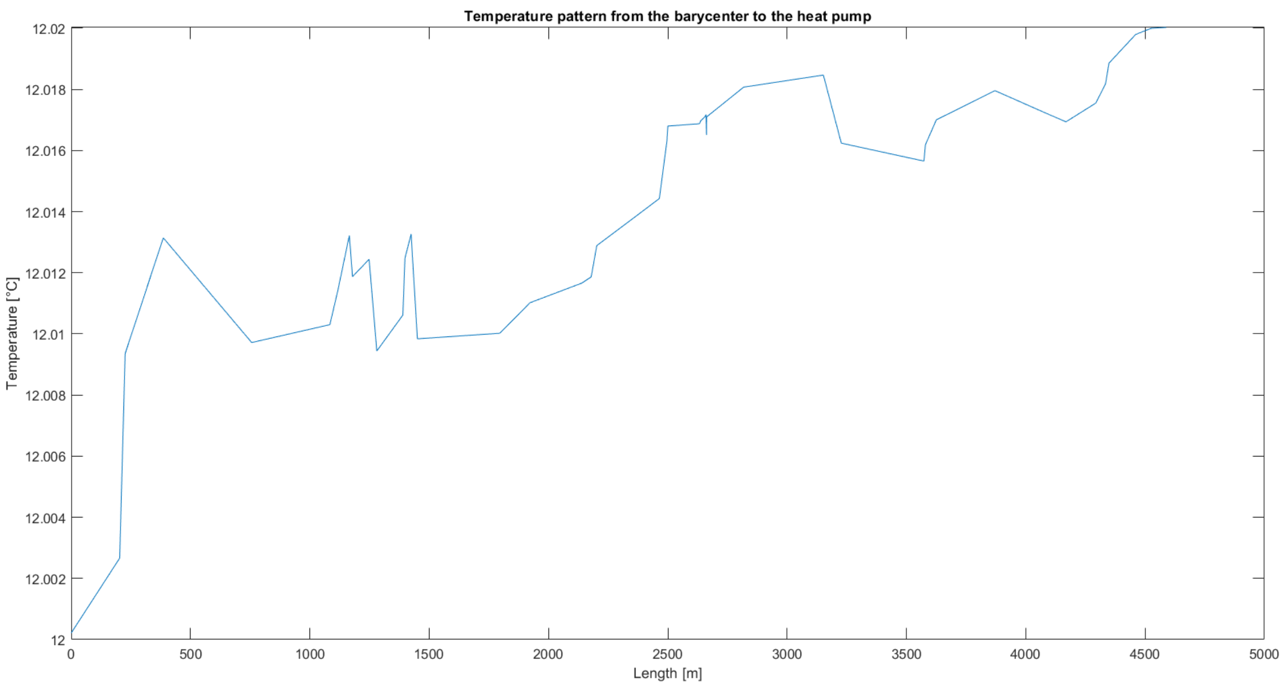

Figure 4.16: LIDP Temperature evolution along one of the return path

In Table 4.5 the simulations outcomes are exposed and compared with the previous one. The increase of the heat losses could represent a problem, but the total electrical energy consumed by the heat pumps in the this configuration will not be much higher than the one consumed in the previous case, the estimation of the increase of the electricity costs suggest that they will be almost negligible compared to the total costs. As anticipated, the greatest advantage of this solution consists in the reduction of the pipes cost. It was calculated a saving of -41% could be easily reached with a further cut to the electricity cost (-20%). Globally, it possible to avoid an expense of 15.6 millions corresponding to the 35% of the first estimated cost for the optimal configuration with well insulated tubes.

Configuration	Nominal velocity [m/s]	Heat Loss [MW]	Pipe Cost [M€]	Pumping Cost[M€]	Total Cost [M€]
Well insulated pipes	4	0,7	31,3	13,5	44,8
Low insulated pipes	3.5	3,7	18,4	10,8	29,2
			-41%	-20%	-35%

Table 4.5: Well and low insulated pipes results comparison

4.2 Partial Load Analysis

Starting from the preliminary weather data and analysis was possible to extrapolate the outdoor temperature cumulative frequency curve. Then the load duration curve was drawn (Figure 1.23). The system is supposed to work at the nominal power, i.e. 220 MW, when the outdoor temperature is equal or higher then 30 °C, ensuring a maximum temperature difference of 6°C between the room and the external environment. According to the modern regulations and in order to have a more responsible use of the energy, the system will supply energy only in the case the outdoor temperature goes over 26 °C. Under the assumption the change of the supplied power is directly proportional to the temperature difference, four power level are identified with the system working in a range that goes from 100% to 50% of the nominal power as shown in Table 4.6.

Outdoor Temperature [°C]	Power [MW]	Load Percentage[%]
27	110	50
28	146	67
29	183	83
30+	220	100

Table 4.6: Operating partial load levels

The concept of load following capacity is also represented in Figure 4.17. When the temperature is below the 26 °C, there is no supplied power. The 50% of the nominal power represents the base load capacity and corresponds to an outdoor temperature of 27 °C. Once the temperature goes over the 30 °C, the power remains fixed. In fact, the few hours where a higher power level is request do not justify an increment of the total installed power. To solve the problem, it was suggested to install a storage group and to accumulate cold water when the power request is lower than the nominal value as shown in Figure 4.18. With the addition of the storage system the heat pumps will provide the nominal power for approximately 200 hours. The total energy required by the users during the cooling period will be 75 GWh.

