MEETING HEAT DEMANDS IN EXISTING DUTCH HOMES USING LOW TEMPERATURE DISTRICT HEATING

BY SEBASTIAAN KNEPPER

Visser & Smit Hanab
brengt energie

TU Delft

Meeting heat demands in existing Dutch homes using Low Temperature District Heating

Comparison study of several heating networks with Low Temperature Geothermal Heat as main source

By
Sebastiaan Knepper

in partial fulfillment of the requirements for the degree of

Master of Science
in Sustainable Energy Technology

at the Delft University of Technology,
to be defended publicly on Tuesday June 25, 2019 at 09:30 AM.

Supervisor:	Dr.ir. I.W.M. Pothof,	TU Delft
Thesis committee:	Prof.dr. L.C.M. Itard,	TU Delft
	Dr.ir. C.A. Infante Ferreira,	TU Delft
	Dr.ir. I.W.M. Pothof,	TU Delft
	Ir. M. de Vrieze,	Visser & Smit Hanab

This thesis is confidential and cannot be made public until July 31, 2019.

Preface

In front of you is the thesis ‘Meeting heat demands in existing Dutch homes using Low Temperature District Heating’; a study into suitable heat technologies to be used with the Low Temperature Geothermal Heat source of Visser & Smit Hanab (V&SH), for district heating for existing homes in the Netherlands. This thesis is written in partial fulfillment of the requirements for the degree of Master of Science in Sustainable Energy Technology at the Delft University of Technology (TUD). The study was conducted and the thesis written in the period from September 2018 to June 2019, at V&SH and the TUD.

This project was set up by Ivo Pothof (TUD), Mark de Vrieze (V&SH), and me. V&SH developed a source of geothermal energy, which is extracted through water at a lower temperature than conventional sources but is able to produce a higher mass flow.

The first subject was to investigate how well Low Temperature District Heating (LTDH) would perform during very cold moments in the Netherlands with the geothermal source from V&SH. Later, we discovered that an entire network and year energy balance has to be made to investigate this problem. Therefore we adjusted to a total package for an LTDH with the geothermal source of V&SH.

While working on my thesis I experienced pleasant and less pleasant moments. Designing the LTDH concepts, speaking with people in the field, and developing a calculation model were moments I enjoyed. I could spar with Ivo every 2 weeks on my subject, which I consider as energetic moments. With Mark, I often received practical tips for both successful implementation of this project and the operation of the LTGH source. Thank you both for your help. I had more difficulty with writing the report and I experienced some tough moments, but with the help of Ivo, Mark, and later also Carlos and Laure (both TUD), I succeeded in writing this report.

Therefore, I would like to thank the thesis committee for their excellent guidance and support during this process. Without it, I would not have been able to evolve in so many different ways. I also want to thank my colleagues at the LTGH department of V&SH for their input and cooperation during my thesis.

I also want to thank my family and the rugby club SRC Thor for their support during my project. I have been able to discuss about my thesis with many of you, both technically and emotionally. That helped me a lot. Also Jelle, thank you for your time to check my thesis on the English language. I could not write this report without your help.

And finally I want to thank Mahana. I have benefited enormously from your support, positivity, feedback, and discussion moments about the concepts to be designed and the layout of the report. Thank you all very much.

Lastly, I want to give you the following advice. If it gets cold in your house, first put on a nice warm and cozy sweater. By consuming less heat, or other ways of consuming, you can help a bit preventing climate change. In addition, everyone around you will get a smile on their faces from your beautiful sweater!

I hope you will enjoy your reading

S. Knepper

Delft, June 18, 2019

Executive summary

Dutch homes use 70% of their total energy consumption for domestic hot water purposes and space heating. Currently, this energy is yielded through the use of natural gas. In order to meet Dutch Climate Agreement goals, which were agreed upon December 2018, Low Temperature District Heating (LTDH) is expected as being the most promising sustainable heat energy system solution for dense populated districts. Several studies are now considering how to implement LTDH in the Netherlands and which sustainable energy production and other technologies are required.

To produce sustainable heat, Visser & Smit Hanab (V&SH) have developed a geothermal source which extracts heat from shallow surfaces, between 500 and 1250 meters. Currently, this system is only used to provide heat for greenhouses. Greenhouses are in need of heat supply for more than 5000 hours per year. This thesis presents which other technologies are required to make LTDH with Low Temperature Geothermal Heat (LTGH) as main source a success for heating in district areas. Therefore, the following main research question is investigated.

'What is the best way to meet heat demands, in existing Dutch homes, with Low Temperature District Heating and with Low Temperature Geothermal Heat as the main source, based on Key Performance Indicators?'

This thesis aims to answer this question through a comparative study for a representative case district in the Netherlands. Heat demand and building typologies for this case are known. The case district is at present connected to the current Dutch gas network.

For the case, there are 5 LTDH concepts designed to supply heat to the livings with LTGH. The designed LTDH varies in storage methods, supply temperature in the network, and peak heat supply technologies. The used storage methods are Aquifer Thermal Energy Storage (ATES) and a water tank of 250 liters for each living. The used peak heat supply technologies are decentralized heat pumps, electrical heaters, and a biomass boiler. The following LTDH concepts are designed.

1a. *Collective peak supply 70 ^oC* 2a. *Decentral peak supply 70 ^oC*
1b. *Collective peak supply 50 ^oC* 2b. *Decentral peak supply 50 ^oC*
3. *Decentralized heat pumps using 30 ^oC supply temperature*

The heat demand strategies that are applied for the LTDH concepts are as follows:

1. Stay with the current heat demand strategy; no form of demand side management.
2. Shave the peak by preheating a home, before the outside temperature decreases.
3. Improve the insulation of the buildings.

To compare the designs, a reference heat concept is designed, which consists of the 'all-electric' concept; each home has an individual air heat pump for space heat and an electric boiler for domestic hot water purposes. The comparison is based on the following Key Performance Indicators (KPIs).

1. CO_2 emissions
2. Electricity usage
3. Levelized costs of energy (LCOE)

The results of the comparison study are presented in the graph below. The graph shows what the savings are from 5 LTDH for the KPIs CO_2 emissions and costs of produced heat, compared to the reference point. The heat demand strategy is the improvement of thermal insulation, this led to the best results.

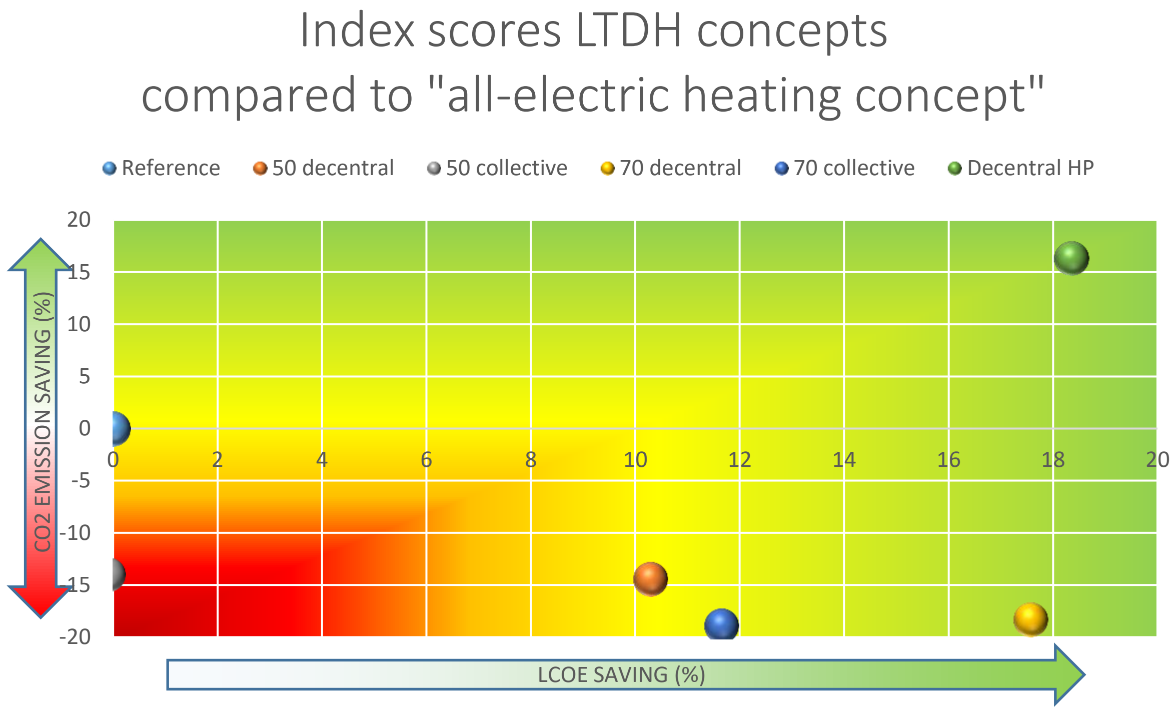


Figure 0-1 Savings of the LCOE and CO_2 emissions of LTDH concepts with extra insulation measures, compared to an all-electric scenario.

The figure shows that despite the fact that high peak demands from homes occur less frequently than for greenhouses, an LTDH with LTGH as the main heat source has less costs than heating each home with a single air-heat pump and electrical boiler. So an LTGH is not only sufficient for heating greenhouses, but also for homes in dense populated district area.

Figure 0-1 shows that a heat network with an LTGH and decentralized heat pumps, LTDH concept 3, saves the most costs and CO_2 emission. This is mainly because this system consumes the least electricity over a year. If a central heat pump is applied, a supply temperature of 70 ^oC and decentral peak supply saves the most costs. As soon as a supply temperature of 70 ^oC is applied, the pipe diameters in the network decrease so many costs can be saved. Additionally, the costs and consumption of a water tank and heaters per household are less than the installation and use of a central biomass boiler. If a central heat pump is applied, most CO_2 emissions are saved when the supply temperature is 50 ^oC and the peak heat demands are supplied by a biomass boiler. This is because this option consumes the least electricity of all the concepts with a central heat pump.

It is striking that only LTDH concept 3 scores better on all KPIs than the all-electric concept. That is because the central heat pump, of the other concepts, consumes the most electricity of all the technologies in the system and is always on throughout the entire year. The average efficiency, over a year, of an air heat pump is higher than that of the central heat pump at the LTGH. This is because the air heat pump is switched off when there is no heat demand and with an LTDH, there are losses in the network and the ATES.

The question may then be whether this is a fair comparison because this study did not include the impact of the peak moments on the electricity grid. An LTDH concept with 50 ^{o}C and a biomass boiler consumes a maximum of 0.84 kW electricity in an hour, while an air heat pump consumes 3.04 kW in an hour per home. Without improving the electricity grid, the answer to the main question is that the best LTDH design is an LTGH without a central heat pump and to improve the insulation of the homes. 30 ^{o}C water will flow through the network and is upgraded to the desired temperature with a decentral heat pump at the homes. This LTDH concept saves 16.3 %, 18.4 %, and 16.3 % on the CO_2 emission, LCOE, and electricity usage compared to an all-electric concept.

Future research must be done on the electricity consumption of the central heat pump from the LTGH. If the heat pump can consume less electricity, the load on the electricity during cold hours can be reduced and throughout a year CO_2 emissions can be reduced. Also, future research must be done on optimizing the LTDH concepts, so that the savings in CO_2 emissions and LCOE will improve. In addition, an NPV analysis should be done to determine how the costs are distributed over the stakeholders.

Contents

Nomenclature

Symbols

Symbol	Description	Unit
A	Surface	m^2
c_p	Specific heat capacity	J/kg K
D	Diameter	m
F	Fuel costs	€
f	Simultaneously factor	-
g	Gravity value	m/s^2
I	Investment costs	€
M	Maintenance costs	€
m	Mass	kg
$\dot{m}$	Mass flow	kg/s
n	Number	-
p	Pressure	Pa
P_{el}	Electricity power	W
Q	Capacity / energy	J
$\dot{Q}$	Heat / power	W
r	Interest rate	%
Re	Reynolds number	-
T	Temperature	^oC
U	Heat transfer coefficient	W/m^2K
v	Speed	m/s
V	Volume	m^3
$\dot{V}$	Volume flow	m^3/s
z	Elevation	m

Greek letters

Letter	Description	Unit
ε	Wall roughness	m
η	Efficiency	-
λ	Friction factor	-
μ	Dynamic viscosity	Pa·s
ρ	Density	kg/m^3

Abbreviations

Acronym	Description
ATES	Aquifer Thermal Energy Storage
BEP	Best Efficiency Point
BHP	Booster Heat Pump
CAPEX	Capital Expenditures
COP	Coefficient of Performance
DH	District Heating
DHW	Domestic Hot Water
DSM	Demand Side Management
EPC	Energy Performance Coefficient
GDD	Geothermal Directional Drilling
HDD	Heating Degree Days
HEX	Heat Exchanger

HT	High Temperature
HTDH	High Temperature District Heating
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCOE	Levelized Cost Of Energy
LTDH	Low Temperature District Heating
LT	Low Temperature
LTGH	Low Temperature Geothermal Heat
NPV	Net Present Value
OPEX	Operational Expenditures
P&ID	Piping and instrumentation diagram
PB	Polybutylene
PCM	Phase Change Materials
ROI	Return of Investment
PUR	Polyurethane
TCM	Thermochemical materials
TUD	Delft University of Technology
V&SH	Visser & Smit Hanab

Part 1 Research structure

The first part of this study describes the assignment and examines what already exists in current literature on heat networks. With the knowledge of this information, key performance indicators are set for a design of a sustainable heat network. Finally, a methodology is established to investigate which combination of technologies can be used in a sustainable heat network to meet the key performance indicators.

1. Introduction

1.1 Motivation

In 2015, 34% of the total energy usage in the Netherlands was caused by from the built environment. 70% of the energy usage in this sector was for heating homes, cooking food and the preparation of hot water, while the remaining was for electricity usage (Kremer et al., 2017). With the current climate developments, earthquakes as a result of natural gas extraction in the northern parts of the Netherlands and a transition in public thinking towards making the world more sustainable, an investigation of alternative ways of supplying heat to Dutch homes has become increasingly relevant.

The heating system in the Netherlands is mainly based on natural gas. Of the total heat produced in 2015, 78% came from natural gas, 5.3% of heat production consisted of renewables and the remaining heat production came from residual gases, petroleum and coal (Kremer et al., 2017). In Dutch households, 219 PJ of natural gas was used for heating homes, 60 PJ was used for domestic hot water supply, and 6 PJ for cooking. The amount of renewables used for these applications was 40.6 PJ (including electricity use) (Kremer et al., 2017). The Dutch government wants to disconnect Dutch livings from the existing gas distribution network by 2050, and wants to stop natural gas extraction (Netherlands Ministry of Economic Affairs, 2016). Heating homes, cooking, and the preparation of hot water should use a different energy carrier and be connected to a new network.

District heating systems, together with heat pumps, is the most commonly suggested scenario for replacing the natural gas distribution network in the Netherlands for densely populated urban areas. The 4th heat generation district heating will be implemented in Europe, because of legislation and regulations such as ‘Energy Efficiency Directive’ (European Parliament, 2012). This law states that most countries in Europe should reduce their energy consumption by increasing the efficiency of energy use. Low Temperature District Heating (LTDH) is one of the most relevant solution for the Netherlands, because it has higher efficiency and is easier to connect to sustainable heating sources than a high temperature district heating network (Lund et al., 2014).

Several Dutch studies have been carried out about the feasibility of LTDH in the Netherlands and there have been promising results (Koenders et al., 2018; van Vliet et al., 2016) and (Verhaegh, 2018). However, what these studies have in common is that it is difficult to meet heat demands during cold- hours. In spite of these difficulties, European studies, such as (Lund et al., 2014; Østergaard & Svendsen, 2017; Sayegh et al., 2017), which showed the feasibility of LTDH, concluded that LTDH would provide a sustainable way of supplying heat to homes. Studies which are highly important to the feasibility of using LTDH for heat supply in Dutch homes, such as the use of current radiators (Østergaard, 2018), are currently being carried out. Moreover, investigations into how peak demands can be met have recently concluded that these moments are crucial for the successful implementation of LTDH as source for heating households.

1.2 Low Temperature Geothermal Heat

The geothermal source, as developed by the Dutch company Visser & Smit Hanab (henceforth: V&SH), is used as main sustainable heat source for this thesis. This is a Low Temperature Geothermal Heat (LTGH) system. Currently, this system is only used to provide heat for greenhouses. Greenhouses are in need of heat supply for more than 5000 hours per year (Koenders et al., 2018). Therefore, there is sufficient demand for employing geothermal systems of heat supply. V&SH wants to implement their LTGH source also for heating in Dutch households. Household heat demands fluctuate more than greenhouse heat demands, and to date it remains unclear whether LTGH can be sufficient to supply heat to urban areas.

