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Methodology for the exploitation of a data center waste heat: system for heating buildings

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0 INTRODUCTION

In the last decade there has been an exponential growth in the number and size of Data Centers (DC) around the world, and this growth is likely to increase. This is due to the spreading of internet and informatics resources, such as data processing and data storage, in every working field and in everyday life.

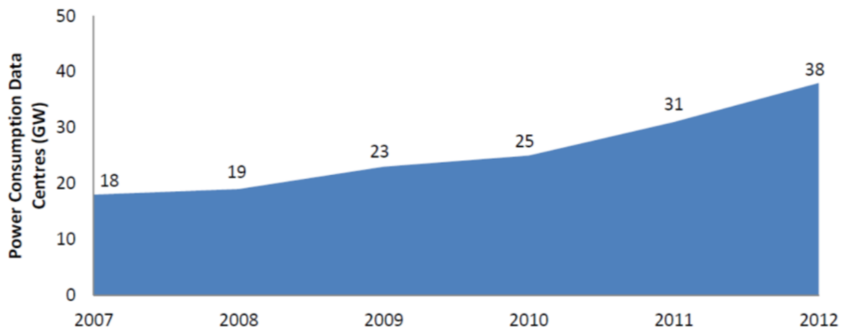


Figure 1-Data center energy consumption growth from 2007 to 2012.

The need of certain performances 24hours/7days makes DC great electricity eaters. It has been calculated that DC are responsible of about 1.1-1.5% of the world's electricity demand [1] with an yearly estimated increase of around 15-20% [2].

This huge amount of electricity is mainly used for two reasons: to power all the IT equipment and to power the cooling equipment. Cooling system is needed to remove the heat generated by the servers and keep the environment at the set point temperature. Once electricity is absorbed, it is almost completely converted into heat [3]which, however, is usually dispersed in the environment creating heat islands.

Initially, as a first solution to this problems, some have tried to find ways to reduce directly the electrical power of servers or chillers. But this effort alone is not enough. Indeed, in order to reach the definition of a true green DC, no source of energy, incoming or outgoing, should be neglected. This applies to the production of energy from renewable sources but also to ensure that no source of heat is wasted.

Considering that, this thesis aims to study a way to re-use the heat produced by a small-sized DC, using it as the primary heat source within a low-temperature district heating grid in the Stockach district of Stuttgart.

1 POTENTIAL OF DATA CENTER FOR HEAT SUPPLY OF CITY QUARTER

A DC is definitely a big consumer of electricity, but also a big heat producer. If not wasted, this heat, can represent on a district scale a stable source of energy to power the district heating network [4], as it is already the case with the waste heat produced by industries.
Before entering the subject it is necessary to clarify in general what a DC is, why it produces waste heat and how this can be used.

1.1 Data Center

In this paragraph some general topics on DC are discussed. Starting from the analysis of what it is, how many categories of them there are, how it is possible to determine its size and location up to a few hints about the corresponding cooling methods.

1.1.1 Definition of Data Center

A Data Center (DC) is a facility that contains all the IT equipment (as shown in *Figure 2*) that companies and organizations use every day to process, organize, exchange and store huge amount of data and information [5].

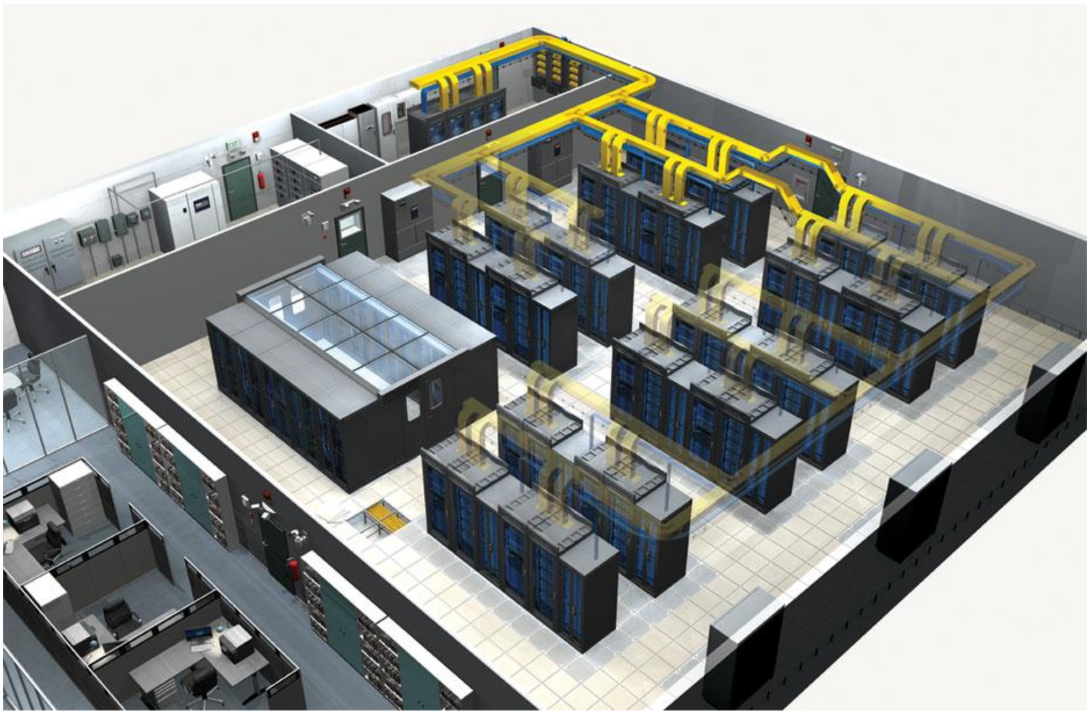


Figure 2- Tipical Data center scheme (http://www.prasa-pl.com)

Data Centers today represent the beating heart of business because they provide all the technical-scientific advice to the various structures in the field of process digitization, electronic data processing, definition of the calculation networks, design and / or implementation of information systems, including all support applications in addition to integration and interfacing with systems outside the organization.

To support the growing demand for systems and solutions, facilities have literally been populated with servers of different capacities and different configurations depending on the activities covered: this is why a synonym of DC is server farm.

A DC, depending on the business needs, can occupy few square meters or even get to occupy an entire building.

Although every DC design depends on many factors, that makes it unique, there are four minimum services that has to be included to call it properly DC and those are: the facility, an It equipment, a support infrastructure and an operative staff [6].

That is why a DC cannot be described as a single element but has to be seen as a conglomeration of elements.

Facility – it represent the usable space, otherwise said "white space" in presence of raised floor. It should be measured in square meters or square feet. The space must be designed to accommodate all IT equipment, the cooling system and any staff offices.

The structure must be safe, supervised by staff, and accessible 24/24.

IT equipment – this term include all the Information and Communication Technology such as racks (shown in *Figure 3*), cabling, servers, storage, management systems and network gear. As well as a variety of information security elements, such as firewalls.

Figure 3- Picture of the two front of a rack (http://www.servernetworkrack.com)

Support infrastructure – this refers to all the equipment that contributes to support and sub stain all the DC operations. Some of this components for supporting infrastructure include:

- **Uninterruptible Power Sources (UPS)** – batteries, generators and redundant power sources.
- **Environmental Control** – computer room air conditioners (CRAC or CRAH), heating, ventilation, and air conditioning systems, and exhaust systems.
- **Physical Security Systems** – biometrics and video surveillance systems.

Operations staff – those people who assure and monitor operations and maintain IT and infrastructural equipment perfectly working.

Thanks to stable and redundant connectivity systems, i.e. through a multiple configuration that ensures operational continuity in case of failures or anomalies of one or more systems, the DCs are able to always guarantee maximum functionality.
Each DC hosts several sets of routers and switches designed and configured to transmit data traffic bidirectionally between servers and the rest of the world.

1.1.2 Typologies

As previously mentioned, each data center is designed to meet specific company needs. Nevertheless it is however possible to identify categories to group these structures.
The first and most important distinction is between private and out-sourced data centers.
In fact, a company may decide to own its DC or make use of external structures that sell these services according to customer requests (outsourced).
Initially the private DCs were the most widespread because they were considered safer.
Today, however, the world of outsourced is rapidly growing (as shown in *Figure 4*), because of the economical situation. Indeed, this kind of service is very advantageous for the customer, who no longer has to face the DC operational costs and can use more efficient infrastructure and can have access to more server, storage or computing capacity on demand.

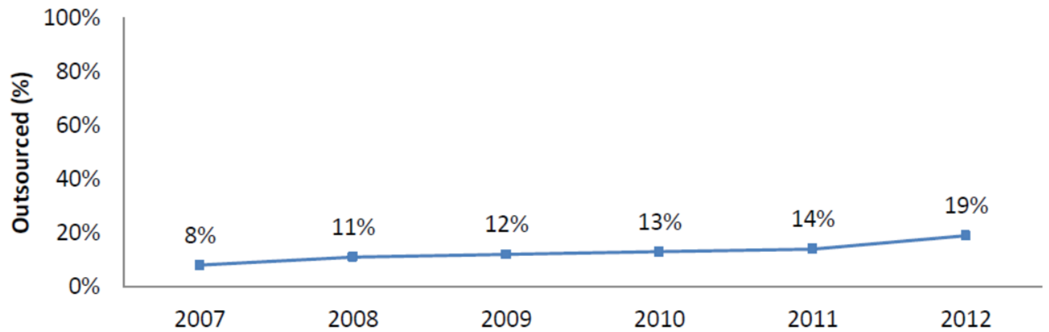


Figure 4-Graph showing the growth over the years of the outsourced DCs (http://www.renewit-project.eu)

There are various levels of outsourced DC. Some providers manage customer-owned or leased infrastructure on the customer's premises, including on-site technical support as needed.

This is the reason why different types of outsourced were born, depending on the service provided [7]. These can be distinguished in: colocation providers, specialized, content-based, cloud, cache and network-neutral DC.

- **colocation (colo)** is a data center facility in which a company can rent space for servers and other computing hardware. Typically, a colo provides the building, cooling, power, bandwidth and physical security while the customer provides servers and storage. Space in the facility is often leased by the rack, cabinet, cage or room. Many colos have extended their offerings to include managed services that support their customers' business initiatives.
- **specialized DCs** host high-frequency trading, supercomputers, etc ; specially created for a purpose.
- **content-based DCs** share information and content like Google, Facebook, etc.
- **cloud DCs** in which a service provider offers online services, such as virtual machines, applications or storage, available to the general public over the internet. Public cloud services may be free or offered on a pay-per-usage model. Examples are Amazon, Rackspace, Microsoft Azure, etc.
- **cache DCs** in which cache servers list the results of common queries for faster access.
- **Network-neutral DCs** (or **carrier-neutral data center**) are data centers which allow interconnection between multiple telecommunication carriers and/or colocation providers.

In 2005, the American National Standards Institute (ANSI) and the Telecommunications Industry Association (TIA) published guidelines for the construction of a data center, the "Telecommunications Infrastructure Standard for Data Centers" called TIA-942.
In general, TIA-942 provides information on the definition of spaces and the design of a DC. These guidelines, however, also include a classification of data centers based on 4 levels of reliability and security of service, called TIER, where the first is the basic one and the last one is the most reliable [8].

- **Tier 1**: requirements are generally utilized by small businesses and feature:

  99.671% Uptime
  no redundancy
  28.8 Hours of downtime per year.

- **Tier 2:**

  99.749% Uptime

  Partial redundancy in power and cooling

  Experience 22 hours of downtime per year.

- **Tier 3**:specifications are utilized by larger businesses and feature:

  99.982% uptime

  N+1 fault tolerant providing at least 72 hour power outage protection

  No more than 1.6 hours of downtime per year

- **Tier 4:** data center certification typically serve enterprise corporations and provide the following:

  99.995% uptime per year

  2N+1 fully redundant infrastructure (the main difference between tier 3 and tier 4 data centers)

  96 hour power outage protection

  26.3 minutes of annual downtime.

So in conclusion we can say that there are really many ways to classify a data center. Indeed, very often a DC can group in it many of the definitions seen above.

1.1.3 Size

When it comes to data centers it is always very difficult to define the size or density of this in an unequivocal way.

These difficulties derive from the fact that, as mentioned in the previous paragraph, a DC is made up of many different elements that work in symbiosis. For this reason it is not easily identifiable a metric that describes its size.

Over the years this ambiguity has led to the spread of an improper and misunderstood jargon among investors, owners, companies and consumers in general.

So what in a country is called "big" can be "small" in another.

The three most common ways used to describe the size of a data center are: the number of square meters of the white space, the maximum power consumption of the IT equipment or it can be expressed with the number of racks, specifying the density.

Each of these three methods, however, contains problems within it.

Defining the size of a DC through the unit of square meters does not allow to understand how much it is its computational power, even if it refers to the only compute space (the area occupied by the racks). To take into account this, it is also necessary to define the density or the power load of a rack.

The definition of an area parameter, however, can help to quantify the growth of this rapidly expanding industrial sector in recent years. The graph below (*Figure 5*) shows the growth of total white space in the world from 2007 to 2012.

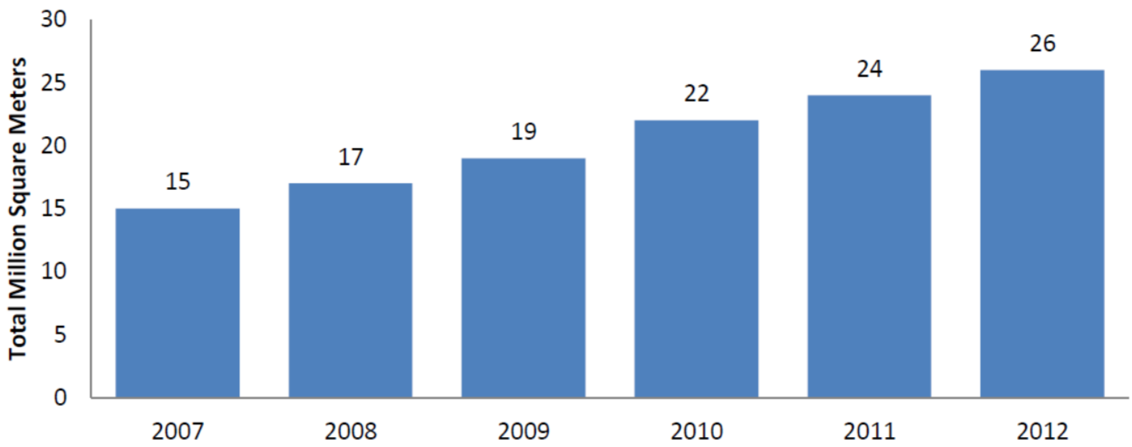


Figure 5-Growth of total white space in the world (http://www.renewit-project.eu)

while the graph below (*Figure 6*) shows that almost 50% of the total white space of all data centers has a size of less than 200 m^2.

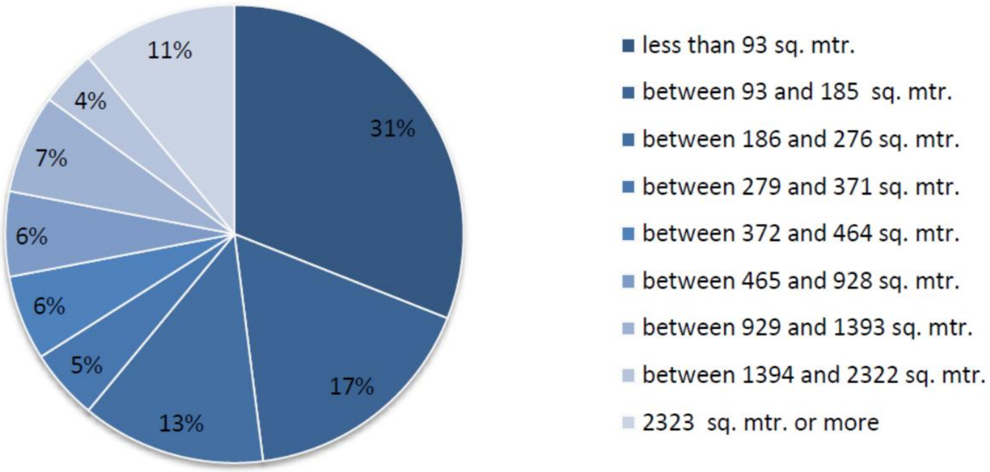


Figure 6-Size of total white space of all data centers in the world (http://www.renewit-project.eu)

Computational density of a rack is another parameter that in recent years is increasing a lot, just think that in 2009 the average density power per rack was 1.5 kW, in 2014 about 3 kW and now is around 6 kW and is still growing [9].

This is to say that, with the same area occupied by a rack, if the density changes also the size of the DC must change.

To solve this ambiguity of metrics, in 2014, the AFCOM Data Center Institute (DCI) created a guideline to standardize the set of data center facility size and density, in order to provide companies and owners a common language [10].

The DCI classification pass through the preliminary definition of some parameters like:

- Rack Area, that is the rack foot print, assumed 2.5 $m^2 \approx 25\ ft^2$
- Rack Yield, that is the racks total number
- Compute Space, that is the total racks area
- Rack density, that is the measured peak load (kW) for the rack
- Compute Space Density, that is the average density per rack measured across the facility compute space.

$$CSD = \frac{measured\ peak\ load}{Rack\ Yield}$$

In conclusion, the classes are grouped as follows:

DATA CENTER SIZE			
Size Metric	Rack Yield	Compute Space	
		SQFT (ft^2)	SQM (m^2)
Mega	>= 9,001	>= 225,001	>= 22,501
Massive	3,001 – 9,000	75,001 – 225,000	7,501 – 22,500
Large	801 – 3,000	20,001 – 75,000	2,001 – 7,500
Medium	201 – 800	5,001 – 20,000	501 – 2,000
Small	11 – 200	251 – 5,000	26 – 500
Mini	1 – 10	1 – 250	1 – 25

Figure 7-AFCOM Data center size groups (https://www.afcom.com)

DATA CENTER DENSITY		
Density Metric	Per Rack	Compute Space
Extreme	>= 16kW	>= 16kW
High	9 – 15 kW	9 – 15 kW
Medium	5 – 8 kW	5 – 8 kW
Low	0 – 4 kW	0 – 4 kW

Figure 8-AFCOM Data center density groups (https://www.afcom.com)

Thanks to this table it is possible not only to create categories but also to distinguish between operating conditions and project conditions.

For example: "*a facility designed for a Rack Yield of 100 racks, at 3.5kW per rack is a SMALL sized facility designed for LOW Density. However, the current operational deployment can reports 52 Racks with an Average Measured Peak kW Load per Rack of 6kW. The resulting Density should be reported as A SMALL Sized data center designed for LOW Density, currently operating at MEDIUM Density at 52% of Rack Yield*" [11].

However, this method of defining size also has some drawbacks. For example, this requires a large amount of information that is often not readily available.

For this reason, very often and also in the case of this project, we resort to the simple indication of the size according to the IT load, following this classification [12]:

- **ROOM SERVER** < 50kW
- **VERY SMALL DATA CENTER** 50-250 kW
- **SMALL DATA CENTER** 250-1000 kW
- **MEDIUM DATA CENTER** 1-2 MW
- **LARGE DATA CENTER** 2-10 MW
- **VERY LARGE DATA CENTER** > 10 MW

This is not a very accurate method but it allows us to immediately understand the entity of the structure we are considering.

1.1.4 Placement strategy

DC is the brain of a company. Indeed, this contains and processes all the information, reserved or not, that a company uses every day.
Having said that, it is immediately clear that a DC first of all must be located in a safe position either in the headquarter of the company or it can be externally located, everywhere, with remote access.
The choice of a DC location is very complex.
It is necessary to take into account many aspects.
Certainly, immediately after the security of the area and the facility, a discriminating element is the availability and the cost of electric power. As the DC is equipped with many devices that consume large amounts of electric power, electricity will be one of the biggest cost items.
Furthermore, the fact of not having to expand the existing electricity grid already allows a significant savings item.
Other factors influencing this decision are: the climatic conditions of the place and the possible risk of natural disasters, as the temporary interruption of the service can damage the company; construction costs and quality, construction cost is often one of the highest cost items; access to major airports and highways, to facilitate easy access to the site in case of emergency; quality of life, to attract and retain future employees; proximity to major costumers and markets; presence of local and state economic development incentives and taxation level; presence of suppliers around the area and availability of telecommunications infrastructure, etc [13].
The data center site selection process begins with a set of project assumptions from the company. These assumptions include geography, capital investment, facility size, utility requirements, real estate requirements, and telecommunications redundancy, among other factors.
Once a geographical area of interest, that contains a certain number of alternatives, has been identified a quantitative analysis is carried out.
The quantitative analysis compares each site under consideration with regard to energy costs, water rates, permitting fees, construction expenses, tax rates, labor quality and costs, and any other factors that are relevant and pertinent to the particular project's objectives. In addition, population numbers, educational levels, airport quality, climate, cost of living, crime rates, health care, commute times, and more are examined.
Once the number of locations has been narrowed down, personal visits are made to each location in order to meet with key local and state governmental authorities and economic development representatives. Initial negotiations begin regarding real estate acquisition, utility contracts, permitting

timeline and costs, and economic development incentives issues are addressed at this stage. This allows the project team to get to the choice of two or three potential location options.
In the end a qualitative analysis takes place. The political stability and politic figures are studied. But, it is the intuition that leads the final decision.
Looking at the European situation, in 2018, we can see that the majority of DCs is located in the centre of Europe.

Figure 9-Overview of all DC in Europe in 2018 (http://www.datacentermap.com)

There are four particular "attractive" cities for the DC market, together they detained 678000 m^2 di white space in 2013.

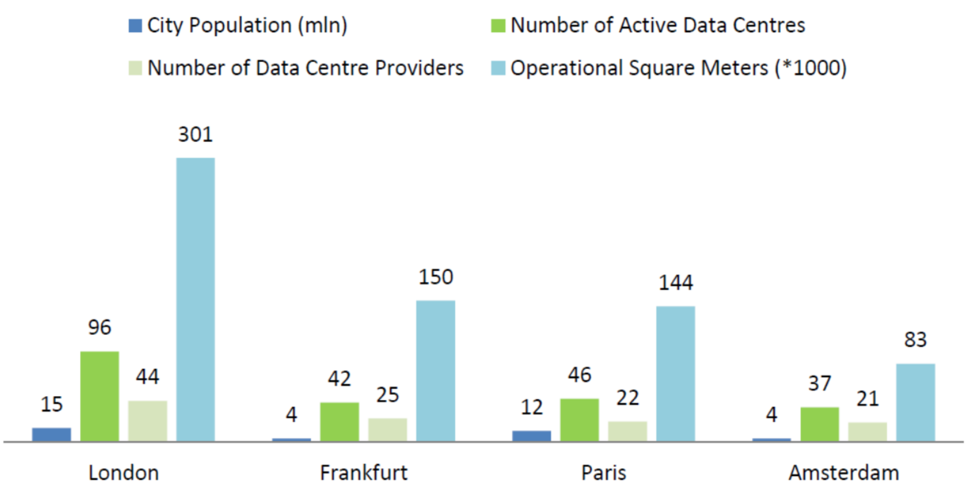


Figure 10- Some data about the 4 cities with the higest numer of DC in Europe (http://www.renewit-project.eu)

This is surely due to the fact that in these big cities the majority of the commercial activities of Europe take place, consequently they are well connected with the various parts of both Europe and the world. In addition also the climatic conditions still allow a good efficiency for systems such as free cooling. In short, they are equipped with most of the features that have been listed previously.
In the last few years, however, the most favored locations are those in the Scandinavian area. Norway, Sweden, Finland and Denmark present the ideal climate to minimize the costs associated with cooling systems. They are safe and politically very stable countries. Although up until a few years ago the big problem was represented by the electricity grid, it is no longer the case. Rather it presents itself as a very reliable network, which uses renewable and low-cost energy.

1.1.5 Cooling system technologies

The only purpose of data center cooling technology is to maintain suitable environmental conditions for the IT equipment. IT components are big electricity consumers and they left behind heat as waste of this process. If this heat remains inside the DC facility it increase the environmental temperature till the point that it damages and then destroys all the servers or electronic devices.
For this reason remove the heat , so cooling the DC facility, is fundamental.
In addition to temperature, humidity and contamination can affect IT equipment. Humidity and contamination only affect IT when it is exposed to unacceptable conditions for a long period of time. About this, temperature guidelines for data centers have been provided by The American Society of Heating and Air-Conditioning Engineers (ASHRAE).

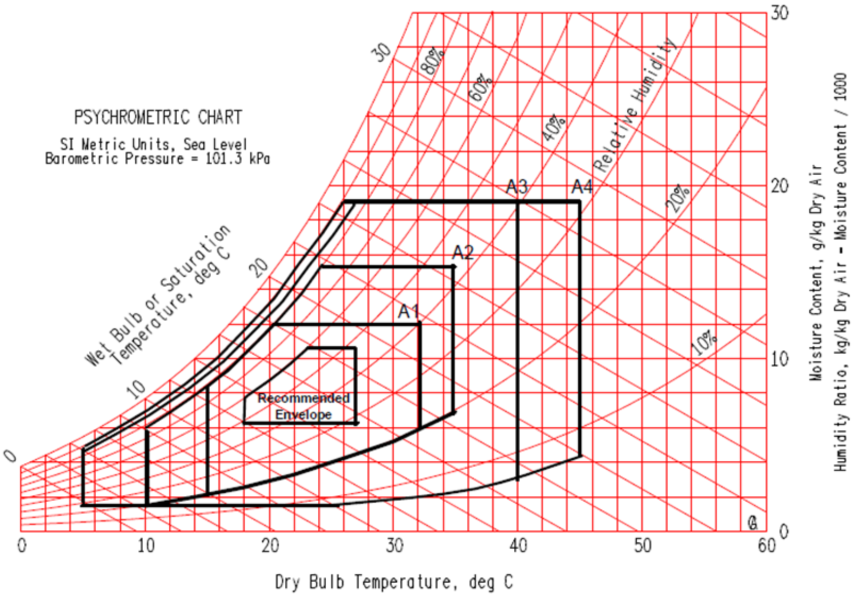


Figure 11-ASHRAE Psychometric chart: classes for Data centers

Committee TC9.9 guideline recommends that the device inlet be between 18-27°C and 20-80% relative humidity to meet the manufacturer’s established criteria.

Four classes (*Figure 11*) have been created that break down the specific requirements according to the operations to be performed in the DC.
Starting from Class A1, typically a DC that has to perform critical operations so with strict parameters to follow, ending in Class A4 that are all the DC like office, laboratory or IT spaces that perform normal or simple operations.
Uptime Institute further recommends that the upper limit be reduced to 25°C to allow for upsets, variable conditions in operation, or to compensate for errors inherent in temperature sensors and/or controls systems [14].
Therefore, the main purpose of the cooling techniques is to move the heat generated by the servers to the external environment. Everyone can easily understand that this heat movement will require the consumption of additional energy to the one already consumed by the ITs themselves. Depending on the cooling technology, it will change not only the type of layout of the DC facility, but it will also change the way in which it is possible to intercept and derive waste heat in order to reuse it and not disperse it in the environment.
Currently there are many DC cooling technological solutions, but it is possible to group them in two main families: the air-cooled systems and the water-cooled systems.

- Air-cooled systems: this type is certainly the most common and widespread in existing DCs. In this case the hot air produced by the servers is collected and channeled into the computer room air conditioner (CRAC), which thanks to chillers or cooling towers, cools it again and conveys it to the servers, expelling heat outside (*Figure 12*).

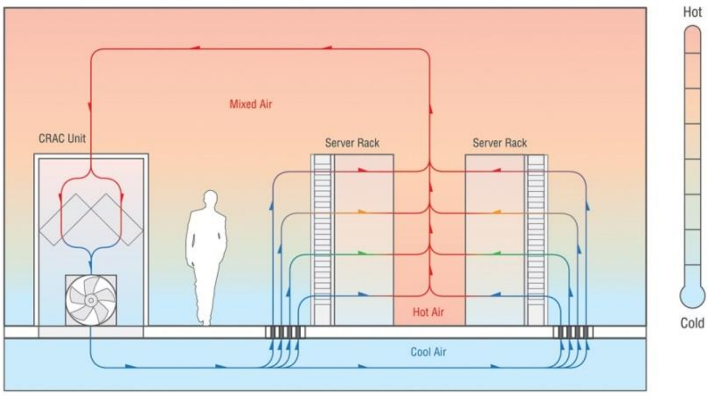


Figure 12- Tipical air cooled system diagram (https://journal.uptimeinstitute.com/a-look-at-data-center-cooling-technologies/)

The air characteristic of providing some degree of separation between hot and cool air can be for sure a vantage but also a disadvantage in the middle part, where they are mixed together.

That is because the commonly solution of the raised floor presents the inconvenient of being inefficient in the upper part of the racks, where the air temperature is not at set point level but higher. Indeed, temperature difference between the bottom and top of the racks can be more than ten degrees.

As said by K.Ebrahimi et al. [15]: " *The airflow recirculation, created by the turbulent mixing of hot and cold airs over the racks, was identified as the major cooling problem in raised floor data center designs*."

To solve this inconvenience and improve the efficiency of the system, some designs involve the formation of warm corridors and cold corridors to further isolate the hot air from the cold air (*Figure 13*). The server's air inlets face the cold aisle and the drain is directed towards a warm corridor. Sometimes, if necessary, to guarantee better insulation, there may be real separation walls between the rack units and the ceiling. Certainly, this kind of solution can provide a great efficiency but, of course, they also are much more expensive.

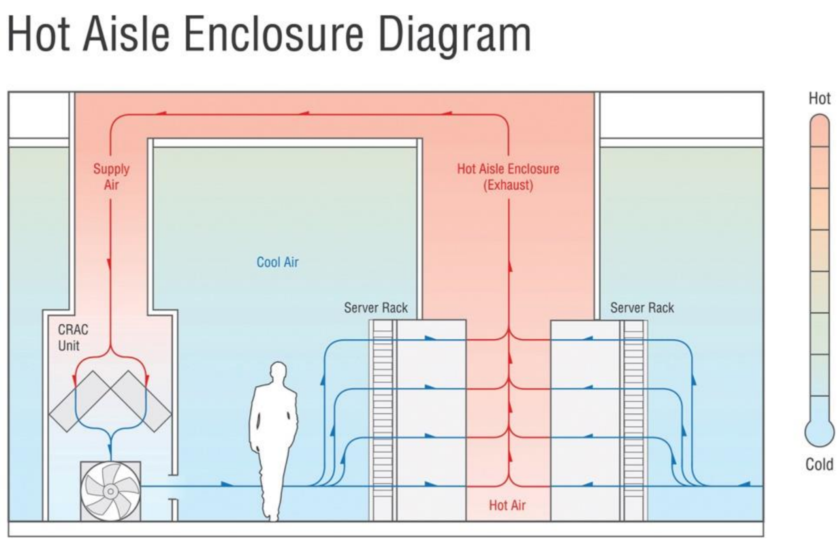


Figure 13- Hot aisle enclosure scheme(https://journal.uptimeinstitute.com/a-look-at-data-center-cooling-technologies)

- Liquid-cooled systems: this kind of solution is used when the rack's density is high and traditional air cooled systems are not enough. Liquids are able to better absorb and carry out the heat, so liquids are more efficient than air.

In this case, the refrigerating unit can be directly focused on the servers instead of the white space, in order to increase the efficiency of the system even further.

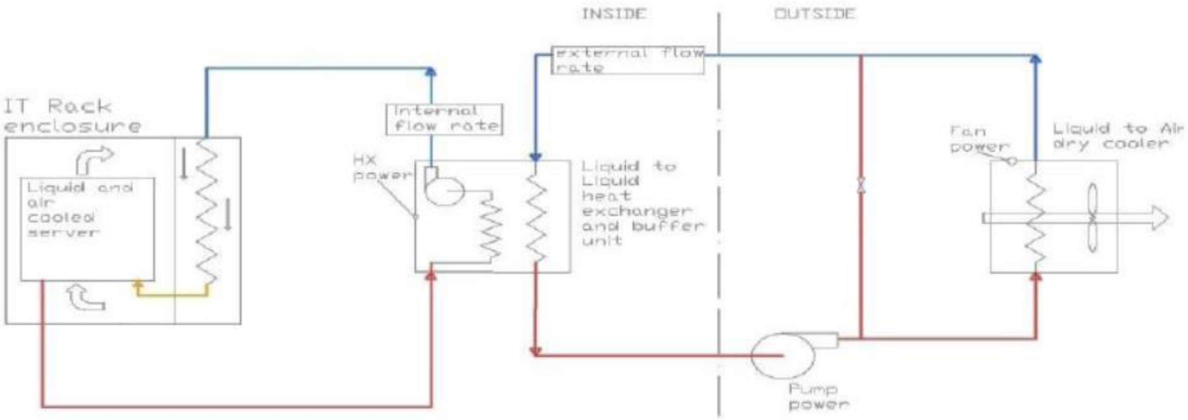


Figure 14-Scheme of a liquid cooled system (Capezzoli et al., 2015, page 488)

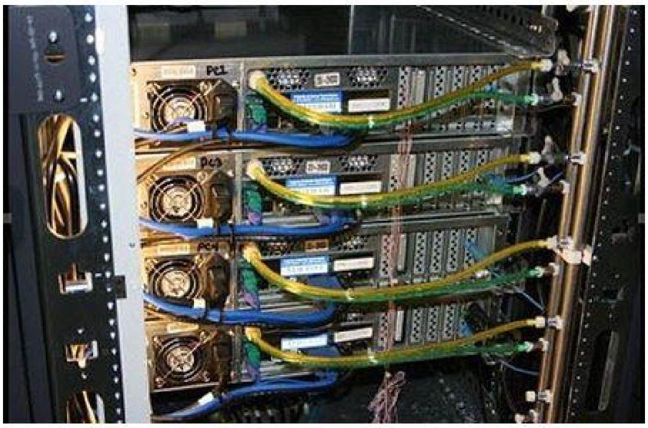


Figure 15- Direct to the chip cooling system (http://www.tomsitpro.com)

Thus, the refrigerant liquid can feed the CRAH unit (computer room air handler) or better, in server cooling systems, a non-conductive liquid can flows or be sprayed through the server unit or even the IT components can be entirely immersed on it.
These solutions have the advantage of producing a higher temperature waste heat than air solutions does and they also increase processor performance by the 33% [16].
In case of servers completely immersed in the cooling liquid, the performances obtained are even better and it is possible to cool very high density racks. Compared to traditional liquid systems, these

provide a greater uniformity of temperature distribution and can solve the problem of the great demand for pumping power required in other cases.

In addition the waste heat from this type of systems is really high quality due to its high temperature.

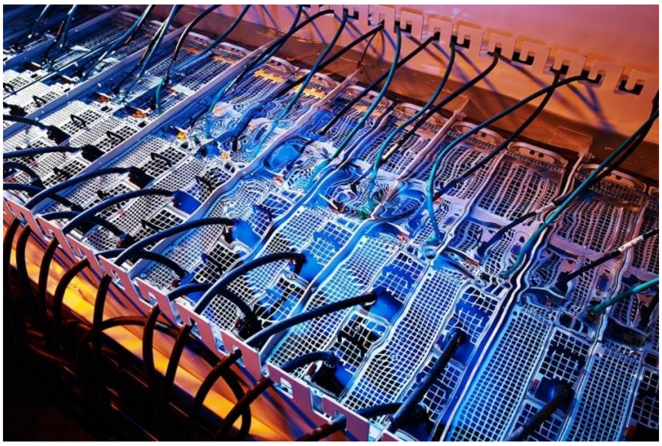


Figure 16- Liquid immersion system (https://www.grcooling.com)

Although not mentioned in the two previous categories we can say there is a third way to cool a data center. This system is often flanked by the main cooling system to reduce consumption and therefore costs. The system we are discussing is the so-called "free cooling".

The word free derives from the fact that we use fresh air or water coming from the external environment that, properly treated and filtered, is directly conveyed into the rack room. In this way what is obtained is a true free cooling of the racks.

There are several kind of free cooling systems. They can be air side or water side depending on the fluid they use. But they can also be directly operated (*Figure 17*), if the fluid is not treated before being conveyed to the racks, or contrarily with indirect operation.