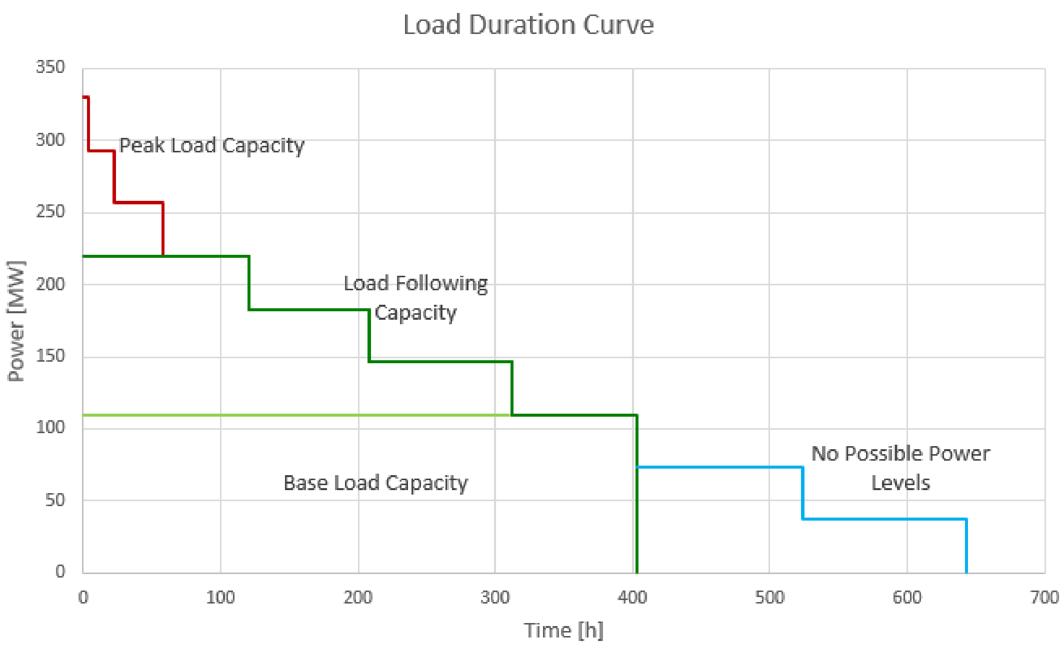

Figure 4.17: System load following capacity

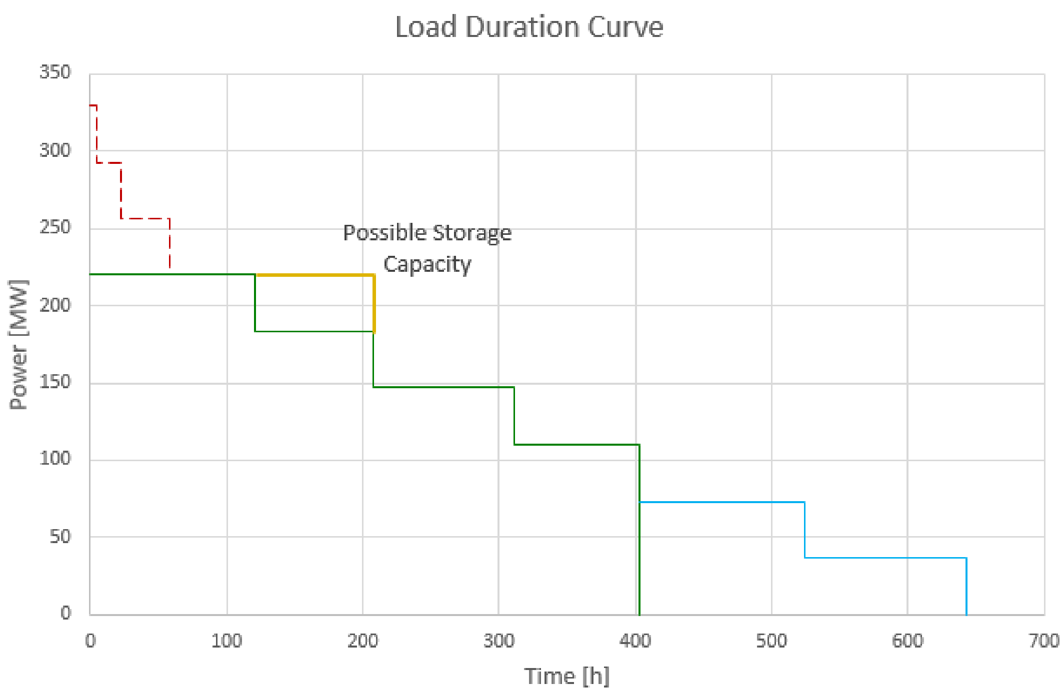

Figure 4.18: Peak load replaced by storage capacity

4.2.1 Partial Load Analysis in case of high insulated pipes

Working at partial load could imply to reduce significantly the system efficiency. For the optimal configurations a study of the network response was conducted. It was shown that the reduction of the power does not cause a significant worsening to the system performance. The pressure drop is strongly affected by the reduction of the supplied power. In fact, in order to reduce the power, it is necessary to reduce proportionally the flow rate extracted and injected, reducing the velocity of the water. Lower flow rate implies lower pressure drops.
The heat losses do not scale with the power, their value remains always the same but its percentage weight augments.
In Figure 4.19 it is shown the progressive rise of the percentage heat loss at lower power levels for the configuration with well insulated pipes.

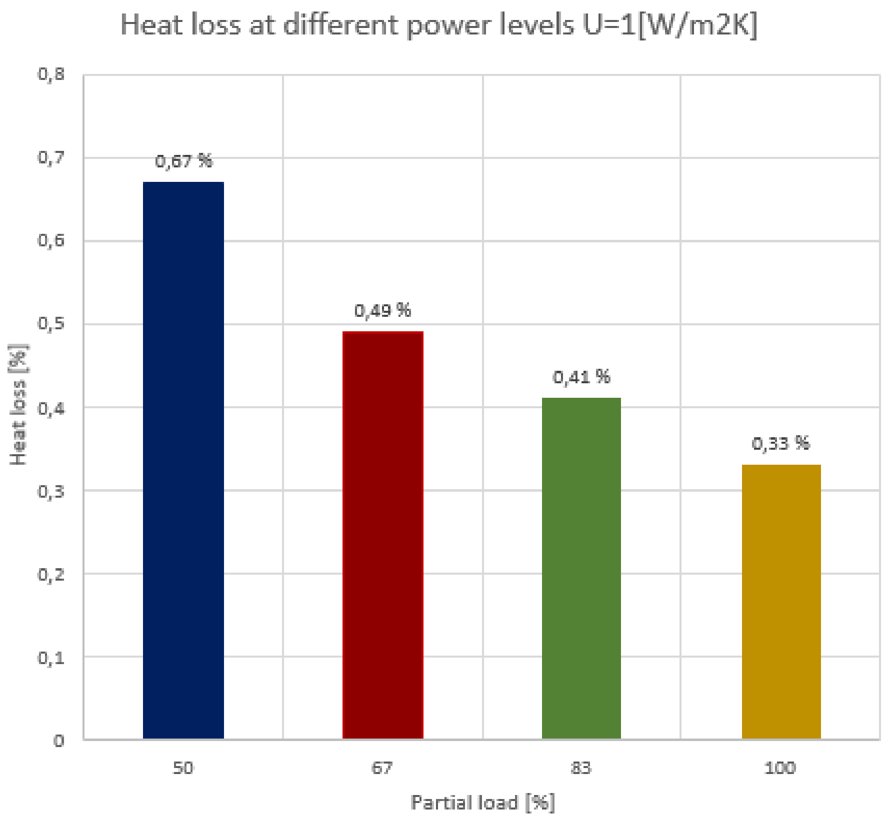

Figure 4.19: Percentage heat loss at different partial loads U=1$[W/(m^2K)]$

Figures 4.20 and 4.22 represent the map of the network with well insulated ducts when the power required is equal to half of nominal value, the maximum temperatures reached in the network are slightly higher than in the case with maximum power required, the velocity of the water decrease and it will exchange more heat with the terrain before reaching the barycenters.