1.3 Aim and scope

The aim of this thesis is to investigate how peak heat demands can be met using LTDH. The main research question for this thesis is:

'What is the best way to meet heat demands, in existing Dutch homes, with LTDH and an LTGH as the main source, based on KPIs?'

To be able to answer the main question, the sub questions in Table 1-1 are formed. Where the answers to the sub questions can be found, is indicated next to the corresponding sub questions.

Table 1-1 Sub questions for the current thesis.

Sub question	Thesis part where the question is discussed
What are relevant technologies in LTDH for peak heat demand moments?	1
What is a suitable method to design a sustainable LTDH?	1
What are suitable combinations of technologies in an LTDH?	2
Does demand side-management have a big influence on LTDH system?	2
How does the system perform during peak moments?	3
How dependent is the system of the supply temperature of the LTGH source?	3
How much electricity, CO_2 emission, and costs can be saved with an LTDH compared to an all-electric heating district?	3
How does this study help in the development of LTDH?	4

This thesis is mainly to investigate how to match the heat peak demand moments and the availability of heat at those moments. This is based on a case district in the Netherlands. The useable techniques and materials alongside LTDH are discussed, as well as the adjustments which can be made to influence the heat demand.

This research does not deal with thermal comfort, the speed between heat supply and heat demand, and how to set up a heat network efficiently. This because these factors would have given too many parameters for the current research, and it is expected that they will not influence how well the main research question can be answered.

1.4 Thesis outline

The present thesis is divided into 4 parts. These are research structure, methodology elaboration, results elaboration and evaluation. The structure of the present thesis is as follows.

Part 1: Research structure

Chapter 2 provides an overview of the related theory about LTGH and LTDH. Details of the supply side of the LTGH and the demand side of residential homes are given. Common peak supply, buffering techniques and design values are provided at the end of Chapter 2. Chapter 3 introduces the key performance indicators (KPI) that have been employed. Next to that, the methodology is explained in this chapter on how to answer the research question.

Part 2: Methodology elaboration

Chapter 4 describes the case-study. This is a representative urban area in the Netherlands, of which the space heat and domestic hot water (DHW) usage are known for one year. This chapter provides useful information on the district typology and other parameters which lead to heat demand. In Chapter 5, 5 LTDH concepts and a reference heat concept are designed. These concepts will be compared with each other according to the KPIs selected in the first part of this thesis. The last section of this chapter describes 3 different heat demands for the case district.

These heat demands will be used, together with the LTDH concepts, as input for the numerical models. These models are explained in Chapter 6.

Part 3: Results elaboration

Chapter 7 presents the results of the yearly energy balance. This is required to determine the number of homes connected to the LTGH source. Chapter 8 presents the results of the heat network lay-out in the case district, when it would be heated by a LTDH. Chapters 9 presents the results of the energy balances of the several heat concepts. The results of these two chapters are needed for Chapter 10. Chapter 10 presents the results of the electricity usage, costs and CO_2 emission by the heat concepts.

Part 4: Evaluation

The results of the previous part are examined in Chapter 11. The outcomes are compared with each other according to the research questions. Chapter 12 and 13 form the conclusion of this thesis and several recommendations of what to do with the present thesis in the future.

2. State of the art of LTGH and LTDH

2.1 Introduction

The aim of this chapter is to present the relevant theory for this thesis. The chapter shows what already exists on the subject of LTDH and which information is still missing for the design of an optimal LTDH. During this study, the exact problem of peak heat demands in a geothermal district heating (DH) is investigated and which existing solutions could be applied during high heat demand moments.

The chapter consists of 5 main sections. First, background information is provided on the use of geothermal heat in district heating and the related bottlenecks, and about the development in LTDH. After that, a description is provided of the heat demand in a district area and how this influences the design of DH. Next to that, an overview is given about current heat technologies and heat storage methods. Finally, key performance indicators (KPIs) for a sustainable LTDH are defined and an overview of current methods of determining these KPIs is provided.

2.2 Background information geothermal energy in district heating

2.2.1 Working principle geothermal energy

Geothermal energy is the extraction of thermal energy (heat) from the earth. The heat is extracted by using the temperature difference on the earth's surface and the geothermal reservoir under the earth. This heat extraction is achieved by a geothermal installation.

A geothermal installation consists of two wells, a production well and an injection well. Hot water is extracted from a heat reservoir in the earth by the production well. The hot water is pumped by the production well to a heat exchanger (HEX) above the earth. The HEX transfers the heat to a secondary water network. The cooled water is pumped back into the earth via the injection well. The installation and operation of a geothermal installation is given in Figure 2-1.

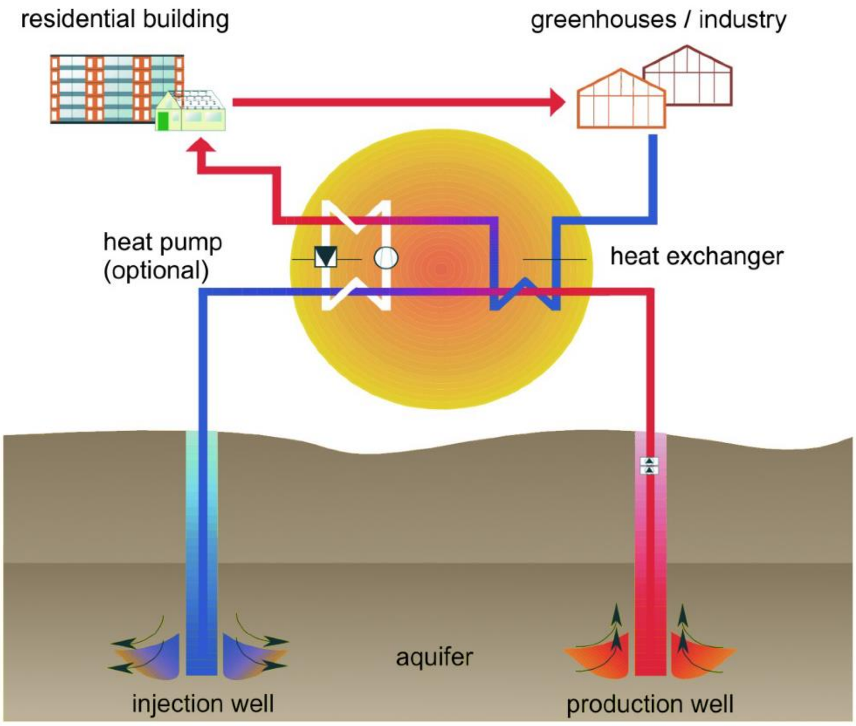


Figure 2-1 Overview of a geothermal installation. Adapted from (Agemar et al., 2014).

The amount of heat, which is extracted by the installation, depends on the mass flow of the water and the temperature difference in the HEX. The temperature of the water extracted depends on the depth at which the heat reservoir is. Water with a higher temperature is extracted at deeper reservoirs (Agemar et al., 2014). The mass flow through the HEX is determined by the pump in the production well.

An important part of the geothermal installation are the filters in the reservoirs under the earth. The filters remove solids out of the water in order to protect the heat exchanger and the wells of the geothermal plant.

2.2.2 Bottlenecks of geothermal energy in DH

Geothermal heat has one major bottleneck (Hirschberg & Wiemer, 2015) for the production of heat. The well pump, of the injection well, must run between a minimal flow and maximum flow. If the flow rate is too low, the heat reservoir, where the end is of the production well, becomes clogged. If the flow rate is too high, the filter installation will be damaged (Hirschberg & Wiemer, 2015). The heat production from the source is therefore poorly adjustable and it is difficult to fluctuate with the heat demand. Other heat production sources, such as biomass, can adjust the heat production much better (Lukawski et al.,2013).

Current geothermal systems use the geothermal heat as a base load and the peak demands are supplied by gas boilers. This is presented in Figure 2-2. It is an example of a 'heat duration curve'. A heat duration curve is a chart which displays the hourly heating demand. It is sorted from the highest heating demand to the lowest heating demand. Figure 2-2 shows that the heat demand for a part of the year can be completely filled by the geothermal heat, but for other moments there are gas boilers needed.

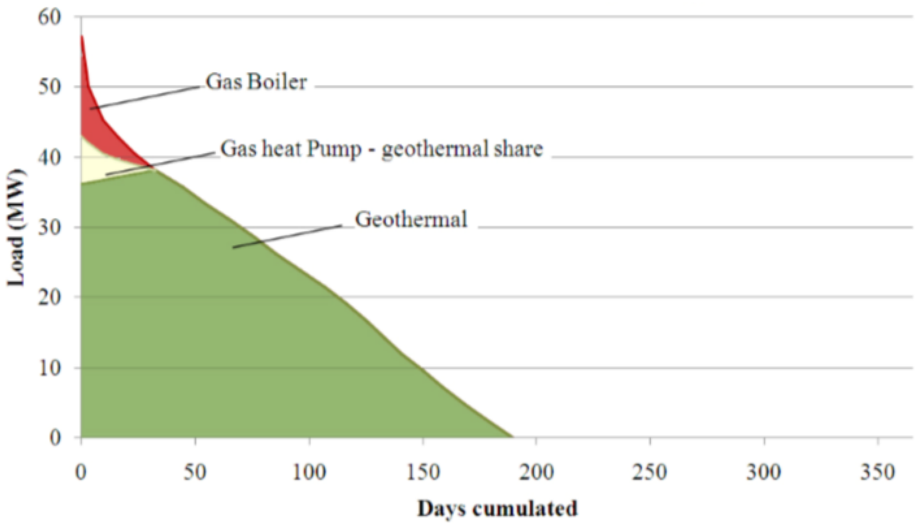


Figure 2-2 Example of a heat duration curve. Adapted from (Erlingsson et al., 2010).

2.2.3 LTGH of V&SH

LTGH is a geothermal energy system developed by V&SH (Koenders et al., 2018). The drilling range is between 500 – 1250 meters and can be used for heating dwellings, industry and green houses. The drilling range is less deep than regular geothermal wells, which are usually 2 – 3 km (Agemar et al., 2014). This results in a lower temperature extraction. Because of the low temperature, which is extracted, it is desired to realize a high flow rate to gain more heat. The formation layers of the reservoirs are relatively thin, so the filters placed in the reservoirs are small. The result of this small filter is a low capacity. A higher capacity will result in extraction of sand and other undesirable materials. This can cause damage to the production well and the heat exchanger. A schematic example can be seen in Figure 2-3.

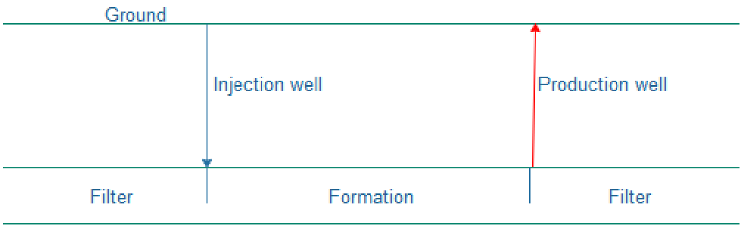


Figure 2-3 Schematic overview of traditional vertical wells.

V&SH can create a horizontal filter, to increase the capacity. With their knowledge of Horizontal Directional Drilling, to avoid obstacles below the ground when installing cables and piping, it is possible to drill horizontally. For LTGH, V&SH drills deeper than usual for Horizontal Directional Drilling, so the combination of vertical drilling and Horizontal Directional Drilling is called Geothermal Directional Drilling (GDD). The main advantage is to be able to drill from one location. GDD drills vertically, until it reaches the formation layer. At that point, the GDD drills horizontally. After drilling the wells, it is possible to create a large horizontal layer in the formation. This is presented in Figure 2-4. The first LTGH drilled is located in Zevenbergen to heat a greenhouse.

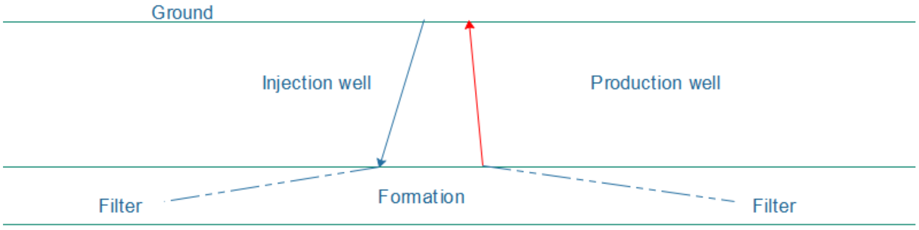


Figure 2-4 Schematic overview of LTGH with horizontal filters.

The benefits of placing horizontal filters are listed below.

- A higher capacity can be reached in a thin formation layer.
- Drilling is done at one location. This has cost and time related advantages.

To use the extracted heat for space heating or DHW, it is required to raise the temperature level of the water in the DH. The LTGH source can raise the temperature with 3 central heat pumps. These heat pumps are connected in series, so that the increase of the temperature, for the required amount of heat for a DH, requires less electricity than 1 central heat pump (de Vrieze, 2018).

It is also possible to raise the temperature of the DH water in the homes. This can be achieved by installing a single heat pump in every home.

2.3 Development of LTDH and gas network

2.3.1 Development of DH over the world

First three district heating generations

District heating is a network which collects heat from producers and provides heat for the collective heat demand for buildings and industry. The first DH network was developed at the end of the 19th century and used waste heat in New York. The system consisted of radiators, which were making use of steam condensation to provide the heat for the dwellings (Sayegh et al., 2017). A DH was made to use the local fuel or heat resources to satisfy local costumers demands for heating, which otherwise would be wasted (Werner, 2017). According to (Werner, 2017),

'The primary merit of district heating is lower heating costs when international fuel prices are high and when lower environmental or climate impacts are valued.'

The second generation DH uses pressurized hot water as distribution material. Therefore, it became possible to create larger DH networks. The third generation DH improved the pipes. The pipes were insulated so that efficiency increased. At last, the flows in the network were measured and monitored.

DH systems can be divided in High Temperature (HT) and Low Temperature (LT) networks (Lauenburg, 2016) (Østergaard & Svendsen, 2017), which refers to the supply temperature in the DH. This is caused by the way of heating the circulation water. There are also systems with much higher temperatures, but this will not be used in the Netherlands so it is left out of the scope. This is also known as 'First and Second generation DH' (Lund et al., 2014). Table 2-1 presents a comparison between the two DH systems.

Table 2-1 Comparison between HT and LT networks. Adapted from (D. Schmidt et al., 2017)

Aspect	HT/MT	LT/ULT
Supply temperature range	70 - 45	45 - 30
Return temperature range	50 - 30	25 - 20
First year used	1980	2005
Material used	Pre-insulated carbon steel and Fiber-reinforced plastic	Same insulation as HT/MT and less expensive plastics
Main heat sources	Fossil fuel based plants Deep geothermal energy Combined Power Plants	Shallow geothermal energy Solar thermal heat Thermal heat of surface water
Advantage compared to other DH	Provides more heat Provides domestic hot water	Less heat losses More sustainable

4th generation district heating

The first three generations of DH made use of high temperatures, because of the available heat sources. The heat was produced at high temperature. The search for sustainable heat sources decreases the temperature in the DH network (van Vliet et al., 2016). The development of connecting sustainable sources and the use of multiple heat sources for a DH network, is called the '4th heat generation' (Lund et al., 2014). The 4th generation DH makes use of a smart thermal grid. It is defined as a network of insulated pipes connecting the buildings in an area, so the buildings can be supplied by multiple heat sources as well as through individual contributions from the connected buildings (Lund et al., 2014).The network has an intelligent control system, so the demand side controls the production side. If there is no need for heat, the heating plants stop generating heat or save the heat for peak moments. An illustration of the 4th HD generation concept / LTDH network is presented in Figure 2-5.