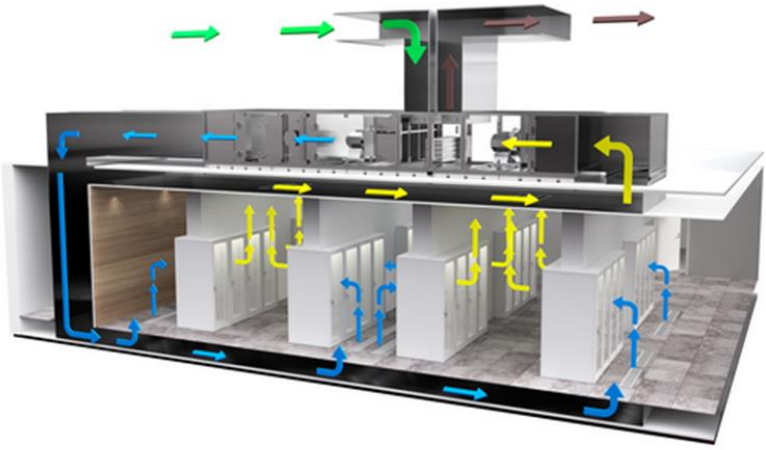


Figure 17-Direct airside economizer (https://www.systemair.com)

This process, depending on the location, allows to save from 5.4% to 7.9% of the electricity otherwise requested by the CRAC / H. [3].
This system is widespread in the countries of central and northern Europe due to the climatic conditions, that make it usable for more than 50% of the year, but also because ASHRAE has recently increased the allowable temperatures for DCs.

1.2 Methodologies for the reuse of waste heat

As mentioned in the previous chapters, IT equipment are powered by electricity that is largely transformed into thermal power.
Although for decades already several techniques are in place to capture and reuse waste heat, for example the one deriving from industrial processes, it cannot be said that the same was true for the DC world.
Surely one of the causes is linked to the fact that DC world is relatively young and still in full expansion, another cause can be related to the fact that the heat produced is low quality, because it is always below 90 degrees.
However, the two biggest problems related to the development of this sector are the impossibility of transporting this heat too far, so it is necessary that the demand is in the neighborhood, and without a doubt the economic aspect, linked to the need to profit both the DC owner and the energy company.
To date the research of techniques for the reuse of waste heat in DC is increasingly urgent, in fact as mentioned by K.Ebrahimi et al. [15]: "*a rack with a 0.65 m^2 footprint has heat dissipation requirements as high as 30 kW, or roughly 30 times higher than the amount of energy dissipated by a typical rack with the same footprint in 1990*".
To study the most appropriate reuse strategy it is therefore essential to have as much information as possible about the DC, but above all, to know the thermal loads and the temperature of waste heat, that depends on the cooling system type.
The cooling systems seen in the previous paragraph are strictly linked to the type of heat reuse we want to choose.
In fact, in air-cooled systems the heat can be recovered at temperatures between 25 and 45 degrees, just before the airflow returns to the CRAC.
While for liquid-cooled systems these temperatures rise to 50-70 degrees, if the heat is captured near the CPU. However, if the liquid cooling is two-phase, even higher sampling temperatures can be reached, i.e. between 70-80 degrees.
This shows how the choice of cooling system influences the DC caracteristics in many aspects.

There are many ways to recover waste heat [15], [3], but for the temperature ranges produced by DC it is possible to identify eight of them. They are: space and water heating of the DC building or other buildings through the district heating; to heat the water of the Rankine cycle of a power plant; absorption cooling; to produce electricity through the organic Rankine cycle; to generate electricity with the piezoelectric and/or thermoelectric generation; the desalinization of water and for biomass processing.

Own consumption	External processes
• Space heating and floor heating • Domestic hot water • Melting snow • Producing cooling energy through absorption refrigeration	• Drying biomass • Preheating water in power plants • District heating • Water desalination • Electricity production (Organic Rankine cycle, Piezoelectricity, thermoelectric generator)

Figure 18-Review of waste heat recovery systems (M.Wahlroos et al., 2018, page 1101)

Among all these recovery methods, the most widespread are those for space heating and for the hot water production.

The heat recovered, in fact, can heat from the offices of the DC building to a real neighborhood close to the DC. All this depends, first of all, on the size of the DC but also on the location in which it is located.

If you want to distribute the heat in an area outside the DC, district heating (DH) is an ideal solution, especially if it works at low temperatures.

So the heat can be used to feed an already existing high temperature district heating (HTDH) network boosting the temperature with heat pumps, or it can be used as a source of a low temperature micro-grid or even used to preheat the domestic hot water that will then be brought to temperature with the help of micro heat pumps [17], [18].

Generally, the heat is extracted in the most suitable location according to the type of cooling system. Then it passes through a heat exchanger that transforms it into hot water that can subsequently be used directly to feed the district heating system or it can be previously overheated by a heat pump.

The advantages deriving from the reuse of the excess heat are not only ecological, avoiding the formation of heat islands and reducing the production of heat from non-renewable sources, but also economical.

If, from a certain point of view, the heat recovery equipment represents an increase of the operating and maintenance costs of the DC, especially in presence of a heat pump that consumes electricity. On the other hand waste heat can be sold, representing a source of direct gain, or used internally, going to eliminate the costs due to the production of space heating and domestic hot water.

The use of this heat is an advantage also from the DH operators point of view. In fact, this reduces the operating costs of the system, decreasing the production of CHP (Central Heat Pump) plants, but also reducing the CO_2 emissions of DH production, where it works with fossil fuels.

The real barrier that hinders the excess heat market is the lack of a real heat market. Investment and business models are not yet readily available as well as state incentives, which are few and unclear. This is due to the fact that among the operators of the DC (private) and DH (private / public) there are very different and difficult to reconcile market logics. If on one hand the owner of a DC can aspire to a very rapid expansion of his activity, and therefore wants to invest with very short return times, the same cannot be said in the case of DH operators. Indeed, the DC market is very fluid and fluctuating while that of supply companies is more stable.

The owner of the DC has an interest in having a heat sales price covering the initial investment and operating costs as soon as possible. While the DH operator wants to buy the excess heat at the lowest possible cost and wants to make sure that the heat production, then the IT load, is as stable and constant over time.

In addition, for reasons of security and reliability, DC operators seek as much as possible to limit the access of the outside world to information regarding their business.

In conclusion we can say that reconciling these two worlds is not easy and each specific case must be addressed individually and in the most transparent way to solve the critical issues and reach different kind of goals.

1.3 Low temperature district heating (LTDH)

Systems such as district heating, and in particular low-temperature ones, aim to reduce the production of polluting gases through the more efficient use of combusted fossil fuels.

In addition, the district heating network is able to form a real energy ring to which many sources can engage. This represents a great advantage because it also allows new production sources that use renewable energy or waste heat to go to implement, even in successive phases, this ring (*Figure 19 a,b*).

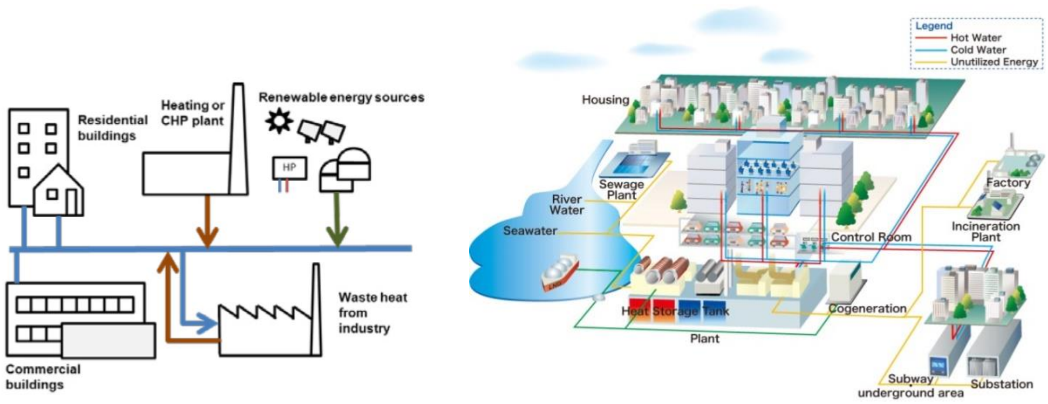


Figure 19 a,b- District heating chain (D. Schmidt et al., 2017, page 27 and http://www.jdhc.or.jp)

These goals have become necessary as the building sector is responsible for around a third of total energy consumption in the world [19].

1.3.1 District heating

District heating is a heat production and distribution system based on three main elements: the production plants, the supply network and a return network for the heat transfer fluid.
There are different types of production plants with different production techniques. The heat can be produced by thermoelectric cogenerative power plants powered by natural gas, fossil fuels, biomass or even by waste-to-energy treatment.
In recent years, production techniques have also been added to exploit renewable energy sources such as geothermal energy and solar heating, as well as free heat sources deriving from industrial process or Data Centers.
The distribution grid consists of single or double, buried insulated pipes (*Figure 20*) that distribute the heat transfer fluid from the production plant up to the heat exchangers located in each building to supply the plant terminals such as radiators, fan coils or raised floors.

Figure 20- Underground installation of insulated district heating pipes (http://www.generationparknorwich.com)

Water is generally used as the main heat transfer fluid but, in older plants, it is also possible to find the water vapor.
Indeed, steam was the first fluid used to transport heat in so-called first generation district heating. Only later, with the introduction of the second generation DH, the fluid used was pressurized water at temperatures above 100 degrees, so as to ensure the operation of the old radiators operating at 80-90 degrees.
More recently, since the 1970s, district heating systems have been introduced with supply temperatures below 100 degrees.

However, this type of network still presents a low efficiency due to the high percentage of thermal losses, around 10-30% [20], but also related to the need of use performative materials for the pipes that can manage with such high temperatures.
Nevertheless, this system also presents multiple advantages.
District heating is configured as a solution with a lower environmental impact, thanks to a single central unit or set of production systems, it is possible to supply a large number of users, avoiding the installation of the boilers in each of them. In this way resources are used more efficiently and the production of pollutants dispersed in the atmosphere is greatly reduced.
Even from the user's point of view, district heating brings many advantages. This is easily adjustable directly from the accommodation, cheap and safe.
With the installation of a single thermal power plant, usually located in the basement of the building, all operating and maintenance costs, related to the old boilers that directly produced inside home, are reduced. Not to mention the fact that all risks related to explosions and gas intoxications are drastically reduced or cancelled.

1.3.2 LTDH: space heating and domestic hot water production

In the last decades the construction techniques as well as used building materials have made both, new and old refurbished buildings, more thermally efficient. This led to a drastic decrease in the heating demand.
Thanks to this scenario and in addition to the stringent measures on polluting emissions, the foundations have been laid for the birth of the so-called fourth generation district heating or LTDH. This foresees a considerable decrease of both the supply and return water temperatures (T_s<50°C and T_r<30°C).
The decrease in water temperature has some immediate advantages such as: the reduction of losses along the grid, the possibility of using cheaper materials and components (plastic pipes, less powerful valves and pumps, etc ...) but also the possibility to use directly in the grid low-grade excess heat, such as DC waste heat, without the use of heat pumps.
Thanks to this network becomes more efficient with much lower heat demands than before. In fact, if before a district heating network was conceivable only in areas with high demand density now even the smallest networks can prove to be efficient and economically appealing.
In particular LTDH proves to be very advantageous if coupled to low temperature space heating systems such as floor heating, etc. This particular heating systems require maximum temperatures of 40 degrees, which perfectly match the temperatures provided by the LTDH.
So it can be said that this type of district heating is well suited to the space heating demand of new or refurbished buildings that have low temperature heating systems. However, this can also be coupled to

old systems such as radiators; in this way LTDH is able to satisfy the request during the period with medium demand but is not self-sufficient during periods of great cold.
As regards domestic hot water (DHW) production, the issue is not simple as with space heating.
In fact, it is necessary to avoid the risk of water contamination by the legionella bacteria but also to guarantee the costumer comfort, deliver water in reasonable time . For these reasons it is required that water is supplied at a temperature range of 45-60 degrees, according to several authors [19], [18], [21].
There are several substations for the DHW production centralized or placed at the individual users.
However, the differences may also relate to the type of production that can be instantaneous (IHEU) or with storage tank (DHSU).

- **Instantaneous Heat Exchanger Unit**:
  in this production subsystem there is simply a heat exchanger that separates the water supplied by the district heating and the supply side to the users.

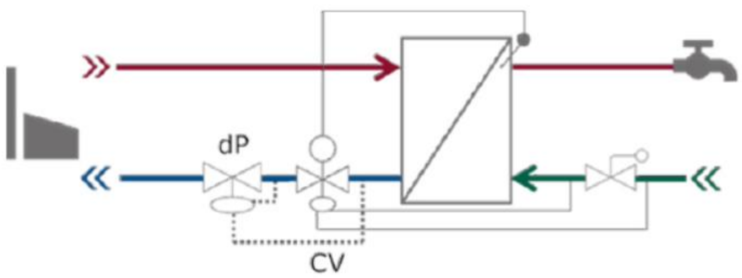


Figure 21- Instantaneous heat exchanger system for domestic hot water production (D. Schmidt et al., 2017, page 30)

In the case of LTDH, this exchanger must have a very high efficiency to minimize the thermal gradient between the two distinct fluids. For this reason special heat exchangers have been created that produce a temperature difference of only 3 degrees [21].

- **Storage Tank Unit:**
  This kind of units includes a storage tank and a pump as well as a heat exchanger.

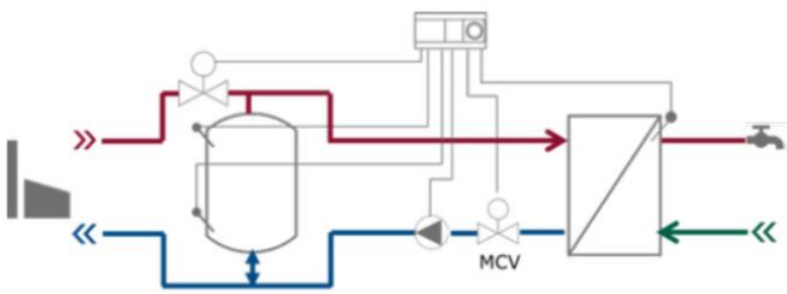


Figure 22- Domestic hot water system production with storage thank (D. Schmidt et al. ,2017, page 30)

The storage presence serves to avoid the formation of peak loads and allows distribution over time. For this reason it must be dimensioned according to local regulations, according to the daily usage forecast of DHW and the DH flow rate.
As regards Germany, the DVGW 551 imposes a maximum storage size of 3 liters [22]. This standard avoids the risk of legionella colony formation regardless of the water temperature in the storage. On the other hand, such a small storage does not allow for a proper load compensation but allows only a shortening of hot water production times.

- **Micro heat pump solution:**
  in case the temperature supplied by DH is not sufficient to reach the 45-50 degrees required for DHW or simply when the DHW demand is too high, like in large buildings, the single heat exchanger is not enough.
  In these cases it is possible to use micro heat pumps that bring the water to the required temperature as shown in *Figure 23* .

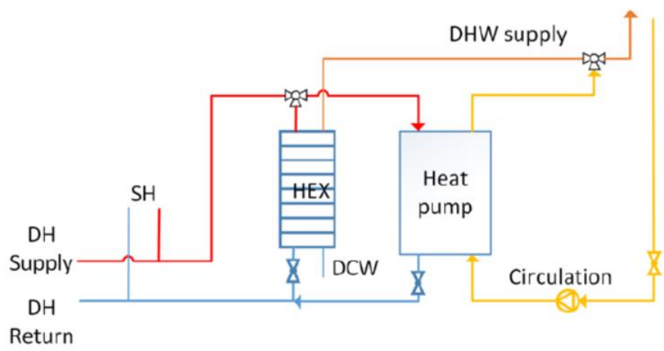


Figure 23- Example of scheme for domestic hot water preparation by a micro heat pump (D. Schmidt et al. 2017 page 32)

2 CASE STUDY DESCRIPTION

The purpose of this study is to test the possibility of reuse the heat wasted by a very small DC hypothetically located in Stuttgart as a primary source for a district heating micro-network feeding 37 buildings.

For the elaboration of this model, the following have been studied: the area and the context in which to insert the district heating network and the type of DC with which the network must interface.

A simulation software called SimSadt was used to relate the heat demand of buildings in the area, and then select some of them to be connected to the grid, and the waste heat production of the DC.

2.1 Stockach area in Stuttgart

The area under study is the Stöckach district and partially also some surrounding areas. This district is part of a larger urban district called Stuttgart East, in turn part of the state capital of Baden-Wuerttenberg in Germany, Stuttgart.

Eight sub-districts belong to Stuttgart East: Gänsheide, Uhlandshöhe, Stöckach, Berg, Ostheim, Gaisburg, Gablenberg, Frauenkopf (*Figure 24*).

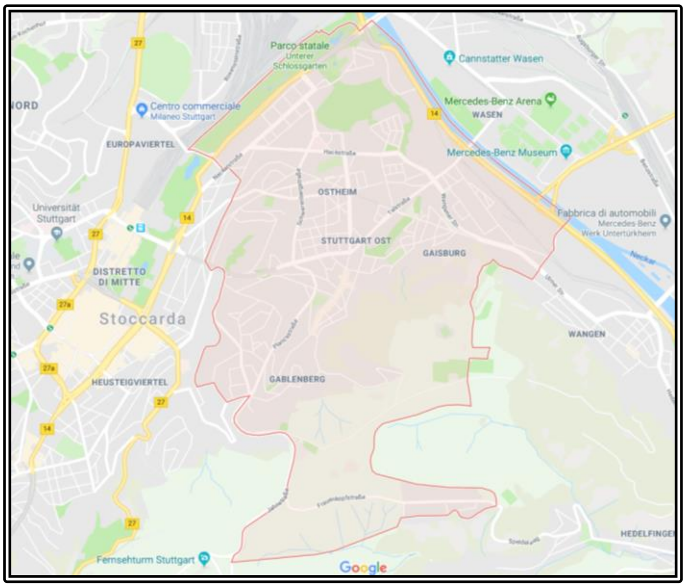


Figure 24- Stuttgart East extension area (www.googlemaps.com)

In particular Stöckach district (*Figure 25*) covers an area of 735,000 square meters and has a population of about 4690 inhabitants (2014 data, wikipedia).

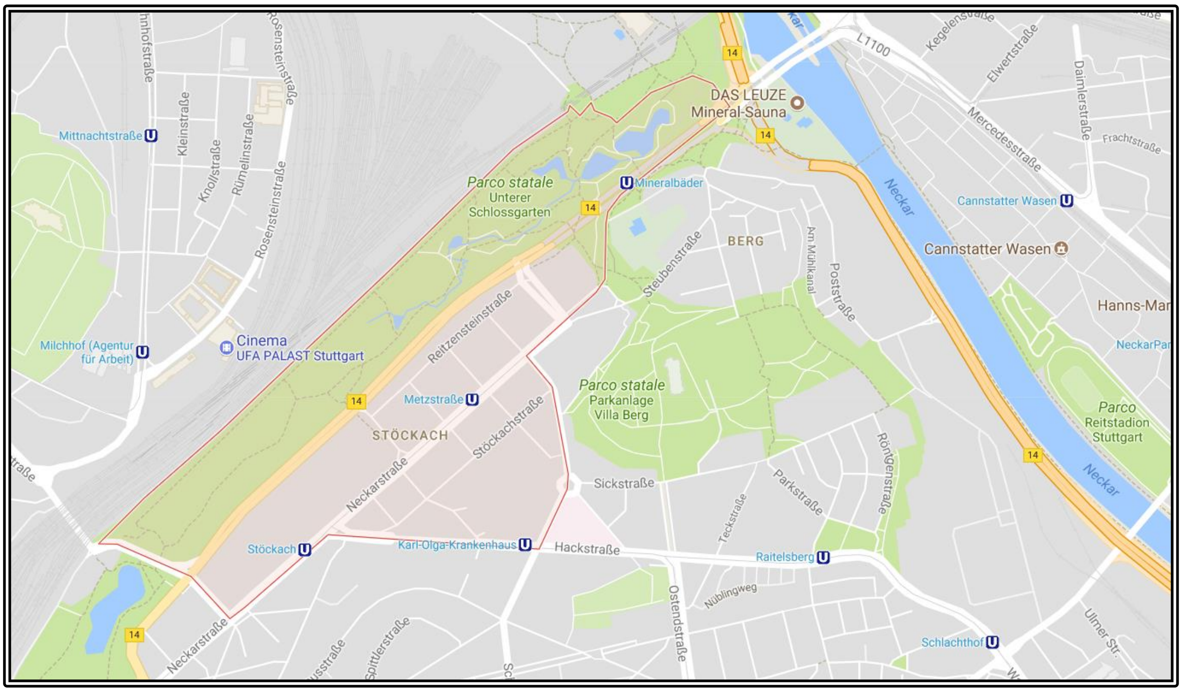


Figure 25- Sockach district (www.googlemaps.com)

The area is a mixed destination. It is possible to find residential conglomerates, as well as large commercial areas, areas of private offices and state offices, schools and hospitals and even the headquarters of regional television. The context is almost entirely surrounded by large parks such as Unterer Shlossgarten and the historic park of Villa Berg.

This area has already been extensively studied during the development of SimStadt, a program through which it is possible to estimate the demand for heat and domestic hot water.

In the following paragraphs will be explained how SimStadt has been used, which data are requested and how results can be easily read and interpreted with the help of ArchGis.

2.2 Data center

The DC analyzed during this study does not really exist but the data are obtained by simulating the implant scheme on the 'Trnsys' software.

This model comes from a study for a master thesis part of a bigger program, conducted in the department of Zafh at the HFT in Stuttgart, called EcoRz.

The purpose of this project is to study DCs that are increasingly sustainable. Both through the reduction of electricity consumption for cooling but also through the integration and use of renewable energy in the DC system.

2.2.1 Data center placement

As already mentioned above the DC under study is not really located in the Stockach area.
The data used in this work come from the simulation of a theoretical project for the cooling system of a small DC whose starting data come from a real DC placed at Ulm.
For this reason, in order to determine which buildings to connect to the DH and how to draw the network, a hypothetical location of the DC was chosen within the study area.
For the choice of the location to be attributed to the DC it was thought to look at those buildings that even in today's reality could contain within them a DC.
This choice fell on the building that houses the headquarters of the local TV called SWR Funkhaus, in fact, this building will certainly contain a DC of which, however, are not known the real characteristics.

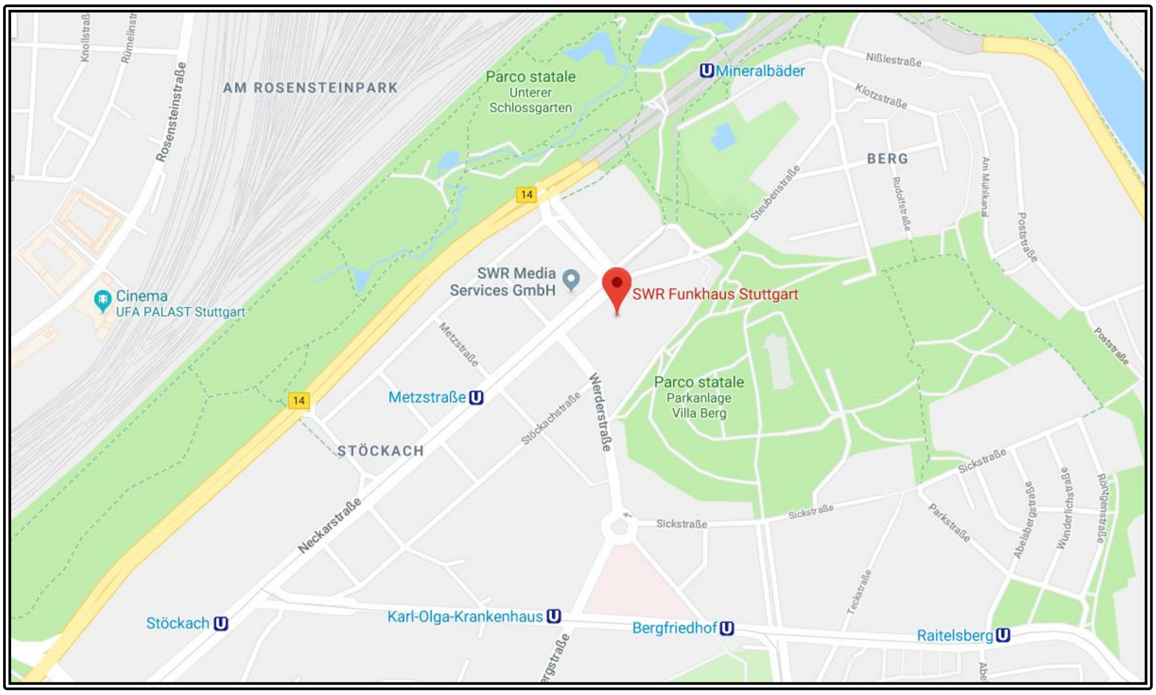


Figure 26- In the figure the object in red indicates the geographic position of the building chosen to host the data center being studied (www.googlemaps.com)

2.2.2 Data center description

The examined DC model was based on real data of a very small DC located in Ulm with an IT load of 200 kW and a percentage of usage of 92%.
The load profiles used are typical of a DC that is always active 7/7 and 24/24 as can be that of a bank or a company. These load profiles assumed fluctuations between peaks of about 5%, which is why these profiles were assumed to be constant during the year. Therefore this source of heat, as already demonstrated in other studies, can be defined as stable and reliable [4].
Although the initial data were real, the scheme of the air cooled system was created in such a way as to integrate a free cooling system from a cooling tower to two 75 kW parallel chillers, that come into operation only if the free cooling is not exploitable.
Starting from the data provided and load profiles, first of all a system was created on the EES tool (Engineering Equation Solver) for the determination of components nominal values .
The air cooled system is designed to maintain an internal temperature of 25 °C in the rack room.
Once the nominal values have been obtained, these have been included in the system diagram elaborated on Trnsys which performs a dynamic simulation, in this case with a period of 15 minutes.
Starting from the scheme of this project, data were obtained regarding the characteristics possessed by the heat leaving the white space or at the entrance to the CRAH and it was assumed to implement the cooling system with a heat recovery system.
The data obtained are shown in the table below :

Data Center caratteristics	
IT Load 100% (kW)	200
IT load 92% (kW)	184
termal load (kW)	184
T outlet (°C)	40
air flow (kg/s)	10,6
WASTE HEAT (kWh/day)	4416

Since the simulation program that was used to calculate the heat demand works on a monthly or annual basis, the amount of heat wasted was also calculated on a monthly basis and converted into MWh / year, as shown in the table below (*Table 1*):

MONTHLY WASTE HEAT (MWh/month)											
JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
136,90	123,65	136,90	132,48	136,90	132,48	136,90	136,90	132,48	136,90	132,48	136,90

Table 1- Montly DC heat production

2.3 Analysis procedure

Once the amount of waste heat of DC on a monthly basis was known, it was necessary to analyze the corresponding monthly heat demand of buildings in the study area to understand how much and what to supply with the new district heating network.

To do this, we used a simulation software for the thermal heat demand of buildings that had previously been created by the Zafh and geoinformatick department at the Hochschule fuer Tecnick in Stuttgart to analyze the area under study.

In this section we will describe the methodology that the software uses to simulate the behavior of buildings, which are the input information to be inserted, which output it provides and what is the reliability of the data it provides.

2.3.1 Heat demand and domestic hot water calculation with SimStadt

SimStadt is an urban simulation software developed by the departments of Zafh and geoinformatik at HFT-Stuttgart. It allows to perform energy simulation analysis on an urban scale and consequently the identification of the potential of various forms of energy through the study of different scenarios also of extreme change.

In the case of this thesis, SimStadt was used in its simplest form, namely that of simulating the space heating and domestic hot water demand for the studied area.

The calculation in SimStadt is based on a monthly balancing method (according to DIN V 18599) that is applied to a 3D city model.

The software determines the heat demand taking into account, among other parameters, also the detailed estimates of the climatic data of the location to be simulated.

The model provides polygons that represent the volume of each building. These polygons are stored in a GML (Geography Markup Language) file along with information on the construction year, the address, the block number, the state of the building, the building's footprint, and other information [23].

This GML file represents the entry data for SimStadt.

The GML file is not uniquely associated with a single building. In fact, a building can also have multiple GML files that describe it. This happens because it is sufficient that even a single attribute differs within the single building (for example the year of construction of an extension or the different destination of use, etc.) to make sure that it must be represented by different GML files. So the GML file can be associated with a single building or even just a part of it.

Figure 27-IWU 2005 building classification (http://www.building-typology.eu)

From the dimension of the calculated polygons SimStadt automatically defines the type of building [23] according with the IWU 2005 classification (*Figure 27*) and the year of construction, that is already included in the GML file, and after that immediately it can associates the corresponding transmission values for building components (walls, floors, roofs, etc.) to the building typology.

The GML file can be defined according to different degrees of detail from the most essential one, the LOD0, to the more detailed one, the LOD4, which comes to define even the furniture.

SimStadt requires a minimum level of detail equal to LOD2 [23].

This means that the information on the roof shape has already been implemented, but the exact dimensions, the number and the size of the windows are not yet considered (*Figure 28*).

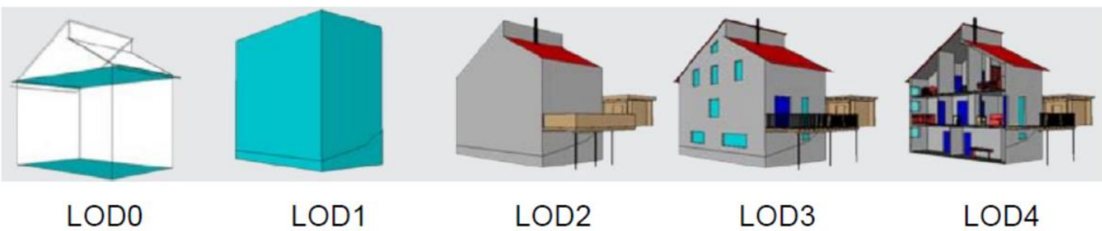


Figure 28- Classification of different levels of detail for GML files (Lara Dobisch, Bachelor thesis, pag. 16)

In order to calculate the number of floors in each building, SimStadt assumes a ceiling height of 3.30 m. In this way the program calculates the ridge height as the difference between the roof height and the upper part of the land (known data) and divides it by 3.30 m, obtaining the desired number of floors.

If, on the other hand, the number of floors is known, the program directly calculates the gross floor area and from this, by means of a known conversion factor, the heated area of the building.

Sloped roofs are assumed by the program as heated in the current simulation. If, however, these have a difference between the eaves and the ridge height of less than 2 m, then they are no longer acceptable as living space, then the program assumes them not heated.

Basements are generally assumed as unheated rooms.

Given the following assumptions and information, the program can calculate the space heating and domestic hot water demand.

The excel output sheet associates with each GMLId (GML identifier) provides a large number of information including: the block number, the barycentric coordinates of the building part, the primary and secondary use, etc. and finally the calculation of energy consumption both on an annual and monthly basis (only in the case of space heating).

The output sheet shows that the heating season in Stuttgart is very extensive, in fact the only two months in which it has total absence of heat demand are June and July. In all other months, even if minimal, there is a request for space heating.

Obviously the months of November, December, January, February and March together represent the major part of the annual demand.

As mentioned above Simstadt is also able to simulate alternative scenarios, in fact it has been possible to estimate also the future heat demand following a medium refurbishment of all the buildings in the database. In this way it was possible to create different scenarios to compare the current situation and the hypothetical future.

These data outputs were provided to me and formed the starting point for my work.

2.3.2 Missing buildings in SimStadt simualtion

Given the large amount of input required by SimStadt to calculate the desired information, not all buildings has been simulated.

In fact, where there is a lack of basic information, the program loses its ability to calculate them.

Therefore, despite the large database of information collected over the years regarding the buildings in the area, still today there are missing buildings that cannot be simulated.

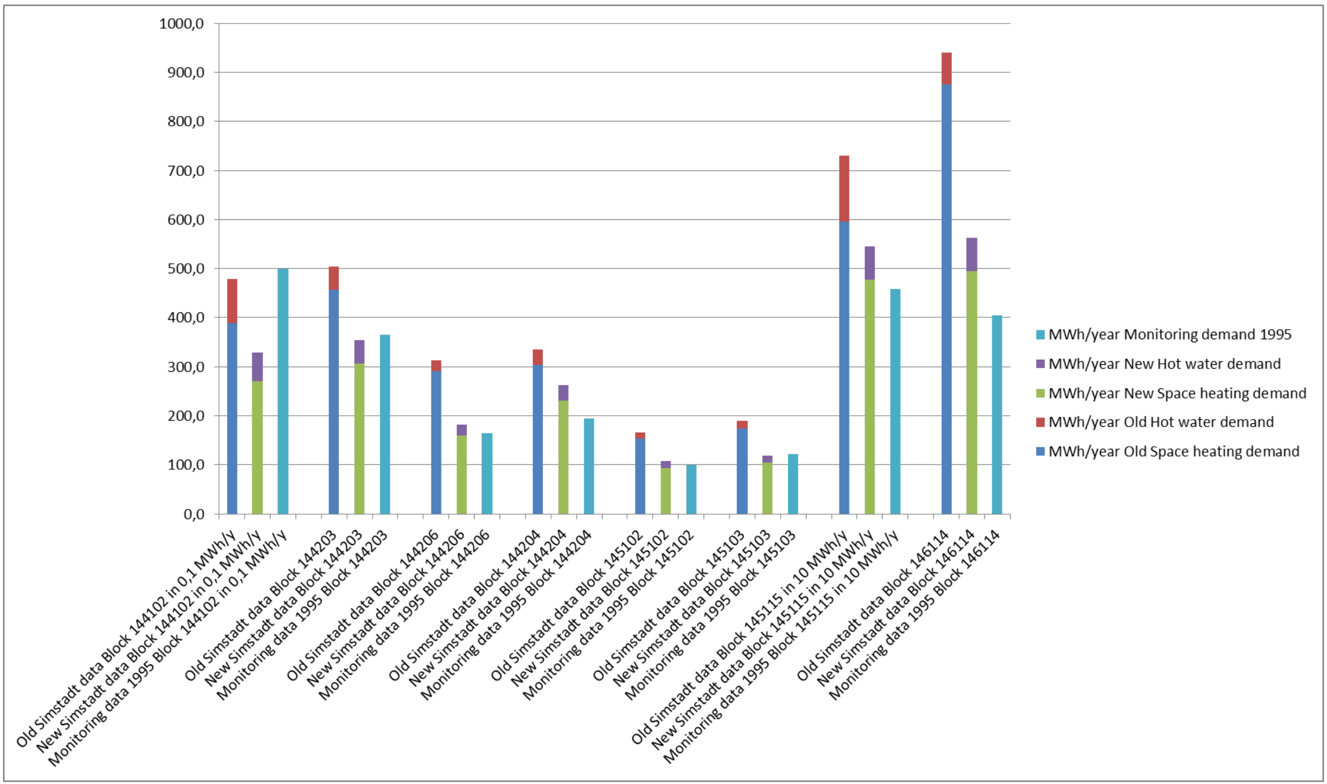
A complete list of all missing buildings identified by GMLId and block number has been drawn up. To estimate the reliability of the model used, these missing buildings have been reviewed and currently amount to about 29% of the total buildings considered.

Total number of GMLId in the area	
2859	
Number of GMLId not simulated	
837	29%

This quantity is certainly consistent but it has been possible to estimate the demands in first approximation starting from the data we have in our possession, as we will see later on.

2.3.3 Validation of SimStadt data

Since the nineties, the city of Stuttgart has started a series of measures for the reduction and control of energy consumption. In this regard, in 1995 measurements were carried out to establish the consumption for the production of heat for each building and also the type of heating used.
These data, for reasons of privacy, have been provided referring to a block number, rather than to the address of the individual home.
The area under examination was then divided into 45 blocks of buildings.
In order to compare these measured data with the simulated data from SimStadt it was necessary that this information on the block number was implemented in the GML file in order to univocally identify the buildings belonging to the same block.
Another requisite needed for the comparison was that the number and description of the buildings on SimStadt actually reflected the real characteristics of the monitored buildings. That is why, for the validation of the data, it was necessary to exclude all those blocks that in SimStad present missing buildings, in this way the comparable blocks were reduced only to 8.
The basis for validation was then compared to the data monitored in 1995, the simulated data obtained by Lara Dobisch during the period of her dissertation and the new simulated data that were now obtained taking into account the correction of errors detected by Lara at the conclusion of her thesis.
During her thesis Lara studied what types of errors occurred in the GML file description who made the SimStadt simulation not exploited well, producing too partial results [23].
Subsequently, these errors were corrected where possible and new results were produced through which the validation was conducted (*Graph 1*).



Graph 1- Validation of the new data produced in 2017 for the 8 complete blocks of building.

As can be seen from the graph above the data generated with the new SimStadt implementation are much more in line with the data monitored in 1995.

However, the 144102, 144204,145115 and 146114 blocks still present a significant divergence between the simulated data and the actual data. In these four blocks the divergence still exceeds 10% with a 34% peak in the case of the 144102 block.