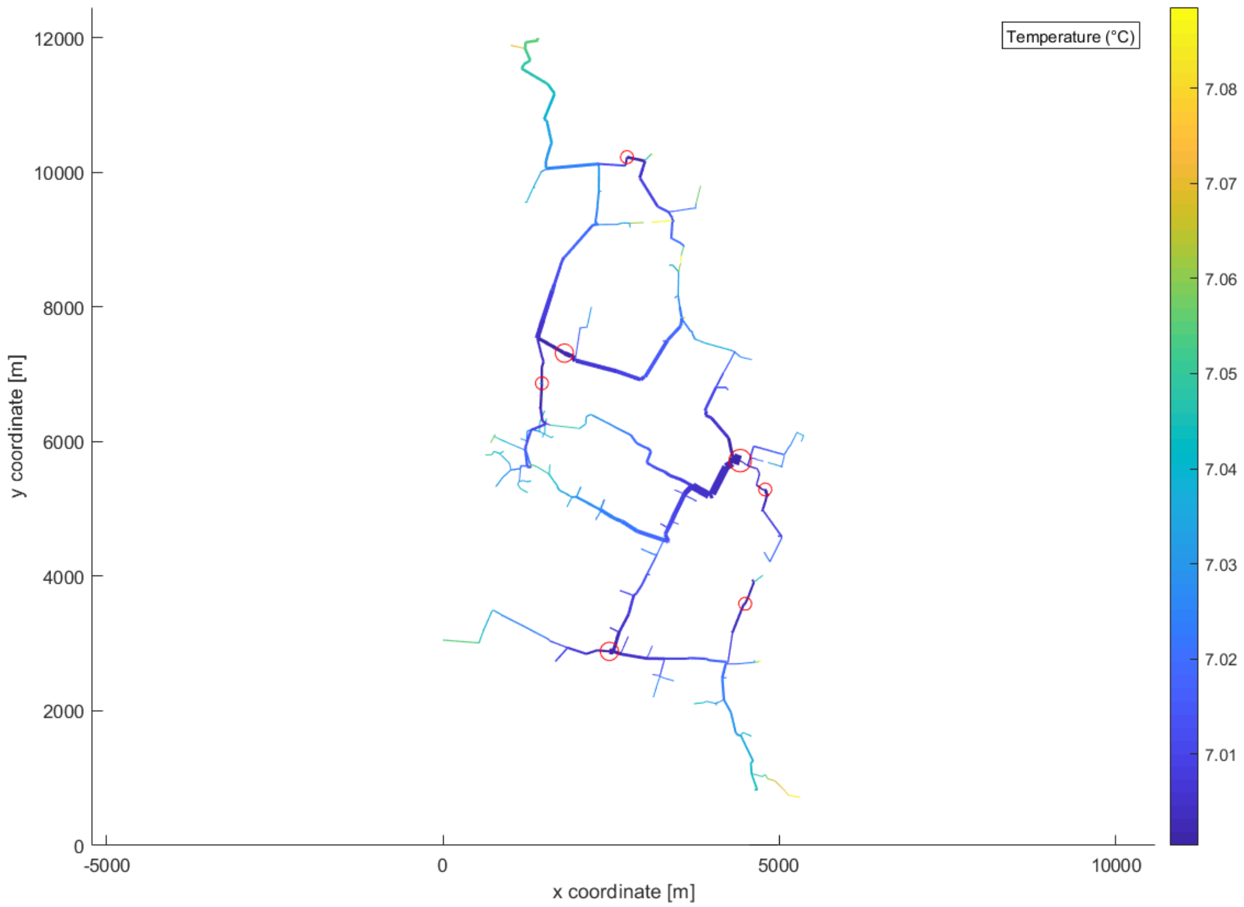

Figure 4.20: 50 % partial load supply temperature map

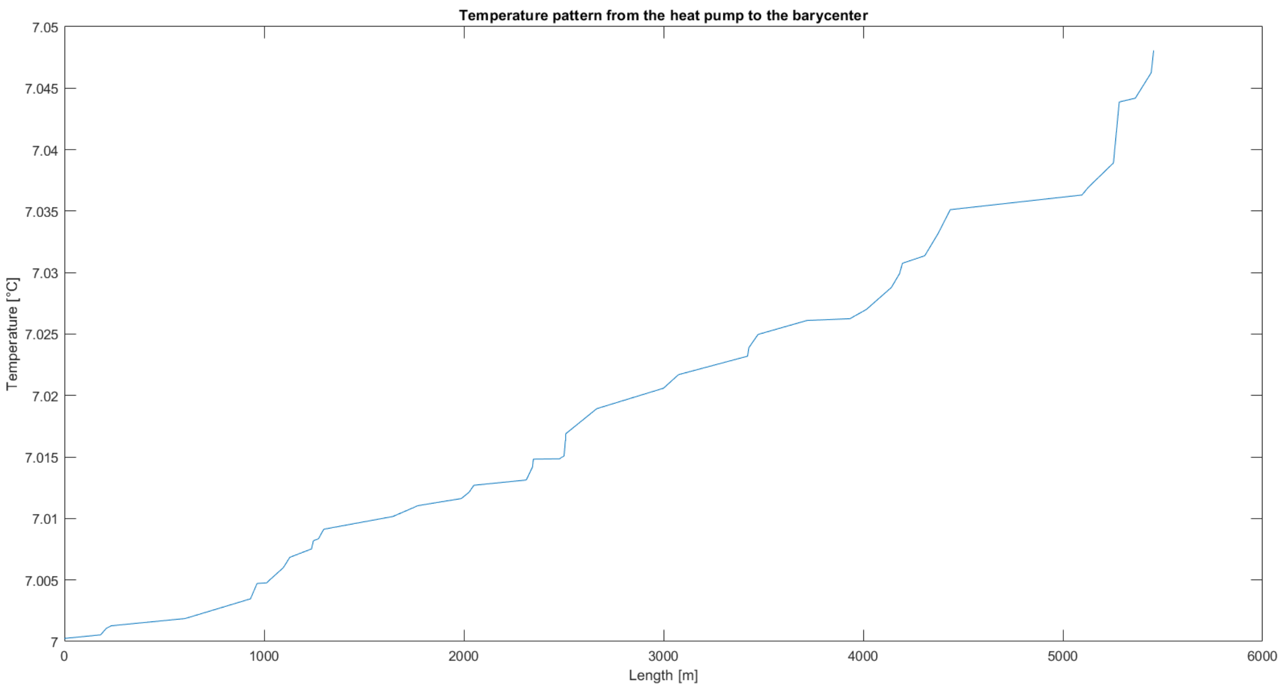

Figure 4.21: ODP Temperature evolution along one of the supply path

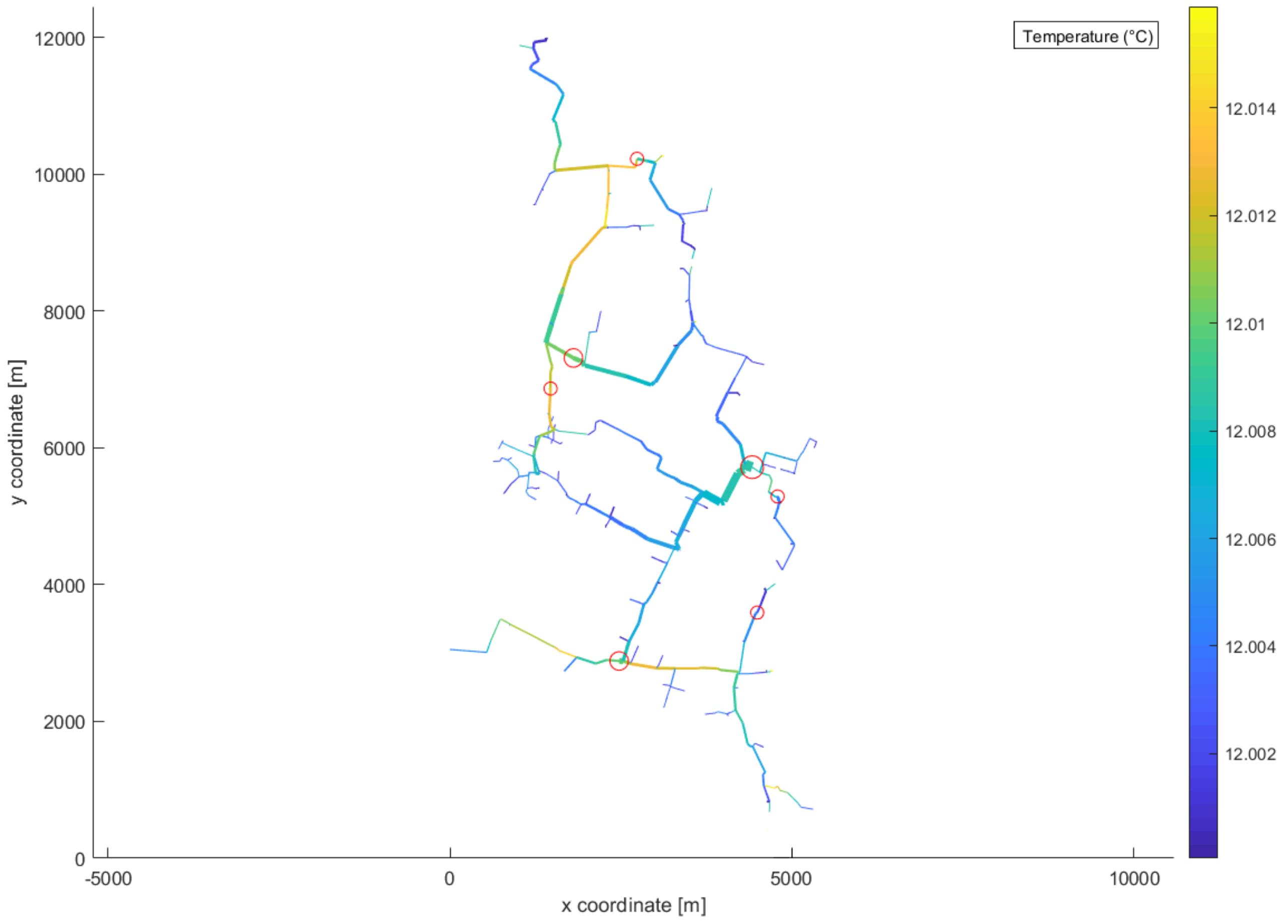

Figure 4.22: 50 % partial load return temperature map

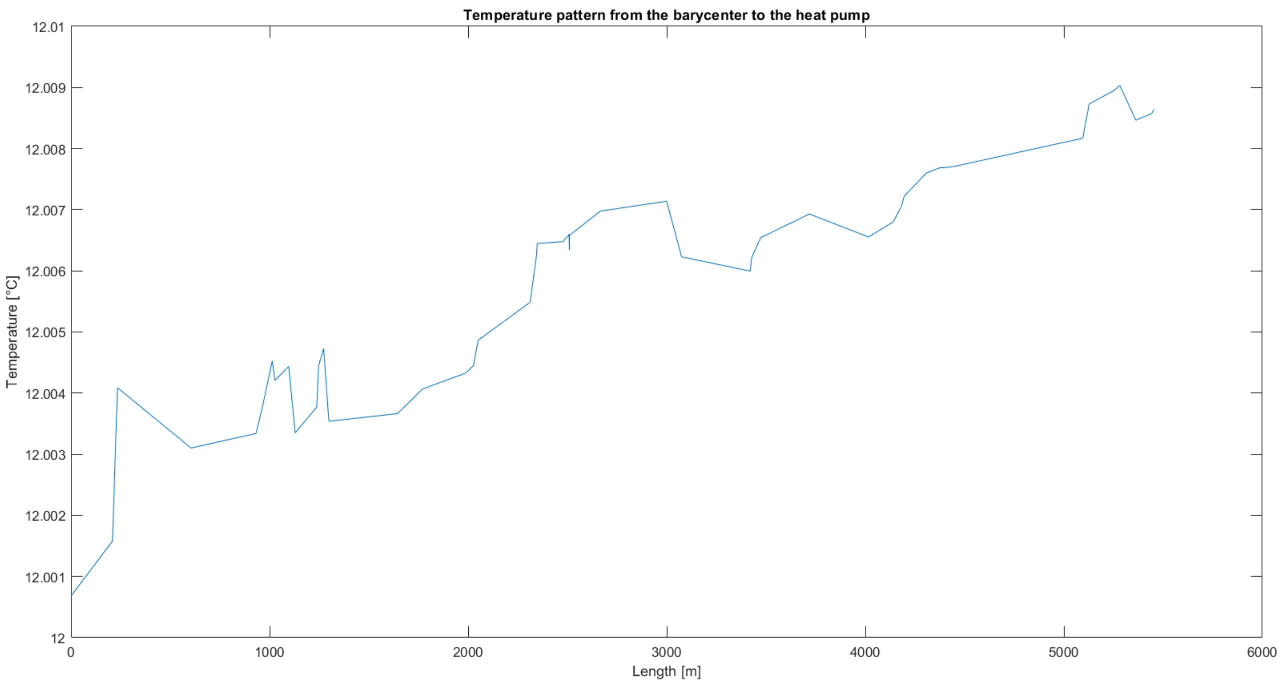

Figure 4.23: ODP Temperature evolution along one of the return path

4.2.2 Partial Load Analysis in case of low insulated pipes

The study at partial load was also carried for the optimal configuration using low insulated pipes. The maps of the network with the temperature evolution in one path are reported in the following figures.