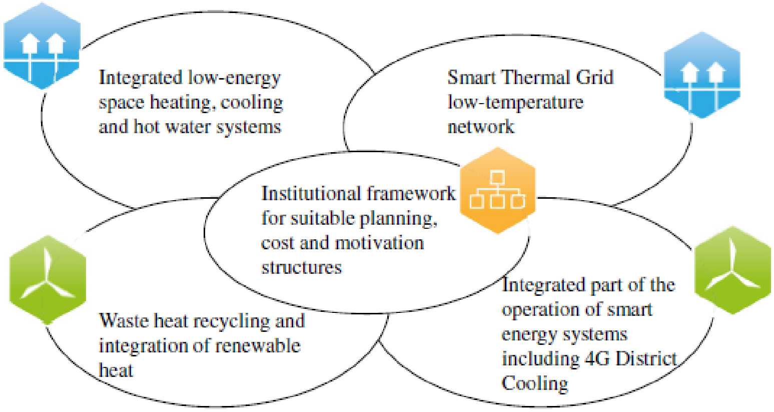


Figure 2-5 Illustration of the concept 4th generation DH with smart thermal grid. Adapted from (Lund et al., 2014).

Development of the pipes

The first and second generation made use of non-insulated pipes. The third generation used insulation and increased the efficiency of the total system. Efficiency became more important and led to an improvement of the pipes. It has now come to the point of prefabrication of the insulation of the pipes and using plastic pipes (Rosa et al., 2011). Polybutylene (PB) is the most common material (Rosa et al., 2011).

PB pipes are becoming more and more interesting in comparison with traditional steel pipes for the following reasons.

- More possibilities in prefabrication. Joints of the main pipe are installed at the factory, so installation time decreases. See Figure 2-6.
- Reduction of sound
- Reduction of friction coefficient
- Increase life time
- Recycling is made possible

Figure 2-6 Installing PB pipes. The joints are on the big roll. Adapted from Thermaflex.

The disadvantage of PB pipes compared to steel pipes is the high price of the material and that high temperatures cannot flow through PB pipes. However, the 4th generation uses low temperatures and therefor it is possible to implement PB pipes.

There is also a distinction made between single pipes and twin pipes. With single pipes, the supply and return are separate pipes. In twin pipes, both pipes are placed in a large insulation layer. The advantage of this is a reduction of the installation costs and heat loss.

2.3.2 Gas network in the Netherlands

Before 2015

From the early 1960s onwards, a massive number of natural gas was found in Groningen, the north of the Netherlands. The government wanted to use this gas, because it provided the Dutch homes cheap, reliable, and clean source of energy for heating, cooking, and hot water supply (Elzen et al., 2004). In 1963, the Netherlands started to build a natural gas network to supply the gas from Groningen to the homes. 98% of the homes was connected to this network in 2011.

Current heat transition in the Netherlands

In view of the developments around the climate and the climate agreements in Paris and the Netherlands (more on that in the next section), the Netherlands has expressed the ambition to abandon the use of natural gas by 2050. According to (Koenders et al., 2018), are the use of a DH, electric heating, and the use of hydrogen the most promising solutions for the supply of heat in the Netherlands. Currently, several researches are deployed about which ways of heating are the most sufficient for a certain district area (Koenders et al., 2018; van Vliet et al., 2016; Verhaegh, 2018). The most research concludes that DH is the most sufficient and sustainable distribution method for dense populated district areas. For sparsely populated districts, this is either all-electric or hydrogen. This depends on the developments regarding the use of hydrogen in the Netherlands.

Studies like mentioned in the paragraph above have already shown that it is possible to use sustainable sources such as geothermal heat, solar heat, and ocean heat for an LTDH. These studies have in common that it is unclear if LTDH is reliable during extremely cold weather conditions, so when there is a peak heat demand. Regulating the heat supply for these sources is quite difficult and currently the suggestion are to install gas-controlled peak boilers for the peak moments.

Another bottleneck for an LTDH is the communication between the stakeholders. According to (Jong Warmtenetwerk, 2018) and (Neels, 2018), it remains unclear for residents what is going to happen and who is going to pay when their neighborhood needs to be disconnected from the gas network.

Example 4th generation DH in the Netherlands

An example is of a 4th DH grid is developed by Mijnwater B.V. and called ‘Mijnwater’. This DH grid is installed in 2008 and is still developing to connect more homes to the grid. Mijnwater is a concept for extraction, exchange, and distribution of sustainable heat and cold via a thermal energy network (Koenders et al., 2018). Heat is distributed at a low temperature and can be used in the following three ways.

- Low temperature (~30°C). The heat from the network is directly used for well-insulated homes. An alternative way is needed for producing DHW.
- Middle temperature (~60°C). Decentral heat pumps upgrade the heat from the network to the right temperature and can be used for existing dwellings with less insulation. The heat pump can also produce hot tap water.
- High temperature (~90°C). Dwellings with no or little insulation can use the same heat pumps as the middle temperature scenario for the basic load. Peak boilers are required for the peak demands. During a transition phase, this is a solution. If the heat pumps are installed, the dwellings can be insulated, so the homes can be heated as far as the middle temperature method.

Mijnwater is a smart thermal energy network that works based on the demand. Heat or cold are only extracted when there is a demand for it. In addition, all available residual flows of energy are also used and residual heat and cold are stored in buffers, when there is more supply than demand.

According to (Koenders et al., 2018), Mijnwater in combination with LTGH can be a potential heating system for future homes in the Netherlands.

2.3.3 Dutch regulations impacting the heat transition

The 4th heat generation is under development in Europe, because of legislation and regulations such as ‘Energy Efficiency Directive’ (European Parliament, 2012). This directive states that the most countries in Europe should reduce their energy consumption by increasing the efficiency of energy use. For the heating of homes, this means that existing homes should implement better insulation.

One important reason for implementing LTDH in the Netherlands is because of the ‘Klimaatakkoord’ (Nijpels, 2018). The Klimaatakkoord provides, under Chapter ‘Gebouwde Omgevingen’, that the supply of sustainable heat must be increased. It also states that the use of geothermal energy must increase. The ambition is to raise the geothermal energy from 3 PJ today to 50 PJ in 2030 and 200+ PJ in 2050.

Other regulations that need to be taken into account are the avoidance of the growth of legionella, and the temperature and depth of heat storage. Legionella can grow for DHW between 25 and 50 ^{0}C (European Committee for Standardization, 2012). To prevent this growth, Dutch regulations decided that DHW must be prepared at minimum 60 ^{0}C, according to NEN 1006.

Heat storage is an interesting technique for geothermal DH installations. The technical aspects are discussed in section 2.5.3. However, there are some rules in the Netherlands. In the Netherlands, heat storage in an aquifer with temperatures above 25 ° C is permitted, provided that this has demonstrated to have no or acceptable consequences for the underground environment (Drijver et al., 2012; Vandeweijer, 2013). However, these rules will be adjusted due to the energy transition in the Netherlands. It is expected that these rules will change quickly and that it is possible to store thermal energy with higher temperatures and deeper below the surface (Bloemendal, 2018).

2.4 Heat demand side

This section covers the heat demand in homes. The aspects that create a heat demand and how these aspects can influence the design of DH are discussed. The heat demand is an important boundary condition for the design of LTDH.

2.4.1 Heat demand in district area and influence on design of DH

A distinction in heat demand in a district is made between space heat demand and domestic hot water (DHW) demand. When people inside a building feel cold, a demand for space heat takes place. Heat gains and losses inside a building depend on transmission, ventilation & infiltration, internal gains and solar gains (van Bueren et al., 2012). DHW is needed for the bathroom (shower and bath) and for cooking (doing dishes or getting hot water). The sum of these two demands for the whole neighborhood is the heat demand in the district.

The study from (Lundström & Wallin, 2016), showed that the peak heat demand is mainly caused by the space heat demand in the winter. In the summer, the peak heat demand is caused by the DHW. Space heat demand has the most influence on the total heat demand in a district (Lundström & Wallin, 2016). As an example of a data series from Breda Biesdonk (district in the Netherlands) in 2016, the total space heat demand for 1650 homes was 14813 MWh and the DHW demand was 3451 MWh (Verhaegh, 2018).

When designing a DH and only the heat demand is known for one home, the designer can multiply the heat demand with the number of homes in a district and the related simultaneously factor (Lundström & Wallin, 2016). The simultaneously factor is a value which indicates the simultaneous heat demand in a district. The simultaneously factors are given in Dutch Standard ISSO 7.

The heat demand is the most important boundary condition for the design of an LTDH, because this determines the type and size of the pipes (Lundström & Wallin, 2016). Because LTDH uses low supply temperature, the temperature difference between the supply and return pipe is small. To supply the same amount of heat through an LTDH instead of a HTDH, the diameters should increase.

When designing an DH, the designer must ask him/herself where the peak heat supply will be produced. If the peak heat supply goes through the pipe network, the diameters of the pipes increase. If only the basic heat demand goes through the pipe network and the peak heat demand is produced near the homes, the diameters of the pipes can become smaller (Lundström & Wallin, 2016). More on the difference between collectively and decentralized heating systems can be found in section 2.5.1.

Another boundary condition is the supply of DHW. As said in section 2.3.3, the required temperature for domestic hot water in the Netherlands is minimal 60 °C, otherwise Legionella can possibly develop in the water. For LTDH this is difficult to realize, so a need for post-heating is required. Post-heating can be done with a Booster Heat Pump (BHP). More on the BHP can be found in section 2.5.2. If the DH water enters the house with 60 °C or higher, only a heat exchanger (HEX) is needed.

2.4.2 Heat demand related to daily and seasonal base

The energy balance differs on daily base and on seasonal base (Gadd & Werner, 2013). Peak demands occur in the morning and evening on a daily base. Residents wake up in the morning and prepare to start their day. During the day, fewer people are present in a neighborhood, which means the heat demand is lower. Most of the residents come back to their homes in the evening. They want to make it comfortable, which means they will increase the heat usage. On a daily base, the peaks depend mainly on when the residents are at home. Occupancy level of people can be found in (Ahmed et al., 2017). Seasonal peaks are different. These are based on the weather. In winter, when the temperature is lower, heat demand is higher than in summer.

2.4.3 Demand side management

Demand-side management (DSM) is a strategy of a resident to manipulate the heat load (Faruqui & Chamberlin, 1993). Faruqui and Chamberlin describe DSM as follows:

'*DSM includes all programs designed to influence the customer's energy use, focusing on changing the shape of the load and thereby helping to optimize the whole power system from generation to delivery, to end use'*

This means that for a whole power system, which is LTDH, DSM can be a helpful strategy to optimize the network. Since the shape of the load is difficult to regulate for a LTGH, this thesis looks into the energy use of the consumer. For a resident, there are three important ways to use DSM. These are listed below (Faruqui & Chamberlin, 1993).

1. Peak shaving. This refers to a way that the heat usage during peak hours is less, because heaters are turned on before the peak hour starts. An example is to increase the night set temperature up to the day set temperature to flatten the heat demand during the day. The resulting heat demand profile will show a higher heat demand during the night than during the day because of colder ambient temperature and smaller internal heat production.
2. Load shifting. This refers to use the building mass as a buffer. A building with a higher mass can maintain the inside temperature longer.
   However, it will take longer to heat up the building again. If the occupancy level is known, the building can be preheated, so the peak is flattened.

3. Conservation. This refers to reduction of consumption by residents. This is possible when homes have better insulation.

An example of such strategies is given in Figure 2-7. It shows the heat usage with and without DSM. It can be seen that the heat use with DSM is less. Such a strategy flattens the demand and therefore can help to meet the peak moments with a LTGH source.

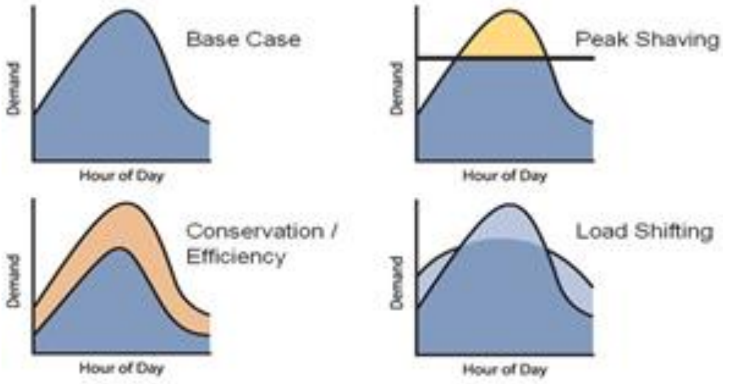


Figure 2-7 Energy demand curves with three DSM strategies. Adapted from (Powergrove, n.d.)

The last two methods of DSM, load shifting and conservation, can be done by insulating the building. The thermal mass of the building becomes thicker and the transmission and infiltration losses will reduce. According to (Airaksinen & Vuolle, 2013), this measure leads to a saving of 55 – 62 % of the space heating consumption. However, the difference in peak heat demand was only 28 – 34 %. These numbers are lower for homes in a cold climate.

The reduction in peak heat demand is lower, because the peak load inside the building zones (rooms) were different due to the room location and ventilation. The study of (Airaksinen & Vuolle, 2013) shows that each room should have individual control units in order to reduce the peak heat demand and maintain comfortable indoor conditions.

The methods of conservation and load shifting are efficient ways to reduce the total heat demand, but to reduce the peak heat demand, peak shaving is the best method.

2.5 Heating systems for districts

According to (Rezaie & Rosen, 2012), a DH can be divided into three subsystems: heat production, heat transportation and heat consumption. Section 2.3 discussed the heat transportation and section 2.4 discussed the heat consumption. This section discusses relevant heat production and storage systems for an LTDH and how the heat can be consumed.

2.5.1 Collective versus decentral heating

A heating system for a neighborhood can be done collectively or decentralized (Rezaie & Rosen, 2012). The difference indicates where the heat source is located. In a collective heating system, the heat is produced far from the location of the end-users and it produces heat for the whole district and distributes the heat via a large distribution network. A decentral heating system produces heat close to the end-user and has a smaller or no distribution network.

The same applies for storage methods. Collectively storage is located far from the end-user and decentral storage is located close to the end-user. Collective storage is storage depending on the seasonal heat demand and decentral storage system depends on hourly demand (Alva, Lin, & Fang, 2018).

Collective and decentral heating systems have both their advantages and disadvantages compared to each other. In general it can be said that decentral heating systems become more relevant for low density neighborhoods and collectively heating is relevant for highly density neighborhoods.

2.5.2 Current heat technologies to replace gas boilers

For an LTDH network, there are a few sustainable collective and decentralized heat sources (Rezaie & Rosen, 2012). These are listed in Table 2-2.

According to (Bloemendal, 2018; Infante Ferreira, 2018; Lund et al., 2010; Pothof, 2018), the heating technologies next to a geothermal heat source are a central biomass boiler, electrical heaters and decentralized heat pumps are currently the most suitable technologies next to an LTGH to replace gas boilers. These technologies cause the smallest adjustments of the homes and are more applied than the other technologies.

Table 2-2 Overview of possible heat supply technologies for an LTDH.

Technology	Short description
Collective heating systems	
Solar thermal heat	Solar collectors use the heat of the sun to increase the temperature of the flowing water through the collectors. The heated water can be used for heating purposes.
Biomass	A biomass feedstock can be converted into heat via bio-chemical and thermo-chemical conversion processes, like combustion, gasification, pyrolysis and anaerobic digestion.
Thermal energy of surface water	The heat of the surface water in the summer is extracted by a HEX and directly stored, so the heat can be used in the winter.
Waste heat	The rest heat, produced by industries, is used to heat water. It is a promising heat source for districts close to industrial areas.
Combined heat power	This system generates heat and electricity by burning fuel. Now a days, these fuels are mainly fossil fuel.
Decentral heating systems	
Electrical heaters	This system converts electricity into heat. The heater is a large electrical resistor.
Infrared panels	This system converts electricity into radiant heat. This system does not heat the air, but objects (such as persons).
Air heat pumps	The heat pump uses the heat of the outside air for the evaporator side of the heat pump and provides heat directly to the living.
Decentralized heat pumps	The heat pump uses heat of a water circuit for the evaporator side of the heat pump and provides heat directly to the living.
Ground source heat pumps	This system pumps hot water from the ground to a building.
Pellet boiler	This system generates heat by burning pellets
Micro-CHP	This system generates heat and electricity by burning green-gas or hydrogen.
Decentralized solar heating system	This system works exactly like the collective way of solar thermal heat, only the solar collectors are on the roof of a home. Next to that, a water tank is installed to store the heat.

Biomass boiler collective

A biomass boiler burns biomass. This reaction is exothermic, so the produced heat can be used for heating purposes. At home level, the heat is directly used to increase the temperature in a room. This is done with a pellet stove. At central/district heating level, the boiler is used to increase the temperature of the supply water for the network.

The advantages of a biomass boiler are the low investment costs and the frequency of the heat supply can be well controlled (Planbureau voor de leefomgeving, 2014). In addition, the capacity of the biomass boiler can easily be increased and therefore it is possible to connect future buildings to the DH.