This can be explained by the fact that the simulation program still classifies buildings as if they were residential. Therefore, in correspondence with buildings for different use, too high inconsistencies still occur.

In fact the first block is a building used as administrative offices of a state broadcaster Südwestrundfunk (SWR), the second contains in addition to residential buildings a nursery school and the third block includes an entire building for educational use.

Regarding the block 146114 the speech is a bit different, in fact it is intended for residential use entirely but it has a very special form that still makes some errors related to the shape.

It is therefore possible to affirm that the data obtained through the SimStadt tool can be used to estimate only the heat demand of the residential buildings. In the case of blocks with missing buildings these can be estimated as we will see in Chapter 4.

3 CASE STUDY ANALYSIS

In order to select the group of buildings to be supplied with the district heating network, it was necessary to establish criteria with which to select them, using a tool that would allow the comparison of these criteria in a direct way.
To do this, we used the ArchGis program that allowed a graphic reading of the data referring to the individual buildings, directly associating a certain attribute to the corresponding building in the map. This allowed us to create real georeferenced thematic maps (as seen in the following paragraphs) which, through the previously established criteria, led to the choice of the 37 buildings to be supplied.

3.1 Importing the SimStadt output in the ArchGis tool

As stated in the previous Chapter 2, SimStadt produces as output an Excel file which associates a pair of coordinates to each GMLId. In this way the data is geo-referenced.
This happens because the GML file is already geolocated in space and this can easily be verified through a GML viewer.
In the case of a district heating network project, this data condition is particularly advantageous for two reasons. By importing such data into any GIS (geographic information system) it is possible not only to have a graphical reading of data and information, and then a reading of the spatial distribution of the heat demand , but also, once the buildings to be connected have been chosen, to draw a network whose exact physical characteristics are known.
The creation of works such as district heating networks are closely linked to the social-territorial aspect that surrounds them. To make this system as efficient as possible, integration with territorial systems is of fundamental importance [24].

3.2 Pre-processing of the data

To create the working base on the ArcGIS tool it was necessary to have a building map of the city. This was found on the Geofabrik website [25] [26]which is a German company that offers open source maps of various locations and with different kind of informations.
Once the initial shapefile has been obtained, the Excel output file of SimStadt has also been imported into the instrument (through 'Add data') whose data have subsequently been exported as layer and geolocated according to the WGS84 system.
At this point the data were represented by a layer of points representing the individual GMLId, as it can be seen in the picture below (*Figure 29*).

Figure 29- Image of the GMLId point layer imported into the worksheet containing the buildings shapefile.

To avoid having to work with a large amount of superfluous buildings, the layer containing the map has been intersected ('Arc tool- Analysis tools- Over lay- Intersect') with the new point layer and so only the part of the map containing Stöckach and the surrounding areas has been selected.
Subsequently it was necessary to connect each point to its corresponding building on the map, this process was carried forward through the command 'Join by position'.
As some buildings were described by several points to find an overall heat demand from the building, the 'Join by position' was achieved by imposing the sum of the attributes. Only at a later time the other information that could not be added (year of construction, intended use, etc.) were correlated at the correspondent building polygon through a 'spatial join' ('Arc tool- Analysis tools- Over lay- Spatial- Join').
Thanks to the information obtained during the 1995 monitoring it was also possible to see which buildings were already connected to the high-temperature district heating network that is present in the area.
The information was provided by block number so it was enough to import the Excel with the data, export it as a layer and create a join and base it on the block number.
Once this process was completed, 91% of the points were associated with the corresponding building. Of the 1277 total points, 112 were excluded from the join.
Trying to solve the problem, an analysis was carried out to identify the cause of this incongruity. In some cases the error was due to the incorrectness of the shapefile of the map of certain buildings or

there were problems with the coordinates assigned to the GMLId, the point was in fact outside the area described by the building.
The table with the aforementioned analysis is shown in the "*Attachment I*".
If the missed join was to be attributed to the wrong positioning of the coordinates of the SimStadt output point, an attempt was made to correct it by creating another spatial join but with a search radius outside the 5 m polygon. To do this, all the polygons that were not connected at any point were selected by conducting a search using attributes (' Select- Select by attributes- "GMLId=0"').
After selecting the objects, these were extracted into a new temporary layer and with this layer the new 'Spatial join' was carried out with a radius of 5 m. It was not possible to extend the beam further because doing so could have led to the risk of drawing data from points corresponding to other buildings.
With this procedure, other 10 buildings were connected to the corresponding Simstadt data.
Despite this, 102 buildings that are simulated in SimStadt are not shown on ArcGis.
To calculate the error made in neglecting this problem we estimated the percentage of buildings not connected and the heated area lost in this process (*Table 2*).

Simulated building parts as points	Points outside features	Error
1277	102	8%

Simulated heated area (m^2)	Lost heated area (m^2)	Error
886995,8	29094,1	3%

Table 2- Estimated percentage error committed by importing SimStadt output into ArcGis.

The committed percentage error was considered acceptable mainly for two reasons. First we must say that the process of project scenarios, the calculation of losses, the power of the pump and others that we will see later were conducted on Excel and not directly on the GIS tool, so the data used came directly from the SimStadt output . Secondly, the considered area of study, which we will see later, does not present this type of error in any building.
Concluding, therefore, we can say that in this specific case, in which the GIS has been an instrument of reading and interpretation of the urban fabric and a tool of planning of the network, the error committed is acceptable.
In the event that the GIS was also used as a tool for calculating parameters such as losses, etc. this error would not have been acceptable.

3.3 Selection criteria for a subset of buildings

Once the pre-processing operation of the data structure was completed, we moved on to reading the information.
In fact, in this phase it was necessary to identify the right location where the fictional Data Center will have taken place and above all which blocks of buildings we can connect with the low temperature micro-network.
Firstly, blocks of buildings that were already connected to the existing district heating network were excluded (see *Attachment II*, Table 2).
Secondly, we tried to connect buildings that were intended for primary residential usage (see *Attachment II* , Table 3) to avoid that the difference between real and simulated data was too high.
Lastly we tried to connect at least one block that had a specific heat demand rather high to make the network more efficient (see *Attachment II*, Table 4).
Then another fundamental condition for the choice of buildings to be feeded is that they have to be as close as possible to the source of energy to reduce losses along the way.
Trying to take these parameters into account, the building blocks in the vicinity of the dummy DC were studied and two blocks were suitable for the requests.

3.4 Identification of studied area

Note the position of the DC, in the immediate vicinity of this structure, there were four blocks of buildings not yet connected to district heating : block 144105, 144104, 143216 and finally the 144206.
The 144105 block was not considered suitable because inside it has a nursing home and a hospital structure, so the block was not totally for primary residential use.
The adjacent block 144104 was not even suitable because, although totally residential, alone presented a demand for heat too low.
The two remaining blocks, on the other hand, met all the asked requirements and were therefore chosen.
In conclusion, therefore, the analyzed district heating network has as its main source of heat the DC located in block 144102 and feeds the two blocks 143216 and 144206 positioned in front of it (*Figure 30*).

Figure 30- Image of the building blocks considered in the analysis for the choice of houses to be connected to the district heating network.

All the tables obtained with ArcGis with the respective legends are reported in the '*Attachment II*'.

4 SIMULATION OF THE CASE STUDY

Once the initial data were obtained, the simulation model could be elaborated.
The model provides for the study of four different scenarios, two set in 2018, then with no refurbished buildings and two set in 2030 with totally renovated buildings. The network feeds 37 buildings and always follows the same path for all the scenarios, what changes are the physical parameters of the network. Two scenarios involve the use of a centralized heat pump.
In order to design the network, estimate the losses along the path and finally calculate the power to be attributed to the circulation pumps, a static model was adopted, using an Excel spreadsheet, starting from some specific assumptions that we will see in the following paragraphs.
The aim is to compare the four scenarios obtained according to three parameters: the primary energy factor, the total heat distribution cost and the payback time for investment.

4.1 Studied scenarios

Four scenarios have been created, two in the present and two in 2030 when it is assumed that all 37 buildings will be totally renovated to comply with the new laws on energy consumption.
Following the European Directive 31/2010, in fact, the new buildings but also all those subject to renovation work will have to become NZEB (Nearly Zero Energy Buildings).
Germany, and in particular the state of Baden Württemberg, is encouraging to ensure that more people adapt their homes to these standards.
Considering that and also the fact that the homes in the analyzed area are more dosed, the assumption of total renovation of these buildings until 2030 is not so unrealistic.
These scenarios in addition to being interpreted individually can also be viewed in a more fluid manner.
In fact we can say that the first two scenarios A and B in 2018 could then evolve in the corresponding scenarios 1 and 2 set in 2030.

4.1.1 Scenario A

Scenario A involves the use of a heat pump in order to increase the supply temperature in the network and reduce the outlet temperature to the DC side.
In fact, thanks to the heat pump, it is possible to switch from a supply temperature of 35°C to one of 65 °C.
So in this case we consider a medium-temperature district heating network (65/45°C).
In this way temperatures are suitable to be coupled also to traditional heating terminals and for DHW production.

The fact of supplying the heat pump with already heated fluid means that the ΔT and therefore also the electrical power required to supply the heat pump is reduced.

In order to avoid the daily demand peaks, in each scenario, a thermal storage of 20 m^3 has been assumed, coupled to the heat exchanger, which allows to store 450 kW or about 3 hours of DC production.

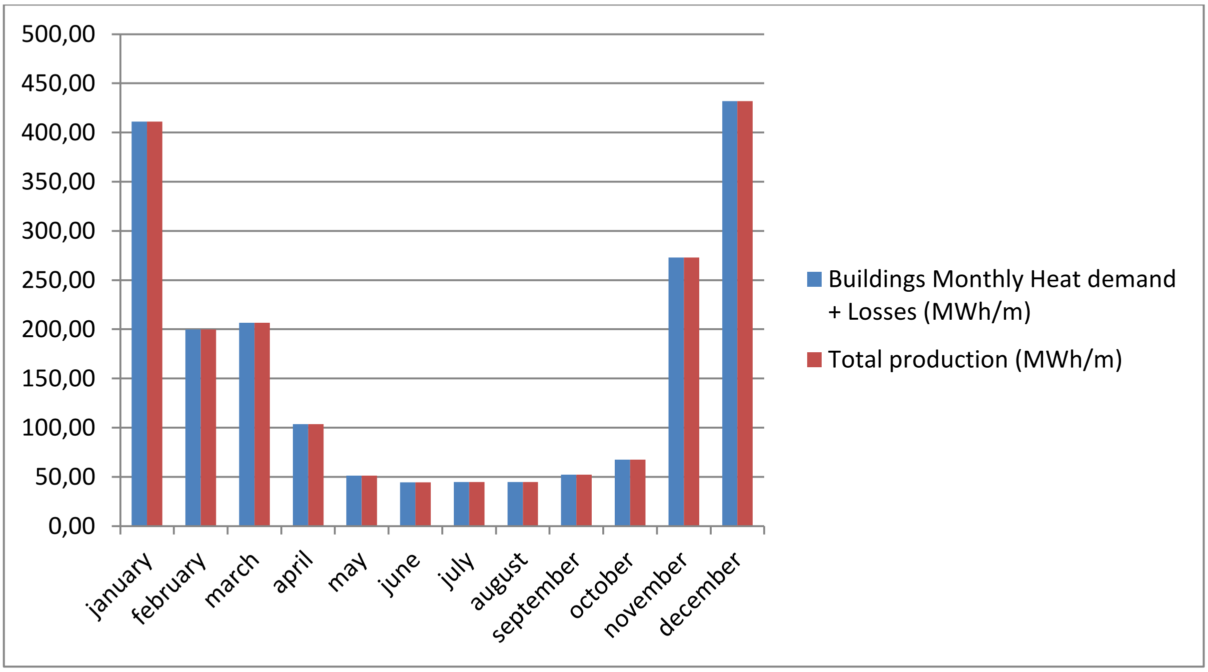
In addition to this centralized storage, it is planned to install storage located inside each building to compensate for the daily demand peaks of DHW. Such storage is considered included in the exchange substation between the network and the building.

Within each building a substation, that is a heat exchanger, is planned instead of the old production sources of gas and oil.

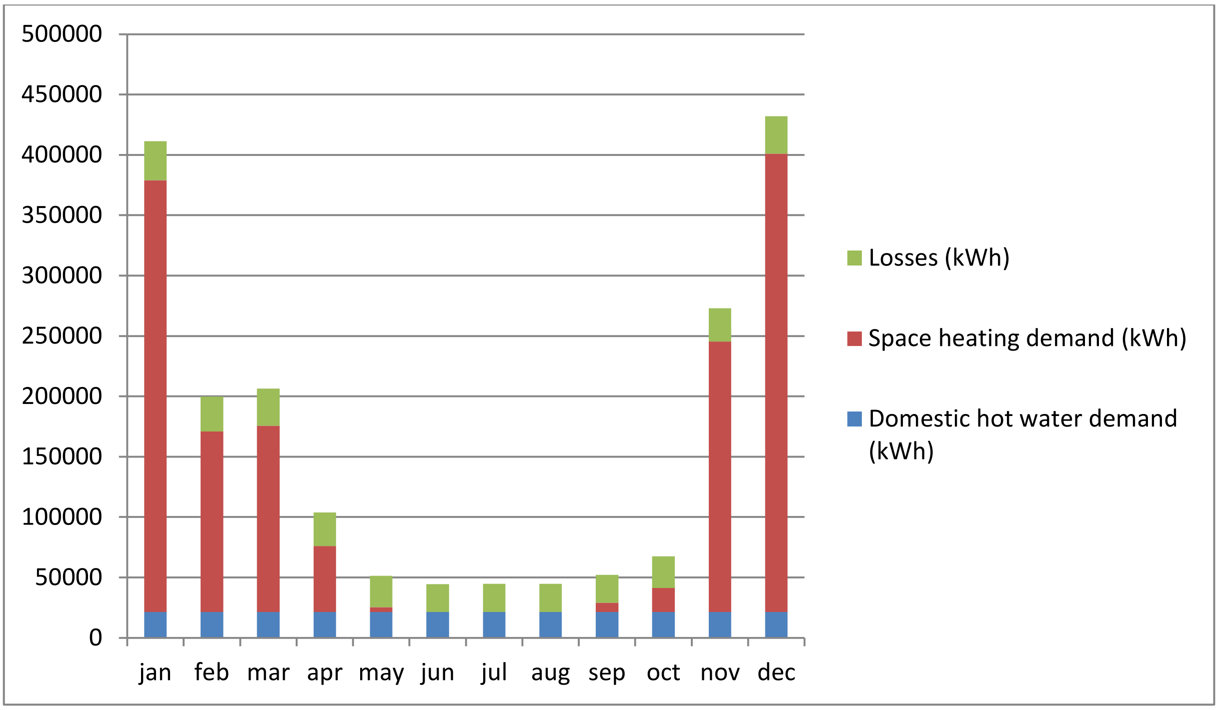
The table and the graphs below show all data on a monthly basis of this scenario, in terms of demand and production.

	37 Buildings no refurbishment (2018)											
	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Total monthly demand (kWh)	379070	170867	175648	76032	25364	21422	21273	21273	29040	41334	245311	401030
Domestic hot water demand (kWh)	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273
Space heating demand (kWh)	357797	149595	154375	54759	4092	149	0	0	7767	20061	224039	379757
Losses (kWh)	32135	29003	30858	27718	26067	23059	23585	23588	23066	26077	27728	30865
Data center production (kWh)	136896	123648	136896	132480	136896	132480	136896	136896	132480	136896	132480	136896
Utilized heat from DC (kWh)	136896	107622	111196	55865	27694	23951	24154	24156	28057	36298	132480	136896
Heat Pump production (kWh)	274308	92248	95310	47885	23738	20530	20704	20705	24049	31113	140559	294999
Total Production (kWh)	411204	199870	206506	103750	51432	44481	44858	44861	52106	67411	273039	431895

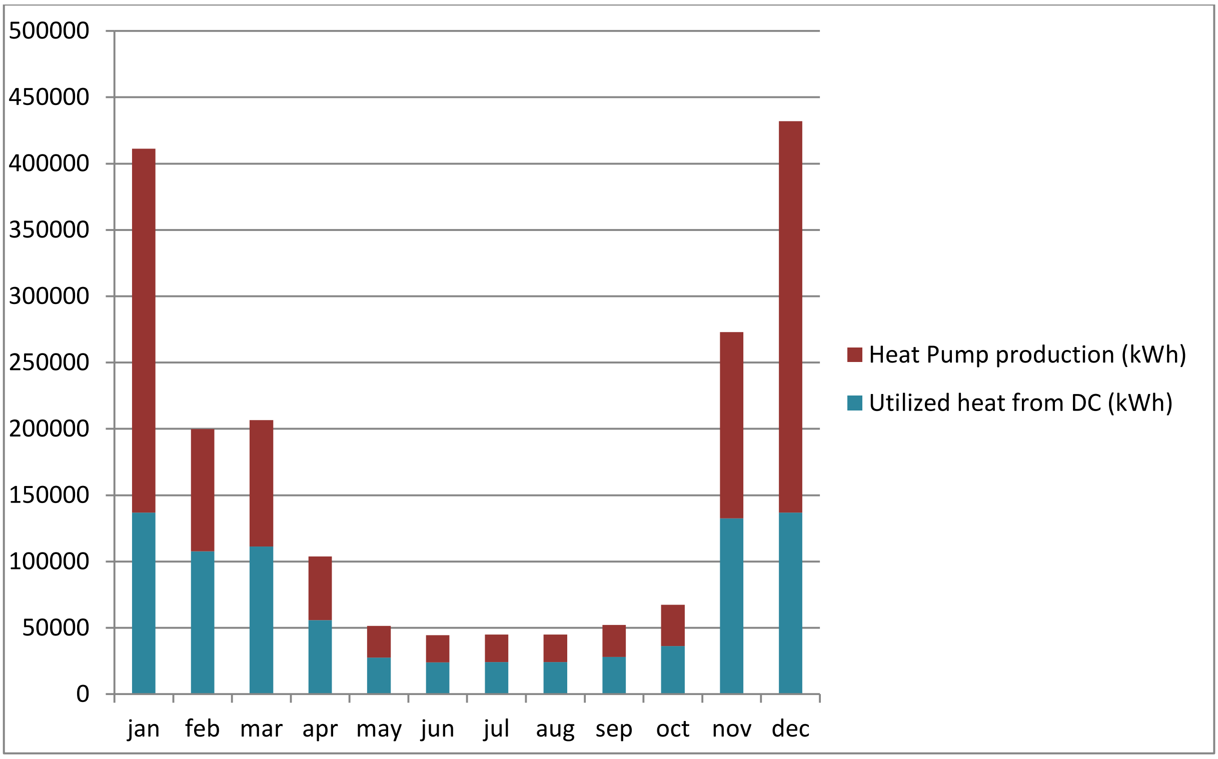
Table 3-This table summarizes the demand and heat production of Scenario A on a monthly basis, subdividing all the individual components of which the two are composed.



Graph 2- The graph shows the heat demand and distribution losses compared to the total heat production of scenario A on a monthly basis.



Graph 3- The graph illustrates the total heat demand decomposed into its three components: distribution losses, space heating demand and domestic hot water demand of scenario A on a monthly basis.



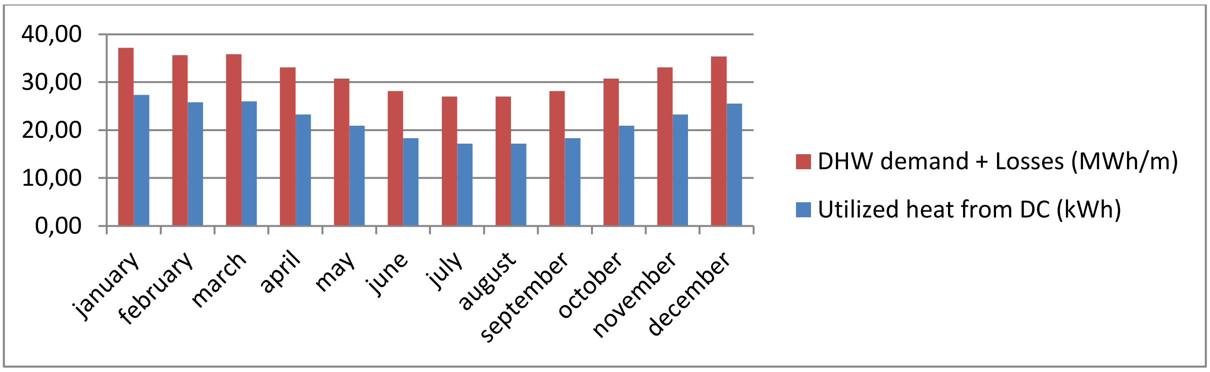
Graph 4- The graph shows the total production of heat decomposed into its two components: the one directly produced by the data center and the one produced by the heat pump of scenario A on a monthly basis.

4.1.2 Scenario B

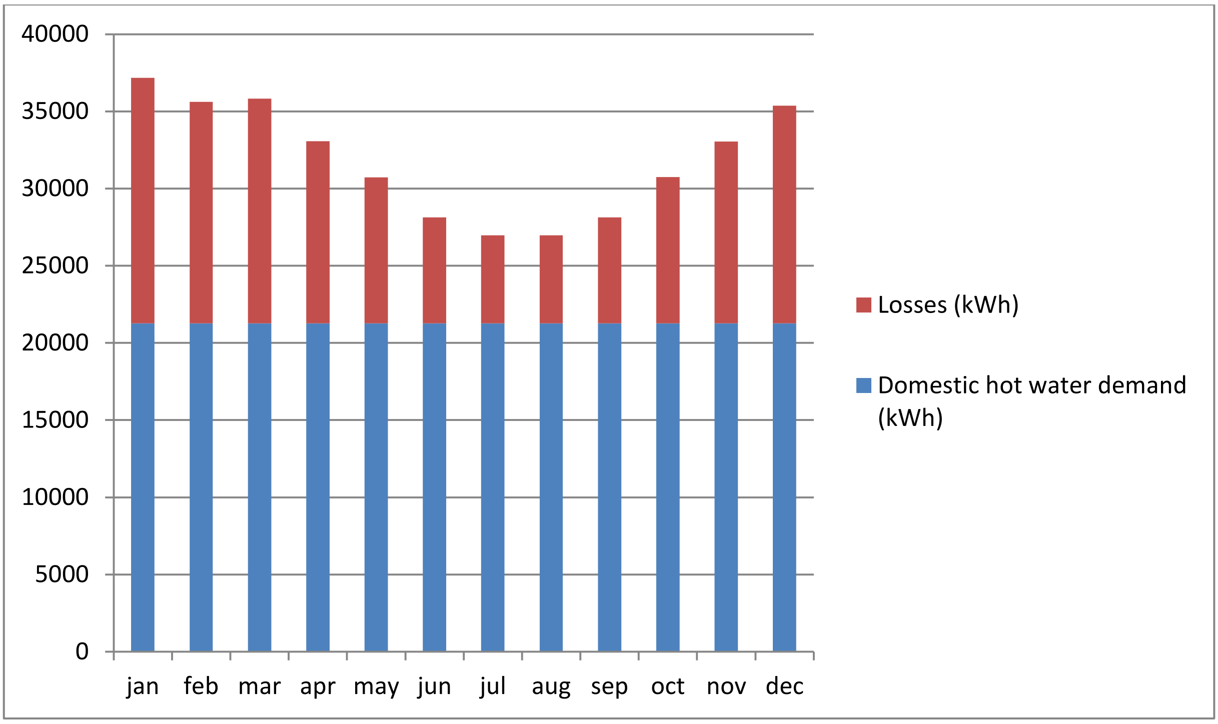
In this scenario, the DC directly feeds the low temperature district heating network (35°C/20°C) by means of a heat exchanger.
The heat exchanger transforms the hot air to 40°C at the output of the DC in hot water at 35°C.
Also in this case, as for Scenario A, the heat exchanger is coupled to a thermal storage to compensate for the daily peaks.
In this case the buildings still have old heating and DHW production systems that use gas or oil coupled to high temperature working terminals such as radiators.
In this scenario the only way to use the heat coming from the DC is to assign to the district heating a water pre-heating function that will then be used for DHW.
The district heating substation in the building containing the exchanger intercepts the water supply network and overheats the liquid that would otherwise arrive directly at the boiler at 6/10°C degrees, reducing the temperature difference.
So in this case it is assumed a use of both heat sources, the new one coming from the data center and the old ones ie gas and oil.
This is due to the fact that the temperature provided by the district heating is too low to be coupled to higher temperature systems and is not even sufficient to produce DHW to be delivered at 45/50°C.
The table and the graphs below show all data on a monthly basis of this scenario, in terms of demand and production.

	37 Buildings no refurbishment (2018)											
	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Total monthly demand (kWh)	379070	170867	175648	76032	25364	21422	21273	21273	29040	41334	245311	401030
Space heating demand (kWh)	357797	149595	154375	54759	4092	149	0	0	7767	20061	224039	379757
Domestic hot water demand (kWh)	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273	21273
Losses (kWh)	15904	14342	14548	11801	9459	6852	5705	5708	6860	9470	11775	14087
Data center production (kWh)	136896	123648	136896	132480	136896	132480	136896	136896	132480	136896	132480	136896
Utilized heat from DC (kWh)	27359	25796	26003	23255	20914	18307	17160	17163	18314	20925	23230	25541

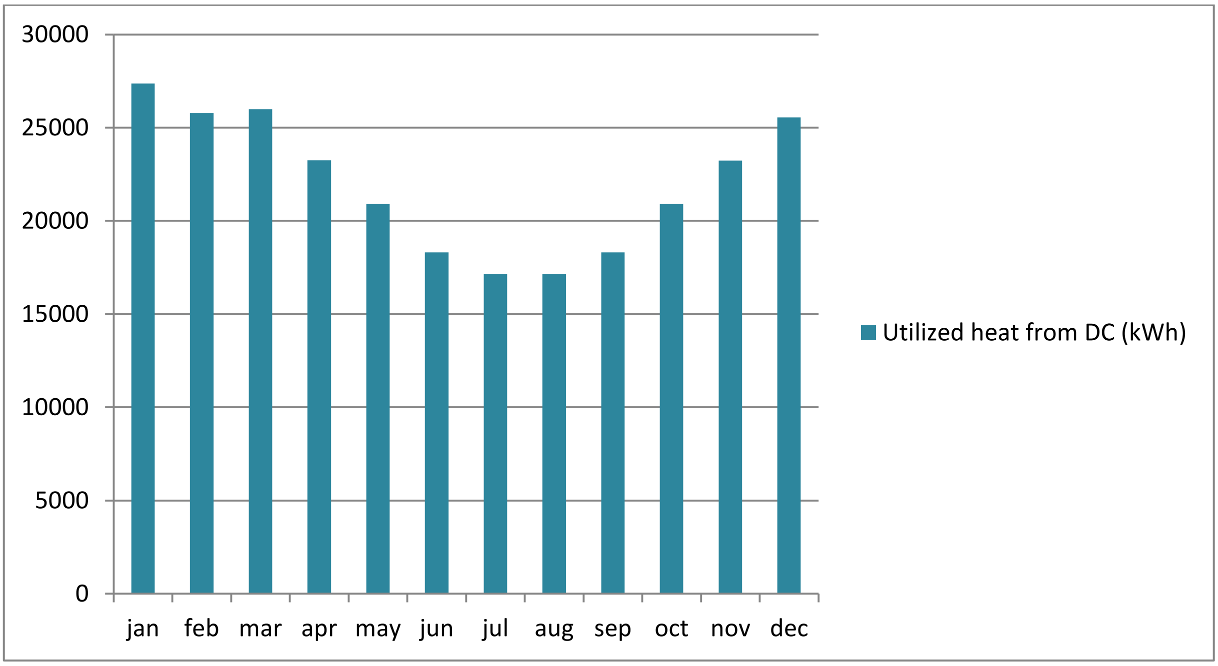
Table 4- This table summarizes the demand and heat production of Scenario B on a monthly basis, subdividing all the individual components of which the two are composed.



Graph 5- The graph shows the heat demand and distribution losses compared to the total heat production of scenario B on a monthly basis.



Graph 6- The graph illustrates the total heat demand decomposed into its two components: distribution losses and domestic hot water demand of scenario B on a monthly basis.



Graph 7- The graph illustrates the amount of heat produced by the data center and actually used in scenario B on a monthly basis.

4.1.3 Scenario 1

This scenario has the same features as the basic Scenario A, but it is set in 2030.
So the district heating network is powered by the waste heat of the DC but this heat is boosted by a heat pump, creating a medium-temperature network (65/45°C).
The only things that change are the heat demand of buildings, which as a result of the refurbishment is lower, and the plant terminals to which the district heating substation is coupled, that are no more high temperature terminals.
The water temperature after the substation with the heat exchanger is directly usable as DHW.
Also in this case a water storage is provided, that is able to compensate for daily demand peaks in multi-family buildings.
The substation type scheme is provided in the image (*Figure 31*).

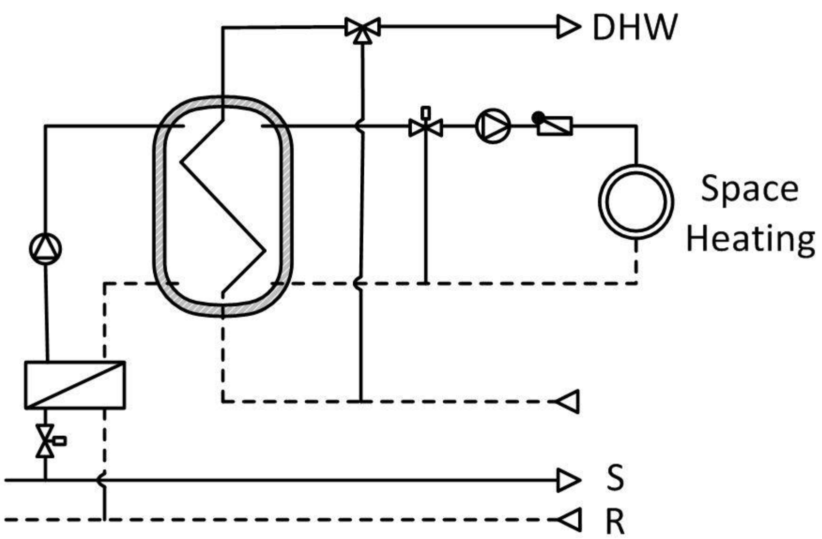
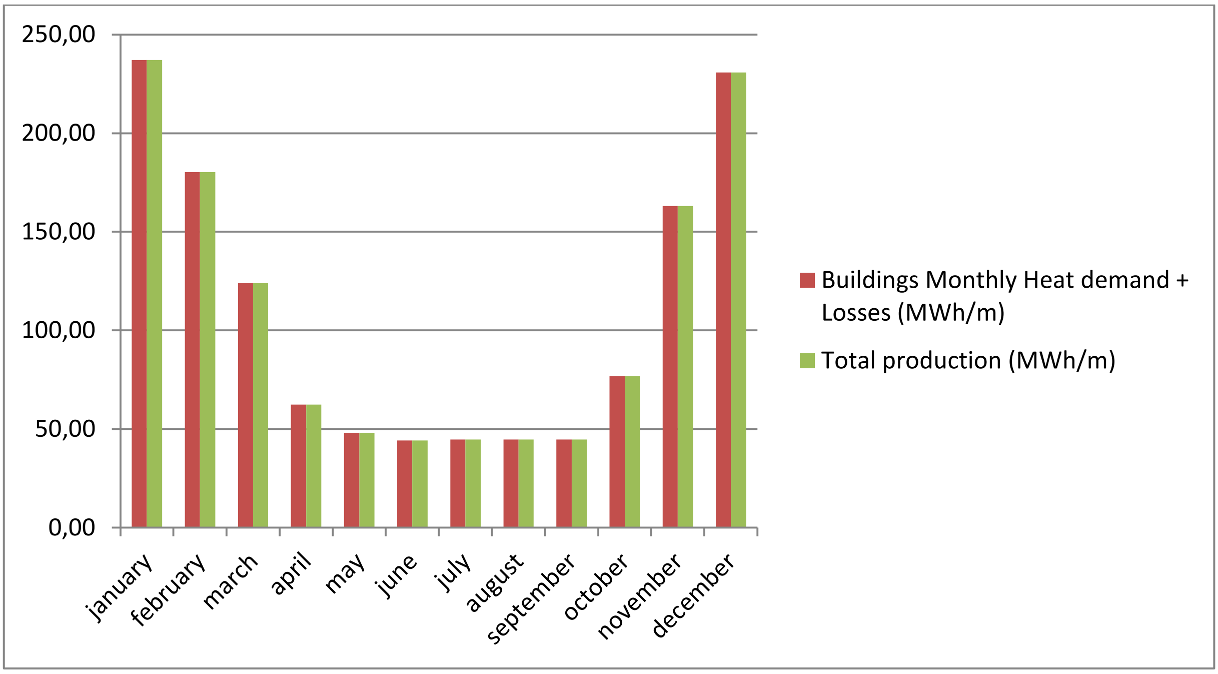


Figure 31-Type diagram of the medium-temperature district-building substation (Eicker U., 2015)

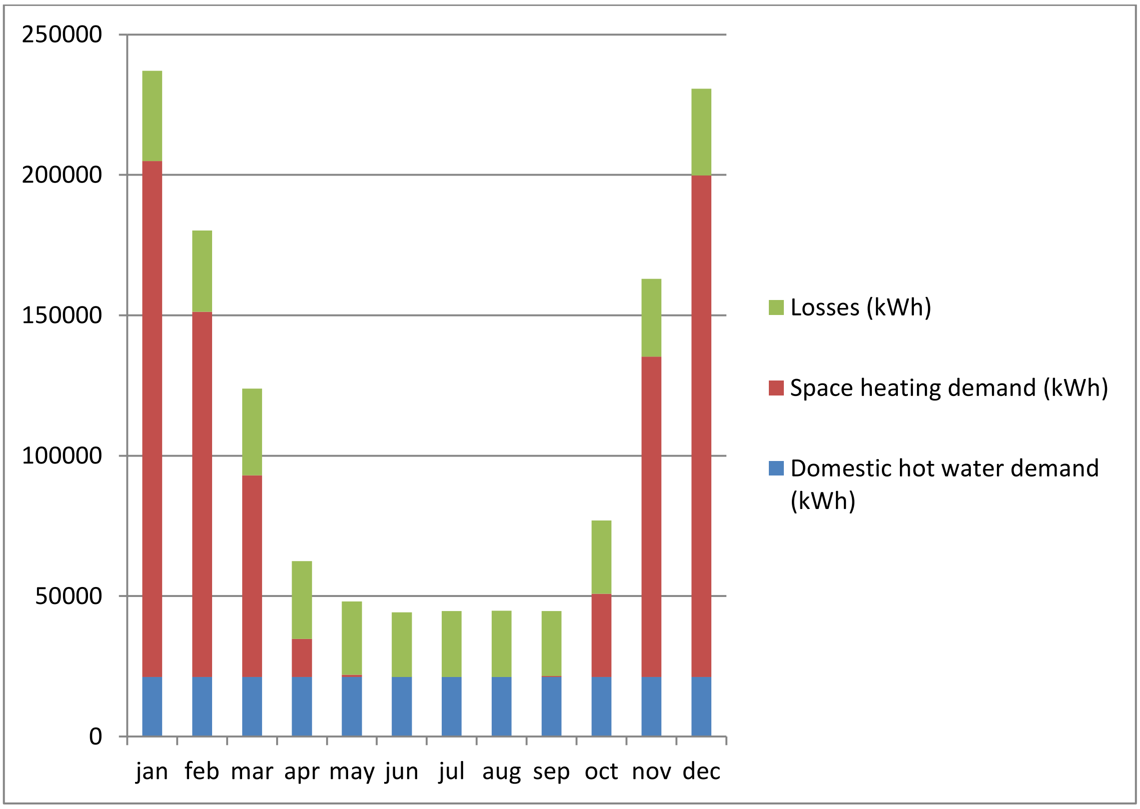
The table and the graphs below show all data on a monthly basis of this scenario, in terms of demand and production.