Figure 4.24: 50 % partial load supply temperature map - low insulated pipes

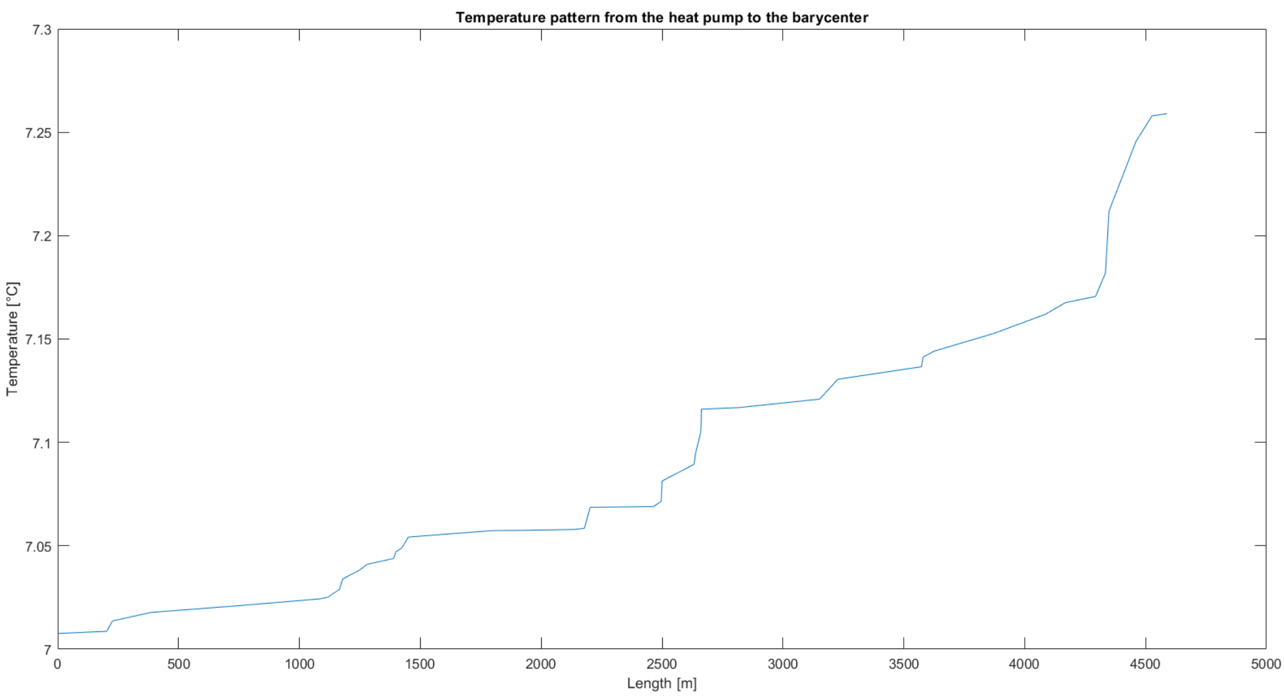

Figure 4.25: LIDP Temperature evolution along one of the supply path

Figure 4.26: 50 % partial load return temperature map - low insulated pipes

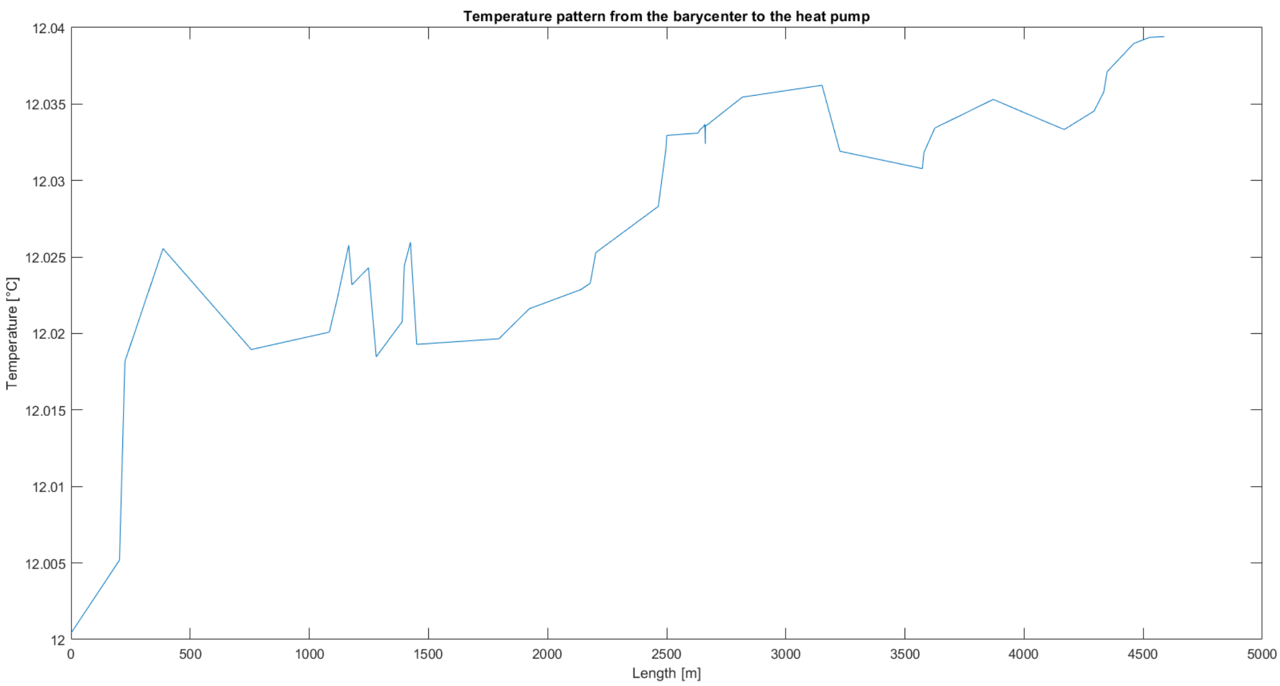

Figure 4.27: LIDP Temperature evolution along one of the return path

The thermal dispersion goes from 1,7 % at full load to 3,4% when the demand is the halved.

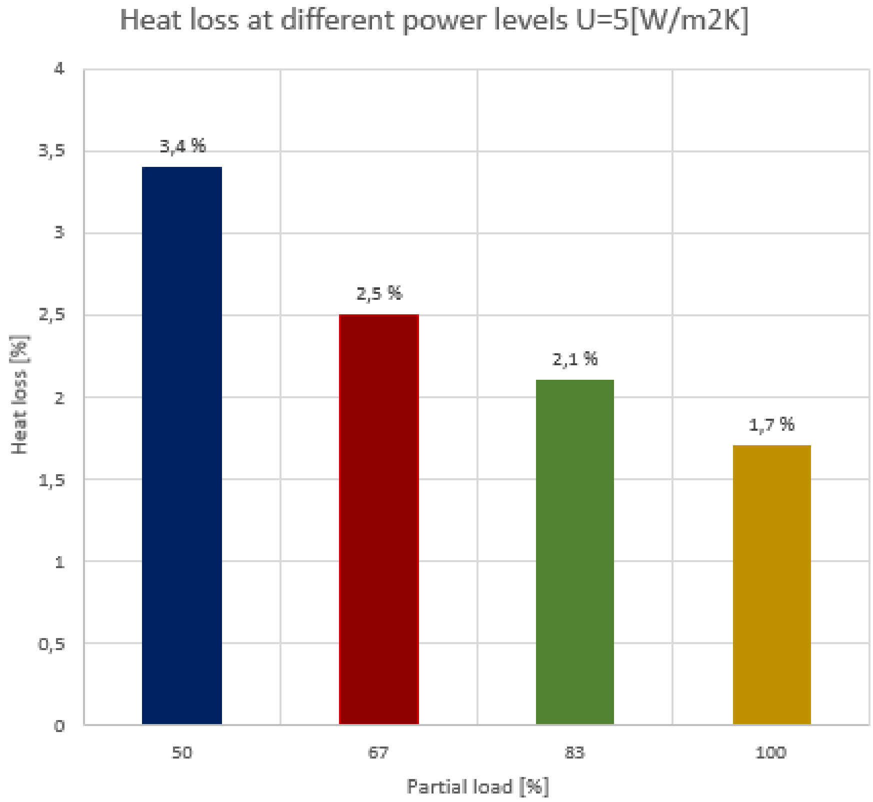

Figure 4.28: Percentage heat loss at different partial loads U=5[$W/(m^2K)$]

4.3 Booster pumping stations placement optimization

In this chapter the placement of the booster pumping stations will be analyzed in the case of the optimal HP configurations using pypes with both U=1 $W/(m^2K)$ and U=5 $W/(m^2K)$. This process aims to reduce the electrical consumption required at the heat pumps positions - the return water is withdrawn from the grid, cooled down and pumped back at higher pressure in the supply grid - and the booster pumping stations along the network. Due to the friction phenomena and to the rough deviations of the branches, the pressure is largely reduced before reaching the Users. The same happens to the returning water flow. To ensure the system stability it is required to install different booster pumping stations along the network. Also, the presence of these components permits to have a lower pumping power requested at the heat pumps positions. In the following chapter the outcomes of the BPS placement optimization are exposed. In table 4.7 the pressure drops characterizing each configurations, before the placement of the stations along the lines, are reported. It is possible to note how these drops are much higher than the maximum pressure value the tubes can tolerate. All these solutions require additional pumping along the branches.