An example of a schematic network with a peak boiler is for a proposed DH of a University campus, where the boiler produces heat when the geothermal source cannot produce enough heat for the demand (Lukawski et al., 2013).

Electrical heaters and infrared panels
Next to radiators and underfloor heating, a home can also be heated with electric heat elements. These are infrared panels and electric heaters (CE Delft, 2016). Electricity is converted into heat. A central heating station is not required. Infrared panels are mainly used as additional heating for areas where heat is required for a limited part in a room. These technique can be used in addition to LTDH to preheat a room during a peak moment.

The disadvantage of these techniques is that less than 100% of the electricity is converted into usable heat and they are therefore less efficient than a heat pump and a boiler is needed for DHW.

Decentralized heat pump
A decentralized heat pump is a water-to-water heat pump and raises the temperature of the supply water to the desired value for the particular application (Østergaard & Svendsen, 2017). This can be used for DHW purposes, small ATES and for LTDH. The advantage is that the heat pump has a higher COP value than an air-to-water heat pump, and can absorb the base load and the peak load. The disadvantage is that a DH must be created and the costs of such a network will therefore be high (Østergaard & Svendsen, 2017).

2.5.3 Relevant storage methods for DH

For an LTDH network, there are a several storage methods (Alva et al., 2018). Just like the heat technologies, the storage methods can be divided in collective and decentral systems. These are listed in Table 2-3.

Table 2-3 Overview of possible thermal storage methods for an LTDH.

Technology	Short description
Collective storage systems	
Aquifer Thermal energy Storage (ATES)	Heat is stored in the summer in an aquifer underneath the ground and is extracted in the summer.
Borehole thermal energy storage	Heat is stored in the summer in an underground structure, an array of boreholes, and is extracted in the summer.
Sensible storage tanks	Heat is provided to a sensible material with a high specific heat capacity. During the heat adsorption process, the temperature of the material increases. Commonly, the material is a liquad and saved in a tank.
Decentral storage systems	
Phase change materials	This material stores latent heat during a phase change. Heat is absorbed or released when the material changes in phase.
Thermochemical materials	These systems use reversible reactions which involve absorption and release of heat. During storage, an endothermic reaction takes place. During heat extraction, an exothermic reaction tales place.
Sensible storage tanks	This is the same as the collective storage, but is in here it is applied for smaller capacities.
Thermal mass	It is a property which enables it to store heat. This systems heat the walls of a building and keeps the heat, so a shift in heat demand happens.

According to (Alva et al., 2018; Lund et al., 2014), the storage methods ATES and water tank are currently the most suitable storage methods for an LTDH, because of these systems have low installing costs and are more applied than the other technologies.

Water tank

The water tank can be installed to help the network during daily peak moments (Alva et al., 2018). The water tank is charged by the LTDH when the supply by the network is higher than the heat demand. The water tank is discharged by the resident when the heat demand is higher than the supply of the network. A heat exchanger is placed in the tank and connected to the supply set in the home. Hot water from the supply set goes through the heat exchanger, so the water in the tank is heated to the right temperature.

ATES

ATES is a technology which is used for seasonal storage. Heat is extracted from the ATES during the winter and heat is injected during the summer. ATES works as follows. Hot water is injected into a suitable aquifer and is stored. The volume of the storage increases with the flow of the hot water. The volume decreases when the stored energy is extracted. Figure 2-8 presents how the ATES can be charged from the supply heat in the summer and how it can provide heat to the system during the winter.

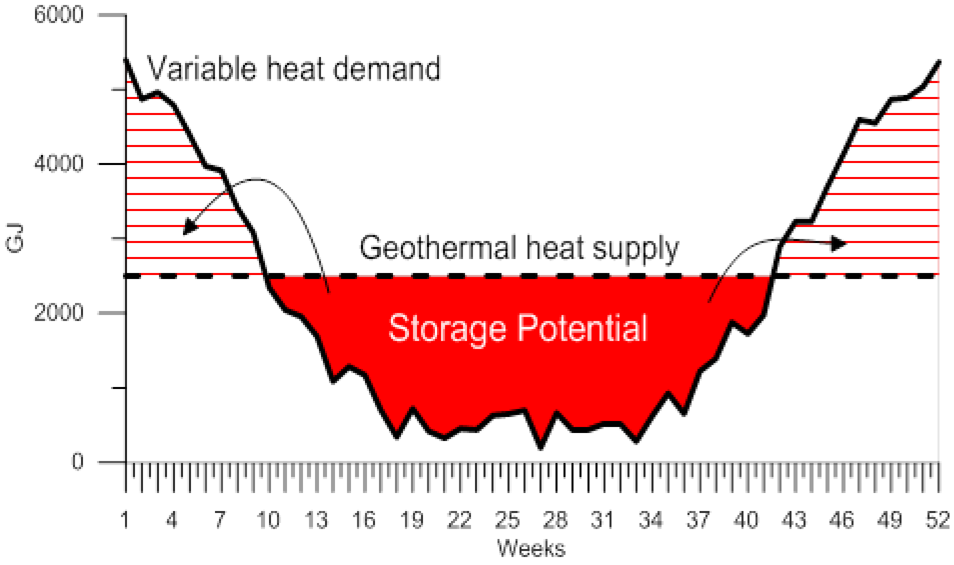


Figure 2-8 Yearly heat demand profile with a base load and variable load. During the summer it is possible to store the heat and supply the stored heat in the winter. Adapted from (Beerink et al., 2018).

The selected aquifer, where the ATES is installed, has influence on the storage temperature and the maximum flow rate of adding/subtracting heat (Drijver et al., 2012; Vandeweijer, 2013). The most favorable aquifer, which has the least heat loss to its surroundings, has a high porosity, low vertical permeability, high horizontal permeability, and the aquifer above should have a low permeability (Bloemendal & Hartog, 2018).

The recovery efficiency of an ATES well is defined as the amount of injected thermal energy that is recovered after the injected volume has been extracted (Bloemendal & Hartog, 2018). The heat loss that occurs is due to displacement by groundwater flow and by dispersion and conduction. However, the thermal energy that is lost, is at the boundary of the stored temperature volume (Bloemendal & Hartog, 2018). This is only noticed by the end of the wells' extraction period in the season after. Interaction between ATES wells at the boundary of their temperature fields may affect their recovery efficiency.

2.5.4 Heat consumption techniques

The heat supply must be converted into useful heat for the residents. This subsection describes how the supplied heat can be used for DHW and space heating purposes.

Supply set

The supply set is the connection between the LTDH and the inside installation of the consumer. It is an installation for the heat transfer for special heating and/or domestic hot water. This set contains equipment for pressure and/or temperature control system and the housing in which the supply set is installed (RVO, 2014). These sets must meet the Dutch standards NEN1006 (general requirements for tap water installations) and NEN 2768 (technical area and associated facilities in a residential function). An example of a supply set is the Orion from the company Danfoss. Figure 2-9 provides a picture of the Orion supply set.

Figure 2-9 Supply set Orion from Danfoss. The supply set can receive DH water between 30 and 80 ^{o}C, and can control the return temperature to the district between 25 and 45 ^{o}C. Adapted from (Danfoss, n.d.)

DHW supply

The DHW can be supplied by the following three technologies in a home (Schmidt & Kallert, 2016).

- Booster heat pump (BHP)

A BHP has the same working principle as a regular heat pump and is designed for upgrading water to the required temperature. The DH supply water flows through the heat pump evaporator. The DHW water flows through the heat pump condenser. Due to the heat pump and heat supply from DH, the temperature of the water for the DHW is raised to 60 ^{o}C.

- HEX

The HEX transfers the supplied heat from the LTDH to a distribution net in the house for DHW purposes.

- Electric boiler

This is a system which is independent of the LTDH. Cold drinking water is subtracted from the drinking water network and heated up in the boiler to the required temperature. The advantage of the electrical boiler is that the LTDH does not have to take care of the DHW supply. However, the total cost for a home can increase.

Space heating supply

The connection between the LTDH and the inside radiators and DHW devices is done with a supply set. It is an installation for the heat transfer for special heating and/or domestic hot water. This set contains equipment for pressure and/or temperature control system and the housing in which the installation is installed (RVO, 2014). These sets must meet the Dutch standards NEN1006 (general requirements for tap water installations) and NEN 2768 (technical area and associated facilities in a residential function). These standards explain that the domestic hot water at tap water point need to reach a minimum temperature of 60 ^{o}C and the heat loss in the housing of the supply set cannot be more than 100 W_{th}.

An interesting research (Østergaard, 2018) tells us that current radiators in a home can still be used at lower supply temperatures. This research has carried out practical tests with existing homes in Denmark of building years in the 1960's, 1970's and 1980's. The houses were provided with different supply temperatures of a DH and checked whether the same heat was still supplied. The result was that the same heat can be supplied at lower temperatures. It appears that the existing radiators are over-dimensioned. This is already done by making the radiators in the factory and that such houses have already taken small insulation measures. As a result, the radiator is over dimensioned and therefore lower supply temperatures can be connected to the radiators.

Figure 2-10 shows the test results from a recent study by Østergaard (Østergaard, 2018). It shows what the supply and return temperatures from radiators using LTDH for 4 existing homes and what the outside temperature was in 2016 in Denmark. In general, the return temperature is around 30 ^{o}C and the supply temperatures are between 50 and 40 ^{o}C. The temperature in that year was never below 0 ^{o}C. The inside temperature was kept at 20 ^{o}C.

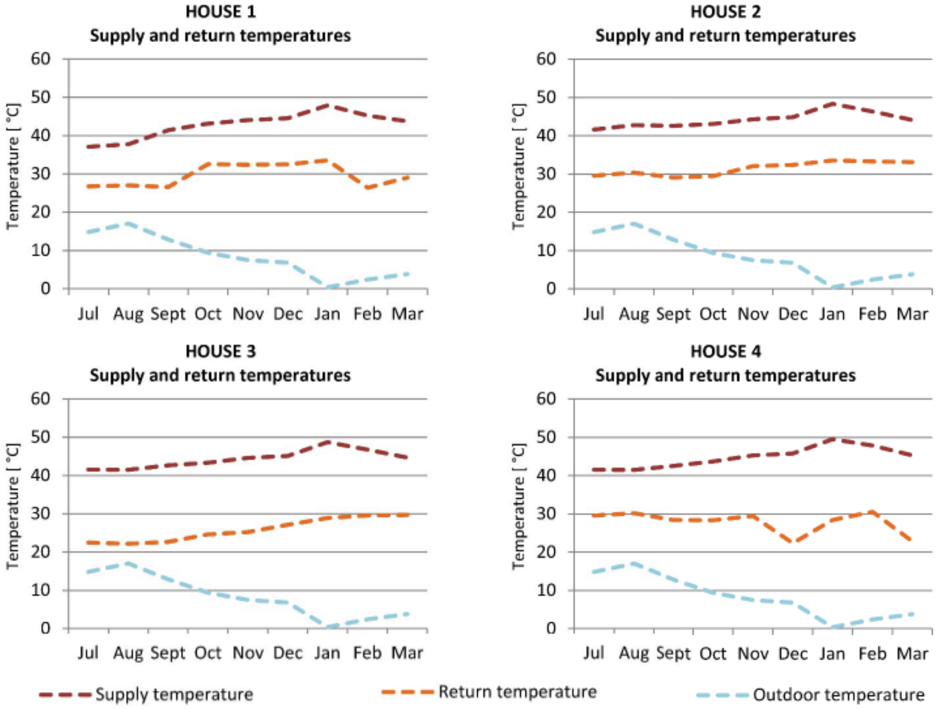


Figure 2-10 Supply and return temperatures of the radiators in four houses from the 1980, measured in 2016. Adapted from (Østergaard, 2018).

Figure 2-11 shows the return temperatures of existing radiators with varying supply and outside temperatures. The lines in the graph represents the measured radiators and the related radiator factor. The radiator factor is the ratio between the design heat output of the radiator and the actual heat output of the radiator. A radiator factor of 1 implies that the designed output is the same as the actual output. The radiators in Figure 2-10 have radiator factors between 0.8 and 2. Figure 2-11 shows that the return temperature for a higher radiator factor is between 35 and 25 ^{o}C.

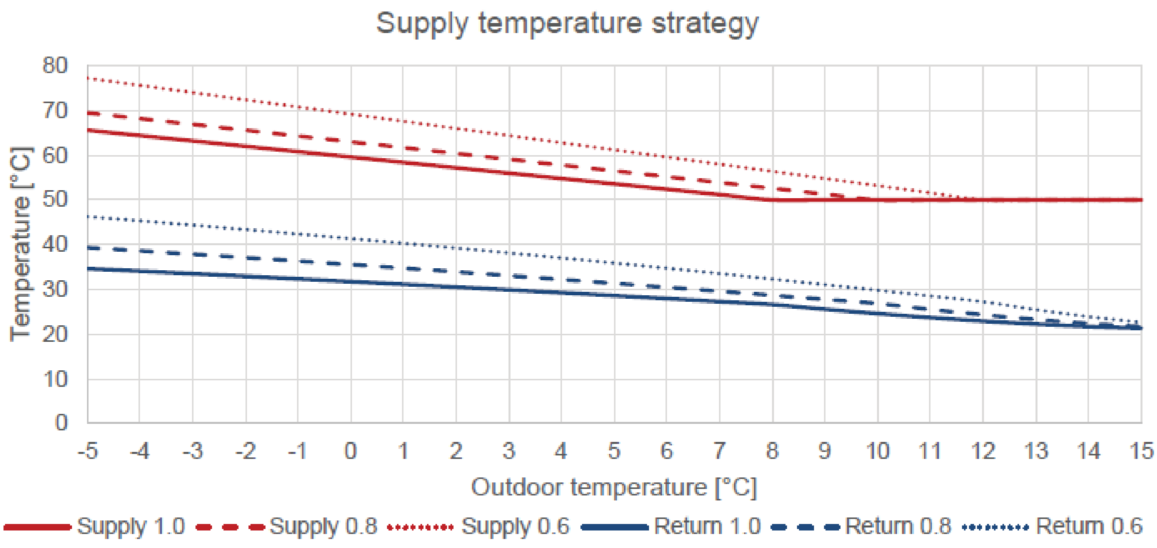


Figure 2-11 Return temperatures with varying supply and outdoor temperature for radiators with radiator factors 1, 0.8, and 0.6. Adapted from (Østergaard, 2018).

2.6 Overview of DH design methods and calculation models

Designing an LTDH has done before. There are several methods available to design an LTDH and several design criteria for measuring an LTDH. This section provides an overview of the Key Performance Indicators (KPIs) for designing a sustainable DH and which methods and calculation tools can be used to measure these KPIs.

2.6.1 Key performance indicators for sustainable DH

A KPI is a type of performance measurement and evaluates the success of a final design (Fitz-Gibbon, 1990). KPIs are well-known indicators for conducting a comparison study and for measuring existing installations to see if improvement to the installation is required.

An example of measuring an existing installation with KPIs is the geothermal DH in Afyon, Turkey (Keçebaş, 2011). The geothermal DH is measured to the thermodynamic and thermo-economic performance. Actual data is used to measure these KPIs. The results provide some key information for the people working in the area of better design, analysis, and operation of the geothermal DH of Afyon. The performance of that DH can be improved if the heat exchangers, reinjection, pipeline losses exergy flow rate are recovered accordingly and used in the system.

An example of a comparison study based on KPIs is carried out by (Köfinger et al., 2016). This study compared 4 existing LTDH to design an optimal LTDH concept on economic and ecological ground. The results show that LTDH networks can be an economic, ecologic and energetic advantageous solution for the supply of space heating and DHW, but the optimum design and the applied operational strategies depend highly on the local conditions and cannot be solved in a generalized way.

The KPIs for technical installations change over the years. So is the emission of CO_2 a KPI which was not measured in the past, but is now one of the most relevant KPIs. An example of creating new KPIs is done in the study of (Cabeza et al., 2015). This study draws up a number of KPIs for selecting a thermal energy storage system. There were 11 KPIs spread over the 3 categories increase of efficiency and reduction of costs, improvement of dispatchability, and improvement of the environmental profile. Per storage system (sensible, latent heat and TCM) is described how well these solutions score on the several KPIs. So it is easier for a designer to choose a certain thermal energy storage system.

According to (Köfinger et al., 2016), the following KPIs are the most common now a days for designing an LTDH.