	Refurbishment: 100% of the 37 buildings											
	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Total monthly demand (kWh)	204949	151242	93068	34738	22034	21190	21171	21171	21587	50823	135284	199857
Domestic hot water demand (kWh)	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171
Space heating demand (kWh)	183778	130071	71897	13567	863	19	0	0	416	29652	114114	178687
Losses (kWh)	32135	29003	30858	27718	26067	23059	23585	23588	23066	26077	27728	30865
Data center production (kWh)	136896	123648	136896	132480	136896	132480	136896	136896	132480	136896	132480	136896
Utilized heat from DC (kWh)	127661	97055	66729	33630	25900	23826	24099	24101	24044	41408	87776	124235
Heat Pump production (kWh)	109423	83190	57197	28826	22200	20423	20657	20658	20609	35492	75236	106487
Total Production (kWh)	237084	180245	123926	62456	48101	44249	44756	44759	44653	76900	163012	230723

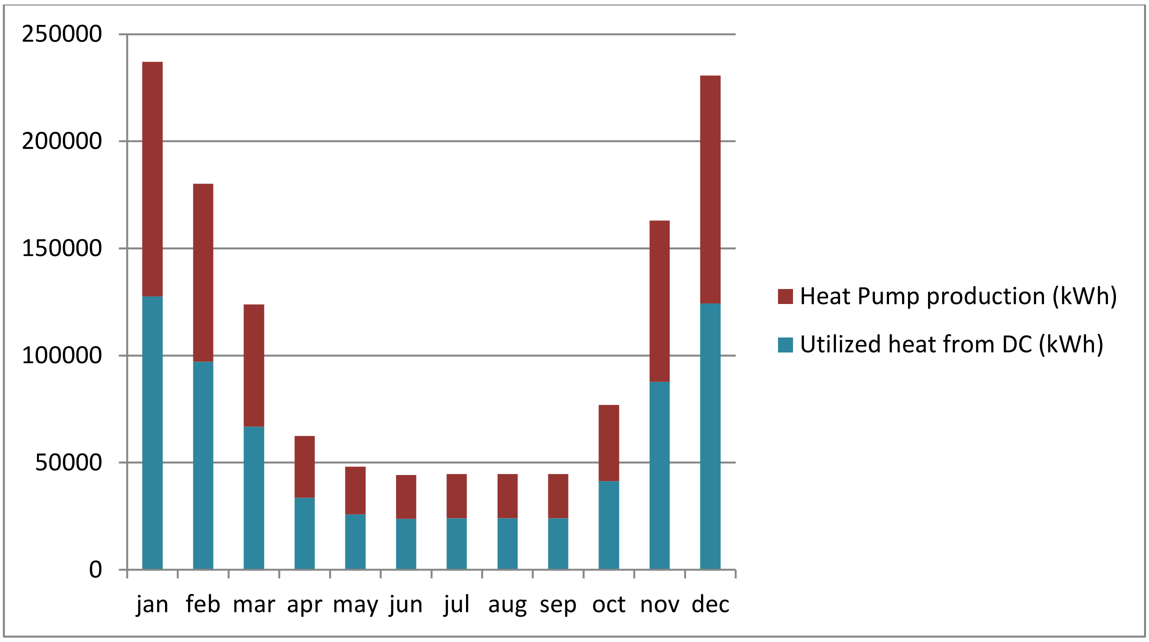
Table 5-This table summarizes the demand and heat production of Scenario 1 on a monthly basis, subdividing all the individual components of which the two are composed.



Graph 8- The graph shows the heat demand and distribution losses compared to the total heat production of scenario 1 on a monthly basis.



Graph 9- The graph illustrates the total heat demand decomposed into its three components: distribution losses, space heating demand and domestic hot water demand of scenario 1 on a monthly basis.



Graph 10- The graph shows the total production of heat decomposed into its two components: the one directly produced by the data center and the one produced by the heat pump of scenario 1 on a monthly basis.

4.1.4 Scenario 2

This scenario has the same features as the basic Scenario B, but it is set in 2030.
The low temperature district heating network (35°C/20°C) is directly powered by the waste heat of the DC.
The only things that change are the heat demand of buildings, which as a result of the refurbishment is lower, and the plant terminals to which the district heating substation is coupled, that are low temperature terminals such as raising floors,etc.
The flow temperature is however too low for DHW production. To overcome this problem, the heat exchange substation inside each building is equipped with a decentralized micro heat pump that raises temperature before DHW or during periods particularly cold where the heat demand is higher.
As in the other scenarios, the substation will be equipped with a storage in order to buffer peak loads.
The substation type scheme is provided in the image (*Figure 32*).

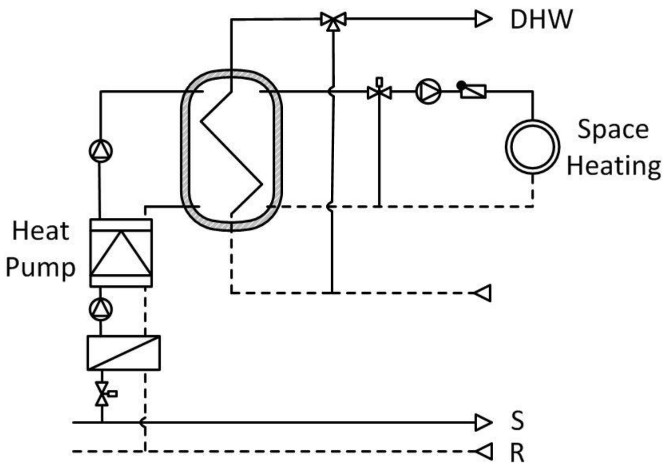
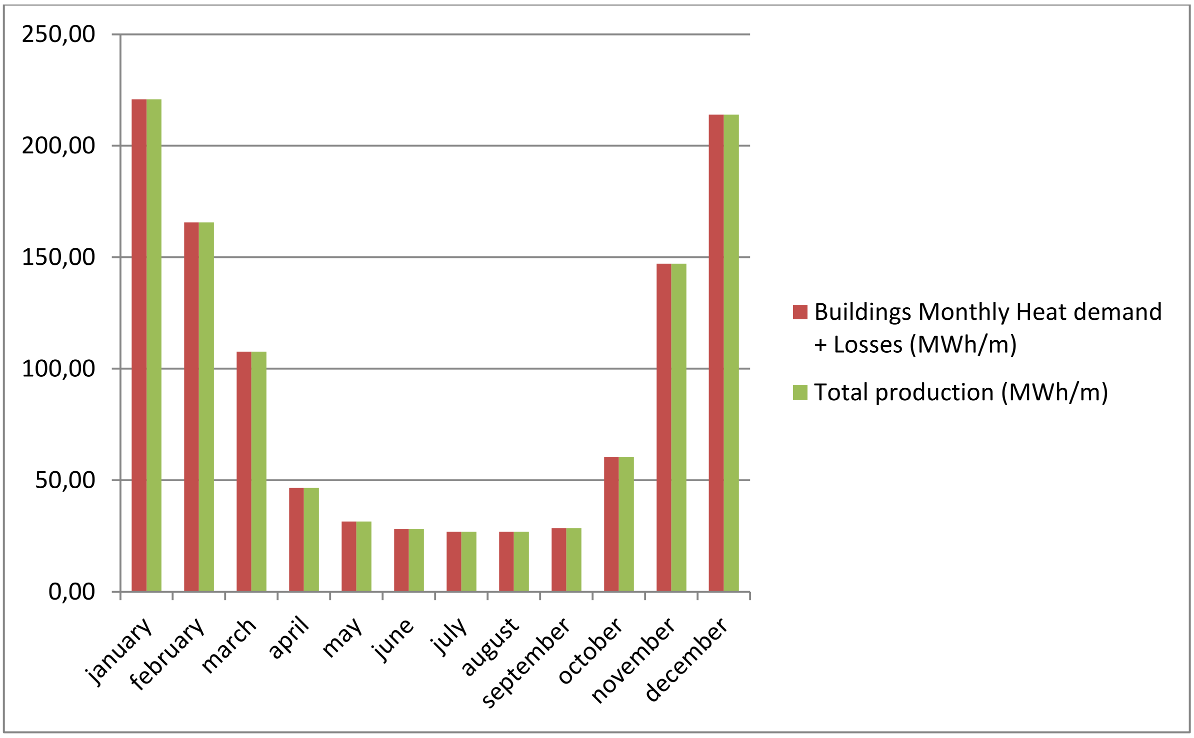


Figure 32- Type diagram of the low-temperature district-building substation (Eicker U., 2015)

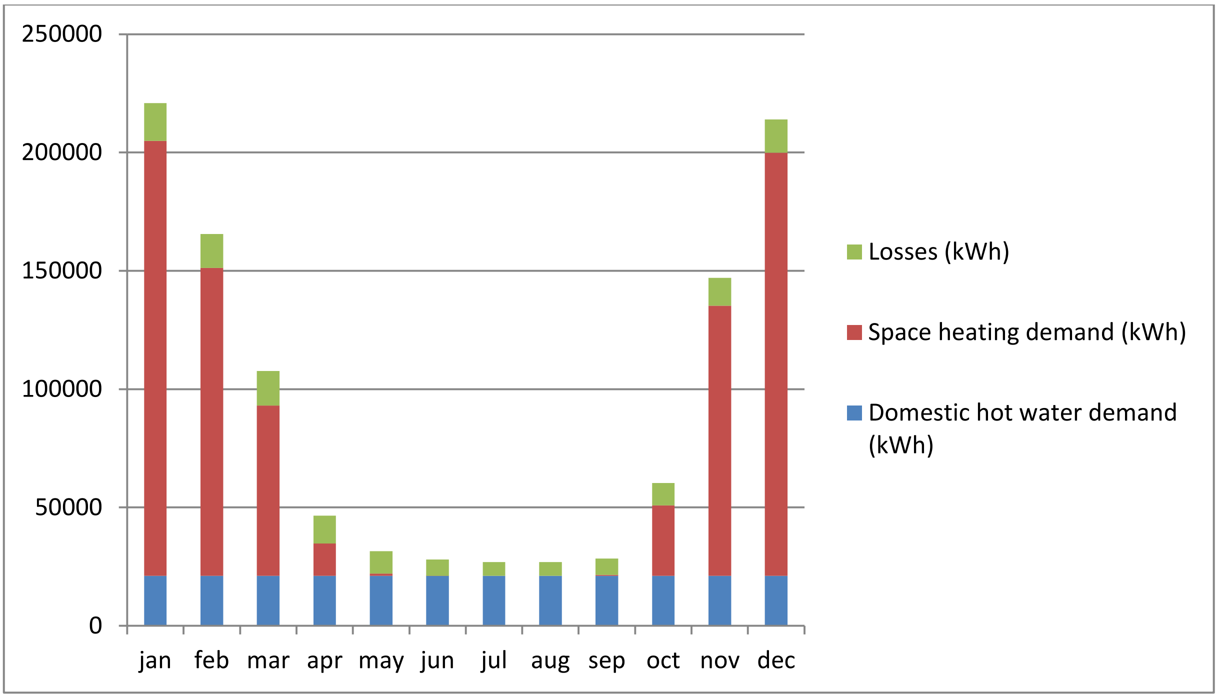
The table and the graphs below show all data on a monthly basis of this scenario, in terms of demand and production.

	Refurbishment: 100% of the 37 buildings											
	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Total monthly demand (kWh)	204949	151242	93068	34738	22034	21190	21171	21171	21587	50823	135284	199857
Domestic hot water demand (kWh)	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171	21171
Space heating demand (kWh)	183778	130071	71897	13567	863	19	0	0	416	29652	114114	178687
Losses (kWh)	15904	14342	14548	11801	9459	6852	5705	5708	6860	9470	11775	14087
Data center production (kWh)	136896	123648	136896	132480	136896	132480	136896	136896	132480	136896	132480	136896
Utilized heat from DC (kWh)	136896	123648	97845	36767	21722	18271	17105	17108	18675	50522	132480	136896
Micro heat pump production (kWh)	83957	41936	9771	9771	9771	9771	9771	9771	9771	9771	14580	77048
Total Production (kWh)	220853	165584	107616	46539	31493	28042	26876	26879	28446	60293	147060	213944

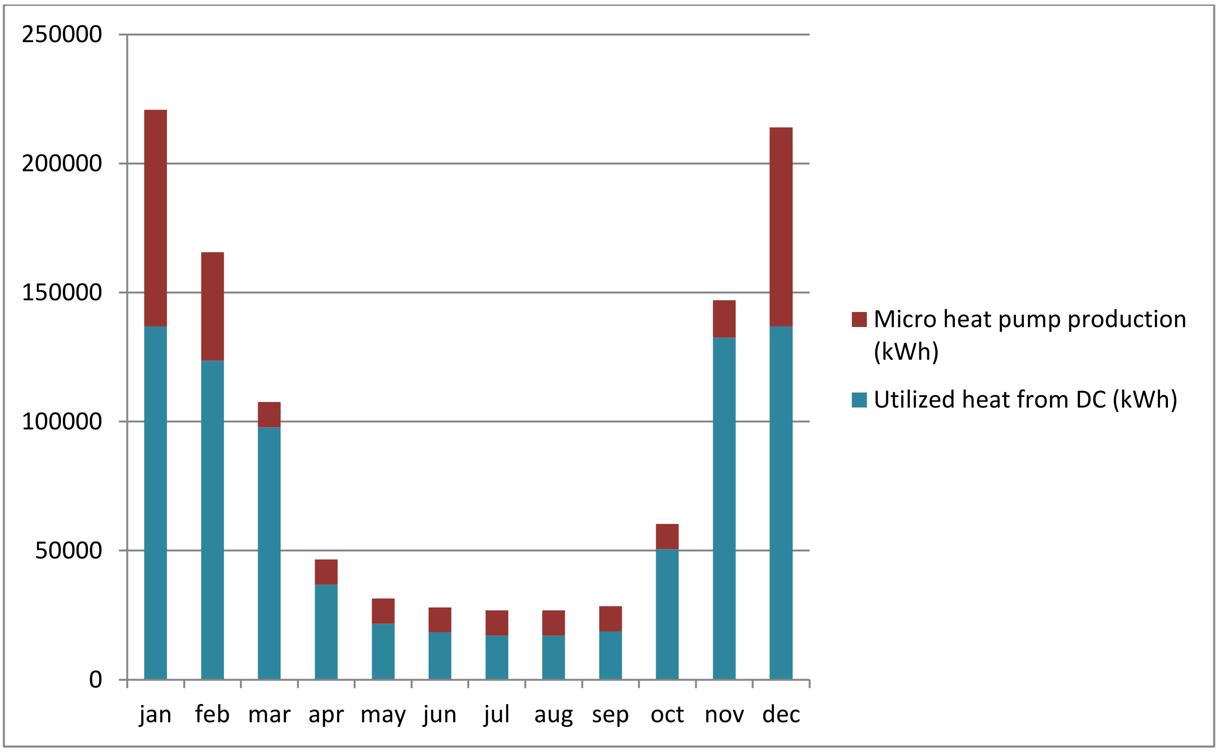
Table 6- This table summarizes the demand and heat production of Scenario 2 on a monthly basis, subdividing all the individual components of which the two are composed.



Graph 11- The graph shows the heat demand and distribution losses compared to the total heat production of scenario 2 on a monthly basis.



Graph 12- The graph illustrates the total heat demand decomposed into its three components: distribution losses, space heating demand and domestic hot water demand of scenario A on a monthly basis.



Graph 13- The graph shows the total production of heat decomposed into its two components: the one directly produced by the data center and the one produced by the decentralized micro heat pump of scenario 2 on a monthly basis.

4.2 Heat demand determination for missing buildings in SimStadt

SimStadt is a software able to simulate the demand for heat and the domestic hot water demand on a monthly and annual basis of a certain area of territory starting from a GML file containing within it a number of fundamental information.

It is sufficient that one of these information is missing so that the program can no longer simulate that part or the whole of the building, as already seen in Chapter 2.

In order to be able to determine the demand for missing buildings as a first approximation, reference was made to the data monitored in 1995 for each block and compared with the simulated data for the same block from SimStadt.

First, the specific heat demand of the missing buildings was calculated with the following formula:

$$\text{miss heat demand} = \frac{(\text{monitoring data} - \text{siulated total demand})}{\text{heated area missing buildings}}$$

To determine the heated area of each non-simulated building, firstly the footprint was measured on ArchGis and multiplied by the number of floors, and subsequently this was multiplied again by a corrective factor of 0.78.

This factor was determined to take into account the fact that the heated area does not coincide with the total area of the building.

To find the percentage of heated area compared to the total area of the missing buildings, this ratio was analyzed for all the buildings simulated and then the average reusulting ratio equal to 78% was determined.

Once the heated area is known and therefore the heat demand for heating, the demand for DHW has been calculated as a percentage of the latter. Always analyzing the simulated buildings correctly we have seen that on average the demand for DHW corresponds to about 18% of the demand for SH, so it is assumed that relationship.

In this way the total annual heat demand was obtained. To determine a demand on a monthly basis, the average monthly distribution ratios for the simulated buildings were calculated and those were applied. For DHW, on the other hand, the assumption of constant consumption during the year was maintained and therefore it was enough to divide it by 12.

This procedure was carried out for the scenarios without refurbishment because comparing the heat demand of a building with low heat demand (LowEx) with the heat demand monitored in 1995 would not have led to reliable data.

Therefore, in order to determine this demand, a corrective factor was calculated to be applied to the heat requests obtained previously. This factor has been determined and assumed equal to 0.5 always starting from the data of the simulated buildings, in the scenario without restructuring and the one with.

So in conclusion the SH application for the refurbished buildings was calculated as 50% of the total of the old demand, and then distributed on a monthly basis as seen above, while the demand for DHW was assumed equal to the past one.

A part of the results obtained for the missing buildings is shown by way of example, highlighting the only block studied containing a not simulated building (*Table 7*).

	footprint (m^2)	storey number	footprint*n storey (m^2)	heated area (m^2)	Heat demand (MWh/y)	Domestic hot water (MWh/y)
143216	146,4	4	585,7	458,5	8,75	1,58
145122	194,9	5	974,3	762,6	119,42	21,50
	195,0	5	975,0	763,2	119,50	21,51
	234,8	5	1174,1	919,0	143,91	25,90
	165,5	5	827,5	647,7	101,43	18,26
	180,7	5	903,3	707,0	110,71	19,93
	238,5	5	1192,3	933,3	146,13	26,30
	144,8	5	724,0	566,7	88,74	15,97
	106,3	3	318,9	249,6	39,09	7,04
	167,2	5	835,9	654,3	102,46	18,44
	156,3	5	781,4	611,7	95,78	17,24
	211,8	4	847,3	663,2	103,85	18,69
	211,8	4	847,3	663,2	103,85	18,69
145124	227,5	5	1137,5	890,4	38,44	6,92
	170,5	5	852,5	667,3	28,81	5,19
	185,6	5	928,0	726,4	31,36	5,64
	163,3	5	816,5	639,1	27,59	4,97
	176,4	5	882,2	690,6	29,81	5,37
	238,2	5	1191,1	932,4	40,25	7,25
	254,9	5	1274,3	997,5	43,06	7,75
143201	229,1	4	916,5	717,4	124,26	22,37
145109	264,6	4	1058,2	828,4	44,06	7,93
	272,4	4	1089,7	853,0	45,37	8,17
	272,3	4	1089,1	852,5	45,34	8,16
	272,3	4	1089,1	852,5	45,34	8,16
	233,1	5	1165,7	912,4	48,53	8,74

Table 7- Starting data obtained for the heat demand of missing buildings for scenarios without refurbishment.

4.3 Design of the grid

Once the buildings to be supplied with district heating have been chosen, with the criteria analyzed in 'Chapter 2', a branched network has been drawn that follows the road layout. The network is divided into two main grids, with larger diameters, and in secondary branches to connect to the individual housing units.

The network path is unique for all scenarios, what changes are the diameters of the pipes, the water flow rates, etc.

The single-line layout of the network is shown in the figure (*Figure 33*), even if the network is always to be understood as double, that is always composed of a delivery and return pipe.

Figure 33- Single-line diagram of the branched route representing the new micro district heating network.

Each branch has been assigned an identifying FID, in such a way as to assign it an unequivocal physical characteristics, as we will see in the following paragraphs.

This identifying FID goes from 0, i.e. from the DC to 42.

The two main ridges are represented by paths 1-22 and 26-33.

The temperature of the fluid in the network was considered constant along the path, both in the supply and in the return circuit.

4.3.1 Calculation of the design power and flow rates

Having already available the thermal energy required by each building, both on a monthly and annual basis, in order to determine the required power, it was enough to divide the required energy of the most unfavorable month for the period of operation of the plant in that month.
SimStadt provides the daily profiles of heating usage and for a deep winter day it is estimated as 16 hours.
As for DHW consumption, the program does not provide hours of daily usage, so a standard profile (*Figure 33*) provided by the literature [26] was used, which provides a peak daily consumption of about 7 hours (from 7 to 10 and from 19 to 23).

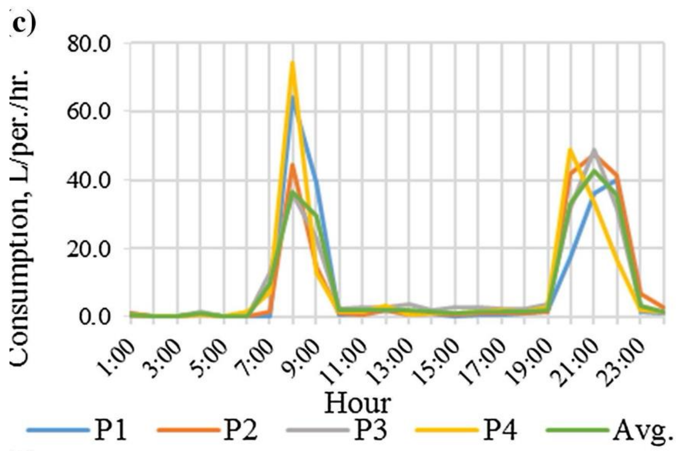


Figure 34- Curve of DHW hourly use in the day by 4 different user samples (De Santiago J. et al, 2017)

Starting from these considerations, the operating time of the heating system for the month with the highest demand, December for scenario A and B or January for scenario 1 and 2, amounted to 496 while they amounted to 217 for the consumption of DHW.
Note the hours of operation were calculated thermal powers: the one for space heating, the one for domestic hot water and the total one, with the underlying formula (3.1):

$$Q\ (kW) = \frac{E\ (kWh)}{operating\ time\ (h)} \quad (3.1)$$

For each building and for each scenario the individual maximum water flows required for SH or DHW have been calculated to keep in mind the fact that the two circuits are completely different, that of the DHW is in fact open while that of the SH is a ring closed. For the calculation, this balance equation (3.2) was set between the two systems, district heating and building:

$$m_{DH} * c_p * \Delta T_{DH} = m_{dhw} * c_p * \Delta T_{dhw} + m_{sh} * c_p * \Delta T_{sh} \quad (3.2)$$

Deriving from the most general formula (3.3):

$$Q = m * c_p * \Delta T \quad (3.3)$$

Where:

- m=flow rate (kg/s)

-cp= 4,187 kJ/(kg*°C)

-ΔT= temperature difference (°C)

All the results obtained are shown in "*Attachment III*".

4.3.2 Calculation of the utilized diameters

Once all the powers and capacities required by each building have been known, the same quantities have been determined but for the individual pipeline arms, simply adding the quantities relating to buildings belonging to the same path.

In the case of this study, in a simplified way, the outgoing water flow rates distributed along the path were assumed concentrated in the first useful node.

Subsequently, the diameters of the individual pipelines were determined.

The diameters were designed for Scenarios 1 and 2, ie those following the total renovation, and then it was verified that imposing such diameters to the basic scenarios A and B did not reach forbidden speeds.

This choice was made with a view to imagining the basic scenarios as a possible prequel to scenarios 1 and 2. From this point of view, it was preferred to size the smaller pipes, reducing the investment costs for the material, and then provide for a circulation pump that is more powerful initially but can then be easily adapted to the future waning heat demand.

In reality, as regards scenario B, the power and therefore the required flow is even lower than in scenario 2, because the district heating is only used as preheating for DHW. For this reason, it was considered necessary to size the network according to the future demand of scenario 2.

Furthermore, it must be made clear that the diameters have been determined according to the maximum required flow rate, ie calculated for the month with the highest demand. So we can say that anyway, with this assumption, the diameters will still be a little overestimated in the case of the two refurbished scenarios.

So ultimately the scenarios were designed as follows:

- **Scenarios 1 and 2**:

In this case the diameter of the pipes was determined by the underlying equation (3.4), in the hypothesis of constant velocity in the pipe.

$$D = \sqrt{\frac{4 * m}{v * \pi}} \quad (3.4)$$

Where:

-D= diameter (m)

- m=maximum flow rate (m^3/s)

- v= speed (m/s)

Typical speeds in this type of networks vary from 1 to 2 m/s, a speed of 1.3 m/s has been assumed. The diameter determined with the overlying formula is the minimum diameter that can be used but does not represent the commercial diameter. In fact, once the minimum diameter has been obtained, it is necessary to choose between the diameters in which the immediately larger diameter is obtained, determining the nominal diameter of the tube (DN). Once the nominal diameter is chosen and a manufacturer is chosen, it is possible to know the thermal transmittance of the pipe (W/mK). Following there are tables (*Table 8,9*) with the corresponding characteristics, for each branch, for the two scenarios:

Grid Design-Scenario 1							
FID	LENGHT (m)	P (kW)	Water flow (l/s)	m^3/s	D (mm)	DN (mm)	U (W/m^2K)
0	35,23	510,76	6,313	0,006313	79	90	0,206
1	135,78	227,17	2,808	0,002808	52	63	0,177
2	8,21	18,31	0,226	0,000226	15	25	0,096
3	8,1	2,68	0,033	0,000033	6	25	0,096
4	7,99	23,42	0,289	0,000289	17	25	0,096
5	6,75	20,24	0,250	0,000250	16	25	0,096
6	6,66	16,18	0,200	0,000200	14	25	0,096
7	6,92	15,52	0,192	0,000192	14	25	0,096
8	6,49	16,22	0,200	0,000200	14	25	0,096
9	6,37	18,26	0,226	0,000226	15	25	0,096
10	6,27	17,91	0,221	0,000221	15	25	0,096
11	12,01	7,29	0,090	0,000090	9	25	0,096
12	12,00	3,25	0,040	0,000040	6	25	0,096
13	11,96	3,16	0,039	0,000039	6	25	0,096
14	11,93	3,17	0,039	0,000039	6	25	0,096
15	11,95	4,00	0,049	0,000049	7	25	0,096
16	12,05	3,47	0,043	0,000043	6	25	0,096
17	12,10	3,31	0,041	0,000041	6	25	0,096
18	12,11	3,32	0,041	0,000041	6	25	0,096
19	12,34	4,03	0,050	0,000050	7	25	0,096
20	12,34	3,41	0,042	0,000042	6	25	0,096
21	13,06	3,69	0,046	0,000046	7	25	0,096
22	25,62	36,35	0,449	0,000449	21	25	0,096
23	10,70	4,20	0,052	0,000052	7	25	0,096

Grid Design-Scenario 1							
24	10,20	4,20	0,052	0,000052	7	25	0,096
25	11,16	4,77	0,059	0,000059	8	25	0,096
26	108,31	283,59	3,505	0,003505	59	63	0,177
27	5,19	29,62	0,366	0,000366	19	25	0,096
28	4,96	25,75	0,318	0,000318	18	25	0,096
29	12,10	44,94	0,555	0,000555	23	25	0,096
30	4,10	21,84	0,270	0,000270	16	25	0,096
31	19,30	23,10	0,285	0,000285	17	25	0,096
32	16,77	23,18	0,286	0,000286	17	25	0,096
33	122,82	183,29	2,265	0,002265	47	50	0,155
34	3,20	25,72	0,318	0,000318	18	25	0,096
35	3,27	23,41	0,289	0,000289	17	25	0,096
36	3,27	21,36	0,264	0,000264	16	25	0,096
37	3,34	20,89	0,258	0,000258	16	25	0,096
38	3,39	20,58	0,254	0,000254	16	25	0,096
39	3,48	20,42	0,252	0,000252	16	25	0,096
40	3,47	24,07	0,298	0,000298	17	25	0,096
41	3,46	14,00	0,173	0,000173	13	25	0,096
42	3,44	12,86	0,159	0,000159	12	25	0,096

Table 8- Physical characteristics of each branch of the medium temperature district heating network (Scenario 1).

Grid Design- Scenario 2							
FID	LENGHT (m)	P (kW)	Water flow (l/s)	m^3/s	D (mm)	DN (mm)	U (W/m2K)
0	35,23	510,76	8,417	0,0084	91	110	0,296
1	135,78	227,17	3,744	0,0037	61	63	0,177
2	8,21	18,31	0,302	0,0003	17	25	0,096
3	8,1	2,68	0,044	0,0000	7	25	0,096
4	7,99	23,42	0,386	0,0004	19	25	0,096
5	6,75	20,24	0,334	0,0003	18	25	0,096
6	6,66	16,18	0,267	0,0003	16	25	0,096
7	6,92	15,52	0,256	0,0003	16	25	0,096
8	6,49	16,22	0,267	0,0003	16	25	0,096
9	6,37	18,26	0,301	0,0003	17	25	0,096
10	6,27	17,91	0,295	0,0003	17	25	0,096
11	12,01	7,29	0,120	0,0001	11	25	0,096
12	12	3,25	0,054	0,0001	7	25	0,096
13	11,96	3,16	0,052	0,0001	7	25	0,096
14	11,93	3,17	0,052	0,0001	7	25	0,096
15	11,95	4,00	0,066	0,0001	8	25	0,096
16	12,05	3,47	0,057	0,0001	7	25	0,096
17	12,1	3,31	0,054	0,0001	7	25	0,096
18	12,11	3,32	0,055	0,0001	7	25	0,096
19	12,34	4,03	0,066	0,0001	8	25	0,096

Grid Design- Scenario 2							
20	12,34	3,41	0,056	0,0001	7	25	0,096
21	13,06	3,69	0,061	0,0001	8	25	0,096
22	25,62	36,35	0,599	0,0006	24	25	0,096
23	10,7	4,20	0,069	0,0001	8	25	0,096
24	10,2	4,20	0,069	0,0001	8	25	0,096
25	11,16	4,77	0,079	0,0001	9	25	0,096
26	108,31	283,59	4,674	0,0047	68	75	0,162
27	5,19	29,62	0,488	0,0005	22	25	0,096
28	4,96	25,75	0,424	0,0004	20	25	0,096
29	12,1	44,94	0,741	0,0007	27	32	0,121
30	4,1	21,84	0,360	0,0004	19	25	0,096
31	19,3	23,10	0,381	0,0004	19	25	0,096
32	16,77	23,18	0,382	0,0004	19	25	0,096
33	122,82	183,29	3,021	0,0030	54	63	0,177
34	3,2	25,72	0,424	0,0004	20	25	0,096
35	3,27	23,41	0,386	0,0004	19	25	0,096
36	3,27	21,36	0,352	0,0004	19	25	0,096
37	3,34	20,89	0,344	0,0003	18	25	0,096
38	3,39	20,58	0,339	0,0003	18	25	0,096
39	3,48	20,42	0,336	0,0003	18	25	0,096
40	3,47	24,07	0,397	0,0004	20	25	0,096
41	3,46	14,00	0,231	0,0002	15	25	0,096
42	3,44	12,86	0,212	0,0002	14	25	0,096

Table 9- Physical characteristics of each branch of the low temperature district heating network (Scenario 2).

- **Scenarios A and B**:

Contrary to what was seen for scenarios 1 and 2, this time the diameters were set and the speeds in the pipelines with the inverse formula (3.5) were calculated:

$$v = \frac{4 * m}{D^2 * \pi} \quad (3.5)$$

Where:

-D= diameter (m)

- m= flow rate (m^3/s)

- v= speed (m/s)

The assumed diameters correspond to the nominal diameters determined in the scenarios 1 and 2.
Finally, it was checked that at no point exceeded 2.0 m/s speed.
Following there are tables (*Table 8,9*) with the corresponding characteristics, for each branch, for the two scenarios:

Grid Design - Scenario A							
FID	LENGHT (m)	P (kW)	Water flow (l/s)	m^3/s	v (m/s)	DN (mm)	U (W/m^2K)
0	35,23	862,28	10,658	0,01066	1,68	90	0,206
1	135,78	397,51	4,913	0,00491	1,58	63	0,177
2	8,21	35,17	0,435	0,00043	0,89	25	0,096
3	8,1	5,54	0,069	0,00007	0,14	25	0,096
4	7,99	33,45	0,413	0,00041	0,84	25	0,096
5	6,75	37,30	0,461	0,00046	0,94	25	0,096
6	6,66	31,22	0,386	0,00039	0,79	25	0,096
7	6,92	19,60	0,242	0,00024	0,49	25	0,096
8	6,49	28,74	0,355	0,00036	0,72	25	0,096
9	6,37	29,96	0,370	0,00037	0,75	25	0,096
10	6,27	31,02	0,383	0,00038	0,78	25	0,096
11	12,01	15,38	0,190	0,00019	0,39	25	0,096
12	12	6,23	0,077	0,00008	0,16	25	0,096
13	11,96	6,03	0,075	0,00007	0,15	25	0,096
14	11,93	4,04	0,050	0,00005	0,10	25	0,096
15	11,95	7,62	0,094	0,00009	0,19	25	0,096
16	12,05	6,59	0,081	0,00008	0,17	25	0,096
17	12,1	5,95	0,073	0,00007	0,15	25	0,096
18	12,11	5,96	0,074	0,00007	0,15	25	0,096
19	12,34	7,68	0,095	0,00009	0,19	25	0,096
20	12,34	4,95	0,061	0,00006	0,12	25	0,096
21	13,06	7,06	0,087	0,00009	0,18	25	0,096
22	25,62	44,19	0,546	0,00055	1,11	25	0,121
23	10,7	7,44	0,092	0,00009	0,19	25	0,096
24	10,2	7,09	0,088	0,00009	0,18	25	0,096
25	11,16	6,49	0,080	0,00008	0,16	25	0,096
26	108,31	464,77	5,744	0,00574	1,84	63	0,177
27	5,19	39,50	0,488	0,00049	1,00	25	0,096
28	4,96	45,60	0,564	0,00056	1,15	25	0,096
29	12,1	79,14	0,978	0,00098	1,99	25	0,096
30	4,10	39,36	0,487	0,00049	0,99	25	0,096
31	19,30	39,77	0,492	0,00049	1,00	25	0,096
32	16,77	23,18	0,286	0,00029	0,58	25	0,096
33	122,82	300,54	3,715	0,00371	1,89	50	0,155
34	3,2	49,35	0,610	0,00061	1,24	25	0,096
35	3,27	45,31	0,560	0,00056	1,14	25	0,096
36	3,27	30,30	0,375	0,00037	0,76	25	0,096
37	3,34	30,35	0,375	0,00038	0,76	25	0,096
38	3,39	39,37	0,487	0,00049	0,99	25	0,096
39	3,48	28,79	0,356	0,00036	0,73	25	0,096
40	3,47	32,91	0,407	0,00041	0,83	25	0,096
41	3,46	21,82	0,270	0,00027	0,55	25	0,096
42	3,44	22,35	0,276	0,00028	0,56	25	0,096

Table 10- Physical characteristics of each branch of the medium temperature district heating network (Scenario A).

Grid Design - Scenario B							
FID	LENGHT (m)	P (kW)	Water flow (l/s)	m^3/s	v (m/s)	DN (mm)	U (W/m2K)
0	35,23	98,03	1,616	0,0016	0,17	110	0,296
1	135,78	29,76	0,490	0,0005	0,16	63	0,177
2	8,21	2,90	0,048	0,0000	0,10	25	0,096
3	8,1	0,61	0,010	0,0000	0,02	25	0,096
4	7,99	4,28	0,071	0,0001	0,14	25	0,096
5	6,75	3,68	0,061	0,0001	0,12	25	0,096
6	6,66	3,20	0,053	0,0001	0,11	25	0,096
7	6,92	4,47	0,074	0,0001	0,15	25	0,096
8	6,49	3,20	0,053	0,0001	0,11	25	0,096
9	6,37	3,71	0,061	0,0001	0,12	25	0,096
10	6,27	3,34	0,055	0,0001	0,11	25	0,096
11	12,01	1,00	0,017	0,0000	0,03	25	0,096
12	12	0,51	0,008	0,0000	0,02	25	0,096
13	11,96	0,49	0,008	0,0000	0,02	25	0,096
14	11,93	0,49	0,008	0,0000	0,02	25	0,096
15	11,95	0,64	0,010	0,0000	0,02	25	0,096
16	12,05	0,55	0,009	0,0000	0,02	25	0,096
17	12,1	0,51	0,008	0,0000	0,02	25	0,096
18	12,11	0,51	0,008	0,0000	0,02	25	0,096
19	12,34	0,64	0,011	0,0000	0,02	25	0,096
20	12,34	0,56	0,009	0,0000	0,02	25	0,096
21	13,06	0,57	0,009	0,0000	0,02	25	0,096
22	25,62	6,09	0,100	0,0001	0,20	25	0,096
23	10,7	0,72	0,012	0,0000	0,02	25	0,096
24	10,2	0,71	0,012	0,0000	0,02	25	0,096
25	11,16	0,70	0,012	0,0000	0,02	25	0,096
26	108,31	68,27	1,125	0,0011	0,25	75	0,162
27	5,19	7,57	0,125	0,0001	0,25	25	0,096
28	4,96	5,93	0,098	0,0001	0,20	25	0,096
29	12,1	8,24	0,136	0,0001	0,17	32	0,121
30	4,1	3,92	0,065	0,0001	0,13	25	0,096
31	19,3	4,32	0,071	0,0001	0,15	25	0,096
32	16,77	3,96	0,065	0,0001	0,13	25	0,096
33	122,82	34,33	0,566	0,0006	0,18	63	0,177
34	3,2	4,39	0,072	0,0001	0,15	25	0,096
35	3,27	3,66	0,060	0,0001	0,12	25	0,096
36	3,27	3,86	0,064	0,0001	0,13	25	0,096
37	3,34	3,62	0,060	0,0001	0,12	25	0,096
38	3,39	3,40	0,056	0,0001	0,11	25	0,096
39	3,48	3,79	0,063	0,0001	0,13	25	0,096
40	3,47	5,77	0,095	0,0001	0,19	25	0,096
41	3,46	3,69	0,061	0,0001	0,12	25	0,096
42	3,44	2,13	0,035	0,0000	0,07	25	0,096

Table 11- Physical characteristics of each branch of the low temperature district heating network (Scenario B).