The optimal configurations have lower pressure drops respect to the distributed and the centralized production cases. The optimal configuration with low insulated pipes is the one with the minimum pressure drop since the nominal velocity of the water in the pipes is the lowest 3.5 m/s, while all the other configurations have nominal velocity equal to 4 m/s.

Configuration	Centralized Production	Distributed production	Optimum U=1$[W/(m^2K)]$	Optimum U=5$[W/(m^2K)]$
Pressure drop [bar]	45	50	29	20

Table 4.7: Pressure drop in the different configurations

4.3.1 BPS optimal configuration high insulated pipes

In Figure 4.29 and 4.31 the pressure evolution along the pipeline is represented in the case of the optimal configuration with high insulated pipes. When the water flow reaches the stations, identified by black dots, the pressure increases. When the water gets to one barycenter, it is sent to the User through a distribution network where the pressure drops are estimated to be at least equal to 2 bar.
In Figure 4.30 it is illustrated the fluid pressure evolution in one of the several path connecting the heat pumps to the barycenter. The branch is characterized by a significant pressure drop. In fact a reduction of 3 bar takes place only in the first half of the path. The BP station pumps back the fluid to 16 bar making the water able to reach the final point with the requested pressure.
Figure 4.32 represents the water flow coming from the distribution grid and going back to the heat pump. A BPS is placed close where the water is injected, the pressure goes up to over 10 bar and then decrease travelling in the pipes.
The simulation returned 26 positions with BPS, 13 in the supply network and 13 in the return one. The electrical power adsorbed by these pumps is estimated to be approximately 3,3 MW as shown in Table 4.9 and 4.13. Even if some of the pumps require little power demand (they are placed in branches with a small mass flow), they are still necessary because providing an important pressure gain. Furthermore the BPS reduce the total power required by the system respect to the case where no pumping was placed along the line 4.11.

	Initial configuration	Optimized BPS placement
Electrical Power [MW]	29,8	16.2
Percentage reduction		-45.6 %

Table 4.8: Electrical consumption after BPS installation

As explained in the chapter 3.4 the algorithm developed aims to find a solution with the lowest number of BPS. If minimizing the number of BPS is not considered as a constraint, the final solution characterized by more than 50 branches with pumps but a lower overall electrical consumption, equal to 15.4 MW. However this little advantage does not justify the great increment in complexity of the system.

Booster pumping station	Pressure increment [bar]	Electrical Power [kW]
1	3,6	255
2	4,6	62
3	0,9	72
4	3,6	227
5	4,1	61
6	4,3	219
7	5,3	566
8	3,3	265
9	1,5	50
10	3,9	211
11	1.7	243
12	3.2	243
13	3.4	4
Total		2231

Table 4.9: Booster pumping stations - delivery

Booster pumping station	Pressure increment [bar]	Electrical Power [kW]
1	3,4	10
2	6,6	14
3	4,0	3
4	6,2	86
5	3,8	112
6	2,3	130
7	2,2	17
8	5,6	337
9	2,1	46
10	6,4	222
11	5,7	72
12	0.7	9
13	1.0	14
Total		1049