1. Safety features

Safety features are an important KPI for any technical installation. This applies to the entire life cycle of the installation, i.e. during production, installation, usage, and decommissioning. An example of an heating network, which can be seen as unsafe, is the gas network in the Netherlands. In January 2019 there was a gas leak, which caused an explosion in a home (RTL Nieuws, 2019).

2. Energetic and ecologic evaluation

This KPI measures the amount of energy used through the life cycle of a technology or system. The ecological evaluation is related to the amount of energy used and which energy carrier is used. With climate change, it is important that new technologies have low environmental impact.

For LTDH it is important to see how much electricity is used, because next to the heat, electricity needs to be produced as well. To prevent overloading of the electricity grid, it is desired to keep this as low as possible.

3. Economic evaluation

This KPI evaluates the costs and benefits of a technique through its life cycle. The performance of a technique on this KPI depends on what the stakeholders in the analysis require.

4. Socio evaluation

This KPI looks on the market and evaluates the opportunities/barriers and especially the needs of the different stakeholders. Otherwise there is the risk that technical solutions are available on the market, but nobody really knows about the advantages and so the market penetration of such “new technologies” might be very low.

2.6.2 Methods for DH design and KPIs measure

There are several methods available to design a DH and how to quantify a design based on KPIs. This section provides a brief overview of the available DH design methods and KPI measures methods.

DH design

The following design methods are useful for the design of a sustainable LTDH.

1. The mechanical design proces (Ullman, 1992)

This method, developed by D. Ullman, is often used to design products. It is a roadmap which divides the design in several functions. For every function several solutions will be created. To create a design, one solution per function will be selected and combined, so there is a design for the product.

2. Layout of network

In Annex TS 1 from the IEA (D. Schmidt et al., 2017), there are several methods explained how the layout of the pipes in a DH can be realized. The concept of a ‘ring network’ can be used to equalize the available differential pressure for the consumer close to the power plant and for the consumer far from the power plant. (Laajalehto et al., 2014) explains how cascading can help extracting more heat from the same water.

3. Sustainable roadmaps

There are several roadmaps available to set up a sustainable energy system. In the Netherlands, certain municipalities are still searching for a suitable roadmap to make the energy system in their municipality more sustainable. The roadmaps which are better known in municipalities are from Stremke, Energy Potential Mapping, and Oudes and Stremke.

Stremke (Stremke, 2012) developed a conceptual framework for the planning and design of the energy transition. Another approach is the Energy Potential mapping (Van Den Dobbelsteen, Broersma, & Stremke, 2011), this concept gives insight into the potential of sustainable energy in a specific area. The study of (Oudes & Stremke, 2018) is inspired by these two methods and presents the method called spatial transition analyses which gives a step by step approach for stakeholders in the energy transition.

CO_2 emission / Life Cycle Assessment
Life-Cycle Assessment (LCA) is one of the most common methods to evaluate the CO_2 emission of a product. This framework is described in ISO14040. LCA is an analysis to assess environmental impact of a product at all stages during the product life time (Vogtlander, 2012). This starts from raw material and ends with the disposal or recycling of the materials.

Economic analysis
The following methods are suitable to perform an economic analysis.

1. <u>Levelized cost of energy (LCOE)</u>

LCOE is measure of the costs an energy system through its life cycle per produced or consumed energy.

2. <u>Net Present Value (NPV)</u>

NPV represents the cash flow for an energy system for every year. The first year for the NPV is the year when the energy system is produced or installed and the last year is the decommissioning of the energy system.

3. <u>Return on Investment (ROI)</u>

ROI is a ratio between the net profit and cost of investment resulting from an investment of a new energy system.

2.6.3 Calculation models

There are many tools available which can help an engineer with designing a LTDH network. These calculation tools are presented in Table 2-4. The table presents which criteria can be calculated or which possibilities a tool has. A selection of the tools is made with (Schmidt & Kallert, 2016) (Naber, Schepers, & Rooijers, 2016) and (NetbeheerNederland, n.d.).

Table 2-4 shows that EDA and EnergyPlan are useful models for the design of an LTDH. However, none of these models executes an analyses of how well an LTDH works during extreme cold moments.

Table 2-4 Existing calculation models for designing a DH, with criteria. X means that the criteria is available in the tool and – means it is not available.

Criteria	Easy District Analysis (EDA)	EnergyPLAN	DIDO	District ECA	Low Ex-CAT	Heat NET	Quintell (ETM)	CHESS	CEGOIA	Energy PLUS
Costs	X	X	X	X	-	-	X	X	X	X
Electricity demand for heat supply	-	X	X	X	-	-	-	X	-	-
CO_2 emission	X	X	X	X	-	-	X	X	-	X
Geothermal as input	X	X	-	X	X	X	-	X	X	
Hourly demand input	X	X	-	-	X	-	X	X	X	-
Heat supply behavior	X	X	-	-	X	X	-	X	X	X
Storage possibilities	X	X	-	-	X	X	-	X	X	-
Heat losses in network	X	X	-	X	X	X	-	X		-
Heat for district level	X	X	-	X	X	X	-	X		-
Heat production technologies	X	X	-	X	X	X	X	X	X	X
Network design	-	-	-	-	-	-	-	-	-	-
Free to use	X	X	-	X	-	-	X	-	-	X

2.7 Chapter summary

LTGH and LTDH (2.2 and 2.3)

This overview showed the working principle of geothermal installations and the benefits of the LTGH from V&SH. Drilling less deep for heat offers many advantages over more traditional geothermal systems. LTGH can be used as a base source for the supply of heat in a DH. For providing the total heat demand in an urban area, however merely a LTGH is not efficient enough, because the constant heat supply can be difficult to match with the variable heat demand.

One way to use LTGH in a DH is with LTDH. After several generations of heat networks, the era of the low temperature network has arrived. By using a low temperature heat network, the heat losses will decrease and it is easier to connect sustainable sources, such as LTGH. Although, it remains unclear how the peak moments can be supplied with a sustainable source.

Influences of heat demand (2.4)

Heat demand consists of space heating and DHW and is the major boundary condition for designing an LTDH. An important question for the designer is where to produce the peak heat demand. Space heating can be influenced by various DSM strategies, like peak shaving, load shifting and conservation. The hot water consumption cannot be influenced by different measures, only the user self has influence on the DHW demand. If the temperature in the network is 60 ^{o}C or more, only a HEX is needed for the DHW. Otherwise, a BHP is needed.

Heating systems (2.5)

In addition to an LTGH, storage capabilities and external peak sources are interesting technologies for designing a sustainable LTDH. The storage options are important for both seasonal (ATES) and daily basis (water tank). The peak sources can be a biomass boiler, a decentralized heat pump, and electrical heating elements. These technologies can be divided into collective and decentral technologies, depending on their location.

LTDH Design methods and requirements (2.6)

Sustainability and efficiency can be weighted according to a few KPIs. For a DH, this can be assessed based on energy consumption, environmental impact, and costs. The energy consumption needs to be determined for the CO_2 emission and costs, and also to see by how much the electricity network is extra loaded. The LCA is the most common used method to determine the CO_2 emissions for a system. The economic analysis can be employed with several methods. If the designer only wants to determine the costs, the LCOE is a useful method. If the designer wants to determine the profits per stakeholder as well, the NPV is a more suitable method.

There are several calculation models which help a designer to give insight in the KPIs a designer sets. However, none of them performs a critical analysis on the peak heat demands.

3. Research methodology

3.1 Introduction

The previous chapter shows many available technologies which can be used in LTDH to support the LTGH with supplying the peak heat demand. To investigate which combination of technologies is the most sustainable and efficient for the peak heat demand, a methodology is established. First, the KPIs, to decide how sustainable and efficient an LTDH is, are set up. After that, the method, to calculate the KPIs, is explained step by step and what the boundaries are of the developed methodology.

3.2 Key performance indicators

To investigate which LTDH can supply the peak demand efficiently and sustainably, the following KPIs are set and will be calculated.

- CO_2 emission. CO_2 emission is the main reason why LTDH networks are investigated. This should be as low as possible.
- Levelized cost of energy (LCOE). As described in section 2.6, this parameter gives the best insight into the costs per produced kWh of heat. This should be as low as possible for over 30 years.
- Electricity usage. Electricity usage is an input for the LCOE and the CO_2. Apart from that, it is desired to have low electricity usage, in order for the electricity net not to be overloaded. In consequence, the electricity net can be used for most parts for electricity purposes and just a small part for heating purposes.
- Availability. The behavior of the network during cold days has been criticized by (van Vliet et al., 2016) because of the high temperature difference. The reliability for residents is indicative of how well the network behaves during cold days. It can be calculated with an energy balance. If there are moments when the supply cannot meet the demand or the storage systems are empty, then the availability is low. When the supply meets the demand and the storage systems are full, then the availability is high.

All the concepts will be measured for these requirements. The results are presented in Chapter 10. In addition, the following requirements will be reviewed as well.

- Impact of installation. The impact of installation describes the size of the supply set for the residents, the building time for their livings and district, and the safety features. For social housing, 70% of the residents have to agree with the measures taken for their livings and neighborhood. To achieve this, the impact of installation should be low (Jong Warmtenetwerk, 2018).
- Reliability. This indicates how often the consumer can use the available heat. Low availability means that there is much maintenance or other reasons for failure of the system.

These requirements will be dealt with in Chapter 11. The best LTDH is based on a general high score for these KPIs.

3.3 Research approach

A comparison study will be performed to calculate the KPIs from the previous section. The established method is a variation of the method from (Ullman, 1992). This has been selected, because it is a widely used methodology to compare different designs using KPIs. Figure 3-1 shows the flow diagram of the steps to be carried out with this method. The methodology consist of 9 general steps.

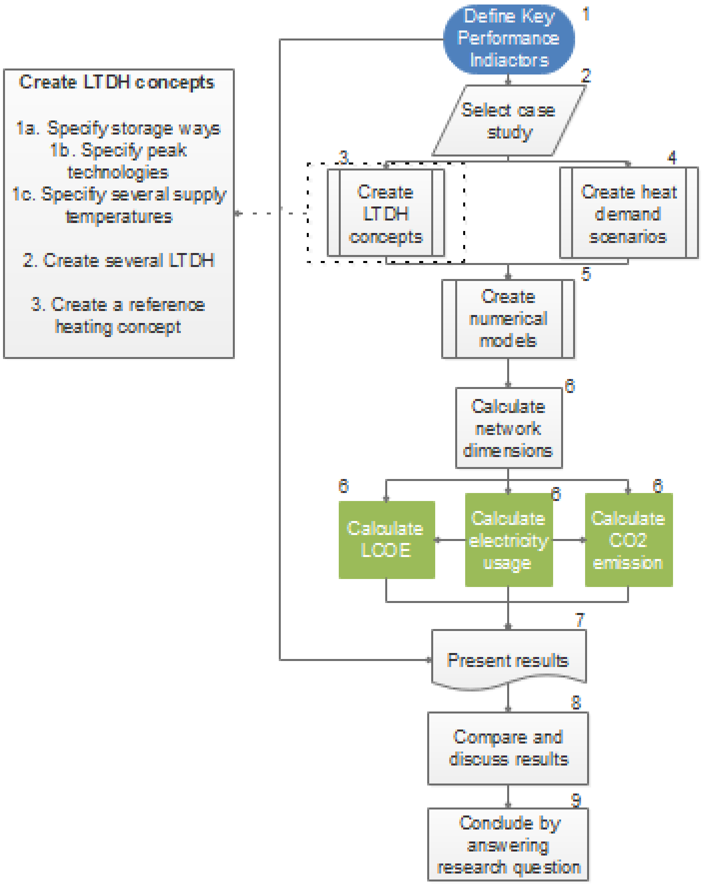


Figure 3-1 Flow diagram of the used method in the current thesis.

Next to step 3, 'create LTDH concepts', there is another process block. This describes how the LTDH concepts are generated. In the end, 5 LTDH concepts are designed. These are combinations of several storage methods, peak technologies and supply temperatures by the net.

1. <u>Define KPIs</u>

The various LTDH concepts can be compared on the basis of these requirements. This is described in section 3.2.

2. <u>Select case study as representative district in the Netherlands</u>

A case district is needed to know what the heat demand is for a district in the Netherlands. The case district should be representative for most district areas in the Netherlands, so that a general answer can be given to the main question. This is discussed in Chapter 4.

3. Create 5 LTDH concepts and a reference concept to compare

In this step, 5 LTDH concepts are designed to be compared with each other. The LTDH concepts vary in storage methods, technologies to supply the peak, and supply temperatures in the DH. In addition, one heat concept is made which serves as a point of reference. With this heat concept as a reference point, results can be expressed in index numbers instead of real values. The LTDH concepts will be compared with the reference scenario. The design of the LTDH and reference concepts is discussed in Chapter 5.

4. Create 3 heat demand strategies as input to compare the LTDH concepts

As discussed in section 2.4, there are a few ways to influence a heat demand. The impact of peak shaving and insulation can have a significant influence on the design of a heat network. That is why it is interesting to include different heat demand strategies in the research. 3 different heat demand strategies will be used as input for the LTDH concepts, which are designed in the previous step. These heat demand strategies are discussed in Chapter 5.

5. Create numerical models

This step sets up the numerical calculation models. The aim of the models is to calculate a part of the KPIs from section 3.2. This is discussed in Chapter 6.

6. Calculate the network dimensions

The pipe type and diameters to be used have a big impact on the total costs. That is why extra attention is paid to calculating the correct pipe diameters. This is discussed in Chapter 8.

7. Calculate the LTDH concepts to the requirements

This step calculates the LTDH concepts according to the KPIs. This is discussed in Chapters 9 and 10.

8. Analyze results

This step compares the results from the previous step. With this analysis it is possible to answer the research questions. This is discussed in Chapters 11.

9. Answer the research questions

If all the previous steps are executed well, the research questions can be answered. The answer to the research questions is discussed in Chapter 12.

3.4 Limits of methodology

The chosen method has a number of limitations, otherwise the present thesis becomes too large. The limitations are listed below.

1. **The focus does not lie on finding optimal parameters**

The chosen method is a comparison study. This method determines the best option of the 5 designed LTDH. This method is very suitable for giving answer to the question of which LTDH design would be most suitable for the peak moments. It will not determine how this concept can be optimized.

To optimize the technologies, such as the optimum supply temperature by the LTGH or the optimum size of a storage tank, further research must be executed.

2. **Not every KPI is covered in detail**

The technical aspects are calculated with this method, but the other KPIs, as the impact of installations, will not be discussed in detail. Because of these KPIs, this research becomes too large due to several stakeholders being involved.

A follow-up research to work out these KPIs in detail, with the results of this study, can be performed. This will help realizing the selected LTDH design in the future.

3. **The revenues and costs distribution among the stakeholders are not displayed**

The LCOE calculates the total costs per MWh of heat produced. This is chosen, so that there is a clear overview of the total costs and to compare the LTDH concepts. In order to involve the stakeholders, the size of the research increases and is no longer feasible in the set time.

A follow-up research could be done to perform an NPV analysis. The financial feasibility of the chosen LTDH concepts becomes clearer for the stakeholders and what the distribution of the costs and profits is.

4. **Impact of CO_2 is only calculated during heat production**

The production, installation and decommissioning of the LTDH concepts are not included in the CO_2 emission analysis, due to the efforts to calculate these components. It is also expected that there is no need for research into this, since most emissions are caused by the production of the heat by a geothermal source (Lacirignola & Blanc, 2013).

Part 2 Methodology elaboration

Part 1 ends with the explanation of the method. This part elaborates on this method. The case study is described and LTDH concepts are designed for the case. These LTDH concepts will be compared with each other based on a reference concept. After designing the LTDHs, 3 heat demand strategies are presented. Part 2 with explanations of the used numerical models.

4. Case study

4.1 Introduction

The method, as described in the previous chapter, is performed for an urban area in the Netherlands. The case is the urban area Breda Biesdonk. This area has been chosen, as heat demands for this area are known and the urban area is representative for urban areas in the Netherlands. This chapter presents the typology of the area, the heat consumption in 2016 and the corresponding weather, and the LTDH and temperature adjustment.

4.2 Breda Biesdonk typology

Figure 4-1 Satellite photo of Breda Hoge Vucht. Adapted from (Google, n.d.).

The buildings in Breda Biesdonk were built in the 1970's. Biesdonk is part of the collective urban area 'Hoge Vucht'. It is in the north of Breda. Biesdonk had 4995 residents and 2230 homes in 2015. For this thesis, heat demands are known for 650 single livings and 1000 apartments. The single livings are low-rise buildings. Other buildings, such as shopping centers, schools, and churches are also present in the area. Heat demands for those buildings are not known and not in the scope of this thesis. A map of Biesdonk and the heat demands are presented in Figure 4-2 and Figure 4-5 ('Hoge Vucht Biesdonk', n.d.).