4.3.3 Pipes used in the project

The pipes chosen for the project of the new micro district heating network belong to the Rauthermex line of the German company Rehau.
This great company deals with studying and creating solutions regarding all the energy aspects of a building, from plants to insulation materials.
is a company that is particularly attentive to environmental sustainability and to the research of reducing CO2 emissions.
In addition to this the products it offers present excellent performance at very competitive costs.
The pipes used, single-pipe with same diameter for delivery and recovery, consist of high-pressure cross-linked polyethylene (according to DIN 16892/93), while the thermal insulation is made of polyurethane plus an additional coating layer.
For these pipelines, the service life is estimated at 50 years.
All data and prices of the pipes are provided by Rehau web site [27].

Figure 35-Picture of the utilized pipe, UNO-Rauthermex (https://www.rehau.com)

4.3.4 Final characteristics of the network

In conclusion then the network provides two design options: the one for scenarios A and 1, ie in the presence of a heat pump that boost the temperature of the waste heat of the DC to create a grid at medium temperature, or that of the scenarios B and 2, or scenarios with low temperature network.
The length of each single network segment was easily determined from the file in ArcGis.
Once the path was drawn with linear features, a layer called 'grid' was created. Each feature was automatically assigned an identifying FID to which the corresponding measurement was subsequently assigned, determined with the 'measure feature' tool.
The external diameter parameter (DE) associated with a corresponding DN, necessary for the subsequent determination of thermal losses, was taken directly from the technical data sheet provided in the web site [27].
The final characteristics of the two district heating network variants are shown below (*Tables 12,13*).

Grid caratteristics - A and 1				
FID	LENGHT (m)	DN (mm)	U (W/m^2K)	D_{ext} (mm)
0	35,23	90	0,206	163
1	135,78	63	0,177	128
2	8,21	25	0,096	93
3	8,10	25	0,096	93
4	7,99	25	0,096	93
5	6,75	25	0,096	93
6	6,66	25	0,096	93
7	6,92	25	0,096	93
8	6,49	25	0,096	93
9	6,37	25	0,096	93
10	6,27	25	0,096	93
11	12,01	25	0,096	93
12	12,00	25	0,096	93
13	11,96	25	0,096	93
14	11,93	25	0,096	93
15	11,95	25	0,096	93
16	12,05	25	0,096	93
17	12,10	25	0,096	93
18	12,11	25	0,096	93
19	12,34	25	0,096	93
20	12,34	25	0,096	93
21	13,06	25	0,096	93
22	25,62	25	0,096	93
23	10,70	25	0,096	93
24	10,20	25	0,096	93
25	11,16	25	0,096	93
26	108,31	63	0,177	93
27	5,19	25	0,096	93
28	4,96	25	0,096	93
29	12,10	25	0,096	93
30	4,10	25	0,096	93
31	19,30	25	0,096	93
32	16,77	25	0,096	93
33	122,82	50	0,155	128
34	3,20	25	0,096	93
35	3,27	25	0,096	93
36	3,27	25	0,096	93
37	3,34	25	0,096	93
38	3,39	25	0,096	93
39	3,48	25	0,096	93
40	3,47	25	0,096	93
41	3,46	25	0,096	93
42	3,44	25	0,096	93

Table 12-Design features of the medium-temperature district heating network (Scenarios A and 1).

Grid caratteristics - B and 2				
FID	LENGHT (m)	DN (mm)	U (W/m^{2}K)	D_{ext} (mm)
0	35,23	110	0,296	163
1	135,78	63	0,177	128
2	8,21	25	0,096	93
3	8,10	25	0,096	93
4	7,99	25	0,096	93
5	6,75	25	0,096	93
6	6,66	25	0,096	93
7	6,92	25	0,096	93
8	6,49	25	0,096	93
9	6,37	25	0,096	93
10	6,27	25	0,096	93
11	12,01	25	0,096	93
12	12,00	25	0,096	93
13	11,96	25	0,096	93
14	11,93	25	0,096	93
15	11,95	25	0,096	93
16	12,05	25	0,096	93
17	12,10	25	0,096	93
18	12,11	25	0,096	93
19	12,34	25	0,096	93
20	12,34	25	0,096	93
21	13,06	25	0,096	93
22	25,62	25	0,096	93
23	10,70	25	0,096	93
24	10,20	25	0,096	93
25	11,16	25	0,096	93
26	108,31	75	0,162	163
27	5,19	25	0,096	93
28	4,96	25	0,096	93
29	12,10	32	0,121	93
30	4,10	25	0,096	93
31	19,30	25	0,096	93
32	16,77	25	0,096	93
33	122,82	63	0,177	128
34	3,20	25	0,096	93
35	3,27	25	0,096	93
36	3,27	25	0,096	93
37	3,34	25	0,096	93
38	3,39	25	0,096	93
39	3,48	25	0,096	93
40	3,47	25	0,096	93
41	3,46	25	0,096	93
42	3,44	25	0,096	93

Table 13- Design features of the low-temperature district heating network (Scenarios B and 2).

4.4 Thermal losses determination

Temperature difference between the thermal carrier fluid in the network and the surrounding environment, ground or air, causes a dissipation of heat which is detrimental to the distribution system. Therefore, it must be designed in such a way as to be able to compensate for energy losses along the way.

A good way to reduce such dispersions is certainly to increase and improve the insulation layer between the pipe and the ground, lowering the thermal conductivity λ (W/m^2K).

Nevertheless, since these losses depend on the temperature difference between the fluid and the ground, they can also be reduced by reducing this difference; therefore reducing the temperature of the heat transfer fluid.

In fact, as can be seen from the formula below (3.6) [28], heat losses mainly depend on three parameters: the difference in temperature, the total thermal resistance of the network and the length of the track.

$$Q = \frac{T_i - T_g}{\sum R} * L \quad (3.6)$$

The term in the denominator of this equation depends on many factors, but above all on the type of the layout chosen for the network.

In general, however, we can say that this represents the resistance to the passage of heat between the inside of the tube and the external environment and consists mainly of four contributions.

The first represents the resistance to heat exchange by convection that occurs between the fluid and the pipe wall.

The second represents the resistance to heat exchange by conduction between all the layers of which the tube is made.

The third always represents resistance to a heat exchange by convection, but this time between the last layer of coating of the tube and the ground or the air, depending on the method of installation.

Lastly, the last contribution takes into account the presence of another adjacent pipe, whose thermal losses reduce the losses of the pipe in question.

In the case of this project, it was decided to install two separate pipes, one for the delivery and one for the recovery, but with the same diameter.

The detailed analysis of the individual thermal resistance contributions valid for this model are detailed in the following paragraphs.

4.4.1 Ground temperature

As seen in the formula at the beginning of the chapter, the heat dispersed by a pipe traversed by a certain heat transfer fluid is influenced by the difference in temperature that exists between the fluid and the environment outside the pipe.

If the piping is laid outdoor this will be subject to continuous changes in temperature due to the fact that, even during the day, the air temperature varies greatly.

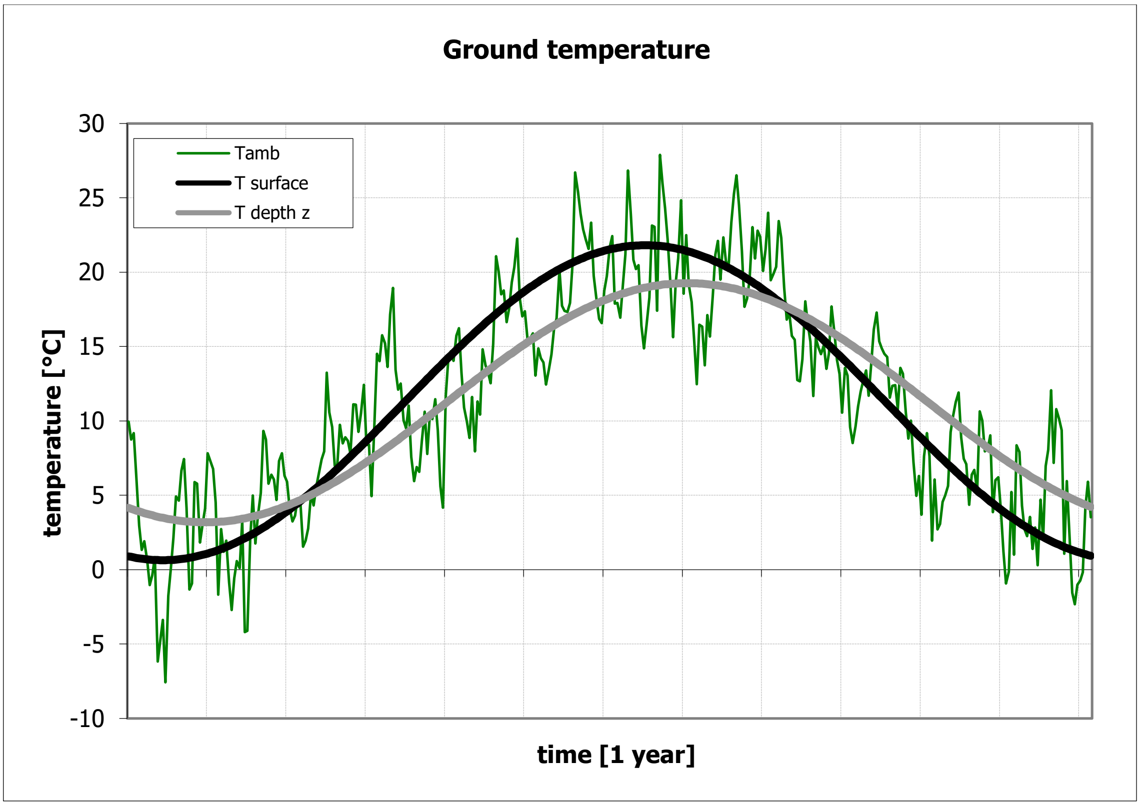
On the other hand, if the pipeline is laid in an underground excavation, this variability is very attenuated, the variations are more of a seasonal nature. Even, if the installation depth increases, the soil temperature tends to stabilize on a practically constant value during the year.

This is due to the fact that the first layer of soil still tends to be influenced by climatic phenomena such as rains, snow, outdoor air temperature, solar irradiation, humidity but also by the chemical and physical composition of the soil itself. Over 9-12 m the influence of these factors is attenuated and the temperature becomes practically constant throughout the year [29].

The installation depths of district heating pipes are still in the superficial layer of soil, immediately below the asphalt bedding layers if we are in the city, at an average depth that can vary between 60 and 100 cm. This is to facilitate and make less expensive the laying and subsequent maintenance / repair.

For these reasons we need a precise model of soil behavior, the area of intervention, which shows the average monthly or daily temperatures of the soil as the depth variation.

This spreadsheet for Stuttgart was directly provided to me by the department and by inserting in the model the desired laying depth (90 cm) we obtained (*Graph 14, Table 14*):



Graph 14- The graph shows the annual temperature variation of the outdoor air, the surface layer of the ground and the temperature at a depth of 90 cm.

Monthly Mean Ground Temperatures	
	[°C]
JAN	3,51
FEB	3,55
MAR	5,55
APR	9,10
MAI	13,23
JUN	16,82
JUL	18,89
AUG	18,89
SEP	16,81
OCT	13,21
NOV	9,09
DEC	5,54

Table 14- Average monthly soil temperatures at 90 cm depth in Stuttgart.

These temperatures were used to determine the thermal losses of the network in the different scenarios, with heat pump and without, on a monthly basis.

4.4.2 Calculation model for pipes of equal diameter

As anticipated at the beginning of the chapter the heat losses of a pipe are influenced among other factors also by the presence of another adjacent pipe. In this case, the calculation formulas used will be explained considering two underground pipes, one of delivery and one of recovery, of the same diameter ($U_{12} = U_{21}$) so the same thermal resistance R_{12}. This condition allows a considerable simplification of the loss calculations.

Specifically, we analyze the contributions of the summation to the denominator of the formula (3.6) in this specific case.

The first term represents the resistance to heat exchange of the tube, it includes both the convective contribution (3.7) between fluid and tube and the conductive contribution (3.8) between the layers of the pipe:

$$R_{conv}=\frac{1}{\alpha_i * \pi * d_i} \quad (3.7) \qquad\qquad R_{cond}=\frac{1}{2\pi * \lambda_i} * \ln\frac{d_{j+1}}{d_j} \quad (3.8)$$

Which in the case of the pipe becomes (3.9) [28]:

$$R_{pipe}=\frac{1}{\alpha_i * \pi * d_i} + \frac{1}{2\pi * \lambda_t} * \ln\frac{D}{d_i} + \frac{1}{2\pi * \lambda_{ins}} * \ln\frac{D_{ins}}{D} + \frac{1}{2\pi * \lambda_p} * \ln\frac{D_e}{D_{ins}} \quad (3.9)$$

The subscripts of which refer to the following figure (*Figure 36*):

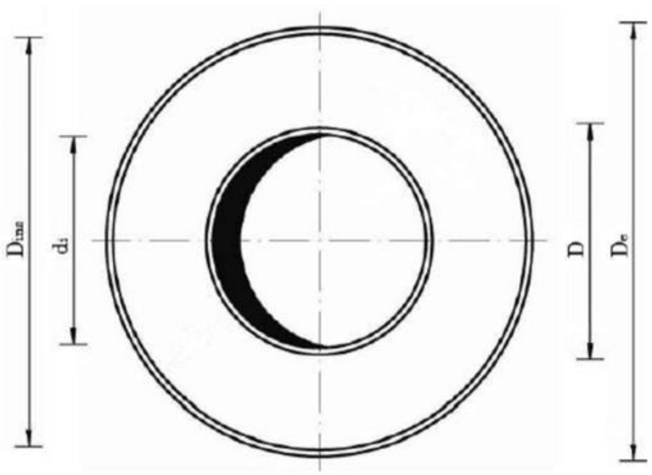


Figure 36-Image of the pipe section (Scanagatta F.,Master thesis, 2016)

In this specific case, the term R_{pipe} has been not calculated analytically because the pipe manufacturer directly provides the U-value of the whole pipe according to the diameter so it was enough to reverse this value (see *Table 12/13*).

The second term (3.10) represents the thermal resistance offered by the ground. This correlation depends on the thermal conductivity of the soil λ_f, on the equivalent thermal resistance α_{eq}, on the external diameter D_e of the pipe and on the installation depth H:

$$R_{Ground}=\frac{1}{2\pi*\lambda_f}*\cos\frac{1}{h}*(\frac{2*H}{D_e}+\alpha_{eq}\lambda_f) \quad (3.10)$$

The last component is the one that represents the thermal resistance due to the presence of another pipe adjacent to the considered pipe. This relationship (3.11), in the case of pipes of the same diameter, is very simplified because $U_{12} = U_{21}$ and so the two terms are balanced. What remains in the relationship is the dependence on the thermal conductivity of the soil λ_f, the depth of installation H and the distance between the two pipes C:

$$R_{12}=\frac{1}{2\pi*\lambda_f}*\ln(1+\frac{(2*H)^2}{C^2}) \quad (3.11)$$

Where :

$$H = h + \frac{D_e}{2}$$

$$C = c + \frac{D_e}{2}$$

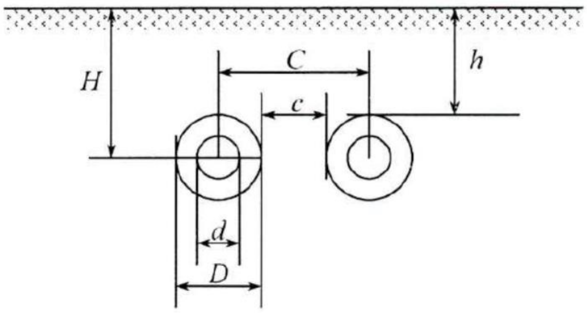


Figure 37- Piping installation diagram (Scanagatta F.,Master thesis, 2016)

All the values assumed for the two different networks, the one with the heat pump (*Table 15*) and the low temperature one (*Table 16*) are shown in the tables below:

Scenarios A and 1	
Ds=Dr	U12=U21
λ_f (W/m^{2}K)	1,6
h (m)	0,8
α_{eq} (m^{2}k/W)	0,0685
c (m)	0,2
T_s (°C)	65
T_r (°C)	10

Table 15-Assumed values for scenarios with MTDH

Scenarios B and 2	
Ds=Dr	U12=U21
λ_f (W/m^{2}K)	1,6
h (m)	0,8
α_{eq} (m^{2}k/W)	0,0685
c (m)	0,2
T_s (°C)	35
T_r (°C)	20

Table 16- Assumed values for scenarios with LTDH

After assuming these values, it was possible to calculate the thermal power dissipated per unit of length (W/m) for the supply and return pipes according to the formulas (3.12) and (3.13) below. Finally, the two contributions were added together to obtain the total dissipated heat output (3.14).

$$q_s = \frac{(T_s - T_g) * (R_g + R_{pipe}) - (T_r - T_g) * R_{12}}{(R_g + R_{pipe}) * (R_g + R_{pipe}) - R_{12}^2} \quad (3.12)$$

$$q_r = \frac{(T_r - T_g) * (R_g + R_{pipe}) - (T_s - T_g) * R_{12}}{(R_g + R_{pipe}) * (R_g + R_{pipe}) - R_{12}^2} \quad (3.13)$$

$$q_{tot} = q_s + q_r \quad (3.14)$$

4.4.3 Results

The total specific dissipated power was calculated for the two network variants, for each month of the year, for each segment of the network characterized by a specific FID.

To find the total power (kW) it was sufficient to multiply this value for the length of the section considered and finally multiplying this value for the operating hours of the plant for each month was calculated the dispersed thermal energy (kWh).

All detailed results are provided in the "*Attachment IV*".

Following is attached a table summarizing the total thermal losses of the network on a monthly basis, for the two variants (Scenarios A and 1 or Scenarios Be 2):

Thermal Losses-Scenario A/1			
	kWh	MWh	
January	32135	32,13	
February	29003	29,00	
March	30858	30,86	
April	27718	27,72	
May	26067	26,07	
June	23059	23,06	
July	23585	23,59	
August	23588	23,59	
September	23066	23,07	
October	26077	26,08	
November	27728	27,73	percentage of thermal losses
December	30865	30,87	
Total	323750	323,75	
Demand Scenario A	1607662	1607,66	17%
Demand Scenario 1	977112	977,11	25%

Table 17- Thermal losses in kWh, in MWh on a monthly basis of the MTDH network and percentage of such losses on total heat demand.

Thermal Losses-Scenario B/2			
	kWh	MWh	
January	15904	15,90	
February	14342	14,34	
March	14548	14,55	
April	11801	11,80	
May	9459	9,46	
June	6852	6,85	
July	5705	5,71	
August	5708	5,71	
September	6860	6,86	
October	9470	9,47	
November	11775	11,78	percentage of thermal losses
December	14087	14,09	
Total	126513	126,51	
Demand Scenario b	255272	255,27	33%
Demand Scenario 2	977112	977,11	11%

Table 18- Thermal losses in kWh, in MWh on a monthly basis of the LTDH network and percentage of such losses on total heat demand.

4.5 Hydraulic losses determination

A fluid flowing inside a pipe is subject to hydraulic losses as well as thermal energy losses. The pressure drops can be distributed (major head losses) along the path, ie energy losses due to the viscous friction that exists between the fluid particles and the scabrous material that constitutes the tube, or concentrated losses (minor head losses), or losses of energy due to impacts between the particles which occur in the case of certain changes along the route (curves, changes in pipe section, etc.).

The magnitude of these losses depends on many parameters but certainly depends first on the type of motion that the fluid has inside the conduit.

The fluid may be in a laminar regime and therefore be described as a set of fluid threads all running parallel to the pipe. Or the fluid can move in a cotic way, generating vortexes inside the tube, in this case the motion is called turbulent. The determination of these states of motion depends on many factors including fluid velocity, tube diameter, viscosity, etc.

However there is a very simple method to distinguish them, the detraction of the dimensionless Reynolds number:

$$\mathrm{Re} = \frac{\rho \cdot v \cdot D}{\mu} = \frac{v \cdot D}{\nu} \quad (3.15)$$

Where:

-ρ= fluid density (kg/m^3)

-v= mean flow velocity (m/s)

-D= internal diameter of the pipe (m)

-μ= dynamic viscosity of the fluid (kg/(m*s))

-ν= kinematic viscosity of the fluid (m^2/s), assumed $1{,}01 \cdot 10^{-6}\ \mathrm{m^2/s}$.

Being known, for each stroke, the flow rate m expressed in m^3/s, the installed diameter and the kinematic viscosity ν, the (3.15) becomes:

$$\mathrm{Re} = \frac{4 \cdot m}{\pi \cdot D \cdot \nu} \quad (3.16)$$

If the number of Raynolds is less than 2500 then the motion is laminar, if instead it exceeds 3000 the motion is turbulent. In the interim between these two values, it is clear that the motion is transitional, hence neither laminar nor even truly turbulent.

4.5.1 Calculation model

Once the state of motion is known it is possible to calculate the major and minor head losses.
In this case, the network was assimilated to a long conduct and therefore only the major losses, which are the largest contribution, were calculated analytically.
The major losses can be calculated with the following formula (3.17):

$$\Delta H_H = J \cdot L \quad (3.17)$$

Where:

-J= hydraulic slope, defined by the formula (3.18)

-L= length of the pipe section (m)

$$J = \frac{\lambda \cdot v^2}{2g} \quad (3.18)$$

Where:

-v= mean flow velocity (m/s)

-g= the local acceleration due to gravity ($9{,}806\ \mathrm{m/s^2}$)

-λ= friction factor or Darcy factor, function of a series of parameters depending on the nature of the motion. In detail:

$\lambda = \frac{64}{Re}$ (3.19) for laminar motion

$\frac{1}{\sqrt{\lambda}}$ = -2log($\frac{\varepsilon}{3,71*d_i}$*$\frac{2,51}{Re*\sqrt{\lambda}}$) (3.20) for turbulent motion

Where:

-ε= pipe absolute roughness of the pipe (mm)

- $\frac{\varepsilon}{d_i}$ = pipe relative roughness

The absolute roughness of a pipe depends not only on the material of which it is constituted but also on the degree of wear of the pipe.

The plastic materials are the least rough, while the ceramic materials and concrete are the most rough. Similarly, the newly installed pipes have the lowest roughness associated with their material and going on over the years of use such roughness tends to grow due to deposits or encrustations.

In the case in question, a very low absolute roughness equal to 0.007 mm was assumed because we consider a plastic tube with a low risk of wear.

We have also to note that in case of laminar motion the formula that defines λ is given in closed form, but in the case of turbulent motion it is given in open form, therefore λ appears to both members of the equation and cannot be calculated univocally. To define this parameter there are several ways, including the Moody diagram (*Figure 38*) that allows a graphical definition of the parameter, or simplistic formulas or iterative processes.

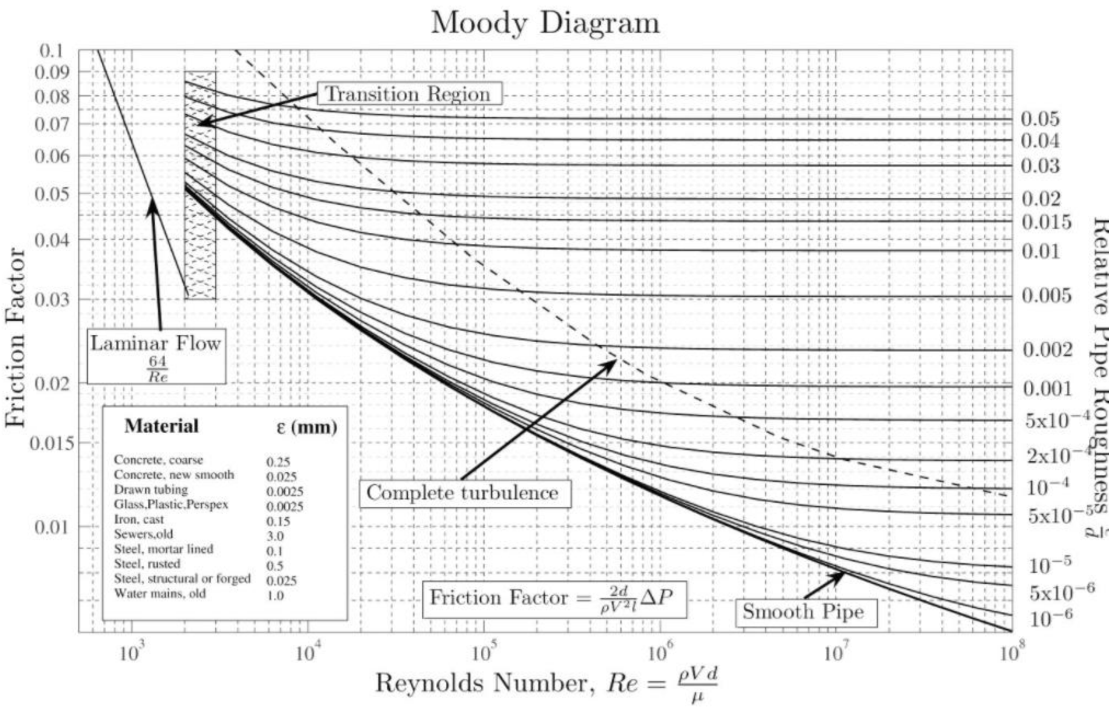


Figure 38- Moody diagram for the graphic determination of the friction factor λ.

In this case, having an Excel spreadsheet available, λ was determined using the objective search

function, imposing that the difference between the right and left contribution were equal to zero.
The hydraulic slope J was calculated only for the return pipe and then considered equal for the supply pipe. This is because it has been estimated that the variation of water temperature does not significantly affect the calculation of the slope (Ronconi E., Master thesis, 2015).
However in order not to risk to underestimate the head losses, in a simplified way, the minor losses were calculated as 20% of the major losses (Scanagatta F.,Master thesis, 2016).

4.5.2 Results

The process of calculating head losses has been carried out on the two network variants, with centralized heat pump and without heat pump, for scenarios with greater fluid velocity and flow rate, ie scenario A in the case of the heat pump and scenario 2 in the case of LTDH.
The calculation tables (*Table 19,20*) obtained are shown below.
The red pressure losses in the tables correspond to the path to the most disadvantaged users.

Friction losses for the return pipes (45 °C) Primary Grid - Scenario A													(65 °C)	
FID	Q [l/s]	D_N [m]	A_{sez} [m^2]	v_{eff} [m/s]	ν [m^2/s]	Re	ε (mm)	ε/D	λ	J [m/m]	L [m]	ΔH_{return} [m]	ΔH_{Supply} [m]	ΔH_{minor} [m]
0	10,66	0,09	0,0064	1,68	1,01E-06	150023	0,007	7,78E-05	0,0171	0,027133	35,23	0,96	0,96	0,38
1	4,91	0,063	0,0031	1,58	1,01E-06	98800	0,007	0,000111	0,0186	0,037391	135,78	5,08	5,08	2,03
2	0,43	0,025	0,0005	0,89	1,01E-06	22029	0,007	0,00028	0,0259	0,04143	8,21	0,34	0,34	0,14
3	0,07	0,025	0,0005	0,14	1,01E-06	3472	0,007	0,00028	0,0419	0,001664	8,10	0,01	0,01	0,01
4	0,41	0,025	0,0005	0,84	1,01E-06	20950	0,007	0,00028	0,0262	0,037898	7,99	0,30	0,30	0,12
5	0,46	0,025	0,0005	0,94	1,01E-06	23362	0,007	0,00028	0,0256	0,045975	6,75	0,31	0,31	0,12
6	0,39	0,025	0,0005	0,79	1,01E-06	19552	0,007	0,00028	0,0266	0,033532	6,66	0,22	0,22	0,09
7	0,24	0,025	0,0005	0,49	1,01E-06	12275	0,007	0,00028	0,0297	0,014765	6,92	0,10	0,10	0,04
8	0,36	0,025	0,0005	0,72	1,01E-06	18002	0,007	0,00028	0,0271	0,028973	6,49	0,19	0,19	0,08
9	0,37	0,025	0,0005	0,75	1,01E-06	18765	0,007	0,00028	0,0269	0,03118	6,37	0,20	0,20	0,08
10	0,38	0,025	0,0005	0,78	1,01E-06	19427	0,007	0,00028	0,0267	0,033154	6,27	0,21	0,21	0,08
11	0,19	0,025	0,0005	0,39	1,01E-06	9631	0,007	0,00028	0,0316	0,009661	12,01	0,12	0,12	0,05
12	0,08	0,025	0,0005	0,16	1,01E-06	3902	0,007	0,00028	0,0405	0,00203	12,00	0,02	0,02	0,01
13	0,07	0,025	0,0005	0,15	1,01E-06	3776	0,007	0,00028	0,0409	0,00192	11,96	0,02	0,02	0,01
14	0,05	0,025	0,0005	0,10	1,01E-06	2533	0,007	0,00028	0,0461	0,000974	11,93	0,01	0,01	0,00
15	0,09	0,025	0,0005	0,19	1,01E-06	4771	0,007	0,00028	0,0382	0,002865	11,95	0,03	0,03	0,01
16	0,08	0,025	0,0005	0,17	1,01E-06	4128	0,007	0,00028	0,0398	0,002236	12,05	0,03	0,03	0,01
17	0,07	0,025	0,0005	0,15	1,01E-06	3725	0,007	0,00028	0,0410	0,001875	12,10	0,02	0,02	0,01
18	0,07	0,025	0,0005	0,15	1,01E-06	3735	0,007	0,00028	0,0410	0,001885	12,11	0,02	0,02	0,01
19	0,09	0,025	0,0005	0,19	1,01E-06	4811	0,007	0,00028	0,0381	0,002907	12,34	0,04	0,04	0,01
20	0,06	0,025	0,0005	0,12	1,01E-06	3103	0,007	0,00028	0,0433	0,001374	12,34	0,02	0,02	0,01
21	0,09	0,025	0,0005	0,18	1,01E-06	4422	0,007	0,00028	0,0390	0,002515	13,06	0,03	0,03	0,01
22	0,55	0,025	0,0005	1,11	1,01E-06	27679	0,007	0,00028	0,0246	0,062207	25,62	1,59	1,59	0,64
23	0,09	0,025	0,0005	0,19	1,01E-06	4657	0,007	0,00028	0,0385	0,002749	10,70	0,03	0,03	0,01
24	0,09	0,025	0,0005	0,18	1,01E-06	4439	0,007	0,00028	0,0390	0,002532	10,20	0,03	0,03	0,01
25	0,08	0,025	0,0005	0,16	1,01E-06	4066	0,007	0,00028	0,0400	0,002178	11,16	0,02	0,02	0,01
26	5,74	0,063	0,0031	1,84	1,01E-06	115519	0,007	0,000111	0,0181	0,049695	108,31	5,38	5,38	2,15
27	0,49	0,025	0,0005	0,99	1,01E-06	24740	0,007	0,00028	0,0253	0,050925	5,19	0,26	0,26	0,11
28	0,56	0,025	0,0005	1,15	1,01E-06	28562	0,007	0,00028	0,0245	0,065793	4,96	0,33	0,33	0,13
29	0,98	0,025	0,0005	1,99	1,01E-06	49566	0,007	0,00028	0,0219	0,177222	12,10	2,14	2,14	0,86
30	0,49	0,025	0,0005	0,99	1,01E-06	24655	0,007	0,00028	0,0253	0,05061	4,10	0,21	0,21	0,08
31	0,49	0,025	0,0005	1,00	1,01E-06	24911	0,007	0,00028	0,0252	0,051556	19,30	1,00	1,00	0,40
32	0,29	0,025	0,0005	0,58	1,01E-06	14516	0,007	0,00028	0,0286	0,019821	16,77	0,33	0,33	0,13
33	3,71	0,05	0,0020	1,89	1,01E-06	94120	0,007	0,00014	0,0189	0,069019	122,82	8,48	8,48	3,39
34	0,61	0,025	0,0005	1,24	1,01E-06	30908	0,007	0,00028	0,0241	0,075764	3,20	0,24	0,24	0,10
35	0,56	0,025	0,0005	1,14	1,01E-06	28380	0,007	0,00028	0,0245	0,065041	3,27	0,21	0,21	0,09
36	0,37	0,025	0,0005	0,76	1,01E-06	18979	0,007	0,00028	0,0268	0,031803	3,27	0,10	0,10	0,04
37	0,38	0,025	0,0005	0,76	1,01E-06	19009	0,007	0,00028	0,0268	0,031902	3,34	0,11	0,11	0,04
38	0,49	0,025	0,0005	0,99	1,01E-06	24656	0,007	0,00028	0,0253	0,050622	3,39	0,17	0,17	0,07
39	0,36	0,025	0,0005	0,72	1,01E-06	18034	0,007	0,00028	0,0271	0,02906	3,48	0,10	0,10	0,04
40	0,41	0,025	0,0005	0,83	1,01E-06	20612	0,007	0,00028	0,0263	0,036821	3,47	0,13	0,13	0,05
41	0,27	0,025	0,0005	0,55	1,01E-06	13665	0,007	0,00028	0,0290	0,017823	3,46	0,06	0,06	0,02
42	0,28	0,025	0,0005	0,56	1,01E-06	13997	0,007	0,00028	0,0288	0,018592	3,44	0,06	0,06	0,03

Table 19- Calculation of head losses, major and minor, indicated in meters of water column for each stretch of network for Scenario A, more unfavorable.