Table 4.10: Booster pumping stations - return

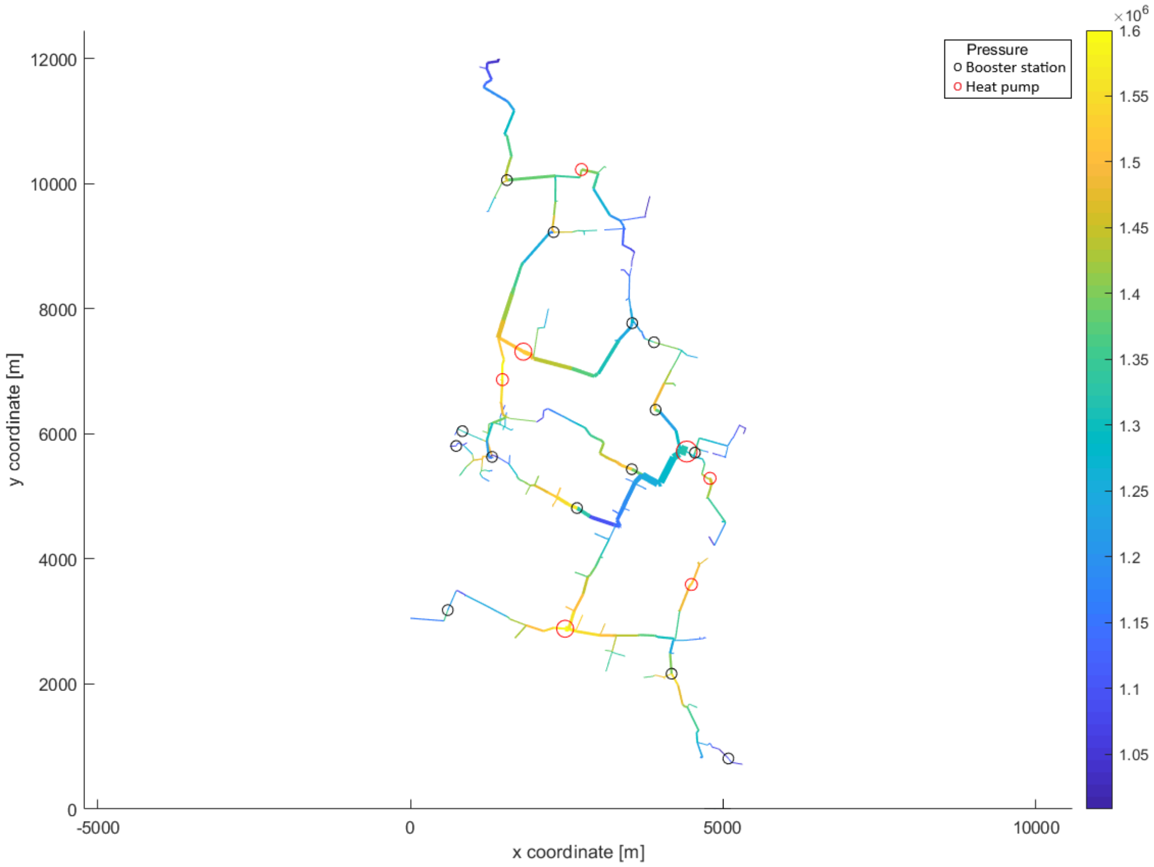

Figure 4.29: Optimized HP position supply pressure map

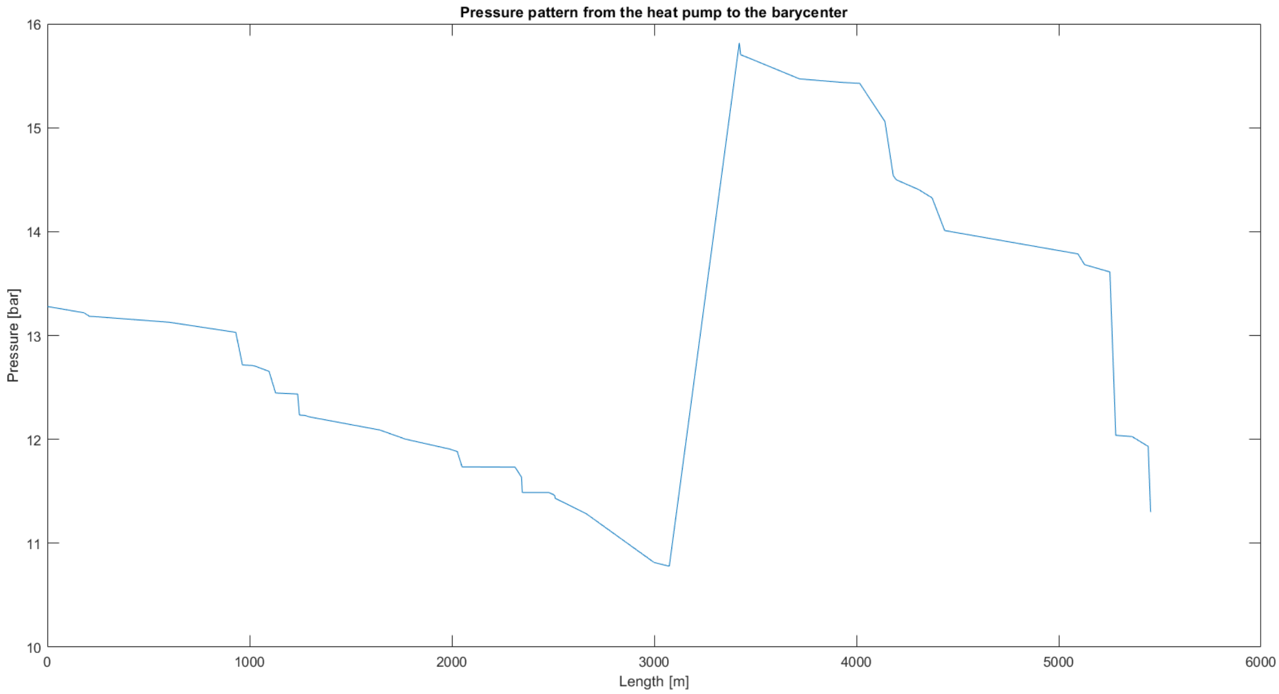

Figure 4.30: Pressure evolution along one of the supply path

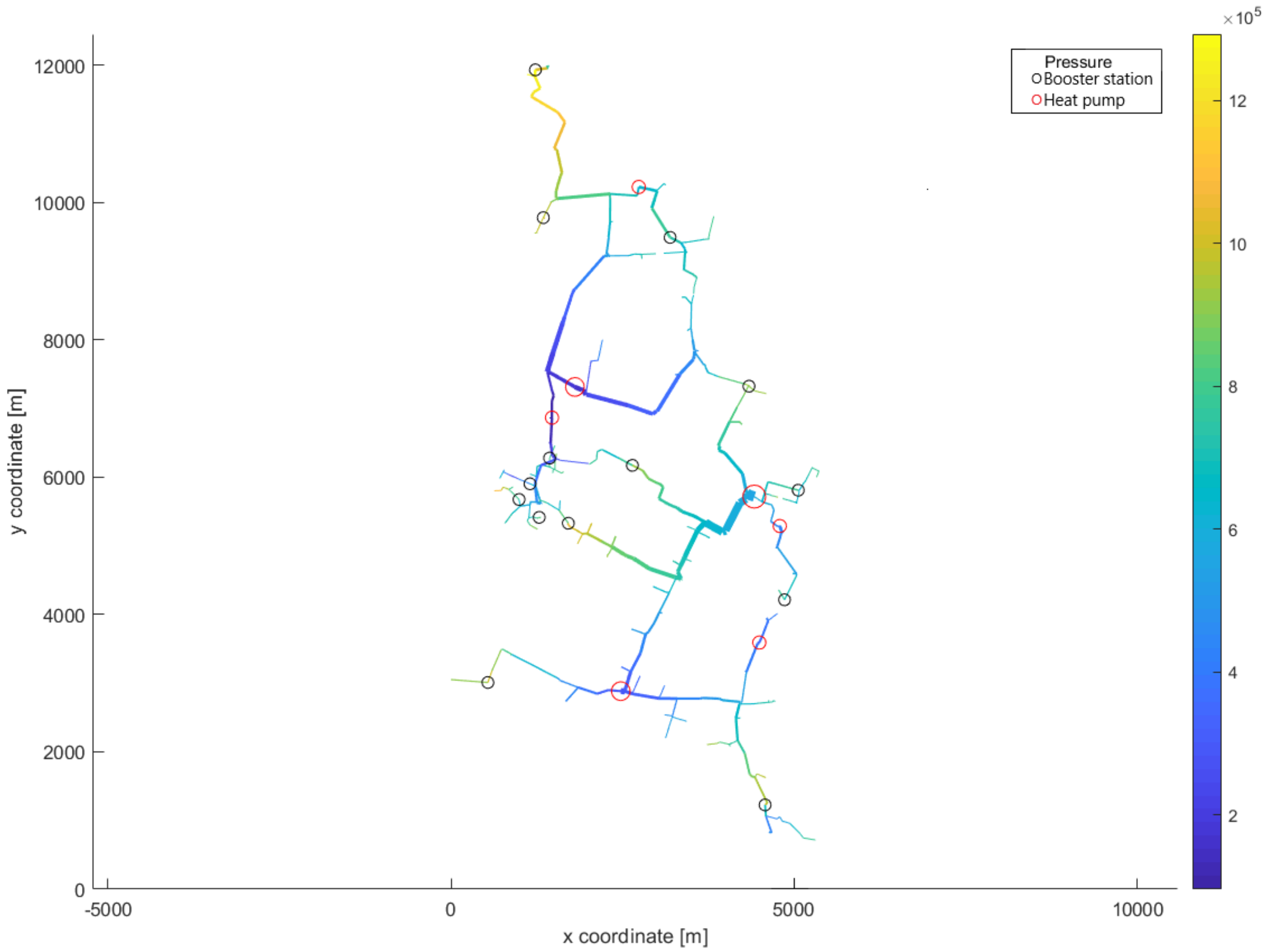

Figure 4.31: Optimized HP position return pressure map

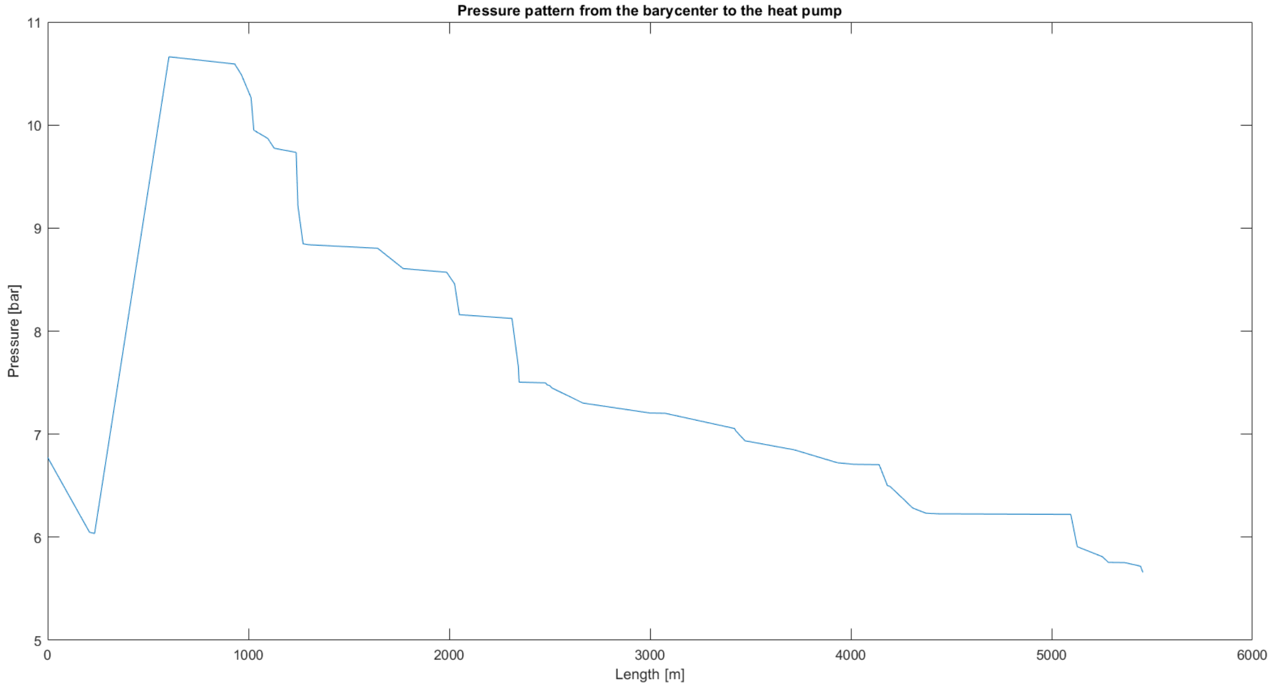

Figure 4.32: Pressure evolution along one of the return path

BPS low insulated pipes configuration

The optimal configuration was also studied in the case low insulated pipes are used. The optimization process had to respect the same constraints of the previous case but, since the total pressure drop of the system is lower, it is expected to have a less BPS installations.
Figure 4.33 and 4.35 display the pressure in the supply and return networks with the heat pumps marked in red and the the booster pumping stations in black. In order to minimize the total electrical consumption, 18 booster pumping stations are needed - 8 on the supply line and 10 on the return. The pressure range goes from 7 bar to 16 bar in supply grid while, in the return one, it goes from 1,5 bar to approximately 10 bar.
In Figure 4.30 it is illustrated the fluid pressure evolution in one of the several path connecting the heat pumps to the barycenter. The water enters the branch with a pressure of 13 bar. Because of the friction effects, there is an important energy loss along the entire branch, almost equal to 6 bar. A BP station is placed after the very first kilometers which restores the original level of pressure.
Figure 4.32 represents the water flow coming from the distribution grid and going back to the heat pump. The effect of the BPS in the supply grid allowes the return flow to have high pressure level. Even if the placement of BPS in this particular path could seem unnecessary, it is fundamental for the multiple branches connected and for the entire system stability.
Table 4.9 and 4.13 report the total pumping power installed on both sides. The electrical power adsorbed in these point is estimated to be approximately 1,1 MW as shown in Table 4.11 and 4.12. The 18 booster pumping stations respect the case without BSs led the electrical consumption to pass from 23,9 MW to 14,1 MW, with a percentage reduction of 42 %.