The apartments have Dutch energy label D and the single livings have Dutch energy label C ('Hoge Vucht Biesdonk', n.d.). Therefore, the insulation layer of the living is quite thick and has double glass windows. However, it is still possible to lose heat, so the insulation layer can be improved. According to (Installatietechniek, 2012), the central heating values for low-rise buildings are 7 kW and 6 kW, depending on the location of the building, and DHW supply value is 21 kW. This means that the maximum heat supply through the net is 28 kW per home. The current heat provision is from natural gas.

Figure 4-2 Map of Breda Biesdonk. Adapted from (Google, n.d.). The marked area is the location of Figure 4-1.

4.3 Heat demand and meteorological data 2016

Heat demand is caused by building properties, outside temperature, solar radiation, wind and internal heat gains. These data are measured by the KNMI at several weather stations, except for internal heat gains and building properties. This thesis only takes into account the outside temperature and building properties, because those are the most dominant factors in causing heat demand. The temperature profile in Figure 4-3 is from the weather station in Hoek van Holland and presents the measured outside temperature for every hour in 2016. The related Heating Degree Days (HDD) is presented in Figure 4-4. The heat demand from Breda Biesdonk in 2016 is presented in Figure 4-5. In Figure 4-5, a distinction is made between space heating (blue line) and the hot water consumption (red line).

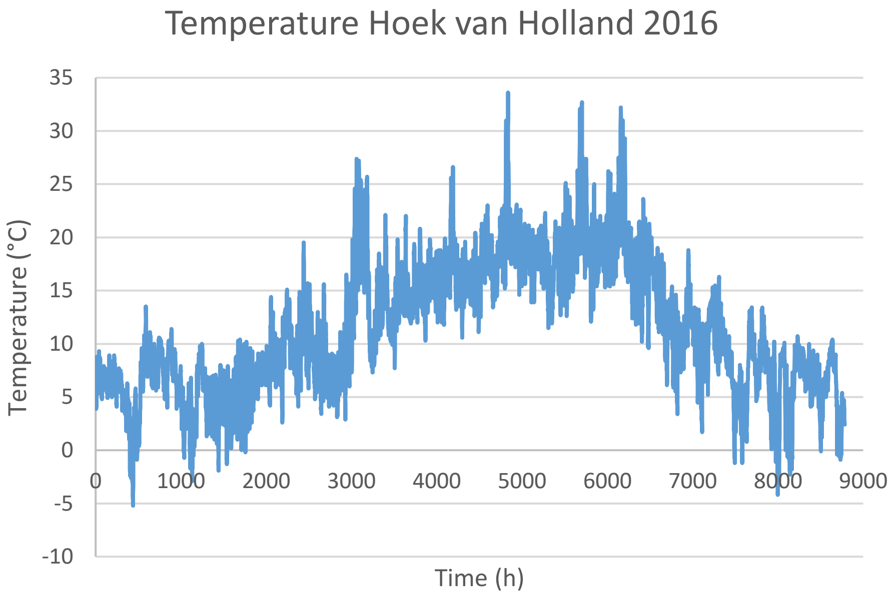


Figure 4-3 Temperature profile of Hoek van Holland 2016. Adapted from (KNMI, 2017).

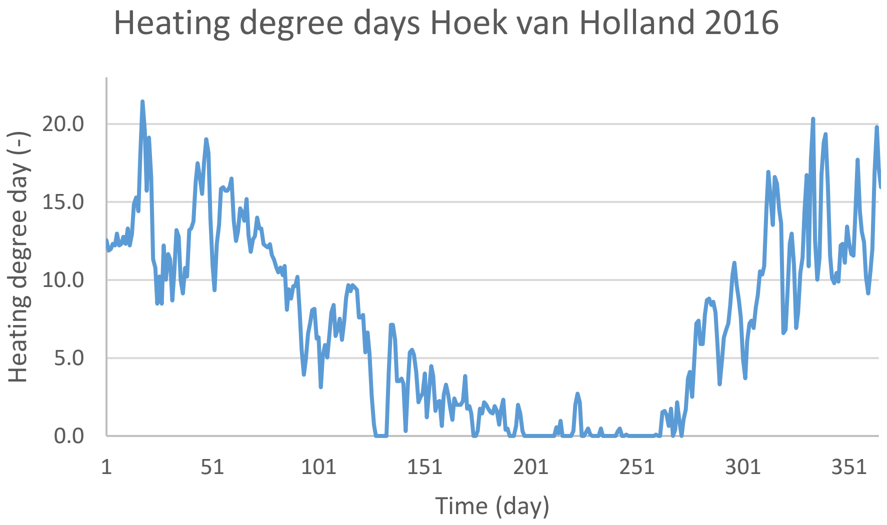


Figure 4-4 Heating degree days in Hoek van Holland. Adapted from (KNMI, 2017)

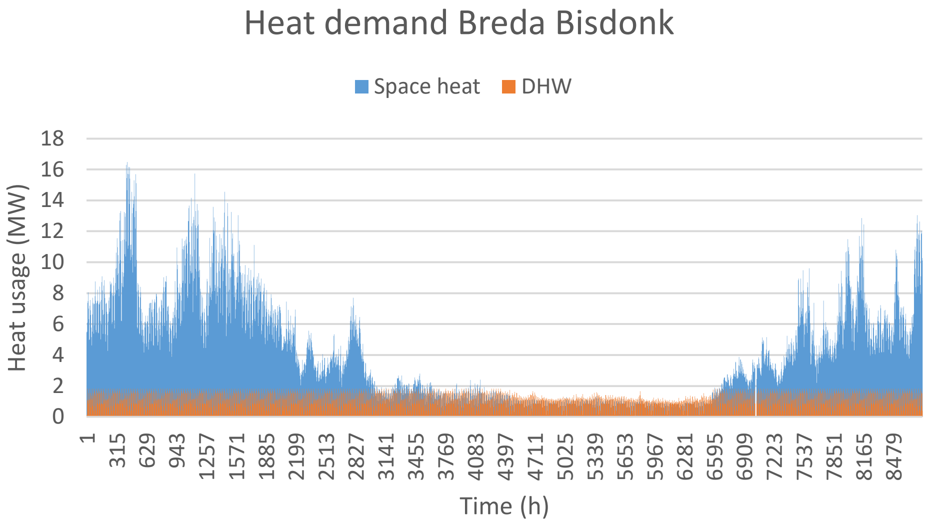


Figure 4-5 Heat demand per hour in Breda Biesdonk. Adapted from (Verhaegh, 2018).

4.4 Adjustment of temperature and heat demand

Figure 4-3 shows that the outside temperature in 2016 was not very low in the winter. The number of HDD are 2545, which is below average (average more than 2700). Since this thesis is a reliable LTDH design, the current heat demand will be transformed into a 'colder year'.

The most dominant factor leading to an increase in heat demand is the difference between the outside and inside temperature. Therefore, the transformation of the current heat demand is based on the HDD. The temperature difference only needs to be increased in the winter, because peak moments occur then. Since 2016 was a relatively warm year, the data has been modified to bring the lowest outside temperature to – 10 °C. This is the common design condition for heating systems. It is assumed and simulated when there is more than 15 HDD at an hour (so the outside temperature is colder than 3 °C), the outside temperature will drop with 5 °C and therefore heat demand will increase. The increase of the heat demand is calculated by equations 1, 2, and 3.

$$\dot{Q}_{old} = U * A * (T_{inside}{}^{1} - T_{outside}) \tag{1}$$

$$if\ HDD > 15, \qquad \dot{Q}_{new} = U * A * ((T_{inside} - T_{outside}) + 5) \tag{2}$$

Therefore, when the HDD is more than 15, the new heat demand can be calculated as following.

$$if\ HDD > 15, \qquad \dot{Q}_{new} = \frac{\dot{Q}_{old}}{(T_{inside} - T_{outside})} * ((T_{inside} - T_{outside}) + 5) \tag{3}$$

The corresponding temperatures and heat demand for the coldest week are presented in Figure 4-6 and Figure 4-7.

---

[1] The inside temperature is set at 18 °C.

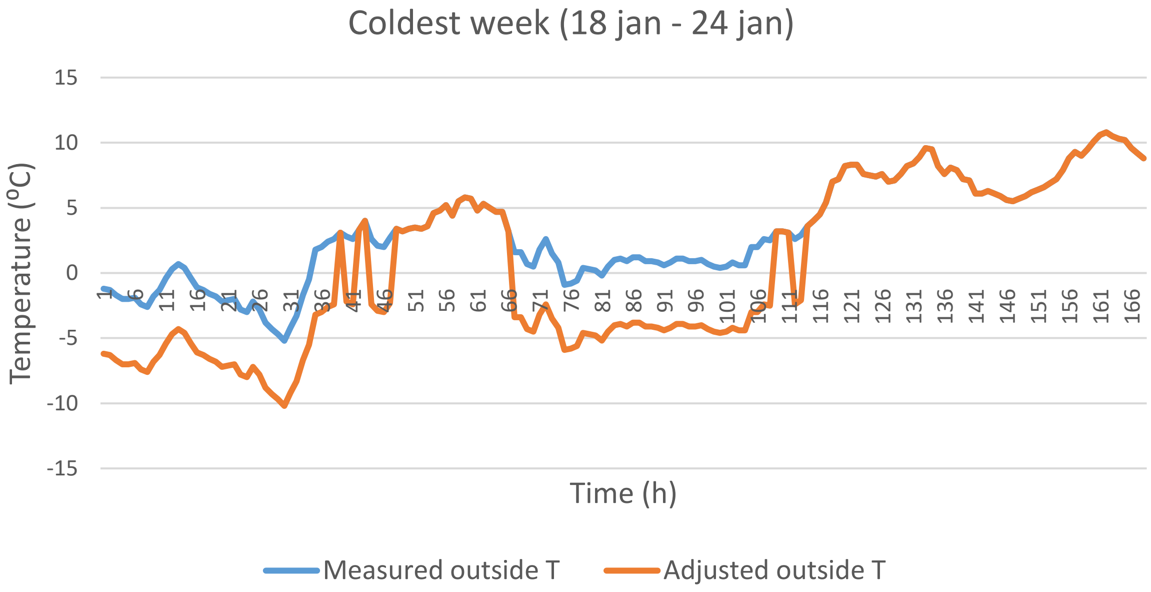


Figure 4-6 Outside temperature and adjusted outside temperature in Hoek van Holland 2016 during a cold week. The blue line is the measured outside temperature, the red line is the converted temperature.

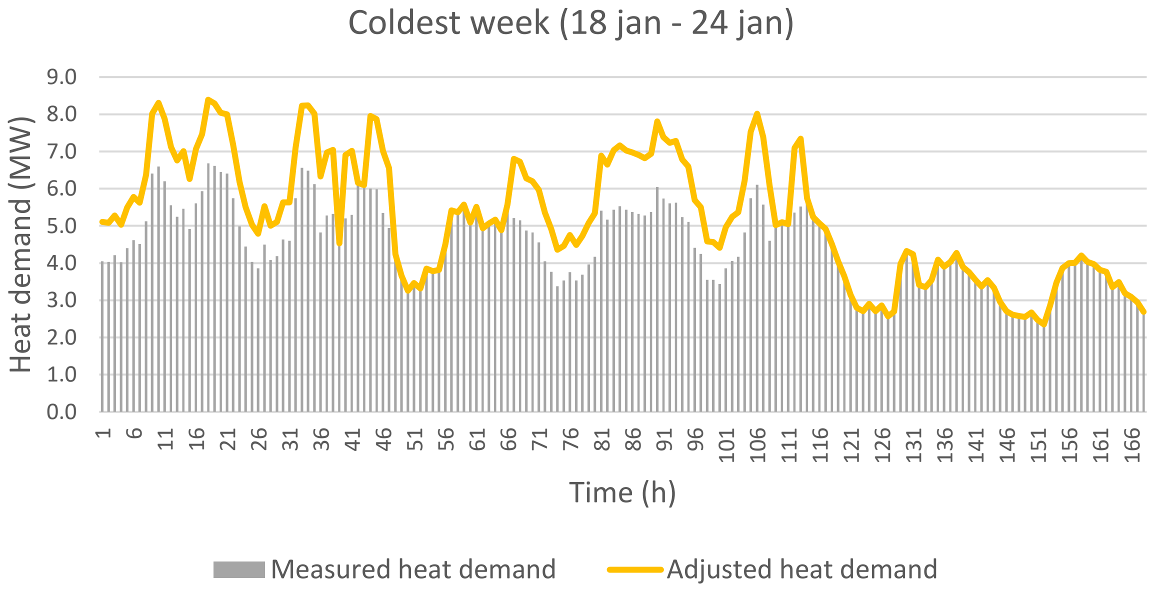


Figure 4-7 Measured heat demand and adjusted heat demand in Breda Biesdonk 2016 during a cold week. The grey bars are the measured heat demand, the yellow line is the converted heat demand.

5. Design of LTDH concepts and heating strategies

5.1 Introduction

The aim of this chapter is to design 5 LTDH concepts, which can be compared with each other, and to develop 3 heating strategies. One of these concepts and heating strategies becomes the answer to the main research question. The following section presents how the LTDH concepts are designed and the heating strategies are set up. Each LTDH concept and heating strategy is explained in the coming sections.

5.2 LTDH design method and function solutions

To create concepts for a LTDH, the method of Ullman is used (Ullman, 1992). The purpose of this method is to create multiple products, or designs, based on established functions. The problem or assignment, for which a design is devised, is divided into functions. After this, the designer looks at how these functions are interrelated. This is done by placing the functions in a 'Function Tree'. The Function Tree has the aim to show the interdependence of the functions. After the function tree is set up, different solutions are devised for each function to see how a specific function can be executed. These solutions are placed in a morphological overview. This presents which solutions are available for a specific function. Finally, combinations are made by choosing one solution per function. This way, multiple concepts can be designed.

The LTDH, which will be designed for this thesis, can be divided into 7 main functions. These are connected to each other in the function tree in Figure 5-1. The solutions per functions are based on the findings from Chapter 2. These solutions are presented in the morphological overview of Table 5-1. These solutions are used to design 7 LTDH.

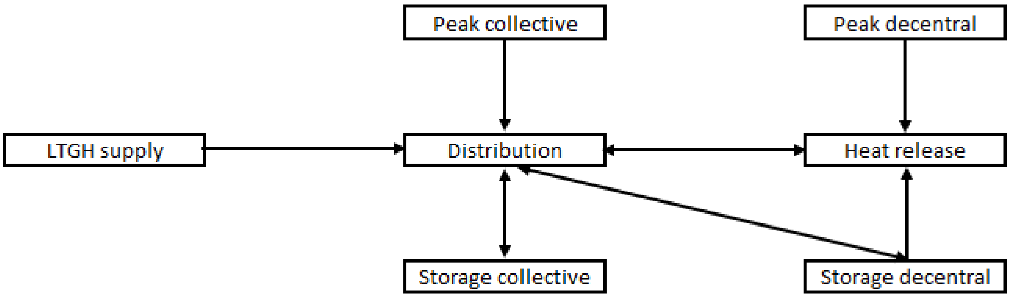


Figure 5-1 Function tree of an LTDH network.

According to Figure 5-1, the first function is the LTGH supply temperature. The LTGH transfers the heat, via the function 'Distribution', to the heat release (the houses). The heat release function is split into space heat and DHW use. In addition to these 3 functions, there are 4 other functions. These are subdivided as storage methods and peak technologies. These are available at both DH level (collective) and at home level (decentralized). The next page explains every function and solution.

Table 5-1 Morphological overview of options in an LTDH with LTGH as main source.

Function	Option 1	Option 2	Option 3
LTGH supply temperature	70 °C	50 °C	30 °C
Storage collective	ATES		
Storage decentral	Water tank		
Peak collective	Biomass boiler		
Peak decentral	Electrical heaters	Water-to-water heat pumps	
Space heat release	Current radiators		
DHW	Heat exchanger	Electrical boiler	Booster heat pump
Distribution	Twin pipes	Single pipes	

LTGH supply temperature

The supply temperature in the network depends on the central heat pump at the LTGH. The central heat pump increases the temperature of the DH from 30 °C, which is available from the LTGH, to 70 or 50 °C. To increase the DH water to a higher supply temperature, the OPEX and CAPEX will increase, but a lower flow can provide more or less the same amount of heat. Next to these supply temperatures, a supply without a central heat pump is possible. The supply temperature in the network is than 30 °C. At the homes, the temperature needs to be raised for the heating purposes. Therefore a water-to-water heat pump is needed at the home, which is described under the function 'Peak decentral'.