Friction losses for the return pipes (20 °C) Primary Grid - Scenario 2													(35 °C)	
FID	Q [l/s]	D_N [m]	A_{sez} [m^2]	v_{eff} [m/s]	ν [m^2/s]	Re	ε (mm)	ε/D	λ	J [m/m]	L [m]	ΔH_{return} [m]	ΔH_{Supply} [m]	ΔH_{minor} [m]
0	8,42	0,11	0,0095	0,89	1,01E-06	96943	0,007	6,36E-05	0,0184	0,006702	35,23	0,24	0,24	0,09
1	3,74	0,063	0,0031	1,20	1,01E-06	75284	0,007	0,000111	0,0196	0,022865	135,78	3,10	3,10	1,24
2	0,30	0,025	0,0005	0,61	1,01E-06	15288	0,007	0,00028	0,0282	0,021715	8,21	0,18	0,18	0,07
3	0,04	0,025	0,0005	0,09	1,01E-06	2236	0,007	0,00028	0,0286	0,000472	8,1	0,00	0,00	0,00
4	0,39	0,025	0,0005	0,79	1,01E-06	19557	0,007	0,00028	0,0266	0,03355	7,99	0,27	0,27	0,11
5	0,33	0,025	0,0005	0,68	1,01E-06	16905	0,007	0,00028	0,0275	0,025926	6,75	0,18	0,18	0,07
6	0,27	0,025	0,0005	0,54	1,01E-06	13512	0,007	0,00028	0,0290	0,017473	6,66	0,12	0,12	0,05
7	0,26	0,025	0,0005	0,52	1,01E-06	12960	0,007	0,00028	0,0293	0,016235	6,92	0,11	0,11	0,04
8	0,27	0,025	0,0005	0,54	1,01E-06	13544	0,007	0,00028	0,0290	0,017546	6,49	0,11	0,11	0,05
9	0,30	0,025	0,0005	0,61	1,01E-06	15248	0,007	0,00028	0,0282	0,021614	6,37	0,14	0,14	0,06
10	0,30	0,025	0,0005	0,60	1,01E-06	14956	0,007	0,00028	0,0283	0,020892	6,27	0,13	0,13	0,05
11	0,12	0,025	0,0005	0,24	1,01E-06	6086	0,007	0,00028	0,0357	0,004357	12,01	0,05	0,05	0,02
12	0,05	0,025	0,0005	0,11	1,01E-06	2717	0,007	0,00028	0,0451	0,001097	12	0,01	0,01	0,01
13	0,05	0,025	0,0005	0,11	1,01E-06	2636	0,007	0,00028	0,0455	0,001042	11,96	0,01	0,01	0,00
14	0,05	0,025	0,0005	0,11	1,01E-06	2651	0,007	0,00028	0,0455	0,001052	11,93	0,01	0,01	0,01
15	0,07	0,025	0,0005	0,13	1,01E-06	3340	0,007	0,00028	0,0424	0,001558	11,95	0,02	0,02	0,01
16	0,06	0,025	0,0005	0,12	1,01E-06	2896	0,007	0,00028	0,0442	0,001223	12,05	0,01	0,01	0,01
17	0,05	0,025	0,0005	0,11	1,01E-06	2761	0,007	0,00028	0,0449	0,001127	12,1	0,01	0,01	0,01
18	0,05	0,025	0,0005	0,11	1,01E-06	2775	0,007	0,00028	0,0448	0,001137	12,11	0,01	0,01	0,01
19	0,07	0,025	0,0005	0,14	1,01E-06	3364	0,007	0,00028	0,0423	0,001577	12,34	0,02	0,02	0,01
20	0,06	0,025	0,0005	0,11	1,01E-06	2848	0,007	0,00028	0,0445	0,001188	12,34	0,01	0,01	0,01
21	0,06	0,025	0,0005	0,12	1,01E-06	3079	0,007	0,00028	0,0434	0,001356	13,06	0,02	0,02	0,01
22	0,60	0,025	0,0005	1,22	1,01E-06	30356	0,007	0,00028	0,0242	0,07336	25,62	1,88	1,88	0,75
23	0,07	0,025	0,0005	0,14	1,01E-06	3509	0,007	0,00028	0,0418	0,001694	10,7	0,02	0,02	0,01
24	0,07	0,025	0,0005	0,14	1,01E-06	3511	0,007	0,00028	0,0418	0,001696	10,2	0,02	0,02	0,01
25	0,08	0,025	0,0005	0,16	1,01E-06	3982	0,007	0,00028	0,0402	0,002102	11,16	0,02	0,02	0,01
26	4,67	0,075	0,0044	1,06	1,01E-06	78945	0,007	9,33E-05	0,0193	0,014707	108,31	1,59	1,59	0,64
27	0,49	0,025	0,0005	0,99	1,01E-06	24732	0,007	0,00028	0,0253	0,050894	5,19	0,26	0,26	0,11
28	0,42	0,025	0,0005	0,86	1,01E-06	21502	0,007	0,00028	0,0261	0,039688	4,96	0,20	0,20	0,08
29	0,74	0,032	0,0008	0,92	1,01E-06	29319	0,007	0,000219	0,0242	0,032667	12,1	0,40	0,40	0,16
30	0,36	0,025	0,0005	0,73	1,01E-06	18237	0,007	0,00028	0,0271	0,029646	4,1	0,12	0,12	0,05
31	0,38	0,025	0,0005	0,78	1,01E-06	19290	0,007	0,00028	0,0267	0,03274	19,3	0,63	0,63	0,25
32	0,38	0,025	0,0005	0,78	1,01E-06	19355	0,007	0,00028	0,0267	0,032935	16,77	0,55	0,55	0,22
33	3,02	0,063	0,0031	0,97	1,01E-06	60743	0,007	0,000111	0,0205	0,015537	122,82	1,91	1,91	0,76
34	0,42	0,025	0,0005	0,86	1,01E-06	21479	0,007	0,00028	0,0261	0,039609	3,2	0,13	0,13	0,05
35	0,39	0,025	0,0005	0,79	1,01E-06	19548	0,007	0,00028	0,0266	0,033514	3,27	0,11	0,11	0,04
36	0,35	0,025	0,0005	0,72	1,01E-06	17834	0,007	0,00028	0,0272	0,028492	3,27	0,09	0,09	0,04
37	0,34	0,025	0,0005	0,70	1,01E-06	17443	0,007	0,00028	0,0273	0,027403	3,34	0,09	0,09	0,04
38	0,34	0,025	0,0005	0,69	1,01E-06	17185	0,007	0,00028	0,0274	0,026689	3,39	0,09	0,09	0,04
39	0,34	0,025	0,0005	0,69	1,01E-06	17050	0,007	0,00028	0,0275	0,026321	3,48	0,09	0,09	0,04
40	0,40	0,025	0,0005	0,81	1,01E-06	20102	0,007	0,00028	0,0265	0,03522	3,47	0,12	0,12	0,05
41	0,23	0,025	0,0005	0,47	1,01E-06	11694	0,007	0,00028	0,0301	0,013561	3,46	0,05	0,05	0,02
42	0,21	0,025	0,0005	0,43	1,01E-06	10740	0,007	0,00028	0,0307	0,011683	3,44	0,04	0,04	0,02

Table 20- Calculation of head losses, major and minor, indicated in meters of water column for each stretch of network for Scenario 2, more unfavorable.

4.5.3 Power calculation of the circulation pumps

Once the most disadvantaged load paths were determined, the total head losses on these routes were calculated (*Table 21,22*), both in terms of water column and in terms of pressure.

Scenario A				
	ΔH_{return}	ΔH_{Supply}	ΔH_{minor}	ΔH_{tot}
TOT ΔH [m]	15,06	15,06	6,02	36,14
TOT ΔH [bar]	1,48	1,48	0,59	3,54
TOT ΔH [Pa]	150577	150577	60231	361385

Table 21- Calculation of hydraulic losses along the route to the most disadvantaged users indicated in meters of water column, in bar and in Pa for scenario A.

Scenario 2				
	ΔH_{return}	ΔH_{Supply}	ΔH_{minor}	ΔH_{tot}
TOT ΔH [m]	5,77	5,77	2,31	13,85
TOT ΔH [bar]	0,57	0,57	0,23	1,36
TOT ΔH [Pa]	57726	57726	23090	138541

Table 22- Calculation of hydraulic losses along the route to the most disadvantaged users indicated in meters of water column, in bar and in Pa for scenario 2.

These head losses were calculated when the flow rate circulating in the network is maximum, ie in the month of highest demand.

In order to cope with these losses, the installation of circulating pumps is necessary.

The power of the circulation pump can be determined by the formula (3.21):

$$P_p = m * \frac{g*h*\rho}{\eta_p} \qquad (3.21)$$

Where:

-m= mass flow rate (m^3/s)

-g= the local acceleration due to gravity (9,806 $^{m}/_{s^2}$)

-h= total head losses (m)

-ρ= fluid density (kg/m^3)

-η_p= pump efficiency, assumed 0,7.

Calculated the power of the pump it is necessary to determine the nominal power that will be installed among the powers available on the market.

Furthermore, it is necessary to consult the tables provided by the manufacturers, which correlate the pump power with the head and the flow, because there are many different types of circulation pumps.

The technical sheet of the circulation pumps chosen for the two scenarios can be found on the company website [30] , followed by the summary tables (*Tables 23,24*) of the characteristics of the aforementioned pumps:

Scenario A	
ρ (kg/m³)	1000
g (m/s²)	9,81
η_P	0,7
Pp (W)	5398
P_N (Kw)	7,5
m³/h	38,37

Table 23- Characteristics of the circulation pump for scenario A: yield, required power, nominal power and maximum design flow.

Scenario 2	
ρ (kg/m³)	1000
g (m/s²)	9,81
η_P	0,7
Pp (W)	1634
P_N (Kw)	3
m³/h	30,30

Table 24- Characteristics of the circulation pump for scenario 2: yield, required power, nominal power and maximum design flow.

The circulation pump is powered by electricity which must be computed in order to estimate the consumption and costs of the plant according to (3.22).

$$P_E = P_P * \eta_p \quad (3.22)$$

4.6 Heat pumps

Heat pumps are devices that can transform heat from a low temperature source and bring it to an higher one using various forms of energy.
Heat pumps exploit the same thermodynamic cycle of refrigerators, only inverted (compression, condenser, expansion, evaporator).
The cycle is kept running using electrical energy.
The ratio between produced thermal energy and electrical energy required by the operating cycle is called the coefficient of performance (COP). This indicator is distinguished from the yield, which

typically can never be greater than one, because on the contrary the values usually take greater values of the unit.
As seen in Chapter 1, the waste heat from the DCs has temperatures that vary according to the type of cooling system. In particular, in the case of air-cooled DCs, the temperature of this heat is particularly low (about 40°C) and therefore it is said that the heat is of a low degree. This is because this temperature allows little opportunity for re-use. Even considering the option of using it to create a low-temperature district heating network, this heat is not suitable to meet the demand for DHW (which requires 45-60 degrees) or for buildings whose production of SH is still left to high temperature system terminals (for example radiators).
For these reasons, low-grade waste heat can represent a good starting source to be upgraded with the aid of heat pumps that make it usable for more fields of use.
In the case in question, two distinct solutions were analyzed: one that involves the use of a centralized heat pump for the construction of a medium-tempered district heating network (65-45 °C) and another one that involves the use of a decentralized heat pumps, single for each building, coupled to a low temperature network (35-20°C).

4.6.1 Centralized heat pump

In scenarios A and 1 a centralized heat pump has been installed to allow a temperature drop from 35 to 65 degrees, in order to create a medium-tempered district heating network.
The power of this heat pump was determined by dividing the total heat demand of each scenario by the annual service life of the pump.

	operating time
jan	496
feb	448
mar	496
apr	90
may	93
jun	90
jul	93
aug	93
sept	90
oct	93
nov	480
dec	496
total	3058

Table 25- Table summarizing the monthly operating hours of the heat pump.

Once assumed a medium COP of 3,5 [17] it was also possible to calculate the electric power required by the pump in the worst case scenario, in order to use the same pump for both scenarios (2018-2030). In this way, from the commercial catalogues, the nominal power that was closest to each other was chosen, ie 100 kW.

COP	3,5
P (kW)	94
PN (kW)	100
Q scenario A (kWh)	1007369
Q scenario 1 (kWh)	542851

Table 26- Calculation of the power required by the centralized heat pump and selection of the corresponding nominal power.

4.6.2 Decentralized heat pump

In the case of scenario B, it was decided to install decentralized heat pumps inside each building that would allow DHW and SH production in the months of highest demand while maintaining a low temperature distribution network.

In this scenario, in addition to reducing the thermal distribution losses, the electricity consumption of the individual heat pumps is also reduced compared to the centralized heat pump because this type of pumps has higher COPs [17], what increases are the investment costs .

The electric power required by the individual heat pumps was determined using the same procedure described in paragraph 3.6.1.

The results obtained are shown in the table:

COP	4,5
Yearly DHW demand (kW)	22,10
Yearly SH extra demand (kW)	28,86
Yearly average demand per building (kW)	1,38

Table 27- Calculation of the power required by the decentralized heat pump.

5 ECONOMICAL AND ENVIRONMENTAL ASSESSMENT

This chapter will deal with a preliminary assessment of the economic feasibility of the project which was carried out through an analysis of the total costs of energy distribution. This parameter, in fact, can be used both to evaluate the economic convenience of the end user and to calculate the return period of the investment of the DH operator.
In the first case, the cost of distribution will be compared with the cost of the current fuel used for heating, while in the second case a cash flow of the economic operation will be performed and the pay back period will be calculated.
Finally, the project alternatives will be evaluated also on the basis of their environmental impact, in particular by evaluating the primary energy consumption linked to each scenario.

5.1 Distribution costs

The cost of energy distribution is defined as the sum of two contributions: capital cost and operating costs (5.1) [31].

$$c_{distr} = c_{cap} + c_{op} \quad (5.1)$$

Generally the capital cost represents the most significant part of the distribution cost because it depends directly on the investment costs while the operating costs take into account the expenses to compensate for thermal and hydraulic losses, service costs and maintenance.

5.1.1 Capital costs

The capital cost represents the largest cost item of the energy distribution because it includes within it the investment costs for materials, installation costs and the annual interest rate of capital. Capital cost is calculated according to the formula below (4.2) and it is expressed in euro cents per kWh.

$$c_c = \frac{I*a}{Q_s} \quad (5.2)$$

Where:

-a= annuity factor (%)

-I= total investment costs (€)

-Q_s= total heat sold in an year (kWh)

The annuity factor depends on the interest rate of the capital and the duration of the investment. The interest rate has a large impact on the cost of capital [31], so in this case study a typical value of 3% was assumed.

As regards the choice of the duration of the investment, on the other hand, it was assumed to be equal to the useful life of the district heating plant, i.e. 25 years.

With the following assumptions the annuity factor was calculated as follows (5.3):

$$a = i * \frac{(1+i)^n}{(1+i)^n - 1} \quad \text{for i>0 (5.3)}$$

$$a = n^{-1} \text{ for i=0 (5.4)}$$

Where:

-i= capital interest rate (%)

-n= duration time of the investment (years)

Capital interest rate (%)	3%
n (years)	25
annuity (%)	6%

Table 28- Values assumed for the calculation of the annuity factor.

The investment costs, on the other hand, depend on all the physical characteristics of the plant as for example: the diameter and the length of the pipes, the type and degree of insulation of the pipe, the power of the pumps to be installed and all the costs related to the installation and implementation of these components.

In the case under examination in the investment costs do not include the expenses related to the plant as the DC is already present and belonging to another economic operator. What is computed, in addition to the investment cost for the network, are all substations both of heat recovery from the DC and those of exchange with the individual users.

A detailed analysis of investment costs was conducted for all scenarios and is shown in the "*Attachment V*".

Retail prices were determined through commercial catalogs, while network construction costs and other installation costs were determined by literature [31], [32], [33] or directly supplied to me by the department.

Finally, the capital cost for the four scenarios was determined and is shown in the table below (*Table 29*):

	Scenario A	Scenario B	Scenario 1	Scenario 2
Qs (kWh/year)	719403	141818	526137	807935
Invest. Costs (€)	€ 472.548,37	€ 417.534,62	€ 472.548,37	€ 508.484,19
Ccap (c€/kWh)	3,77	16,91	5,16	3,61

Table 29- Summary table of the capital cost obtained for each project configuration.

5.1.2 Operation costs

Operating costs (5.5) include the costs associated with the operation of the plant.

These costs are mainly represented by three items: the cost of fuel to offset losses (5.6), the cost of electricity to keep heat pumps and circulation pumps running (5.7) and maintenance costs (5.8). Maintenance costs, in fact, are very often neglected because they represent a truly marginal cost item, around 1% of the capital cost.

$$C_{op} = C_F + C_E + C_M \quad (5.5)$$

$$C_F = f * p_f \quad (5.6)$$

$$C_E = E * p_E \quad (5.7)$$

$$C_M = 1\%\, C_{cap} \quad (5.8)$$

Where:

-f= fuel consumption to cover the losses (kWh/kWh)

-p_f= fuel price (c€/kWh)

-E= electricity consumption (kWh/kWh)

-p_E= electricity price (c€/kWh)

In the particular case of this project the fuel is represented by the waste heat coming from the DC.

In this case the owner of the DC and the DH network do not coincide and therefore the operating cost related to the fuel must be extended to the entire demand and not intended to cover only the losses.

Furthermore, the price of fuel is not easily quantifiable.

In fact, today there are no business plans for this type of solutions, therefore this cost has been hypothesized according to two solutions.

In the first case it was assumed that the company that owns the DH, investing in the heat recovery substation and therefore effectively reducing the costs for cooling of the DC by making it easier for the owner, has in exchange for free this waste heat.

In the second hypothesis, however, while maintaining the unaltered investment scenario it is assumed that in addition the owner of the DC ask for a small flat fee of 1 c€ / kWh for waste heat.

Pe (c€/kWh)	26,55
Pf1 (c€/kWh)	0,00
Pf2 (c€/kWh)	1,00

Table 29- Electricity and waste heat prices assumed for the calculation of operating costs.

Regarding the cost of electricity this was determined on the annual report [34] of the state of services of the Italian state of 2017, which reports all the costs of fuel and electricity in many states (including Germany), for the previous year and depending on any consumption bands.
The tables summarizing the operating costs obtained for the four scenarios in the two different fuel cost hypotheses are shown below:

	Scenario A	**Scenario B**	**Scenario 1**	**Scenario 2**
C_F (c€/kWh)	0,00	0,00	0,00	0,00
C_E (c€/kWh)	4,70	0,000002	3,66	1,81
C_M (c€/kWh)	0,04	0,17	0,05	0,04
C_{OP} (c€/kWh)	4,74	0,17	3,71	1,85

Table 30- Summary table of the operating cost obtained for each project configuration with the hypothesis of free waste heat from the DC.

	Scenario A	**Scenario B**	**Scenario 1**	**Scenario 2**
C_F (c€/kWh)	0,37	0,56	0,40	0,73
C_E (c€/kWh)	4,70	0,000002	3,66	1,81
C_M (c€/kWh)	0,04	0,17	0,05	0,04
C_{OP} (c€/kWh)	5,11	0,72	4,11	2,58

Table 31- Summary table of the operating cost obtained for each project configuration with the hypothesis of paying waste heat from the DC.

The total distribution costs will be reported and discussed in the final section, in chapter 6.

5.2 Cash flow and Pay Back Period (PBP)

To evaluate the economic feasibility of a project there are many methods of more or less accurate estimation, depending on the amount of information available.
A very simple method to evaluate the goodness of an investment in a preliminary phase is to calculate the Pay Back Period (PBP).
The PBP indicates the number of years needed to recover the costs of a given investment, ie the number of periods required for cumulative cash flows to equal investment costs and the investor begins to make money. So the lower the PBP the better the investment will be.
This estimation method has the advantage of being very easy and simple to understand, but has the great limit of not taking into consideration the time factor on the monetary value.

Therefore it represents a risk indicator, due to temporal exposure, and not a yield indicator.
In fact, the cash flows should be discounted according to the discount rate in order to obtain a more precise estimate of the PBP. However, in the case in question, since this was a very preliminary analysis, it was considered acceptable to calculate the simple PBP.
Also with regard to cash flow analysis, simplifications have been made. The items analyzed were: the investment cost, with an amortization period of 10 years, and operating costs relating to the operation of the plant.
The items relating to taxation or tax costs, any government incentives, personnel costs and any other future investments were ignored.
The duration of the investment was assumed to be 25 years, ie equal to the useful life of the plant.
The results of this analysis are reported in *chapter 6*.

5.3 Primary energy factor (PEF)

In the previous paragraphs the procedure for determining the cost of heat distribution was described in order to evaluate design alternatives on an economic basis.
In this paragraph, instead, the primary energy consumption (PE) of each scenario will be determined in order to understand which solution is more ecologically sustainable, or that implies a lower use of PE.
The consumption of PE can be estimated as the sum of all energy carriers used for the corresponding primary energy factor (PEF).

$$PE = \sum Q_i * PEF_i$$

PEF is the factor that expresses how much fuel is needed to produce a certain amount of heat or electricity. Each fuel therefore has its own specific PEF.
The total prime energy factor is generally composed of two contributions, one for fossil energy carriers and the other for renewable sources.

$$PEF_{tot} = PEF_{fossil} + PEF_{renewable}$$

PEF from non-renewable sources have very different values depending on the fossil and also depending on the time frame. Instead, those from renewable sources are generally assumed to be 1.00 if the source is off-site or 0.00 if the source is on-site.
In the case of the waste heat of the DC the PEF was assumed to be equal to 0.00 because it can be considered assimilable to a source of renewable energy on-site.

For each scenario analyzed, the corresponding PEF was calculated as the sum of the energy carriers for the corresponding PEF divided by the total heat demand.

In the case of scenarios A, 1 and 2, the only energy vector from a non-renewable source is electricity required to power the pumps (circulation and heat) therefore the PEF has been calculated using the following formula (5.9):

$$PEF = \frac{\left(\frac{P_{HP}}{COP}\right) * PEF_{el} + P_{P,el} * PEF_{el}}{Total\ demand} \quad (5.9)$$

In the case of scenario B, on the other hand, where the DH serves only to preheat DHW, the use of gas systems is still expected to be added in the PEF calculation as follows (5.10):

$$PEF = \frac{(Gas\ and\ oil\ consumption) * PEF_{oil,gas} + P_{P,el} * PEF_{el}}{Total\ demand}$$

The results obtained for the four scenarios are reported and discussed in chapter 6.

6 CRITICAL ANALYSIS

In this chapter all the results obtained during the work will be discussed.
Firstly, the use of the ArcGis tool in the planning of a district heating network will be discussed.
Finally, all the results obtained in terms of primary energy consumption and heat costs for all four scenarios will be presented and compared.
The method used to conduct this analysis still presents many assumptions and approximations for this reason the proposed results must be considered as a starting point for further detailed analyzes.
However, these data are encouraging and aim to increase the desire to study more and more these types of heat reuse systems.

6.1 Network planning in ArcGis

The design of the district heating micro network, the objective of this project, was partially implemented on the ArcGis program.
This tool allows a very accurate study of the territory while it is able to associate the spatial coordinates of point with information that describe that object.
In the case under examination, all the data related to the energy simulation obtained with the SimStadt software have been associated to the corresponding building in the georeferenced map of the study area.
The great advantage of this type of analysis is that it allows you to graphically display the data obtained from the simulations, allowing the creation of real thematic maps.
Once the criteria for the selection of the buildings to be supplied with the new network have been established and the location of the source (data center) is known, with the help of the thematic maps, it is easier to reach the choice.
Finally note the buildings to be connected you can immediately draw the network, know the coordinates and then the exact lengths of the individual sections.
The program could even be implemented with other software [24] that allow the direct design of the network characteristics starting from the data present on ArcGis. In the case under examination, the actual design instead took place using excel sheet.
In fact, the implementation between SimStadt and ArcGis still produces errors that are too high to consider designing the network directly on the program. As seen in the *paragraph 3.2*, each Simstadt simulated points cannot connect to the corresponding building in the map shape file.
In the case of this work the error generated can be considered negligible, as the GIS elaborated had the sole purpose of providing direct information on the data obtained from the simulation for the selection of buildings to be connected to the network.

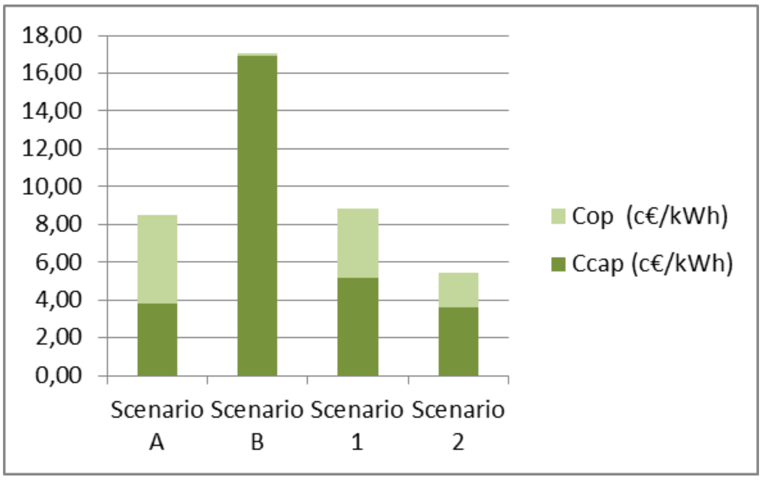
However, even if the program has not been exploited to its full potential, it has proved to be of fundamental importance in the reading of the urban area and for the design phase of the district heating network.

6.2 Distribution costs

As described in paragraph 5.1 the costs of heat distribution were determined as the sum of two contributions, the capital costs and operating costs.
It is necessary to specify that in this preliminary analysis all the investment items, both those relating to the network and those relating to the substations of the single users, as well as the expenses for the DC heat recovery substation have been brought together.
Moreover, not being aware of the price of waste heat of the DC, for the determination of operating costs, two hypotheses were evaluated: heat for free transfer and heat at a fixed cost of 1 cent per kWh. These assumptions have become necessary as far as this type of plant is concerned, many business plans do not yet exist and consequently there is no clear distinction between the economic competences of the individual parties involved (DC owner, DH company and end users).
Following are the results obtained for distribution costs, both in the hypothesis of heat from the free DC (*Table 32,Graph 15*) and in the hypothesis of payment of such heat (*Table 33, Graph 16*):

	Scenario A	Scenario B	Scenario 1	Scenario 2
Ccap (c€/kWh)	3,77	16,91	5,16	3,61
Cop (c€/kWh)	4,74	0,17	3,71	1,85
C_{tot} (c€/kWh)	8,51	17,08	8,87	5,46

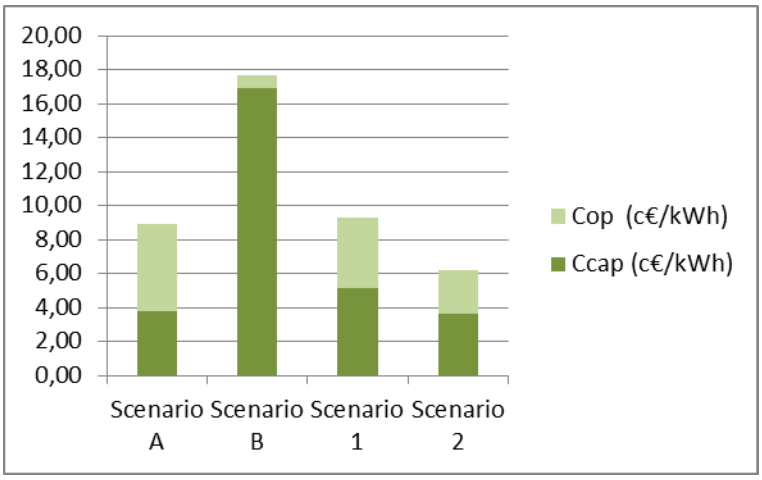
Table 32-Total capital, operational and distribution costs obtained in the hypothesis of free transfer of waste heat by the DC.



Graph 15-Graph showing the distribution of capital and operating costs within distribution costs for the four scenarios studied in the hypothesis of free transfer of heat from the DC

	Scenario A	Scenario B	Scenario 1	Scenario 2
Ccap (c€/kWh)	3,77	16,91	5,16	3,61
C_{OP} (c€/kWh)	5,11	0,72	4,11	2,58
C_{tot} (c€/kWh)	8,88	17,63	9,27	6,19

Table 33-Total capital, operating and distribution costs obtained in the case of the sale of waste heat by the DC to 1 cent per kWh.



Graph 16-Graph showing the distribution of capital and operating costs within distribution costs for the four scenarios studied in the hypothesis of heat sales from DC to 1 cent per kWh.

As can be seen from the results obtained, capital costs represent the most significant part of the distribution cost, especially in scenarios where demand is lower.

The sensitivity of the cost of distribution to the cost of waste heat of the DC, for such low cost values, is very low for all scenarios.

The variation in the price of heat from the DC affects 2% in the hypotheses seen at the beginning of the paragraph, with the exception of scenario 2, where this variation raises or reduces the distribution costs by 6%.

This difference is justified by the fact that scenario 2 is that in proportion to the demand there is a higher heat sale from DC, so the factor *f* seen in formula (5.6) is higher.

In the subsequent subparagraphs the total distribution costs will be compared with the current price of the gas, the current energy carrier used in the study area, to check the eventual economic advantage of this type of system by the users and finally these costs will be used for determine the period of return on investment from the DH company point of view, in order to evaluate the economic feasibility of this investment in the first analysis.

6.2.1 Saving of end users

To check whether the end users benefited from the installation of this type of system, the current cost of the current energy carrier used, the gas, was compared to the results obtained in the distribution costs.

The current cost of gas has been determined by the same document as seen in paragraph 5.12 [34]. In 2016, the cost of gas was 111.49 c € / m^3. Multiplying this value by the lower calorific value of gas H it is possible to obtain this cost in c€ / kWh as shown in the Table:

Gas price (c€/m^3)	111,49
$\Delta_c H_i^o$ Gas (MJ/Nm^3)	35,88
Gas price (c€/kWh)	11,19

Table 34- Gas price and lower calorific value

As can be seen from Tables 32,33 in each scenario, the cost obtained for district heating is lower than the gas one, with the exception of scenario B.

That scenario B would have been inexpensive was foreseeable, as the costs of carrying out the intervention were too high to justify the construction of a network for the only preheating of the domestic hot water.

The results (*Tables 35,36*) show that the use of waste heat from the DC to produce heat in buildings would lead to widespread savings for the end user in a range between 17 and 51% depending on the scenario and the hypotheses considered.

The most cost-effective solution for the user is that of low-temperature district heating that directly uses the waste heat of the DC with the help of decentralized micro heat pumps for DHW production. However, this condition can only be achieved provided that all buildings are renovated and provide for the installation of low temperature terminals, ie when the DH network is interfaced with LowEx or passive buildings.

The solution that provides the aid of the centralized heat pump, however, is already achievable and advantageous for the user to date, compared to the current cost of gas; although the savings margin is lower than that obtainable with the low temperature network.

	Saving (c€/kWh)	Saving (%)	Total saving (€)	Saving per building (€)
Scenario A	2,68	24%	€ 43.039,34	€ 1.163,23
Scenario B	-	-	-	-
Scenario 1	2,32	21%	€ 22.679,66	€ 612,96
Scenario 2	5,73	51%	€ 55.944,41	€ 1.512,01

Table 35-The table shows the savings that would be obtained in each scenario if the new district heating network was used instead of the old gas system, in the hypothesis of free transfer of waste heat from the DC.

	Saving (c€/kWh)	Saving (%)	Total saving (€)	Saving per building (€)
Scenario A	2,30	21%	€ 37.051,21	€ 1.001,38
Scenario B	-	-	-	-
Scenario 1	1,92	17%	€ 18.727,70	€ 506,15
Scenario 2	4,99	45%	€ 48.791,23	€ 1.318,68

Table 36-The table shows the savings that would be obtained in each scenario if the new district heating network was used instead of the old gas system, in the hypothesis of buying the waste heat from the DC.

6.2.2 Economic feasibility of the investment

For each scenario studied, the PBP was calculated, i.e. the return time of the investment, to understand whether this idea of the project was attractive even from the business point of view, even if the proposal is still present in a very preliminary state.

Usually for the evaluation of large investments, as in this case, the lowest PBP solution is chosen and above all a threshold of years is established, the cutoff period, not to be exceeded.

These thresholds should generally be studied and chosen appropriately, although there are no precise rules for deciding this criterion.

In this case it is simply chosen to consider the solution of scenario B as unacceptable in that it presents a double PBP or even triple compared to other alternatives (*Table 37*).

The solution that is therefore less risky, from the point of view of capital exposure, is that of scenario A which presents a 6.2 year PBP. This can be explained by the fact that the district heating network in this scenario is the most efficient given that the heat demand of the buildings is higher than the scenarios set in 2030, where we will have low or passive buildings.

	PBP (years)	Year of construction	Years of amortization
Scenario A	6,2	2018	10
Scenario B	18,2	2018	20
Scenario 1	8,9	2030	10
Scenario 2	9,8	2030	10

Table 37- The table shows the periods of return on investments, the year in which the scenario was created, and the period of time considered to amortize the initial investment calculated for the four scenarios under examination.

6.3 Primary energy consumption

With the method and the assumptions seen in paragraph 5.3, the PEF was calculated for each scenario studied to understand which of these was the most sustainable scenario according to the criterion of primary energy consumption.
The results obtained are shown in the *Table 38*:

PE $_{\text{scenario A}}$	0,32
PE $_{\text{scenario B}}$	0,93
PE $_{\text{scenario 1}}$	0,25
PE $_{\text{scenario 2}}$	0,14

Table 38-PEF values obtained for each scenario.

For district heating plants powered by CHP, in Germany, typical PEF values are around 0.7 [17].
The values obtained in this work are all but one below this value, this surely derives from the fact that the reuse of waste heat directly on site represents a very favorable condition (PEF = 0,00).
In the case of scenario B, however, this favorable condition is not sufficient to offset the consumption of gas for the production of SH and partially of DHW.

7 CONCLUSIONS

The purpose of this study was to investigate the technical and economic feasibility of a district heating network, powered by waste heat from a small-sized DC, which supplied thermal energy for heating and domestic hot water for buildings located in the immediate vicinity of the data center itself. In particular, the possibility of creating a district heating micro network in the Stockach district in the city of Stuttgart has been studied, hypothesising the location of the local television and radio station in the area as possible.
Data relating to the properties of the DC were simulated with the Trnsys software on a project of the department called EcoRz while the data on the heat demand of the buildings were simulated with the program developed by the department called Simstadt.
Once the starting data have been known, these have been implemented in the neighborhood map using the ArcGis software. This step allowed the selection of the buildings to be connected to the network, in such a way that they repeated the specific criteria previously identified.
In order to evaluate which design solution was more performing, four scenarios were studied that differed in terms of energy demand (current demand and demand after complete renovation of the building) but also in terms of temperature of the energy carrier within the district heating network (medium and low temperature).
Subsequently, the network was designed and the investment costs, operating costs and primary energy consumption were analysed for each configuration.
The results obtained for the various design variants have shown that:

- The implementation of energy simulation programs for buildings and territorial systems such as GIS allows effective planning of the district heating networks, once the criteria for the selection of buildings have been established.

- The total distribution costs obtained (6-9 cent/kWh) are completely in line with the typical values determined in other studies for DH schemes with waste heat as their source and as consumers lowEx buildings [32]. This fact means that this system layout is configured as a valid future solution to the exploitation of waste heat even of low quality.

- The use of waste heat of a DC for the production of heat in buildings, through a district heating network, is configured as a valid alternative for the end user who could achieve a saving up of 20% to 50% on the cost of energy per kWh.

- From the entrepreneurial point of view the return times obtained are in line with studies of district heating networks [35].
  In particular, the solution that provides for the use of the centralized heat pump is the most advantageous both from a short-term perspective and analyzing the future scenario.

- From the point of view of sustainability and reduction of the use of fossil fuels the exploitation of waste heat is configured as a necessary condition.
  The values obtained for PEF are almost all below the typical German values for this type of plants, ie below 0.7. In particular scenario 2, set in 2030 and with a low-temperature network and decentralized heat pump, has a PEF of 0.14.

The method used to conduct this analysis still has many limitations and assumptions, both in the network design phase and in the economic analysis part.
The absence of business plans and a specific economic market for systems like the one just described represent a big gap for the development of more accurate economic models. This is the reason why in this paper an analysis was carried out with hypotheses created specifically for the specific case.
However, good results can be considered a starting point for subsequent and more detailed analyzes.