	Initial configuration	Optimized BPS placement
Electrical Power [MW]	24	14
Percentage reduction		-42 %

Table 4.11: Electrical consumption after BPS installation

Booster pumping station	Pressure increment [bar]	Electrical Power [kW]
1	1	52
2	2,3	25
3	0,7	55
4	0,2	6
5	1,2	62
6	0,2	1
7	1	2
8	2,1	2
Total		205

Table 4.12: Booster pumping stations - delivery

Booster pumping station	Pressure increment [bar]	Electrical Power [kW]
1	2,2	7
2	2,6	6
3	2,1	30
4	2	61
5	2,7	159
6	0,2	2
7	6,4	393
8	0,3	7
9	6,0	211
10	1,1	15
Total		891

Table 4.13: Booster pumping stations - return

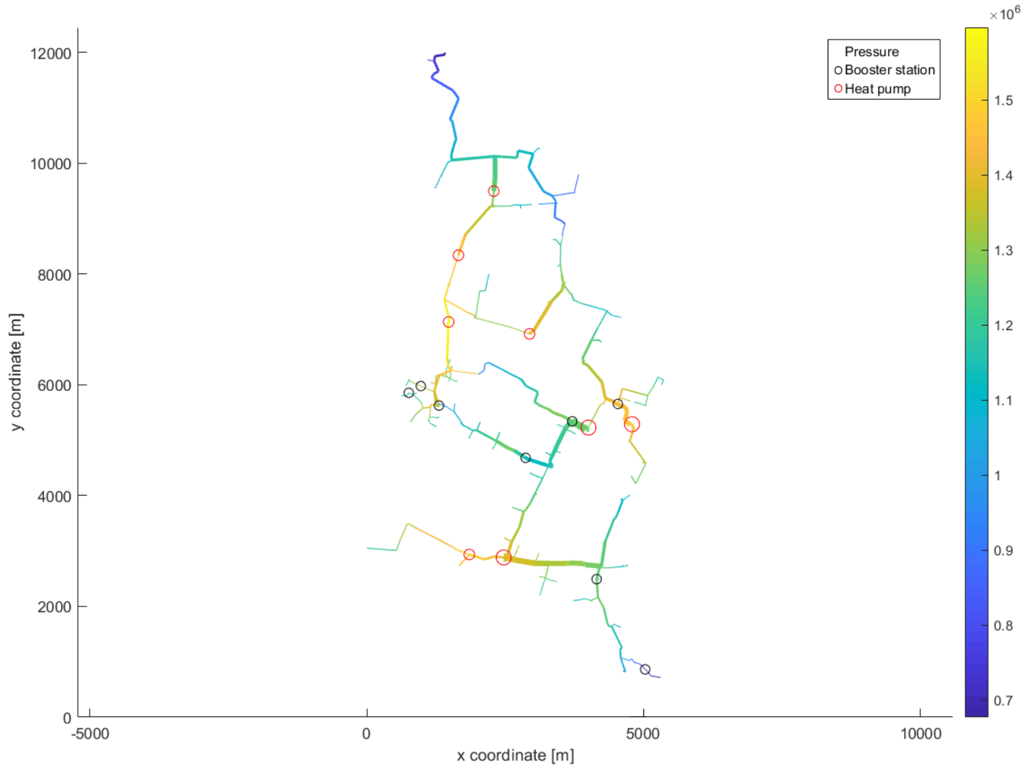

Figure 4.33: Low insulated pipes supply pressure map

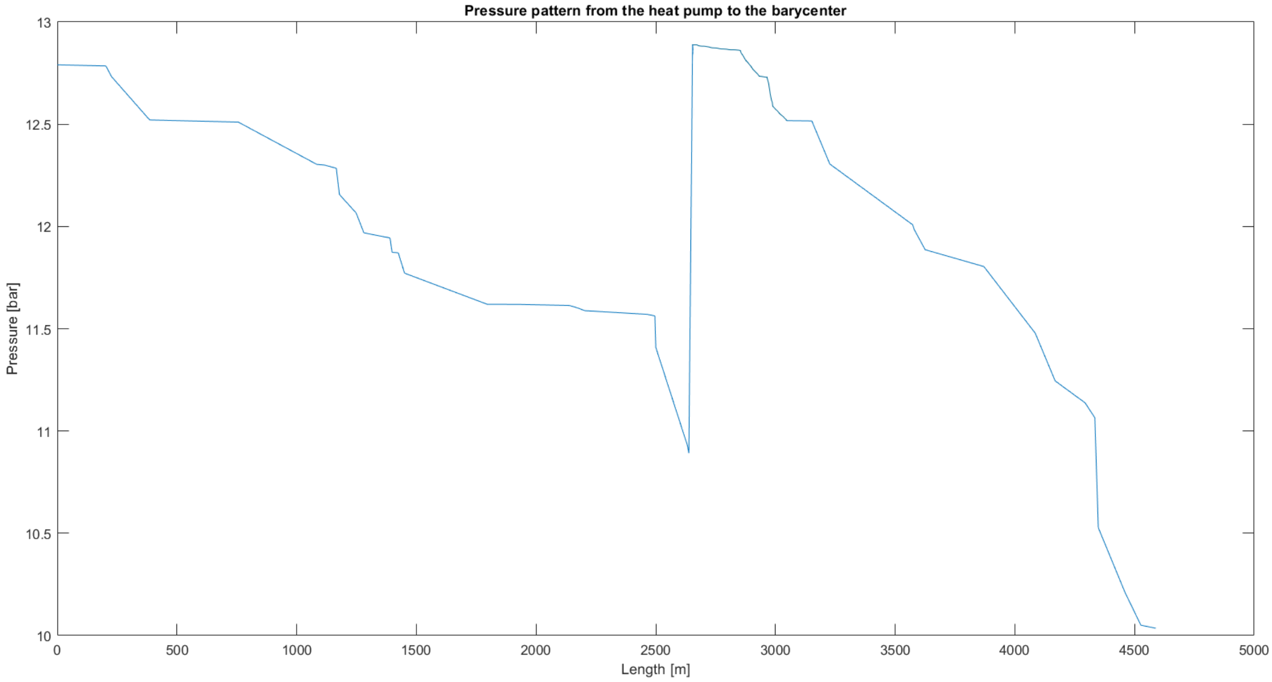

Figure 4.34: Pressure evolution along one of the supply paths

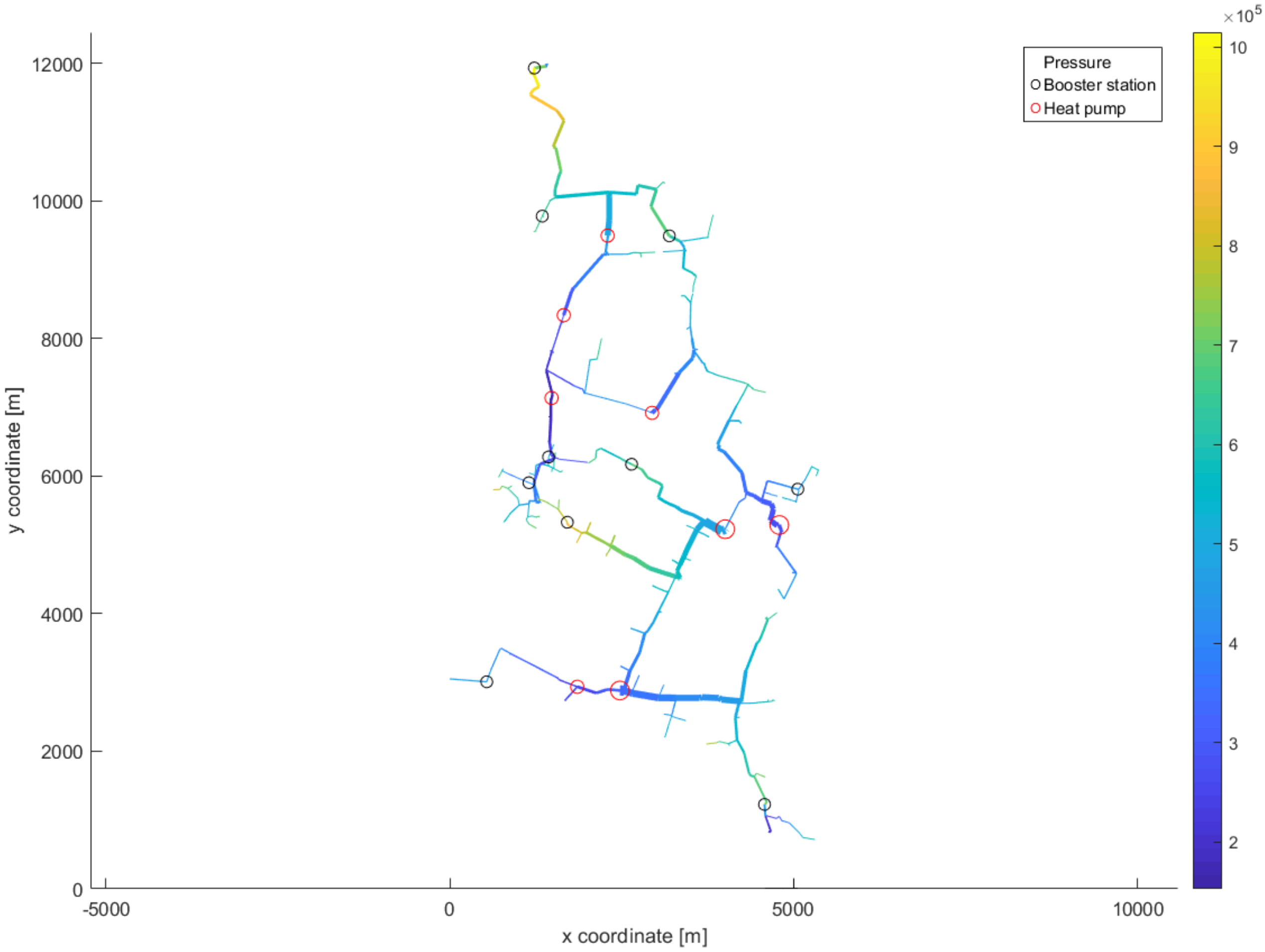

Figure 4.35: Low insulated pipes return pressure map

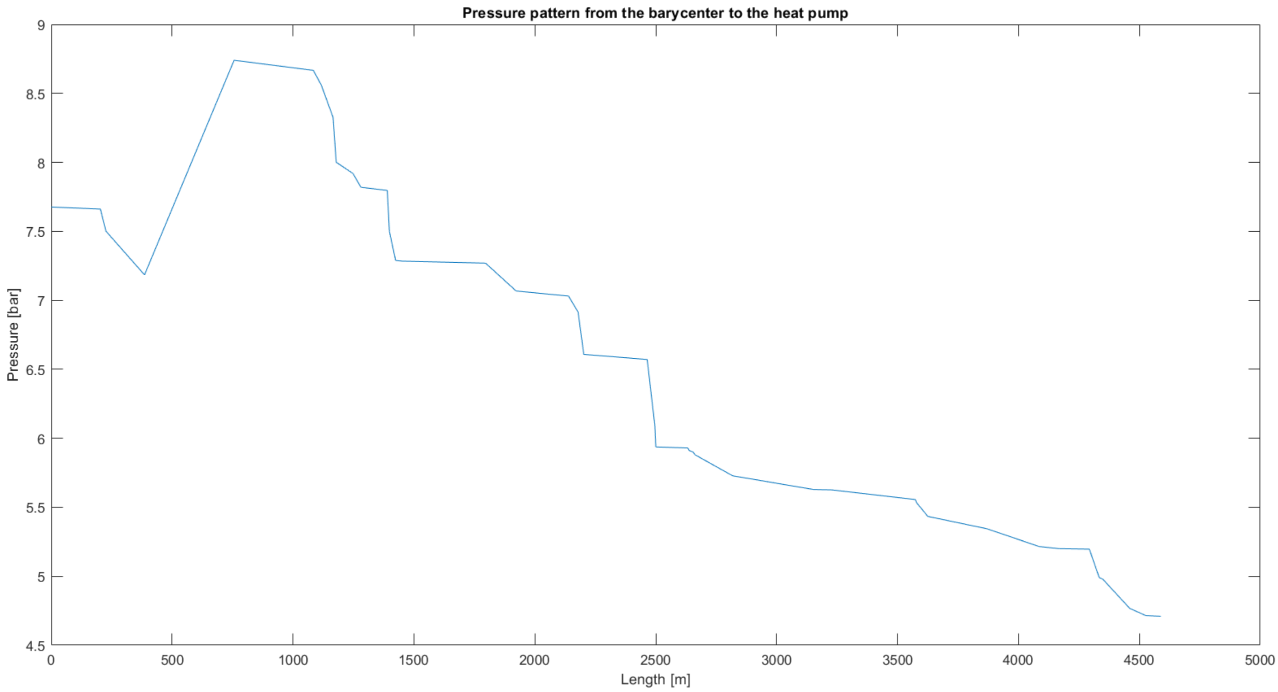

Figure 4.36: Pressure evolution along one of the return paths

4.4 Simulation campaign main results

The system was studied in the following configurations:

- Centralized production of energy;
- Distributed production of energy;
- Distributed production of energy with optimized HP position;
- Distributed production of energy with optimized HP position and low insulated pipes;

The main results are shown in Table 4.14. It is possible to note how the choice of the distributed production brings great savings into the cost of the network as well as a lower thermal loss if compared to the other solutions with the same value of thermal transmittance. The optimized configuration presents a cost almost halved respect to the centralized production as well as half of the thermal losses. The use of low insulated pipes increases this term but the cost of the network and the pumping energy are greatly decreased, since the pipes are cheaper and the optimal velocity of the water in the ducts is lower.

For the configurations with optimized HP positions with well and low insulated tubes the system behaviour at partial loads was analyzed. The thermal losses remained almost the same at partial loads with the percentage increase. The following table 4.15 presents the main results.

Configuration	Heat Loss [MW]	Average diameter [m]	Pipe Cost [M]	Pumping Cost [M]	Total Cost [M]
Centralized production	1,2	0,512	66,1	21,6	87,6
Distributed production	0,6	0,275	26,6	21,5	48,1
Optimized HP positions	0,7	0,313	31,4	13,5	44,9
OHPP low insulated pipes	3,7	0,331	18,4	10,8	29,2

Table 4.14: Simulation campaign main results

Power required [MW]	Percentage heat loss for well insulated pipes	Percentage heat loss for low insulated pipes
220	0,33	1,7
183	0,40	2,1
146	0,50	2,5
110	0.67	3,4

Table 4.15: Partial load analysis

In order to manage the pressure drop in the network and to reduce significantly the electrical consumption the installation of multiple booster pumping stations is necessary. In the case of distributed production of energy with optimized HP positions, with both well insulated and low insulated pipes, the optimization of the BPS was performed. In the first case, 26 positions require pumps installation, 13 on the supply side and 13 on the return one. The total installed power was of approximately 3.3 MW. The optimized placement of the hydraulic machines allowed a reduction of 45.6%, from 28 MW to 16,2 MW, of the global power installed.
The same operation was done in the case of low insulated pipes. Because of the lower velocity - 3.5 m/s - the pressure drop was smaller as well as the number of the booster pumping stations. In fact it was sufficient to install only 18 elements, 8 on the supply side and 10 on the return one. The total installed power along the network is of 1.1 MW. Again the saving in electrical consumption was remarkable and the global power request felt from 24 MW to approximately 14 MW: a reduction of 42% was achieved. Still the optimized HP position configuration with low insulated pipes seems to

	Initial power required [MW]	Optimized power required [MW]	Number of booster pumping stations
Well insulated pipes	28	16	26
Low insulated pipes	24	14	18

Table 4.16: Optimized BPS results