These supply temperatures are chosen, as these temperatures can be generated by the LTGH source. 80 °C supply temperature is too high and 40 °C is too low, with a central heat pump at the LTGH. Moreover, DHW is an interesting factor for these regimes. With a 50 °C supply temperature, a boost of temperature is needed to prevent legionella growth. Still, the supply efficiency through the district is higher than higher supply temperature.

In general, the return temperature for the supply temperatures with the use of central heat pumps are 32 °C. Existing radiators can create a return temperature of 30 °C, but the return water will be increased by 2 °C due to losses in the supply set at home level (Østergaard, 2018). If the ATES provides cold water to the return pipes, the temperature will increase as well. This is explained in section 6.4.2.

The return temperature for the supply temperature without central heat pumps is 18 °C. This can be achieved by the decentral heat pumps (van Vliet et al., 2016). The calculations of the related COP values are given in section 6.6.1.

Storage collective

An ATES is currently the most practical solution for a collective storage system, according to (Bloemendal, 2018; Infante Ferreira, 2018). The capacity of the ATES depends on the supply temperature of the LTGH. The calculations of this are given in section 6.4.2.

Storage decentral

The most practical solution for a decentral storage system is currently a water tank, according to (Alva et al., 2018; Infante Ferreira, 2018). This can help a home to cover the peak moments on daily basis. Figure 5-2 presents how the water tank can be charged from the supply heat during less heat demands and how it can provide heat during high heat demands.

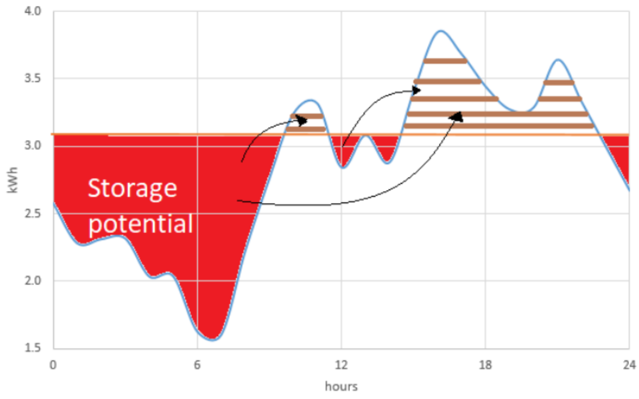


Figure 5-2 Daily heat demand with a base load. When the base load is higher than the demand, heat can be stored. When the base load is lower than the demand, the stored heat can be supplied.

Every single home gets an own water tank and a few water tanks are installed in the technical room of a high-rise building. The calculations of the technical specifications of the water tank are given in section 6.4.3.

Peak collective
To raise the heat supply at LTDH level for the peak moments, a biomass boiler is installed. This will increase temperature and mass flow during the peak moments. The supplied power by the biomass boiler depends on how large the peak moments are. The calculations of the technical specifications of the biomass boiler are given in section 6.4.5.

Peak decentral
The choice between the 2 solutions, electrical heaters or a water-to-water heat pump, depends on the LTGH.
If the LTGH uses a central heat pump, electrical heaters will be used as peak techniques. In addition to the radiators, these will heat the room with more power, so that the desired temperature in the room will be reached faster.
If the LTGH does not use a central heat pump, then every single living has a water-to-water heat pump. The temperature of the supply water in the network will be increased for the use of space heating and DHW.

The calculations of the technical specifications of the electrical heaters and of the water-to-water heat pumps are given in sections 6.6.1 and 6.6.4.

Space heat
According to section 2.5.4, the existing radiators can remain in a home. Therefore, this is the only solution to look at for this thesis. Replacing the radiators for special low temperature radiators or floor heating will cost too much effort and money.

DHW
The supply of DHW depends on the supply temperature in the DH. If the supply temperature is 60 ^{o}C or higher, a HEX in the house is sufficient. Otherwise a booster pump must be used to increase the supply temperature. Another option is the use of an electric boiler. The boiler is not connected to the DH.

Distribution
The distribution mostly contains the pipes. The variation in pipes are the diameters and type of pipe. The way how the pipe diameters are calculated is given section 6.3.2 and the results of the calculations are given in Chapter 8.
It is expected that in the future plastic and twin pipes will be utilized more often, that is why the pipe material will be PB and type of pipe will be twin pipes.

5.3 LTDH concepts

The following subsections presents 5 LTDH concepts which are designed with the morphological overview. These concepts vary in supplying the peak, storage methods, and the temperatures in the network. In addition, one heat concept is made which serves as a point of reference for the examination of the other 5 concepts in part 3.

5.3.1 Concepts 1a and 1b: Collective peak supply

Figure 5-3 presents a schematic of the LTDH layout with the corresponding main techniques. These concepts supply the peak at DH level (collective). Next to the LTGH source, an ATES and a biomass boiler will be installed. The ATES stores the production of the LTGH source in the summer and supplies heat to the system in the winter. The biomass boiler supplies the remaining peak heat.

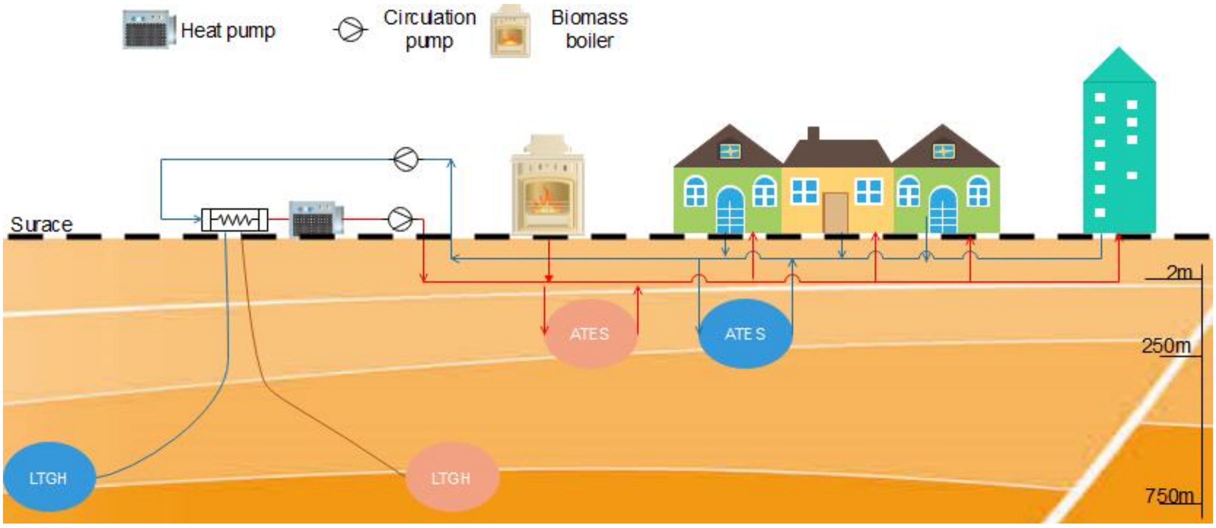


Figure 5-3 Schematic view of LTDH with peak heat supply at collective level.

For this type of LTDH, 2 concepts are devised that vary in supply temperature of the LTGH. The supply temperature in concept 1a is 70 ^{o}C and in concept 1b 50 ^{o}C, which means concept 1a uses a HEX and concept 1b uses a BHP for supplying DHW.

Table 5-2 shows the chosen options, from the morphological overview of Table 5-1, for these concepts. The corresponding technical specifications are given in Chapter 7.

Table 5-2 Function solutions for the designs of concept 1a and 1b.

Function	LTGH supply temperature	Storage collective	Storage decentral	Peak collective	Peak decentral	DHW supply
Concept 1a	70 ^{o}C	ATES	-	Biomass boiler	-	HEX
Concept 1b	50 ^{o}C	ATES	-	Biomass boiler	-	Booster heat pump

Figure 5-4 represents a Piping and instrumentation diagram (P&ID) of concept 1a with the maximum and minimum temperatures which can be present in the pipes. For concept 1b, the temperatures at the supply side is 20 ^{o}C lower.

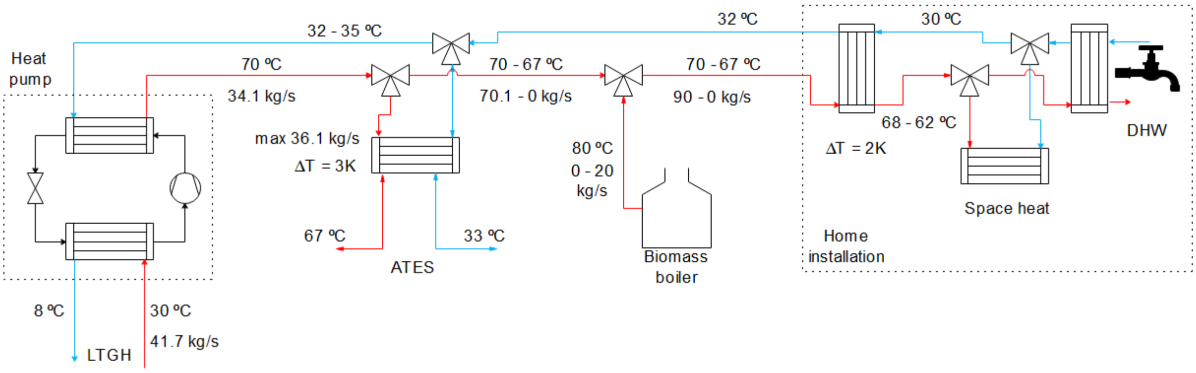


Figure 5-4 P&ID of the first LTDH concepts. The red lines are the supply flows and the blue lines are the return flows. The temperatures and flows are calculated in Appendix B.

5.3.2 Concepts 2a and 2b: Decentral peak supply

Figure 5-5 presents a schematic of the LTDH layout with the corresponding main techniques. These concepts supply the peak at home level (decentral). Next to the LTGH source, an ATES, a water tank in the homes, and an electric heater will be installed. The ATES stores the production of the LTGH source in the summer and supplies heat to the system in the winter. The water tank stores heat during the day when the heat demand in a home is low and provides heat during the day when the heat demand in a building is high. The electrical heaters in the homes supplies the remaining peak heat.

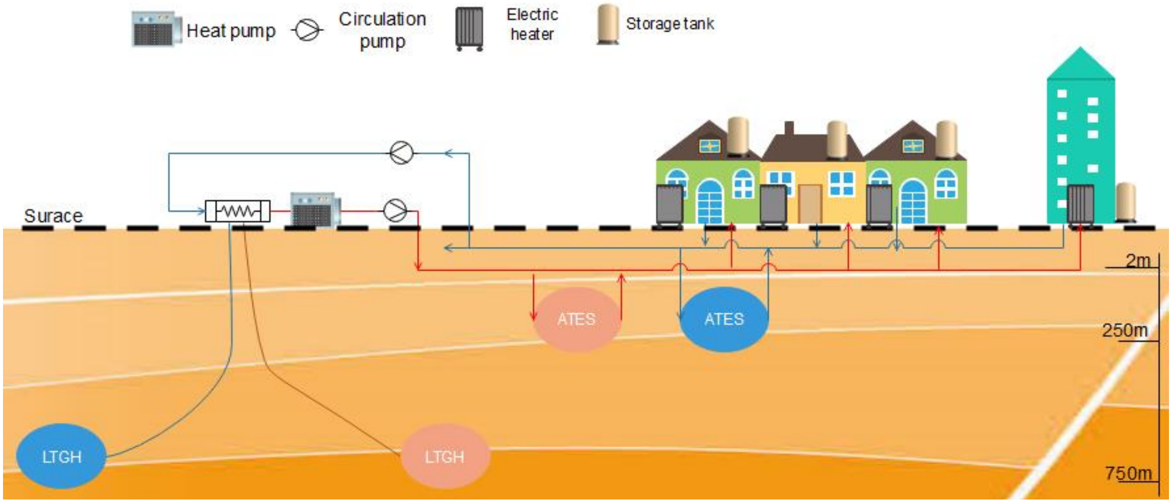


Figure 5-5 Schematic view of LTDH with peak heat supply at decentral level.

For this type of LTDH, 2 concepts are devised that vary in supply temperature of the LTGH. The supply temperature in concept 1a is 70 ^{0}C and in concept 1b 50 ^{0}C, which means concept 1a uses a HEX and concept 1b uses a BHP for supplying DHW. Table 5-3 shows the chosen options, from the morphological overview of Table 5-1, for this concept. The corresponding technical specifications are given in Chapter 7.

Table 5-3 Function solutions for the designs of concept 2a and 2b.

Function	LTGH supply temperature	Storage collective	Storage decentral	Peak collective	Peak decentral	DHW supply
Concept 2a	70 ^{0}C	ATES	Water tank	-	Electrical heater	HEX
Concept 2b	50 ^{0}C	ATES	Water tank	-	Electrical heater	Booster heat pump

Figure 5-6 represents a P&ID of concept 2a with the maximum and minimum temperatures which can be present in the pipes. For concept 2b, the temperatures at the supply side is 20 ^{0}C lower.

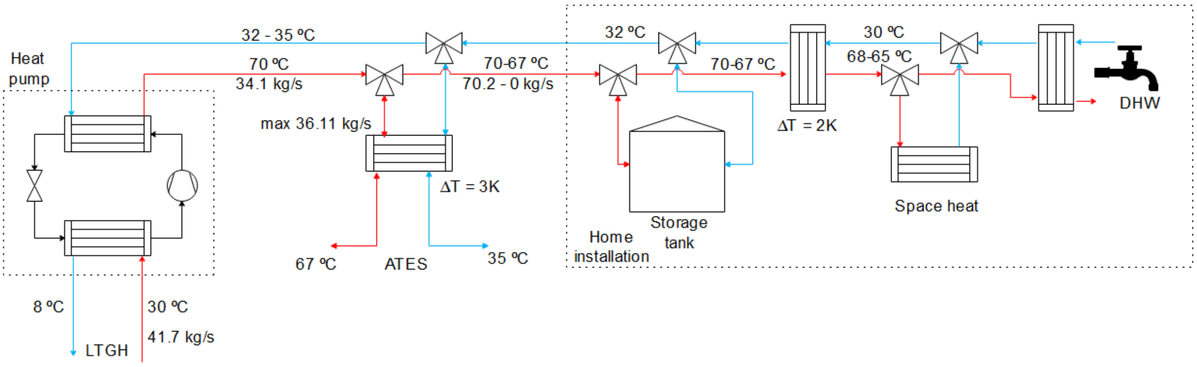


Figure 5-6 P&ID of the second LTDH concepts. The red lines are the supply flows and the blue lines are the return flows. The temperatures and flows are calculated in Appendix B.

5.3.3 Concept 3: Decentralized water-to-water heat pumps

Figure 5-7 presents a schematic of the LTDH layout with the corresponding main techniques. This concept does not use a central heat pump, but a water-to-water heat pump for every home. This heat pump uses the water supplied by the LTGH source. The heat pump can be used to supply both the peak demands and the usual heat demands. There are no storage systems and peak techniques required for this LTDH concept.

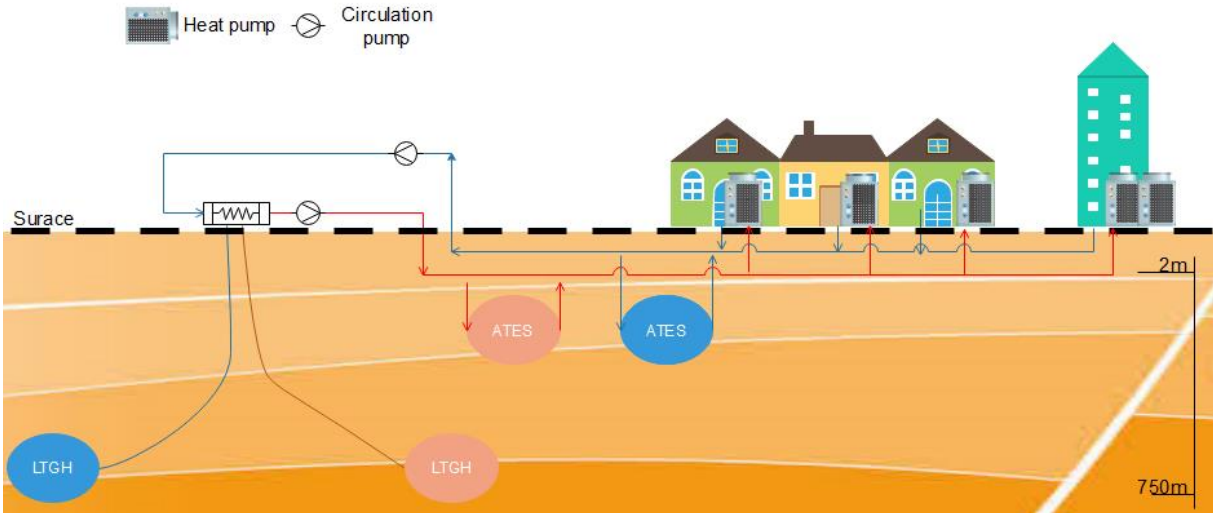


Figure 5-7 Schematic view of LTDH without central heat pump and decentralized heat pumps.