ATTACHMENTS

I-Errors generated when importing the SimStadt output file into ArcGis

GMLId	Block	x-coord	y-coord	Heated area	Cause of the error
DEBW522AA0000b4c8	107227	3514283	5405575	37,5	wrong shape of the feature in the map shape file
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GMLId	Block	x-coord	y-coord	Heated area	Cause of the error
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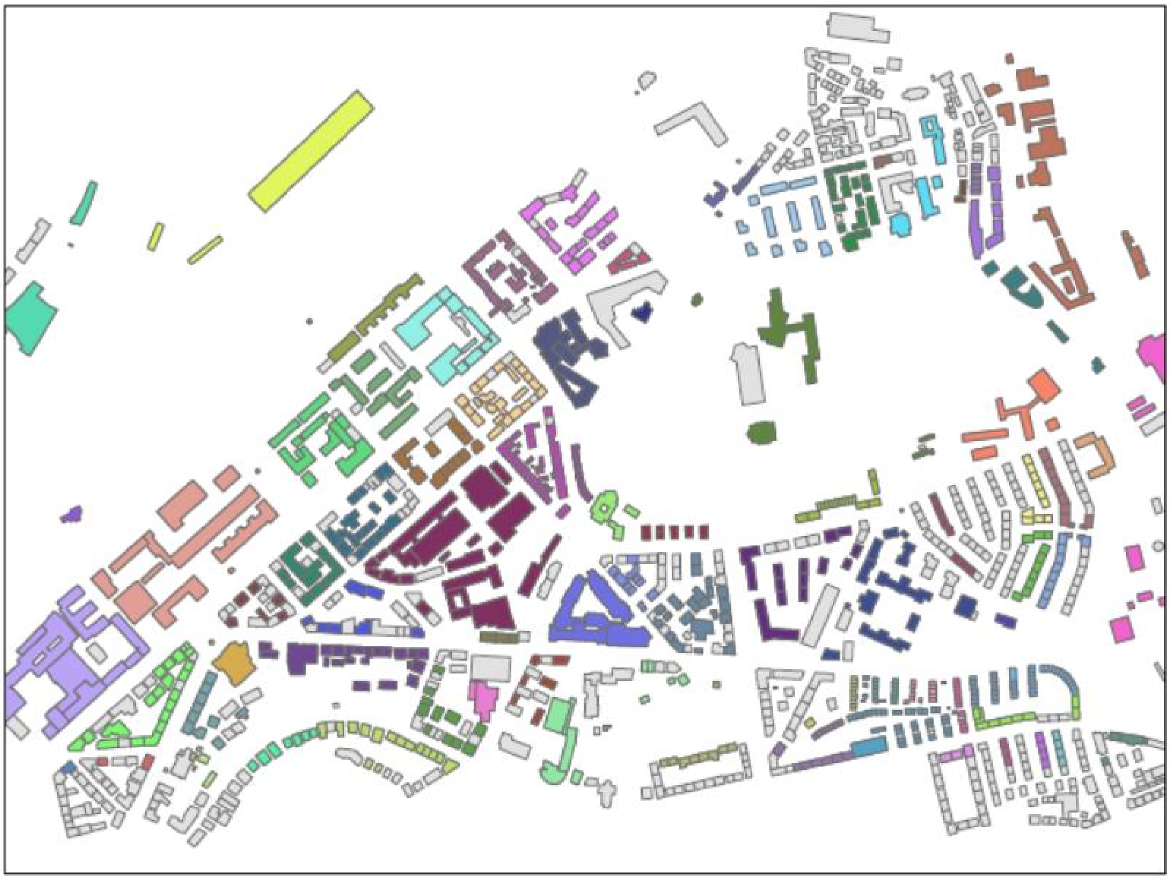
II-Study tables of the area developed with ArcGis

Table 1 - Building block number identification



Legend

Block number

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146201

Table 2 - Building connected with district heating

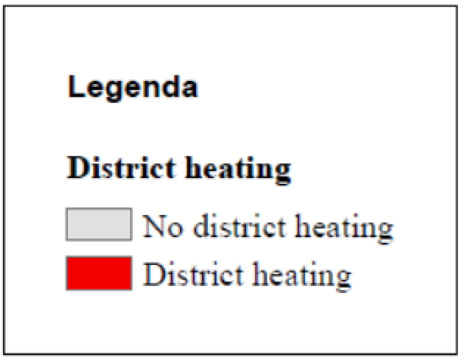
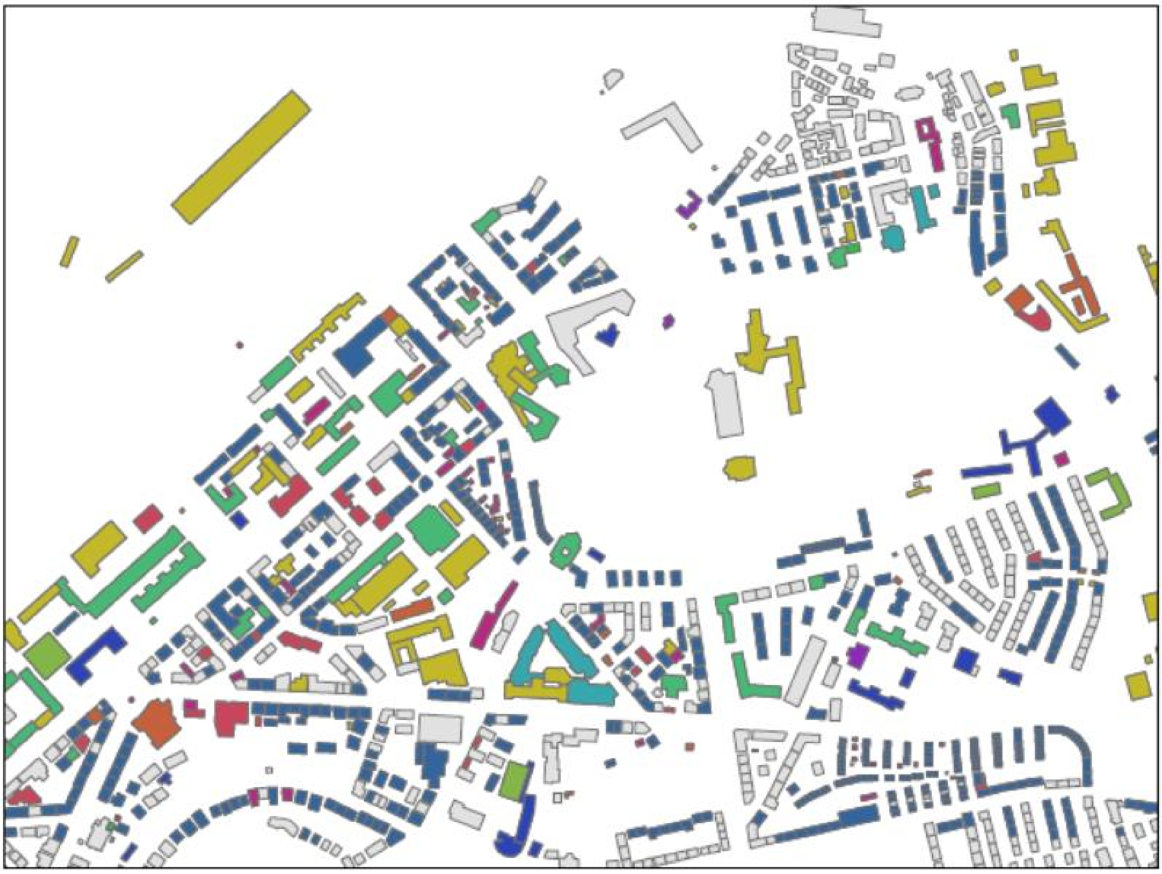


Table 3 - Building primary usage



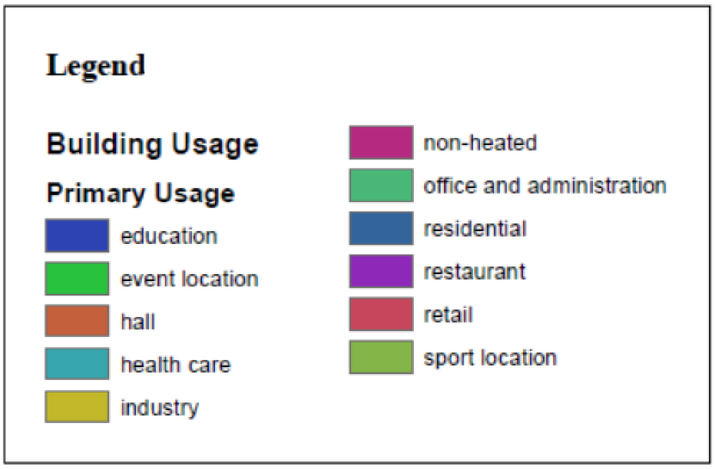
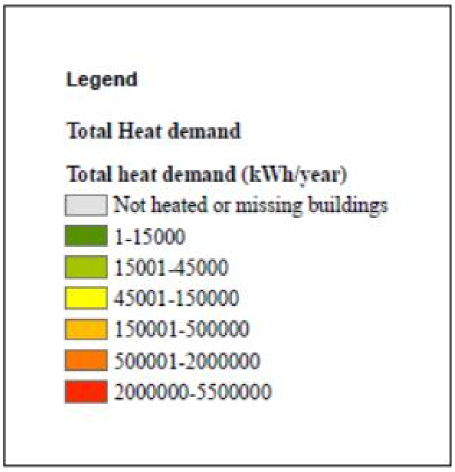
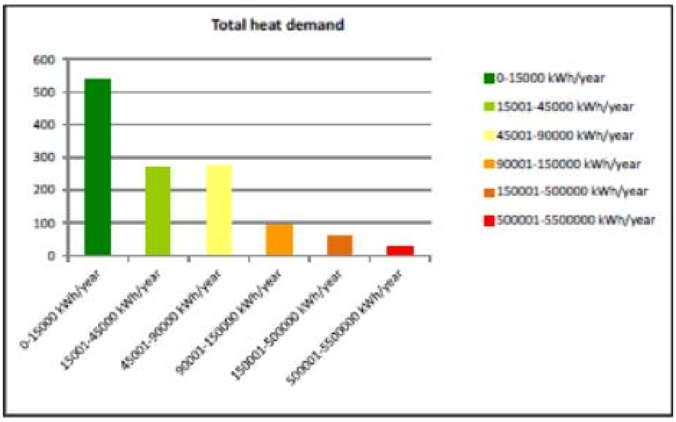


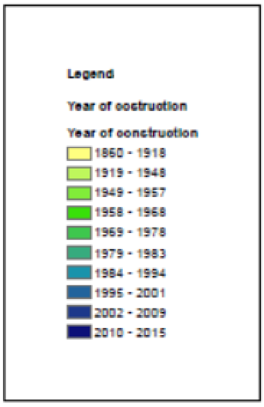
Table 4- Total yearly heat demand



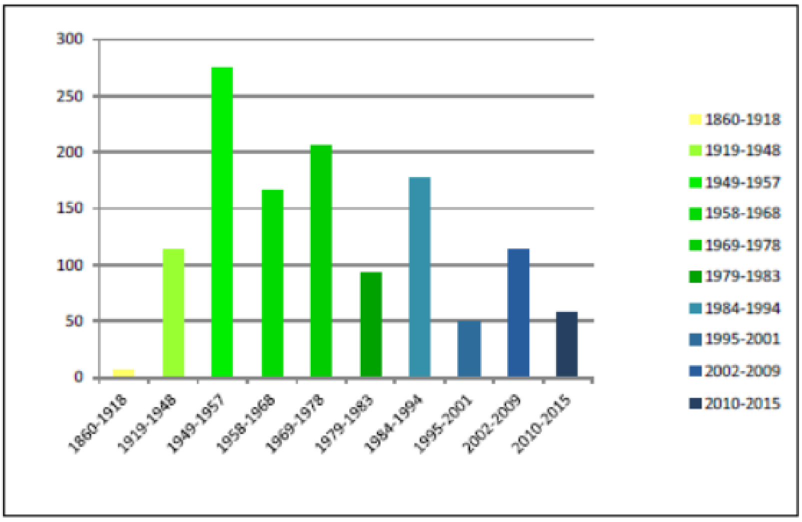


Total heat demand	Number of buildings	
0-15000 kWh/year	539	43%
15001-45000 kWh/year	270	21%
45001-90000 kWh/year	273	22%
90001-150000 kWh/year	92	7%
150001-500000 kWh/year	58	5%
500001-5500000 kWh/year	28	2%

Table 5-Year of building construction



year of construction	number of buildings	
1860-1918	6	0,5%
1919-1948	114	9,1%
1949-1957	275	21,9%
1958-1968	166	13,2%
1969-1978	206	16,4%
1979-1983	93	7,4%
1984-1994	177	14,1%
1995-2001	50	4,0%
2002-2009	113	9,0%
2010-2015	58	4,6%



III-Calculation of design flow rates

SCENARIO A

Cp	ΔT sh	ΔT dhw	ΔT DH	Q sh	Q dhw	Qtot	P sh	P dhw	P tot	m sh	m dhw	m tot
4,187	30	55	20	2449	131	2581	4,94	0,61	5,54	0,0407	0,0027	0,0685
				14466	929	15395	29,17	4,28	33,45	0,4806	0,0192	0,4134
				16676	798	17474	33,62	3,68	37,30	0,5541	0,0165	0,4610
				13896	695	14590	28,02	3,20	31,22	0,4617	0,0144	0,3858
				7502	971	8473	15,12	4,47	19,60	0,2492	0,0201	0,2422
				12668	695	13363	25,54	3,20	28,74	0,4209	0,0144	0,3552
				13022	804	13826	26,25	3,71	29,96	0,4327	0,0167	0,3703
				13727	725	14452	27,68	3,34	31,02	0,4561	0,0150	0,3834
				21354	858	22213	43,05	3,96	47,01	0,7095	0,0178	0,5810
				15836	1643	17479	31,93	7,57	39,50	0,5262	0,0340	0,4882
				19678	1287	20964	39,67	5,93	45,60	0,6538	0,0266	0,5636
				17578	852	18429	35,44	3,92	39,36	0,5840	0,0176	0,4865
				17585	937	18522	35,45	4,32	39,77	0,5843	0,0194	0,4916
				16004	630	16635	32,27	2,90	35,17	0,5317	0,0131	0,4347
				22299	953	23251	44,96	4,39	49,35	0,7409	0,0197	0,6099
				20659	794	21453	41,65	3,66	45,31	0,6864	0,0164	0,5600
				13116	837	13953	26,44	3,86	30,30	0,4358	0,0173	0,3745
				13255	786	14042	26,72	3,62	30,35	0,4404	0,0163	0,3751
				17837	739	18575	35,96	3,40	39,37	0,5926	0,0153	0,4865
				12400	823	13223	25,00	3,79	28,79	0,4120	0,0170	0,3559
				13460	1253	14712	27,14	5,77	32,91	0,4472	0,0259	0,4067
				8989	802	9790	18,12	3,69	21,82	0,2986	0,0166	0,2696
				10025	463	10489	20,21	2,13	22,35	0,3331	0,0096	0,2762
				7128	218	7346	14,37	1,00	15,38	0,2368	0,0045	0,1900
				2837	111	2948	5,72	0,51	6,23	0,0943	0,0023	0,0770
				2746	107	2853	5,54	0,49	6,03	0,0912	0,0022	0,0745
				1761	107	1868	3,55	0,49	4,04	0,0585	0,0022	0,0500
				3463	138	3601	6,98	0,64	7,62	0,1151	0,0029	0,0941
				2997	119	3116	6,04	0,55	6,59	0,0996	0,0025	0,0815
				2696	111	2807	5,44	0,51	5,95	0,0896	0,0023	0,0735
				2707	110	2817	5,46	0,51	5,96	0,0899	0,0023	0,0737
				3493	139	3631	7,04	0,64	7,68	0,1160	0,0029	0,0949
				2181	121	2302	4,40	0,56	4,95	0,0725	0,0025	0,0612
				3217	124	3342	6,49	0,57	7,06	0,1069	0,0026	0,0873
				3331	156	3487	6,72	0,72	7,44	0,1107	0,0032	0,0919
				3162	155	3316	6,37	0,71	7,09	0,1050	0,0032	0,0876
				2871	153	3024	5,79	0,70	6,49	0,0954	0,0032	0,0802

SCENARIO B

Cp	ΔT sh	ΔT dhw	ΔT DH	Q sh	Q dhw	Qtot	P sh	P dhw	P tot	m sh	m dhw	m tot
4,187	0	30	15		131	2581		0,61	0,61		0,0050	0,0100
					929	15395		4,28	4,28		0,0353	0,0706
					798	17474		3,68	3,68		0,0303	0,0606
					695	14590		3,20	3,20		0,0264	0,0528
					971	8473		4,47	4,47		0,0369	0,0737
					695	13363		3,20	3,20		0,0264	0,0528
					804	13826		3,71	3,71		0,0305	0,0611
					725	14452		3,34	3,34		0,0275	0,0551
					858	22213		3,96	3,96		0,0326	0,0652
					1643	17479		7,57	7,57		0,0624	0,1248
					1287	20964		5,93	5,93		0,0489	0,0977
					852	18429		3,92	3,92		0,0323	0,0647
					937	18522		4,32	4,32		0,0356	0,0712
					630	16635		2,90	2,90		0,0239	0,0479
					953	23251		4,39	4,39		0,0362	0,0723
					794	21453		3,66	3,66		0,0302	0,0603
					837	13953		3,86	3,86		0,0318	0,0636
					786	14042		3,62	3,62		0,0299	0,0597
					739	18575		3,40	3,40		0,0280	0,0561
					823	13223		3,79	3,79		0,0313	0,0625
					1253	14712		5,77	5,77		0,0476	0,0951
					802	9790		3,69	3,69		0,0304	0,0609
					463	10489		2,13	2,13		0,0176	0,0352
					218	7346		1,00	1,00		0,0083	0,0166
					111	2948		0,51	0,51		0,0042	0,0084
					107	2853		0,49	0,49		0,0041	0,0081
					107	1868		0,49	0,49		0,0041	0,0081
					138	3601		0,64	0,64		0,0052	0,0105
					119	3116		0,55	0,55		0,0045	0,0090
					111	2807		0,51	0,51		0,0042	0,0084
					110	2817		0,51	0,51		0,0042	0,0083
					139	3631		0,64	0,64		0,0053	0,0105
					121	2302		0,56	0,56		0,0046	0,0092
					124	3342		0,57	0,57		0,0047	0,0094
					156	3487		0,72	0,72		0,0059	0,0119
					155	3316		0,71	0,71		0,0059	0,0117
					153	3024		0,70	0,70		0,0058	0,0116

SCENARIO 1

Cp	ΔT sh	ΔT dhw	ΔT DH	Q sh	Q dhw	Qtot	P sh	P dhw	P tot	m sh	m dhw	m tot
4,187	15	55	20	1178	66	1244	2,38	0,30	2,68	0,0391	0,0014	0,0331
				9497	927	10424	19,15	4,27	23,42	0,3155	0,0192	0,2894
				8221	796	9017	16,57	3,67	20,24	0,2731	0,0165	0,2502
				6441	693	7134	12,99	3,19	16,18	0,2140	0,0144	0,2000
				5478	971	6449	11,04	4,47	15,52	0,1820	0,0201	0,1918
				6459	694	7152	13,02	3,20	16,22	0,2146	0,0144	0,2004
				7222	802	8024	14,56	3,70	18,26	0,2400	0,0166	0,2257
				7229	723	7953	14,58	3,33	17,91	0,2402	0,0150	0,2213
				9538	856	10394	19,23	3,95	23,18	0,3169	0,0177	0,2864
				10935	1642	12578	22,05	7,57	29,62	0,3633	0,0340	0,3660
				9828	1288	11115	19,81	5,93	25,75	0,3265	0,0267	0,3182
				8890	850	9739	17,92	3,92	21,84	0,2954	0,0176	0,2699
				9320	935	10255	18,79	4,31	23,10	0,3097	0,0194	0,2855
				7643	629	8272	15,41	2,90	18,31	0,2539	0,0130	0,2263
				10584	950	11535	21,34	4,38	25,72	0,3517	0,0197	0,3179
				9799	792	10591	19,76	3,65	23,41	0,3256	0,0164	0,2893
				8683	835	9518	17,51	3,85	21,36	0,2885	0,0173	0,2639
				8567	785	9351	17,27	3,62	20,89	0,2846	0,0163	0,2582
				8522	737	9259	17,18	3,40	20,58	0,2831	0,0153	0,2543
				8250	821	9071	16,63	3,78	20,42	0,2741	0,0170	0,2523
				9077	1252	10329	18,30	5,77	24,07	0,3016	0,0259	0,2975
				5113	801	5915	10,31	3,69	14,00	0,1699	0,0166	0,1731
				5322	462	5784	10,73	2,13	12,86	0,1768	0,0096	0,1589
				3118	218	3335	6,29	1,00	7,29	0,1036	0,0045	0,0901
				1361	110	1472	2,74	0,51	3,25	0,0452	0,0023	0,0402
				1322	107	1428	2,66	0,49	3,16	0,0439	0,0022	0,0390
				1331	107	1437	2,68	0,49	3,17	0,0442	0,0022	0,0392
				1669	138	1806	3,36	0,63	4,00	0,0554	0,0029	0,0494
				1449	119	1568	2,92	0,55	3,47	0,0481	0,0025	0,0429
				1387	111	1497	2,80	0,51	3,31	0,0461	0,0023	0,0409
				1398	110	1507	2,82	0,51	3,32	0,0464	0,0023	0,0411
				1682	138	1821	3,39	0,64	4,03	0,0559	0,0029	0,0498
				1416	121	1536	2,85	0,56	3,41	0,0470	0,0025	0,0421
				1545	124	1669	3,12	0,57	3,69	0,0513	0,0026	0,0456
				1728	156	1884	3,48	0,72	4,20	0,0574	0,0032	0,0519
				1732	154	1887	3,49	0,71	4,20	0,0576	0,0032	0,0520
				2016	152	2169	4,07	0,70	4,77	0,0670	0,0032	0,0589

SCENARIO 2												
Cp	ΔT sh	ΔT dhw	ΔT DH	Q sh	Q dhw	Qtot	P sh	P dhw	P tot	m sh	m dhw	m tot
4,187	15	30	15	1178	66	1244	2,38	0,30	2,68	0,0391	0,0025	0,0441
				9497	927	10424	19,15	4,27	23,42	0,3155	0,0352	0,3859
				8221	796	9017	16,57	3,67	20,24	0,2731	0,0302	0,3336
				6441	693	7134	12,99	3,19	16,18	0,2140	0,0263	0,2666
				5478	971	6449	11,04	4,47	15,52	0,1820	0,0369	0,2557
				6459	694	7152	13,02	3,20	16,22	0,2146	0,0263	0,2673
				7222	802	8024	14,56	3,70	18,26	0,2400	0,0305	0,3009
				7229	723	7953	14,58	3,33	17,91	0,2402	0,0275	0,2951
				9538	856	10394	19,23	3,95	23,18	0,3169	0,0325	0,3819
				10935	1642	12578	22,05	7,57	29,62	0,3633	0,0624	0,4880
				9828	1288	11115	19,81	5,93	25,75	0,3265	0,0489	0,4243
				8890	850	9739	17,92	3,92	21,84	0,2954	0,0323	0,3599
				9320	935	10255	18,79	4,31	23,10	0,3097	0,0355	0,3807
				7643	629	8272	15,41	2,90	18,31	0,2539	0,0239	0,3017
				10584	950	11535	21,34	4,38	25,72	0,3517	0,0361	0,4238
				9799	792	10591	19,76	3,65	23,41	0,3256	0,0301	0,3857
				8683	835	9518	17,51	3,85	21,36	0,2885	0,0317	0,3519
				8567	785	9351	17,27	3,62	20,89	0,2846	0,0298	0,3442
				8522	737	9259	17,18	3,40	20,58	0,2831	0,0280	0,3391
				8250	821	9071	16,63	3,78	20,42	0,2741	0,0312	0,3364
				9077	1252	10329	18,30	5,77	24,07	0,3016	0,0475	0,3967
				5113	801	5915	10,31	3,69	14,00	0,1699	0,0304	0,2308
				5322	462	5784	10,73	2,13	12,86	0,1768	0,0175	0,2119
				3118	218	3335	6,29	1,00	7,29	0,1036	0,0083	0,1201
				1361	110	1472	2,74	0,51	3,25	0,0452	0,0042	0,0536
				1322	107	1428	2,66	0,49	3,16	0,0439	0,0040	0,0520
				1331	107	1437	2,68	0,49	3,17	0,0442	0,0040	0,0523
				1669	138	1806	3,36	0,63	4,00	0,0554	0,0052	0,0659
				1449	119	1568	2,92	0,55	3,47	0,0481	0,0045	0,0572
				1387	111	1497	2,80	0,51	3,31	0,0461	0,0042	0,0545
				1398	110	1507	2,82	0,51	3,32	0,0464	0,0042	0,0548
				1682	138	1821	3,39	0,64	4,03	0,0559	0,0052	0,0664
				1416	121	1536	2,85	0,56	3,41	0,0470	0,0046	0,0562
				1545	124	1669	3,12	0,57	3,69	0,0513	0,0047	0,0608
				1728	156	1884	3,48	0,72	4,20	0,0574	0,0059	0,0692
				1732	154	1887	3,49	0,71	4,20	0,0576	0,0059	0,0693
				2016	152	2169	4,07	0,70	4,77	0,0670	0,0058	0,0786

IV-Analytical calculation of thermal losses

- **Scenarios A and 1 (medium temperature district heating):**

Primary Grid -January											
FID	De (m)	H (m)	C (m)	R_{pipe} (m^2K/W)	R_{ground} (m^2K/W)	R_{12} (m^2K/W)	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	0,163	0,88	0,28	4,85	0,34	0,37	83,34	52,86	136,21	4,80	2380
1	0,128	0,86	0,26	5,65	0,43	0,38	68,49	43,81	112,30	15,25	7563
2	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,50	248
3	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,49	244
4	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,49	241
5	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,41	204
6	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,40	201
7	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,42	209
8	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,39	196
9	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,39	192
10	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,38	189
11	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	362
12	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	362
13	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	361
14	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	360
15	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	360
16	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,73	363
17	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,74	365
18	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,74	365
19	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,75	372
20	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,75	372
21	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,79	394
22	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	1,56	773
23	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,65	323
24	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,62	308
25	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,68	337
26	0,093	0,85	0,25	5,65	0,57	0,39	63,66	40,71	104,37	11,30	5607
27	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,32	157
28	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,30	150
29	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,74	365
30	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,25	124
31	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	1,17	582
32	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	1,02	506
33	0,128	0,86	0,26	6,45	0,43	0,38	60,82	39,15	99,97	12,28	6090
34	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,19	96
35	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,20	99
36	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,20	99
37	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,20	101
38	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,21	102
39	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,21	105
40	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,21	105
41	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,21	104
42	0,093	0,85	0,25	10,42	0,57	0,39	36,73	24,07	60,80	0,21	104

	February					March				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	83,29	52,81	136,10	4,79	2148	80,64	50,16	130,79	4,61	2286
1	68,45	43,76	112,21	15,24	6826	66,26	41,57	107,84	14,64	7263
2	36,71	24,04	60,75	0,50	223	35,52	22,86	58,38	0,48	238
3	36,71	24,04	60,75	0,49	220	35,52	22,86	58,38	0,47	235
4	36,71	24,04	60,75	0,49	217	35,52	22,86	58,38	0,47	231
5	36,71	24,04	60,75	0,41	184	35,52	22,86	58,38	0,39	195
6	36,71	24,04	60,75	0,40	181	35,52	22,86	58,38	0,39	193
7	36,71	24,04	60,75	0,42	188	35,52	22,86	58,38	0,40	200
8	36,71	24,04	60,75	0,39	177	35,52	22,86	58,38	0,38	188
9	36,71	24,04	60,75	0,39	173	35,52	22,86	58,38	0,37	184
10	36,71	24,04	60,75	0,38	171	35,52	22,86	58,38	0,37	182
11	36,71	24,04	60,75	0,73	327	35,52	22,86	58,38	0,70	348
12	36,71	24,04	60,75	0,73	327	35,52	22,86	58,38	0,70	347
13	36,71	24,04	60,75	0,73	326	35,52	22,86	58,38	0,70	346
14	36,71	24,04	60,75	0,72	325	35,52	22,86	58,38	0,70	345
15	36,71	24,04	60,75	0,73	325	35,52	22,86	58,38	0,70	346
16	36,71	24,04	60,75	0,73	328	35,52	22,86	58,38	0,70	349
17	36,71	24,04	60,75	0,74	329	35,52	22,86	58,38	0,71	350
18	36,71	24,04	60,75	0,74	330	35,52	22,86	58,38	0,71	351
19	36,71	24,04	60,75	0,75	336	35,52	22,86	58,38	0,72	357
20	36,71	24,04	60,75	0,75	336	35,52	22,86	58,38	0,72	357
21	36,71	24,04	60,75	0,79	355	35,52	22,86	58,38	0,76	378
22	36,71	24,04	60,75	1,56	697	35,52	22,86	58,38	1,50	742
23	36,71	24,04	60,75	0,65	291	35,52	22,86	58,38	0,62	310
24	36,71	24,04	60,75	0,62	278	35,52	22,86	58,38	0,60	295
25	36,71	24,04	60,75	0,68	304	35,52	22,86	58,38	0,65	323
26	63,62	40,67	104,29	11,30	5060	61,58	38,64	100,22	10,85	5384
27	36,71	24,04	60,75	0,32	141	35,52	22,86	58,38	0,30	150
28	36,71	24,04	60,75	0,30	135	35,52	22,86	58,38	0,29	144
29	36,71	24,04	60,75	0,74	329	35,52	22,86	58,38	0,71	350
30	36,71	24,04	60,75	0,25	112	35,52	22,86	58,38	0,24	119
31	36,71	24,04	60,75	1,17	525	35,52	22,86	58,38	1,13	559
32	36,71	24,04	60,75	1,02	456	35,52	22,86	58,38	0,98	486
33	60,78	39,12	99,89	12,27	5497	58,83	37,17	96,00	11,79	5848
34	36,71	24,04	60,75	0,19	87	35,52	22,86	58,38	0,19	93
35	36,71	24,04	60,75	0,20	89	35,52	22,86	58,38	0,19	95
36	36,71	24,04	60,75	0,20	89	35,52	22,86	58,38	0,19	95
37	36,71	24,04	60,75	0,20	91	35,52	22,86	58,38	0,19	97
38	36,71	24,04	60,75	0,21	92	35,52	22,86	58,38	0,20	98
39	36,71	24,04	60,75	0,21	95	35,52	22,86	58,38	0,20	101
40	36,71	24,04	60,75	0,21	94	35,52	22,86	58,38	0,20	100
41	36,71	24,04	60,75	0,21	94	35,52	22,86	58,38	0,20	100
42	36,71	24,04	60,75	0,21	94	35,52	22,86	58,38	0,20	100

	April					May				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	75,94	45,46	121,40	4,28	2053	70,48	40,00	110,49	3,89	1931
1	62,39	37,70	100,09	13,59	6523	57,89	33,20	91,09	12,37	6135
2	33,43	20,76	54,19	0,44	214	30,99	18,33	49,32	0,40	201
3	33,43	20,76	54,19	0,44	211	30,99	18,33	49,32	0,40	198
4	33,43	20,76	54,19	0,43	208	30,99	18,33	49,32	0,39	195
5	33,43	20,76	54,19	0,37	176	30,99	18,33	49,32	0,33	165
6	33,43	20,76	54,19	0,36	173	30,99	18,33	49,32	0,33	163
7	33,43	20,76	54,19	0,37	180	30,99	18,33	49,32	0,34	169
8	33,43	20,76	54,19	0,35	169	30,99	18,33	49,32	0,32	159
9	33,43	20,76	54,19	0,35	166	30,99	18,33	49,32	0,31	156
10	33,43	20,76	54,19	0,34	163	30,99	18,33	49,32	0,31	153
11	33,43	20,76	54,19	0,65	312	30,99	18,33	49,32	0,59	294
12	33,43	20,76	54,19	0,65	312	30,99	18,33	49,32	0,59	294
13	33,43	20,76	54,19	0,65	311	30,99	18,33	49,32	0,59	293
14	33,43	20,76	54,19	0,65	310	30,99	18,33	49,32	0,59	292
15	33,43	20,76	54,19	0,65	311	30,99	18,33	49,32	0,59	292
16	33,43	20,76	54,19	0,65	313	30,99	18,33	49,32	0,59	295
17	33,43	20,76	54,19	0,66	315	30,99	18,33	49,32	0,60	296
18	33,43	20,76	54,19	0,66	315	30,99	18,33	49,32	0,60	296
19	33,43	20,76	54,19	0,67	321	30,99	18,33	49,32	0,61	302
20	33,43	20,76	54,19	0,67	321	30,99	18,33	49,32	0,61	302
21	33,43	20,76	54,19	0,71	340	30,99	18,33	49,32	0,64	319
22	33,43	20,76	54,19	1,39	666	30,99	18,33	49,32	1,26	627
23	33,43	20,76	54,19	0,58	278	30,99	18,33	49,32	0,53	262
24	33,43	20,76	54,19	0,55	265	30,99	18,33	49,32	0,50	250
25	33,43	20,76	54,19	0,60	290	30,99	18,33	49,32	0,55	273
26	57,98	35,04	93,02	10,08	4836	53,80	30,86	84,66	9,17	4548
27	33,43	20,76	54,19	0,28	135	30,99	18,33	49,32	0,26	127
28	33,43	20,76	54,19	0,27	129	30,99	18,33	49,32	0,24	121
29	33,43	20,76	54,19	0,66	315	30,99	18,33	49,32	0,60	296
30	33,43	20,76	54,19	0,22	107	30,99	18,33	49,32	0,20	100
31	33,43	20,76	54,19	1,05	502	30,99	18,33	49,32	0,95	472
32	33,43	20,76	54,19	0,91	436	30,99	18,33	49,32	0,83	410
33	55,38	33,72	89,10	10,94	5253	51,38	29,72	81,09	9,96	4940
34	33,43	20,76	54,19	0,17	83	30,99	18,33	49,32	0,16	78
35	33,43	20,76	54,19	0,18	85	30,99	18,33	49,32	0,16	80
36	33,43	20,76	54,19	0,18	85	30,99	18,33	49,32	0,16	80
37	33,43	20,76	54,19	0,18	87	30,99	18,33	49,32	0,16	82
38	33,43	20,76	54,19	0,18	88	30,99	18,33	49,32	0,17	83
39	33,43	20,76	54,19	0,19	91	30,99	18,33	49,32	0,17	85
40	33,43	20,76	54,19	0,19	90	30,99	18,33	49,32	0,17	85
41	33,43	20,76	54,19	0,19	90	30,99	18,33	49,32	0,17	85
42	33,43	20,76	54,19	0,19	89	30,99	18,33	49,32	0,17	84

	June					July				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	65,74	35,26	101,00	3,56	1708	67,44	32,51	99,96	3,52	1747
1	53,98	29,29	83,27	11,31	5427	55,63	27,03	82,65	11,22	5566
2	28,87	16,21	45,08	0,37	178	29,17	14,98	44,16	0,36	180
3	28,87	16,21	45,08	0,37	175	29,17	14,98	44,16	0,36	177
4	28,87	16,21	45,08	0,36	173	29,17	14,98	44,16	0,35	175
5	28,87	16,21	45,08	0,30	146	29,17	14,98	44,16	0,30	148
6	28,87	16,21	45,08	0,30	144	29,17	14,98	44,16	0,29	146
7	28,87	16,21	45,08	0,31	150	29,17	14,98	44,16	0,31	152
8	28,87	16,21	45,08	0,29	140	29,17	14,98	44,16	0,29	142
9	28,87	16,21	45,08	0,29	138	29,17	14,98	44,16	0,28	140
10	28,87	16,21	45,08	0,28	136	29,17	14,98	44,16	0,28	137
11	28,87	16,21	45,08	0,54	260	29,17	14,98	44,16	0,53	263
12	28,87	16,21	45,08	0,54	260	29,17	14,98	44,16	0,53	263
13	28,87	16,21	45,08	0,54	259	29,17	14,98	44,16	0,53	262
14	28,87	16,21	45,08	0,54	258	29,17	14,98	44,16	0,53	261
15	28,87	16,21	45,08	0,54	259	29,17	14,98	44,16	0,53	262
16	28,87	16,21	45,08	0,54	261	29,17	14,98	44,16	0,53	264
17	28,87	16,21	45,08	0,55	262	29,17	14,98	44,16	0,53	265
18	28,87	16,21	45,08	0,55	262	29,17	14,98	44,16	0,53	265
19	28,87	16,21	45,08	0,56	267	29,17	14,98	44,16	0,54	270
20	28,87	16,21	45,08	0,56	267	29,17	14,98	44,16	0,54	270
21	28,87	16,21	45,08	0,59	283	29,17	14,98	44,16	0,58	286
22	28,87	16,21	45,08	1,15	554	29,17	14,98	44,16	1,13	561
23	28,87	16,21	45,08	0,48	232	29,17	14,98	44,16	0,47	234
24	28,87	16,21	45,08	0,46	221	29,17	14,98	44,16	0,45	223
25	28,87	16,21	45,08	0,50	241	29,17	14,98	44,16	0,49	244
26	50,17	27,22	77,39	8,38	4023	52,95	25,12	78,07	8,46	4194
27	28,87	16,21	45,08	0,23	112	29,17	14,98	44,16	0,23	114
28	28,87	16,21	45,08	0,22	107	29,17	14,98	44,16	0,22	109
29	28,87	16,21	45,08	0,55	262	29,17	14,98	44,16	0,53	265
30	28,87	16,21	45,08	0,18	89	29,17	14,98	44,16	0,18	90
31	28,87	16,21	45,08	0,87	418	29,17	14,98	44,16	0,85	423
32	28,87	16,21	45,08	0,76	363	29,17	14,98	44,16	0,74	367
33	47,89	26,23	74,13	9,10	4370	48,92	24,22	73,14	8,98	4455
34	28,87	16,21	45,08	0,14	69	29,17	14,98	44,16	0,14	70
35	28,87	16,21	45,08	0,15	71	29,17	14,98	44,16	0,14	72
36	28,87	16,21	45,08	0,15	71	29,17	14,98	44,16	0,14	72
37	28,87	16,21	45,08	0,15	72	29,17	14,98	44,16	0,15	73
38	28,87	16,21	45,08	0,15	73	29,17	14,98	44,16	0,15	74
39	28,87	16,21	45,08	0,16	75	29,17	14,98	44,16	0,15	76
40	28,87	16,21	45,08	0,16	75	29,17	14,98	44,16	0,15	76
41	28,87	16,21	45,08	0,16	75	29,17	14,98	44,16	0,15	76
42	28,87	16,21	45,08	0,16	74	29,17	14,98	44,16	0,15	75