be the more convenient choice. The initial installation cost is much lower compared to the previous cases and the thermal loss is still contained. Also the pressure drop is reduced and the booster pumping stations number can be decreased from 26 to 18 units along the grid.

5. Conclusions and Perspective

In this Master thesis a model able to represent a district cooling network for the city of Torino was developed. The study is based on data of the exiting district heating network, a complex grid which presents several loops. To simplify the design operation, the multi-loops system was modified obtaining a tree-shaped network. The program evaluates the temperatures and pressures of every node in the network and the economical effort needed to cover the expenses of the network which comprises the pipes cost and the price of the electricity consumed by the pumps actualized to the construction year.

The main goal of the optimization process was to identify the minimum cost exploring a wide field of possible configurations.

The ideal nominal velocity was estimated for all the considered options. The model was then run with different heat pumps and booster pumping stations positions following the genetic algorithm criteria, a process based on the phenomenon of the natural evolution of the species, able to find the local minimum of an objective function.

The two main configurations studied were centralized and distributed production of energy. The latter most remarkable advantage consists of having a most uniform distribution of the flow rate in the system that lead to a strong reduction of the pipes size and thus of the initial investment.

The use of relatively low insulated pipes was also explored. The results obtained with this new typology of tubes presented several advantages for both the cost of the network and the complexity of the system (the number of booster pumping station required is lower).

To better understand the system strengths and weakness there are still many topics that can be developed at a more in-depth level. First a more complete analysis of the User is necessary. The system is supposed to supply only the residential part of the total demand. The direct consequence is that the system works only during the summer period but considering also other kinds of users, such as hospitals, universities, banks, the working period can be easily stretched to the entire year with an important gain in profitable hours, energy produced and therefore the incoming derived from the sale of the energy.

The comparison between the centralized and distributed production of energy cannot be limited just to the construction and installation costs but it is fundamental to consider the primary energy requested to provide the cold water flow. In the centralized production case there is the possibility to use directly the waste heat coming from the co-generation plants installing big adsorption heat pumps at the end of the thermodynamic cycle. In case of not simultaneous heat and cold demand it is convenient not to build another grid but, contrarily, to supply the different flows in different moments using the same transportation system without sustaining an important investment cost.

On the other hand, the energy request by the heat pumps in the distributed production configuration can be supplied by renewable energy field. The advantages of this solution are an important reduction of the use of fossil fuels, integration of a significant quote of renewable, such as photo-voltaic solar panels or wind turbines, in the energy mix. Still it is very attractive to investigate possible solution to couple the district heating and cooling system adjusting the heat pumps working conditions.

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A. Appendix

A.0.1 Appendix A: Cost of the pipes

Diameter [mm]	DH pipes [€/m]	DC pipes[€/m]
25	33,7	12,9
32	35,4	13,0
40	35,5	13,4
50	37,9	13,6
65	41,0	15,9
80	45,7	18,3
100	52,8	21,8
125	60,4	27,9
150	67,0	34,2
200	86,2	50,2
250	111,7	67,4
300	135,0	83,8
350	160,3	98,1
400	185,8	113,7
450	211,0	131,9
500	269,6	147,8
600	339,1	175,6
700	417,7	219,8
800	484,2	260,1

Table A.1: Pipe Price Catalogue [23]