	August					September				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	67,45	32,52	99,97	3,52	1747	65,75	35,27	101,03	3,56	1708
1	55,63	27,03	82,66	11,22	5567	53,99	29,30	83,30	11,31	5429
2	29,18	14,99	44,16	0,36	180	28,88	16,21	45,09	0,37	178
3	29,18	14,99	44,16	0,36	177	28,88	16,21	45,09	0,37	175
4	29,18	14,99	44,16	0,35	175	28,88	16,21	45,09	0,36	173
5	29,18	14,99	44,16	0,30	148	28,88	16,21	45,09	0,30	146
6	29,18	14,99	44,16	0,29	146	28,88	16,21	45,09	0,30	144
7	29,18	14,99	44,16	0,31	152	28,88	16,21	45,09	0,31	150
8	29,18	14,99	44,16	0,29	142	28,88	16,21	45,09	0,29	140
9	29,18	14,99	44,16	0,28	140	28,88	16,21	45,09	0,29	138
10	29,18	14,99	44,16	0,28	137	28,88	16,21	45,09	0,28	136
11	29,18	14,99	44,16	0,53	263	28,88	16,21	45,09	0,54	260
12	29,18	14,99	44,16	0,53	263	28,88	16,21	45,09	0,54	260
13	29,18	14,99	44,16	0,53	262	28,88	16,21	45,09	0,54	259
14	29,18	14,99	44,16	0,53	261	28,88	16,21	45,09	0,54	258
15	29,18	14,99	44,16	0,53	262	28,88	16,21	45,09	0,54	259
16	29,18	14,99	44,16	0,53	264	28,88	16,21	45,09	0,54	261
17	29,18	14,99	44,16	0,53	265	28,88	16,21	45,09	0,55	262
18	29,18	14,99	44,16	0,53	265	28,88	16,21	45,09	0,55	262
19	29,18	14,99	44,16	0,54	270	28,88	16,21	45,09	0,56	267
20	29,18	14,99	44,16	0,54	270	28,88	16,21	45,09	0,56	267
21	29,18	14,99	44,16	0,58	286	28,88	16,21	45,09	0,59	283
22	29,18	14,99	44,16	1,13	561	28,88	16,21	45,09	1,16	555
23	29,18	14,99	44,16	0,47	234	28,88	16,21	45,09	0,48	232
24	29,18	14,99	44,16	0,45	223	28,88	16,21	45,09	0,46	221
25	29,18	14,99	44,16	0,49	244	28,88	16,21	45,09	0,50	242
26	52,96	25,12	78,08	8,46	4195	50,18	27,23	77,41	8,38	4025
27	29,18	14,99	44,16	0,23	114	28,88	16,21	45,09	0,23	112
28	29,18	14,99	44,16	0,22	109	28,88	16,21	45,09	0,22	107
29	29,18	14,99	44,16	0,53	265	28,88	16,21	45,09	0,55	262
30	29,18	14,99	44,16	0,18	90	28,88	16,21	45,09	0,18	89
31	29,18	14,99	44,16	0,85	423	28,88	16,21	45,09	0,87	418
32	29,18	14,99	44,16	0,74	367	28,88	16,21	45,09	0,76	363
33	48,92	24,22	73,15	8,98	4456	47,91	26,24	74,15	9,11	4371
34	29,18	14,99	44,16	0,14	70	28,88	16,21	45,09	0,14	69
35	29,18	14,99	44,16	0,14	72	28,88	16,21	45,09	0,15	71
36	29,18	14,99	44,16	0,14	72	28,88	16,21	45,09	0,15	71
37	29,18	14,99	44,16	0,15	73	28,88	16,21	45,09	0,15	72
38	29,18	14,99	44,16	0,15	74	28,88	16,21	45,09	0,15	73
39	29,18	14,99	44,16	0,15	76	28,88	16,21	45,09	0,16	75
40	29,18	14,99	44,16	0,15	76	28,88	16,21	45,09	0,16	75
41	29,18	14,99	44,16	0,15	76	28,88	16,21	45,09	0,16	75
42	29,18	14,99	44,16	0,15	75	28,88	16,21	45,09	0,16	74

	October					November				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	70,50	40,03	110,53	3,89	1931	75,96	45,48	121,44	4,28	2054
1	57,91	33,22	91,13	12,37	6137	62,41	37,72	100,13	13,60	6526
2	31,00	18,34	49,34	0,41	201	33,44	20,77	54,21	0,45	214
3	31,00	18,34	49,34	0,40	198	33,44	20,77	54,21	0,44	211
4	31,00	18,34	49,34	0,39	196	33,44	20,77	54,21	0,43	208
5	31,00	18,34	49,34	0,33	165	33,44	20,77	54,21	0,37	176
6	31,00	18,34	49,34	0,33	163	33,44	20,77	54,21	0,36	173
7	31,00	18,34	49,34	0,34	169	33,44	20,77	54,21	0,38	180
8	31,00	18,34	49,34	0,32	159	33,44	20,77	54,21	0,35	169
9	31,00	18,34	49,34	0,31	156	33,44	20,77	54,21	0,35	166
10	31,00	18,34	49,34	0,31	153	33,44	20,77	54,21	0,34	163
11	31,00	18,34	49,34	0,59	294	33,44	20,77	54,21	0,65	312
12	31,00	18,34	49,34	0,59	294	33,44	20,77	54,21	0,65	312
13	31,00	18,34	49,34	0,59	293	33,44	20,77	54,21	0,65	311
14	31,00	18,34	49,34	0,59	292	33,44	20,77	54,21	0,65	310
15	31,00	18,34	49,34	0,59	292	33,44	20,77	54,21	0,65	311
16	31,00	18,34	49,34	0,59	295	33,44	20,77	54,21	0,65	314
17	31,00	18,34	49,34	0,60	296	33,44	20,77	54,21	0,66	315
18	31,00	18,34	49,34	0,60	296	33,44	20,77	54,21	0,66	315
19	31,00	18,34	49,34	0,61	302	33,44	20,77	54,21	0,67	321
20	31,00	18,34	49,34	0,61	302	33,44	20,77	54,21	0,67	321
21	31,00	18,34	49,34	0,64	320	33,44	20,77	54,21	0,71	340
22	31,00	18,34	49,34	1,26	627	33,44	20,77	54,21	1,39	667
23	31,00	18,34	49,34	0,53	262	33,44	20,77	54,21	0,58	278
24	31,00	18,34	49,34	0,50	250	33,44	20,77	54,21	0,55	265
25	31,00	18,34	49,34	0,55	273	33,44	20,77	54,21	0,60	290
26	53,82	30,87	84,69	9,17	4550	58,00	35,06	93,06	10,08	4838
27	31,00	18,34	49,34	0,26	127	33,44	20,77	54,21	0,28	135
28	31,00	18,34	49,34	0,24	121	33,44	20,77	54,21	0,27	129
29	31,00	18,34	49,34	0,60	296	33,44	20,77	54,21	0,66	315
30	31,00	18,34	49,34	0,20	100	33,44	20,77	54,21	0,22	107
31	31,00	18,34	49,34	0,95	472	33,44	20,77	54,21	1,05	502
32	31,00	18,34	49,34	0,83	410	33,44	20,77	54,21	0,91	436
33	51,39	29,73	81,13	9,96	4942	55,40	33,74	89,14	10,95	5255
34	31,00	18,34	49,34	0,16	78	33,44	20,77	54,21	0,17	83
35	31,00	18,34	49,34	0,16	80	33,44	20,77	54,21	0,18	85
36	31,00	18,34	49,34	0,16	80	33,44	20,77	54,21	0,18	85
37	31,00	18,34	49,34	0,16	82	33,44	20,77	54,21	0,18	87
38	31,00	18,34	49,34	0,17	83	33,44	20,77	54,21	0,18	88
39	31,00	18,34	49,34	0,17	85	33,44	20,77	54,21	0,19	91
40	31,00	18,34	49,34	0,17	85	33,44	20,77	54,21	0,19	90
41	31,00	18,34	49,34	0,17	85	33,44	20,77	54,21	0,19	90
42	31,00	18,34	49,34	0,17	84	33,44	20,77	54,21	0,19	90

	December				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	80,65	50,17	130,83	4,61	2286
1	66,28	41,59	107,86	14,65	7264
2	35,53	22,86	58,40	0,48	238
3	35,53	22,86	58,40	0,47	235
4	35,53	22,86	58,40	0,47	231
5	35,53	22,86	58,40	0,39	196
6	35,53	22,86	58,40	0,39	193
7	35,53	22,86	58,40	0,40	200
8	35,53	22,86	58,40	0,38	188
9	35,53	22,86	58,40	0,37	185
10	35,53	22,86	58,40	0,37	182
11	35,53	22,86	58,40	0,70	348
12	35,53	22,86	58,40	0,70	348
13	35,53	22,86	58,40	0,70	346
14	35,53	22,86	58,40	0,70	346
15	35,53	22,86	58,40	0,70	346
16	35,53	22,86	58,40	0,70	349
17	35,53	22,86	58,40	0,71	350
18	35,53	22,86	58,40	0,71	351
19	35,53	22,86	58,40	0,72	357
20	35,53	22,86	58,40	0,72	357
21	35,53	22,86	58,40	0,76	378
22	35,53	22,86	58,40	1,50	742
23	35,53	22,86	58,40	0,62	310
24	35,53	22,86	58,40	0,60	295
25	35,53	22,86	58,40	0,65	323
26	61,60	38,65	100,25	10,86	5385
27	35,53	22,86	58,40	0,30	150
28	35,53	22,86	58,40	0,29	144
29	35,53	22,86	58,40	0,71	350
30	35,53	22,86	58,40	0,24	119
31	35,53	22,86	58,40	1,13	559
32	35,53	22,86	58,40	0,98	486
33	58,84	37,18	96,02	11,79	5850
34	35,53	22,86	58,40	0,19	93
35	35,53	22,86	58,40	0,19	95
36	35,53	22,86	58,40	0,19	95
37	35,53	22,86	58,40	0,20	97
38	35,53	22,86	58,40	0,20	98
39	35,53	22,86	58,40	0,20	101
40	35,53	22,86	58,40	0,20	101
41	35,53	22,86	58,40	0,20	100
42	35,53	22,86	58,40	0,20	100

- **Scenarios B and 2 (low temperature district heating):**

Primary Grid –January											
FID	De (m)	H (m)	C (m)	R_{pipe} (m^2K/W)	R_{ground} (m^2K/W)	R_{12} (m^2K/W)	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	0,163	0,88	0,28	3,38	0,34	0,37	59,36	26,60	85,96	3,03	1502
1	0,128	0,86	0,26	5,65	0,43	0,38	35,42	16,90	52,32	7,10	3524
2	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,23	115
3	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,23	114
4	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,23	112
5	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,19	95
6	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,19	94
7	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,20	97
8	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,18	91
9	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,18	90
10	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,18	88
11	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	169
12	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	169
13	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	168
14	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	168
15	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	168
16	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	169
17	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	170
18	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,34	170
19	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,35	173
20	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,35	173
21	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,37	183
22	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,73	360
23	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,30	150
24	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,29	143
25	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,32	157
26	0,163	0,88	0,28	6,17	0,34	0,37	34,70	16,71	51,40	5,57	2761
27	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,15	73
28	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,14	70
29	0,093	0,85	0,25	8,26	0,57	0,39	23,41	11,50	34,91	0,42	210
30	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,12	58
31	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,55	271
32	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,48	236
33	0,128	0,86	0,26	5,65	0,43	0,38	35,42	16,90	52,32	6,43	3188
34	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,09	45
35	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,09	46
36	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,09	46
37	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,09	47
38	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,10	48
39	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,10	49
40	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,10	49
41	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,10	49
42	0,093	0,85	0,25	10,42	0,57	0,39	18,91	9,41	28,33	0,10	48

	February					March				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	59,29	26,53	85,82	3,02	1354	55,70	22,93	78,63	2,77	1374
1	35,38	16,86	52,24	7,09	3178	33,19	14,67	47,86	6,50	3223
2	18,89	9,39	28,28	0,23	104	17,71	8,21	25,91	0,21	106
3	18,89	9,39	28,28	0,23	103	17,71	8,21	25,91	0,21	104
4	18,89	9,39	28,28	0,23	101	17,71	8,21	25,91	0,21	103
5	18,89	9,39	28,28	0,19	86	17,71	8,21	25,91	0,17	87
6	18,89	9,39	28,28	0,19	84	17,71	8,21	25,91	0,17	86
7	18,89	9,39	28,28	0,20	88	17,71	8,21	25,91	0,18	89
8	18,89	9,39	28,28	0,18	82	17,71	8,21	25,91	0,17	83
9	18,89	9,39	28,28	0,18	81	17,71	8,21	25,91	0,17	82
10	18,89	9,39	28,28	0,18	79	17,71	8,21	25,91	0,16	81
11	18,89	9,39	28,28	0,34	152	17,71	8,21	25,91	0,31	154
12	18,89	9,39	28,28	0,34	152	17,71	8,21	25,91	0,31	154
13	18,89	9,39	28,28	0,34	152	17,71	8,21	25,91	0,31	154
14	18,89	9,39	28,28	0,34	151	17,71	8,21	25,91	0,31	153
15	18,89	9,39	28,28	0,34	151	17,71	8,21	25,91	0,31	154
16	18,89	9,39	28,28	0,34	153	17,71	8,21	25,91	0,31	155
17	18,89	9,39	28,28	0,34	153	17,71	8,21	25,91	0,31	156
18	18,89	9,39	28,28	0,34	153	17,71	8,21	25,91	0,31	156
19	18,89	9,39	28,28	0,35	156	17,71	8,21	25,91	0,32	159
20	18,89	9,39	28,28	0,35	156	17,71	8,21	25,91	0,32	159
21	18,89	9,39	28,28	0,37	165	17,71	8,21	25,91	0,34	168
22	18,89	9,39	28,28	0,72	325	17,71	8,21	25,91	0,66	329
23	18,89	9,39	28,28	0,30	136	17,71	8,21	25,91	0,28	138
24	18,89	9,39	28,28	0,29	129	17,71	8,21	25,91	0,26	131
25	18,89	9,39	28,28	0,32	141	17,71	8,21	25,91	0,29	143
26	34,65	16,66	51,32	5,56	2490	32,50	14,51	47,02	5,09	2526
27	18,89	9,39	28,28	0,15	66	17,71	8,21	25,91	0,13	67
28	18,89	9,39	28,28	0,14	63	17,71	8,21	25,91	0,13	64
29	23,38	11,47	34,86	0,42	189	21,92	10,01	31,94	0,39	192
30	18,89	9,39	28,28	0,12	52	17,71	8,21	25,91	0,11	53
31	18,89	9,39	28,28	0,55	245	17,71	8,21	25,91	0,50	248
32	18,89	9,39	28,28	0,47	212	17,71	8,21	25,91	0,43	216
33	35,38	16,86	52,24	6,42	2874	33,19	14,67	47,86	5,88	2916
34	18,89	9,39	28,28	0,09	41	17,71	8,21	25,91	0,08	41
35	18,89	9,39	28,28	0,09	41	17,71	8,21	25,91	0,08	42
36	18,89	9,39	28,28	0,09	41	17,71	8,21	25,91	0,08	42
37	18,89	9,39	28,28	0,09	42	17,71	8,21	25,91	0,09	43
38	18,89	9,39	28,28	0,10	43	17,71	8,21	25,91	0,09	44
39	18,89	9,39	28,28	0,10	44	17,71	8,21	25,91	0,09	45
40	18,89	9,39	28,28	0,10	44	17,71	8,21	25,91	0,09	45
41	18,89	9,39	28,28	0,10	44	17,71	8,21	25,91	0,09	44
42	18,89	9,39	28,28	0,10	44	17,71	8,21	25,91	0,09	44

	April					May				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	49,33	16,57	65,91	2,32	1115	41,94	9,18	51,13	1,80	893
1	29,32	10,80	40,12	5,45	2615	24,82	6,30	31,12	4,23	2096
2	15,61	6,11	21,72	0,18	86	13,17	3,67	16,85	0,14	69
3	15,61	6,11	21,72	0,18	84	13,17	3,67	16,85	0,14	68
4	15,61	6,11	21,72	0,17	83	13,17	3,67	16,85	0,13	67
5	15,61	6,11	21,72	0,15	70	13,17	3,67	16,85	0,11	56
6	15,61	6,11	21,72	0,14	69	13,17	3,67	16,85	0,11	56
7	15,61	6,11	21,72	0,15	72	13,17	3,67	16,85	0,12	58
8	15,61	6,11	21,72	0,14	68	13,17	3,67	16,85	0,11	54
9	15,61	6,11	21,72	0,14	66	13,17	3,67	16,85	0,11	53
10	15,61	6,11	21,72	0,14	65	13,17	3,67	16,85	0,11	52
11	15,61	6,11	21,72	0,26	125	13,17	3,67	16,85	0,20	100
12	15,61	6,11	21,72	0,26	125	13,17	3,67	16,85	0,20	100
13	15,61	6,11	21,72	0,26	125	13,17	3,67	16,85	0,20	100
14	15,61	6,11	21,72	0,26	124	13,17	3,67	16,85	0,20	100
15	15,61	6,11	21,72	0,26	125	13,17	3,67	16,85	0,20	100
16	15,61	6,11	21,72	0,26	126	13,17	3,67	16,85	0,20	101
17	15,61	6,11	21,72	0,26	126	13,17	3,67	16,85	0,20	101
18	15,61	6,11	21,72	0,26	126	13,17	3,67	16,85	0,20	101
19	15,61	6,11	21,72	0,27	129	13,17	3,67	16,85	0,21	103
20	15,61	6,11	21,72	0,27	129	13,17	3,67	16,85	0,21	103
21	15,61	6,11	21,72	0,28	136	13,17	3,67	16,85	0,22	109
22	15,61	6,11	21,72	0,56	267	13,17	3,67	16,85	0,43	214
23	15,61	6,11	21,72	0,23	112	13,17	3,67	16,85	0,18	89
24	15,61	6,11	21,72	0,22	106	13,17	3,67	16,85	0,17	85
25	15,61	6,11	21,72	0,24	116	13,17	3,67	16,85	0,19	93
26	28,70	10,71	39,41	4,27	2049	24,28	6,29	30,57	3,31	1642
27	15,61	6,11	21,72	0,11	54	13,17	3,67	16,85	0,09	43
28	15,61	6,11	21,72	0,11	52	13,17	3,67	16,85	0,08	41
29	19,34	7,43	26,77	0,32	155	16,34	4,43	20,77	0,25	125
30	15,61	6,11	21,72	0,09	43	13,17	3,67	16,85	0,07	34
31	15,61	6,11	21,72	0,42	201	13,17	3,67	16,85	0,33	161
32	15,61	6,11	21,72	0,36	175	13,17	3,67	16,85	0,28	140
33	29,32	10,80	40,12	4,93	2365	24,82	6,30	31,12	3,82	1896
34	15,61	6,11	21,72	0,07	33	13,17	3,67	16,85	0,05	27
35	15,61	6,11	21,72	0,07	34	13,17	3,67	16,85	0,06	27
36	15,61	6,11	21,72	0,07	34	13,17	3,67	16,85	0,06	27
37	15,61	6,11	21,72	0,07	35	13,17	3,67	16,85	0,06	28
38	15,61	6,11	21,72	0,07	35	13,17	3,67	16,85	0,06	28
39	15,61	6,11	21,72	0,08	36	13,17	3,67	16,85	0,06	29
40	15,61	6,11	21,72	0,08	36	13,17	3,67	16,85	0,06	29
41	15,61	6,11	21,72	0,08	36	13,17	3,67	16,85	0,06	29
42	15,61	6,11	21,72	0,07	36	13,17	3,67	16,85	0,06	29

	June					July				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	35,52	2,75	38,27	1,35	647	31,80	-0,96	30,84	1,09	539
1	20,91	2,39	23,29	3,16	1518	18,64	0,13	18,77	2,55	1264
2	11,06	1,56	12,61	0,10	50	9,83	0,33	10,16	0,08	41
3	11,06	1,56	12,61	0,10	49	9,83	0,33	10,16	0,08	41
4	11,06	1,56	12,61	0,10	48	9,83	0,33	10,16	0,08	40
5	11,06	1,56	12,61	0,09	41	9,83	0,33	10,16	0,07	34
6	11,06	1,56	12,61	0,08	40	9,83	0,33	10,16	0,07	34
7	11,06	1,56	12,61	0,09	42	9,83	0,33	10,16	0,07	35
8	11,06	1,56	12,61	0,08	39	9,83	0,33	10,16	0,07	33
9	11,06	1,56	12,61	0,08	39	9,83	0,33	10,16	0,06	32
10	11,06	1,56	12,61	0,08	38	9,83	0,33	10,16	0,06	32
11	11,06	1,56	12,61	0,15	73	9,83	0,33	10,16	0,12	61
12	11,06	1,56	12,61	0,15	73	9,83	0,33	10,16	0,12	60
13	11,06	1,56	12,61	0,15	72	9,83	0,33	10,16	0,12	60
14	11,06	1,56	12,61	0,15	72	9,83	0,33	10,16	0,12	60
15	11,06	1,56	12,61	0,15	72	9,83	0,33	10,16	0,12	60
16	11,06	1,56	12,61	0,15	73	9,83	0,33	10,16	0,12	61
17	11,06	1,56	12,61	0,15	73	9,83	0,33	10,16	0,12	61
18	11,06	1,56	12,61	0,15	73	9,83	0,33	10,16	0,12	61
19	11,06	1,56	12,61	0,16	75	9,83	0,33	10,16	0,13	62
20	11,06	1,56	12,61	0,16	75	9,83	0,33	10,16	0,13	62
21	11,06	1,56	12,61	0,16	79	9,83	0,33	10,16	0,13	66
22	11,06	1,56	12,61	0,32	155	9,83	0,33	10,16	0,26	129
23	11,06	1,56	12,61	0,13	65	9,83	0,33	10,16	0,11	54
24	11,06	1,56	12,61	0,13	62	9,83	0,33	10,16	0,10	51
25	11,06	1,56	12,61	0,14	68	9,83	0,33	10,16	0,11	56
26	20,44	2,45	22,88	2,48	1190	18,21	0,22	18,44	2,00	991
27	11,06	1,56	12,61	0,07	31	9,83	0,33	10,16	0,05	26
28	11,06	1,56	12,61	0,06	30	9,83	0,33	10,16	0,05	25
29	13,73	1,82	15,54	0,19	90	12,22	0,31	12,52	0,15	75
30	11,06	1,56	12,61	0,05	25	9,83	0,33	10,16	0,04	21
31	11,06	1,56	12,61	0,24	117	9,83	0,33	10,16	0,20	97
32	11,06	1,56	12,61	0,21	102	9,83	0,33	10,16	0,17	85
33	20,91	2,39	23,29	2,86	1373	18,64	0,13	18,77	2,31	1143
34	11,06	1,56	12,61	0,04	19	9,83	0,33	10,16	0,03	16
35	11,06	1,56	12,61	0,04	20	9,83	0,33	10,16	0,03	16
36	11,06	1,56	12,61	0,04	20	9,83	0,33	10,16	0,03	16
37	11,06	1,56	12,61	0,04	20	9,83	0,33	10,16	0,03	17
38	11,06	1,56	12,61	0,04	21	9,83	0,33	10,16	0,03	17
39	11,06	1,56	12,61	0,04	21	9,83	0,33	10,16	0,04	18
40	11,06	1,56	12,61	0,04	21	9,83	0,33	10,16	0,04	17
41	11,06	1,56	12,61	0,04	21	9,83	0,33	10,16	0,04	17
42	11,06	1,56	12,61	0,04	21	9,83	0,33	10,16	0,03	17

	August					September				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	31,81	-0,96	30,85	1,09	539	35,54	2,77	38,31	1,35	648
1	18,65	0,13	18,78	2,55	1265	20,92	2,40	23,32	3,17	1520
2	9,83	0,33	10,17	0,08	41	11,06	1,56	12,63	0,10	50
3	9,83	0,33	10,17	0,08	41	11,06	1,56	12,63	0,10	49
4	9,83	0,33	10,17	0,08	40	11,06	1,56	12,63	0,10	48
5	9,83	0,33	10,17	0,07	34	11,06	1,56	12,63	0,09	41
6	9,83	0,33	10,17	0,07	34	11,06	1,56	12,63	0,08	40
7	9,83	0,33	10,17	0,07	35	11,06	1,56	12,63	0,09	42
8	9,83	0,33	10,17	0,07	33	11,06	1,56	12,63	0,08	39
9	9,83	0,33	10,17	0,06	32	11,06	1,56	12,63	0,08	39
10	9,83	0,33	10,17	0,06	32	11,06	1,56	12,63	0,08	38
11	9,83	0,33	10,17	0,12	61	11,06	1,56	12,63	0,15	73
12	9,83	0,33	10,17	0,12	61	11,06	1,56	12,63	0,15	73
13	9,83	0,33	10,17	0,12	60	11,06	1,56	12,63	0,15	72
14	9,83	0,33	10,17	0,12	60	11,06	1,56	12,63	0,15	72
15	9,83	0,33	10,17	0,12	60	11,06	1,56	12,63	0,15	72
16	9,83	0,33	10,17	0,12	61	11,06	1,56	12,63	0,15	73
17	9,83	0,33	10,17	0,12	61	11,06	1,56	12,63	0,15	73
18	9,83	0,33	10,17	0,12	61	11,06	1,56	12,63	0,15	73
19	9,83	0,33	10,17	0,13	62	11,06	1,56	12,63	0,16	75
20	9,83	0,33	10,17	0,13	62	11,06	1,56	12,63	0,16	75
21	9,83	0,33	10,17	0,13	66	11,06	1,56	12,63	0,16	79
22	9,83	0,33	10,17	0,26	129	11,06	1,56	12,63	0,32	155
23	9,83	0,33	10,17	0,11	54	11,06	1,56	12,63	0,14	65
24	9,83	0,33	10,17	0,10	51	11,06	1,56	12,63	0,13	62
25	9,83	0,33	10,17	0,11	56	11,06	1,56	12,63	0,14	68
26	18,22	0,23	18,45	2,00	991	20,45	2,46	22,91	2,48	1191
27	9,83	0,33	10,17	0,05	26	11,06	1,56	12,63	0,07	31
28	9,83	0,33	10,17	0,05	25	11,06	1,56	12,63	0,06	30
29	12,22	0,31	12,53	0,15	75	13,74	1,83	15,56	0,19	90
30	9,83	0,33	10,17	0,04	21	11,06	1,56	12,63	0,05	25
31	9,83	0,33	10,17	0,20	97	11,06	1,56	12,63	0,24	117
32	9,83	0,33	10,17	0,17	85	11,06	1,56	12,63	0,21	102
33	18,65	0,13	18,78	2,31	1144	20,92	2,40	23,32	2,86	1375
34	9,83	0,33	10,17	0,03	16	11,06	1,56	12,63	0,04	19
35	9,83	0,33	10,17	0,03	16	11,06	1,56	12,63	0,04	20
36	9,83	0,33	10,17	0,03	16	11,06	1,56	12,63	0,04	20
37	9,83	0,33	10,17	0,03	17	11,06	1,56	12,63	0,04	20
38	9,83	0,33	10,17	0,03	17	11,06	1,56	12,63	0,04	21
39	9,83	0,33	10,17	0,04	18	11,06	1,56	12,63	0,04	21
40	9,83	0,33	10,17	0,04	17	11,06	1,56	12,63	0,04	21
41	9,83	0,33	10,17	0,04	17	11,06	1,56	12,63	0,04	21
42	9,83	0,33	10,17	0,03	17	11,06	1,56	12,63	0,04	21

	October					November				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	41,97	9,21	51,18	1,80	894	49,36	16,60	65,96	2,32	1115
1	24,84	6,32	31,16	4,23	2098	29,33	10,82	40,15	5,45	2617
2	13,18	3,68	16,87	0,14	69	15,62	6,12	21,74	0,18	86
3	13,18	3,68	16,87	0,14	68	15,62	6,12	21,74	0,18	85
4	13,18	3,68	16,87	0,13	67	15,62	6,12	21,74	0,17	83
5	13,18	3,68	16,87	0,11	56	15,62	6,12	21,74	0,15	70
6	13,18	3,68	16,87	0,11	56	15,62	6,12	21,74	0,14	69
7	13,18	3,68	16,87	0,12	58	15,62	6,12	21,74	0,15	72
8	13,18	3,68	16,87	0,11	54	15,62	6,12	21,74	0,14	68
9	13,18	3,68	16,87	0,11	53	15,62	6,12	21,74	0,14	66
10	13,18	3,68	16,87	0,11	52	15,62	6,12	21,74	0,14	65
11	13,18	3,68	16,87	0,20	100	15,62	6,12	21,74	0,26	125
12	13,18	3,68	16,87	0,20	100	15,62	6,12	21,74	0,26	125
13	13,18	3,68	16,87	0,20	100	15,62	6,12	21,74	0,26	125
14	13,18	3,68	16,87	0,20	100	15,62	6,12	21,74	0,26	124
15	13,18	3,68	16,87	0,20	100	15,62	6,12	21,74	0,26	125
16	13,18	3,68	16,87	0,20	101	15,62	6,12	21,74	0,26	126
17	13,18	3,68	16,87	0,20	101	15,62	6,12	21,74	0,26	126
18	13,18	3,68	16,87	0,20	101	15,62	6,12	21,74	0,26	126
19	13,18	3,68	16,87	0,21	103	15,62	6,12	21,74	0,27	129
20	13,18	3,68	16,87	0,21	103	15,62	6,12	21,74	0,27	129
21	13,18	3,68	16,87	0,22	109	15,62	6,12	21,74	0,28	136
22	13,18	3,68	16,87	0,43	214	15,62	6,12	21,74	0,56	267
23	13,18	3,68	16,87	0,18	90	15,62	6,12	21,74	0,23	112
24	13,18	3,68	16,87	0,17	85	15,62	6,12	21,74	0,22	106
25	13,18	3,68	16,87	0,19	93	15,62	6,12	21,74	0,24	116
26	24,30	6,31	30,61	3,32	1644	28,72	10,73	39,45	4,27	2051
27	13,18	3,68	16,87	0,09	43	15,62	6,12	21,74	0,11	54
28	13,18	3,68	16,87	0,08	41	15,62	6,12	21,74	0,11	52
29	16,35	4,44	20,79	0,25	125	19,35	7,44	26,79	0,32	156
30	13,18	3,68	16,87	0,07	34	15,62	6,12	21,74	0,09	43
31	13,18	3,68	16,87	0,33	161	15,62	6,12	21,74	0,42	201
32	13,18	3,68	16,87	0,28	140	15,62	6,12	21,74	0,36	175
33	24,84	6,32	31,16	3,83	1898	29,33	10,82	40,15	4,93	2367
34	13,18	3,68	16,87	0,05	27	15,62	6,12	21,74	0,07	33
35	13,18	3,68	16,87	0,06	27	15,62	6,12	21,74	0,07	34
36	13,18	3,68	16,87	0,06	27	15,62	6,12	21,74	0,07	34
37	13,18	3,68	16,87	0,06	28	15,62	6,12	21,74	0,07	35
38	13,18	3,68	16,87	0,06	28	15,62	6,12	21,74	0,07	35
39	13,18	3,68	16,87	0,06	29	15,62	6,12	21,74	0,08	36
40	13,18	3,68	16,87	0,06	29	15,62	6,12	21,74	0,08	36
41	13,18	3,68	16,87	0,06	29	15,62	6,12	21,74	0,08	36
42	13,18	3,68	16,87	0,06	29	15,62	6,12	21,74	0,07	

	December				
FID	q_s (W/m)	q_r (W/m)	q_{tot} (W/m)	kW	kWh
0	55,72	22,95	78,67	2,77	1330
1	33,20	14,69	47,89	6,50	3121
2	17,71	8,21	25,93	0,21	102
3	17,71	8,21	25,93	0,21	101
4	17,71	8,21	25,93	0,21	99
5	17,71	8,21	25,93	0,18	84
6	17,71	8,21	25,93	0,17	83
7	17,71	8,21	25,93	0,18	86
8	17,71	8,21	25,93	0,17	81
9	17,71	8,21	25,93	0,17	79
10	17,71	8,21	25,93	0,16	78
11	17,71	8,21	25,93	0,31	149
12	17,71	8,21	25,93	0,31	149
13	17,71	8,21	25,93	0,31	149
14	17,71	8,21	25,93	0,31	148
15	17,71	8,21	25,93	0,31	149
16	17,71	8,21	25,93	0,31	150
17	17,71	8,21	25,93	0,31	151
18	17,71	8,21	25,93	0,31	151
19	17,71	8,21	25,93	0,32	154
20	17,71	8,21	25,93	0,32	154
21	17,71	8,21	25,93	0,34	163
22	17,71	8,21	25,93	0,66	319
23	17,71	8,21	25,93	0,28	133
24	17,71	8,21	25,93	0,26	127
25	17,71	8,21	25,93	0,29	139
26	32,52	14,53	47,04	5,10	2446
27	17,71	8,21	25,93	0,13	65
28	17,71	8,21	25,93	0,13	62
29	21,93	10,02	31,95	0,39	186
30	17,71	8,21	25,93	0,11	51
31	17,71	8,21	25,93	0,50	240
32	17,71	8,21	25,93	0,43	209
33	33,20	14,69	47,89	5,88	2823
34	17,71	8,21	25,93	0,08	40
35	17,71	8,21	25,93	0,08	41
36	17,71	8,21	25,93	0,08	41
37	17,71	8,21	25,93	0,09	42
38	17,71	8,21	25,93	0,09	42
39	17,71	8,21	25,93	0,09	43
40	17,71	8,21	25,93	0,09	43
41	17,71	8,21	25,93	0,09	43
42	17,71	8,21	25,93	0,09	43

V-Investment costs

- **Pipe Line:**

Diamenter (mm)	Pipe Cost (€/m)	Network construction (€/m)
25	32,14	270
32	37,46	280
40	40,00	285
50	57,00	290
63	76,00	300
75	95,00	310
90	107,00	320
110	167,00	330

Scenario A and 1			
Diameter (mm)	**Total Lenght (m)**	**Pipe Cost (€)**	**Network construction (€)**
25	348,03	11185,68	93968,10
32	0,00	0,00	0,00
40	0,00	0,00	0,00
50	122,82	7000,74	35617,80
63	244,09	18550,84	73227,00
75	0,00	0,00	0,00
90	35,23	3769,61	11273,60
110	0,00	0,00	0,00
Total	**750,17**	**€ 40.506,87**	**€ 214.086,50**

Scenario B and 2			
Diameter (mm)	**Total Lenght (m)**	**Pipe Cost (€)**	**Network construction (€)**
25	335,93	10796,79	90701,10
32	12,10	453,27	3388,00
40	0,00	0,00	0,00
50	0,00	0,00	0,00
63	258,60	19653,60	77580,00
75	108,31	10289,45	33576,10
90	0,00	0,00	0,00
110	35,23	5883,41	11625,90
Total	**750,17**	**€ 47.076,52**	**€ 216.871,10**

- **Thermal storage with heat exchanger:**

Volume (m^3)	20
Price (€/m^3)	€ 3.000,00
Storage life time	25 years
Total price (€)	€ 60.000,00

- **Circulation pump:**

Scenario A and 1	
Model	**Price (€)**
SALMSON JRN 205-18/7,5	€ 3.455,00

Scenario B and 2	
Model	**Price (€)**
SALMSON BRL 65-200/3/4-200	€ 1.087,00

- **Heat exchanger substation:**

Substation+installation cost (€)	€ 2.500,00
Maintenance (€/year)	€ 150,00

- **Central heat pump:**

Scenario A and 1	
COP	3,5
P (kW)	94
PN (kW)	100
Cost (€/kW)	620
Total cost (€)	€ 62.000,00

- **Decentralized micro heat pump:**

Scenario 2	
Price (€/kW)	800,00
Yearly DHW demand (kW)	99,43
Yearly SH extra demand (kW)	129,88
Yearly average demand per building (kW)	6
Total inv. Cost (€)	€ 183.449,57

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