Table 5-4 shows the chosen options, from the morphological overview of Table 5-1, for this concept. The corresponding technical specifications are given in Chapter 7.

Table 5-4 Function solutions for the design of concept 3.

Function	**LTGH supply temperature**	**Storage collective**	**Storage decentral**	**Peak collective**	**Peak decentral**	**DHW supply**
Concept 3	30 ºC	ATES	-	-	Heat pump	Heat pump

Figure 5-8 represents a P&ID of concept 3 with the maximum and minimum temperatures which can be present in the pipes.

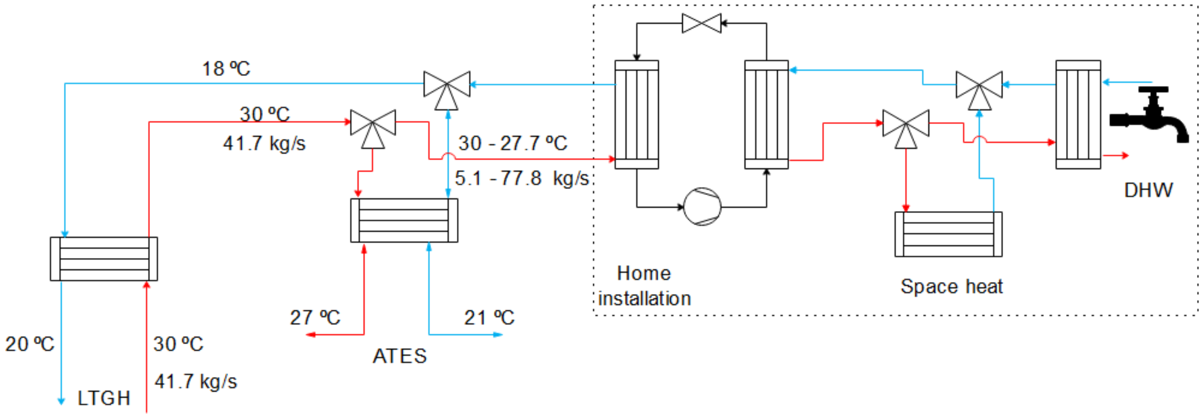


Figure 5-8 P&ID of the third LTDH concept. The red lines are the supply flows and the blue lines are the return flows.

5.3.4 Reference concept: all-electric

The reference concept is based on an alternative way to heat homes in a district. Instead of installing a DH, every home is individually electrically heated. This is also called ‘All-electric’ (Koenders et al., 2018).

The reference concept consist of air-heat pumps for every single household for space heating. DHW is prepared by an electrical boiler. The COP values for the heat pumps are provided in section 6.6.1. The electrical boiler has an efficiency of 95%, a supply power of 3 kW, and contains 200 liters (CE Delft, 2016).

5.3.5 Summary all heat concepts

Table 5-5 presents a brief overview of the discussed heat networks with the corresponding solutions per function and the corresponding technical specifications.

Table 5-5 Overview of the LTDH concepts and related function solutions.

Functions / specs	Concept 1a Peak collective	Concept 1b Peak collective	Concept 2a Peak decentralized	Concept 2b Peak decentralized	Concept 3 Decentralized heat pumps	Reference concept
LTGH supply	70 °C	50 °C	70 °C	50 °C	30 °C	-
Storage collective	ATES	ATES	ATES	ATES	ATES	-
Storage decentral	-	-	Water tank	Water tank	-	-
Peak collective	Biomass boiler	Biomass boiler	-	-	-	-
Peak decentral	-	-	Electrical heater	Electrical heater	Heat pump	Air heat pump
DHW supply	HEX	Booster pump	HEX	Booster pump	Heat pump	Electrical boiler

5.4 Heating strategies

The design of the LTDH depends on the heat demand. Heat demand is the first input to calculate the network specifications. Heat demand depends, as discussed in section 2.4, on the typology of the building and if DSM is applied. 3 combinations of these strategies are considered and used as input for the calculation model for this thesis. This section presents these 3 heat demand strategies.

5.4.1 Heating strategy 1: Current heat demand

This heat demand scenario does not influence the heating behavior of the residents and does not adjust the skin of the home. This has as advantage for residents that the investment costs of LTDH is lower and their heating behavior does not need to be adjusted. The disadvantage of this heating scenario are the high heat demands and massive peak moments.
The heat demand, as explained in section 4.4, is used as input for the numerical calculation models.

5.4.2 Heating strategy 2: Applying peak shaving strategy

As described in section 2.4.3, peak shaving can decrease the amplitude of the heat demand. However, this means that for district heating the total used heat will increase.

This thesis makes use of a heavy form of peak shaving, to see if peak shaving has impact on the design of the network. The difference between the average outside temperature and the set inside temperature, and the heat demand are calculated for a day. When the daily difference between the outside temperature and inside temperature is more than 12, the inside temperature will increase with 2 °C, therefore, heat demand will increase. The increase of the heat demand is calculated as follows.

$$\bar{\dot{Q}}_{current} = U * A * (T_{inside}{}^{2} - \bar{T}_{outside}) \tag{4}$$

$$if\ \overline{HDD} > 12, \qquad \bar{\dot{Q}}_{DSM_{i=24}} = U * A * \left((\bar{T}_{inside} - \bar{T}_{outside}) + 2\right) \tag{5}$$

Therefore, when the HDD is more than 12, the new heat demand can be calculated as follows.

$$if\ \overline{HDD} > 12, \qquad \dot{Q}_{DSM} = \frac{\bar{\dot{Q}}_{old}}{\bar{T}_{inside} - \bar{T}_{outside}} * ((\bar{T}_{inside} - \bar{T}_{outside}) + 2) \tag{6}$$

This form of peak shaving can be realized when each home has a smart thermostat which can regulate the heat demand. This is a challenging form of peak shaving. However, this form has the purpose to see if peak shaving has effects on the KPIs.

5.4.3 Heating strategy 3: Applying insulation measures

Upgrading to a better Energy Performance Coefficient (EPC) label gives a reduction in space heat demand. The demand for DHW is not regulated.

According to (Verhaegh, 2018), improving Dutch apartments from Dutch Energy label D to B (which are related to the EPC label) gives a reduction of 20% in yearly heat demand and improving Dutch single livings from Dutch Energy Label C to B gives a reduction of 8% in yearly heat demand. Together, the total space heat demand reduces with 15.2% per year.

The reduction in space heat differs per hour, with better insulation. However, it is unclear how much this is on an hourly basis. Therefore, this thesis assumes that the space heat demand from the case study reduces with 15.2 % for every hour. The heat demand is used as input for the numerical calculation models, is calculated by equation 7.

$$\dot{Q}_{insulation} = \frac{\dot{Q}_{old\ space\ heat}}{1.152} + \dot{Q}_{DHW} \tag{7}$$

---

[2] The inside temperature is set at 18 °C.

6. Numerical models

6.1 Introduction

Figure 6-1 presents a block scheme for the calculation models. The input, for the calculation models, consist of the heat demand and the type of network system. An energy balance can be deduced with that input. With the energy balance, the KPIs from section 3.2 can be calculated.
The simulation tool used for the energy balance is Matlab and the script can be found in Appendix B. The other models have been created in Microsoft Excel and the sheets can be found in Appendix D, E, and F.

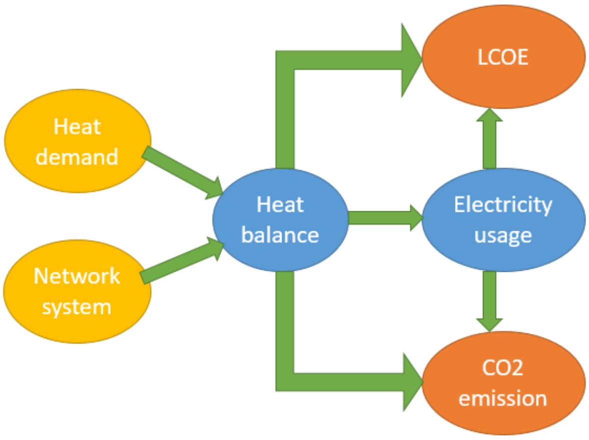


Figure 6-1 Scheme of calculation models. The yellow circles are the input, blue presents necessary calculated values and the KPIs are in red.

The previous three chapters discussed the heat supply concepts and heat demand strategies, which can be compared for the case study. The KPIs CO_2 emission, electricity usage and costs are KPIs that can be calculated. The calculation models, which are used for these KPIs, are explained in this chapter. This is divided into the calculations of the network layout, energy balance, electricity usage, CO_2 emission, and LCOE analysis.

This chapter first shows how the energy balance is set up for a whole year, with the aim to determine the number of homes that can be connected to an LTDH concept with a certain heat demand strategy. After that, it is explained how the network is designed. That section explains how the network layout looks like with the corresponding equations for the determination of the pipe diameters and required circulation pump power. Section 6.4 describes how general parameters are calculated for the techniques in an LTDH. Section 6.5 presents how the hourly energy balance is calculated in a Matlab model. These results are required to examine the KPIs, as given in Figure 6-1. The method for the examination of the KPIs is described in sections 6.5, 6.6, and 6.7. The last section shows how the end results will be communicated.

6.2 Yearly energy balance

Before the numerical models will be made, a conceptual yearly energy balance is set up. The yearly energy balance has the aim to determine what the heat demand can be for a certain heat supply by the LTGH source. It is an estimation to determine the number of homes that can be connected to the LTDH. The heat demand throughout the year needs to be supplied, with the additional heat losses, by the LTGH source and the peak heat sources. The yearly energy balance is given in equation 8.

$$Q_{demand} + Q_{loss} = Q_{LTGH} + Q_{peak\ supply} \tag{8}$$

The heat supply by LTGH depends on the supply temperature in the network, which is explained in section 6.4.1. The various supply temperatures produce different amount of powers.
If the LTGH can generate a greater amount of energy in a year than the demand, the number of homes in the layout of the district can be increased. This is described in section 6.3.1. The calculation of the power production and of the heat losses is explained in section 6.4.1 and 6.4.4. The number of homes in relation to the supply temperatures and heat production of LTGH is given in section 8.2.

The peak supply is required when an extreme increase in heat demand occurs. This happens, for instance when the outside temperature is extremely low. For the yearly energy balance, the first estimation of the amount of energy which needs to be supplied by the peak source, is 0.5%.

The heat losses depend on the heat demand and heat production. For heating strategies 1 and 2, the current heat demand and applying peak shaving, LTGH can supply heat to 2475 homes. The heat demand from section 4.4 increases with a factor of 1.5. For heating strategy 3, applying insulation to the current homes, LTGH can supply heat to 2900 homes, therefore the heat demand from section 4.4 increases with a factor of 1.75.

Total heat loss

The losses at the seasonal storage component, the pipes, and the HEX are simulated. It is assumed that the daily storage tank is well insulated and does not lose heat. Furthermore, the model assumes that there are no heat losses at other components in the network, because these will make the model too complex and it is expected that these losses are marginal. The yearly heat loss is as follows.

$$Q_{loss} = Q_{loss\ HEX} + Q_{loss\ pipes} + Q_{loss\ ATES} \tag{9}$$

The answer to the calculations of this section is given in Chapter 7.

Heat loss by pipes

The heat loss of a pipe is often given by the supplier in Watt per meter. This will be used for the calculation of the energy balance. Heat losses are presented in Table 6-1.

Table 6-1 Overview of the heat loss per meter per supply temperature. Adapted from (Thermaflex, 2017)

DN	160	125	110	90	75	63	50	40	32	25
Heat loss 70 supply (W/m)	18.1	17.0	14.0	13.3	15.3	14.7	13.7	10.3	11.5	8.8
Heat loss 50 supply (W/m)	13.1	12.6	10.4	9.9	11.3	11.2	10.6	8.0	8.9	7.0
Heat loss 30 supply (W/m)	10.2	8.3	6.9	6.5	7.4	4.4	4.4	3.4	3.8	3.0

The yearly heat loss by the network pipes is calculated with the following equation.

$$Q_{loss-pipe} = \dot{Q}_{loss\ pipes} * 8760h \tag{10}$$

The heat loss of the pipes depends on the diameter of the pipes. However, for the conceptual yearly balance, it is unknown what the pipe diameters are. Therefore it is assumed, for the year balance, that the heat loss by the network pipes is 0.5 MW, 0.3 MW and 0.1 MW, for the supply temperatures 70 ^{o}C, 50 ^{o}C, and 30 ^{o}C. Table 6-1 will be used in section 6.4.4 and Chapter 8.

Heat loss by HEX

Various HEXs are presented in the LTDHs. These are located at the ATES and in the supply set, and cause temperature drops. According to (Infante Ferreira, 2018; Pothof, 2018), the temperature drop at the HEX from the ATES is 3 ^oC and at the supply set is 2 ^oC. The supplied temperatures can be calculated with the following equations.

$$T_{store\ ATES} = T_{LTGH} - 3\ °C \tag{11}$$

$$T_{heat\ from\ ATES} = T_{store\ ATES} - 3\ °C \tag{12}$$

$$T_{in\ home} = T_{supply\ T} - 2\ °C \tag{13}$$

Because the supplied temperature in the homes is lower than the produced temperature at the LTGH source, the supplied heat at the homes is lower than the produced heat. For the estimation of the heat loss at the HEX of the ATES, the following formula can be applied.

$$Q_{loss\ hexATES} = U * A_{surface} * (\bar{T}_{ATES} - \bar{T}_{outside}) * 8760h \tag{14}$$

It is assumed that the HEX only loss heat at the surface and is well insulated. Therefore is assumed that the HEX has an insulation thickness of 18 mm, which corresponds to a heat transfer coefficient of 1.5 W/m^{2}K (Infante Ferreira, 2018). A common plate HEX for ATES have a plate size of 1.6 x 0.8 x 2.0 meters. The outside layer is 12.2 m^2. The average outside temperature is assumed to be 10 ^oC for a year. The average temperature in the ATES depends on the chosen LTDH concept.

For the estimation of the heat loss at the HEX of the supply set, the following formula can be applied.

$$Q_{loss\ HEXsupply\ set} = U * A_{surface} * \Delta T_{drop} * n_{homes} * 8760h \tag{15}$$

The same dimensions for the HEX in the ATES applies for the supply set. The temperature drop is, as said before, 2 ^oC.

$$\dot{m}_{house} = \frac{Q_{house}}{cp * (T_{supply\ in\ home} - T_{return\ in\ home})} * \frac{1}{8760} \tag{16}$$

Equation 16 is required to estimate the mass flow for the HEX at the supply set.

Heat loss in the ATES

The capacity loss of the ATES depends on the displacement by ambient groundwater and by dispersion and conduction, as explained in section 2.5.3. The energy balance takes into account a constant heat loss, because these losses make the numerical model too complex and it is expected that these losses do not influence the answer to the research question. The recovery storage efficiency at the end of the summer compared to at the beginning, depends on the temperature storage and is given in Table 6-2. This table is based on (de Wit-Blok, 2017).

Table 6-2 Recovery efficiency of an ATES with the related storage temperatures. Adapted from (de Wit-Blok, 2017).

Temperature storage [^oC]	67	47	27
Recovery efficiency [%]	65	75	85

Figure 6-2 shows an example of heat demand and heat supply by LTGH. The areas B_1 and B_2 show the amount of heat which is required from the ATES to meet the heat demand. The areas A_1, A_2, and A_3 show the amount of heat which needs to be stored. With the recovery efficiencies of Table 6-2, the capacity loss of the ATES can be calculated as follows.

$$Q_{loss\ ATES} = \left(1 - \eta_{recovery}\right) * (B_1 + B_2) \tag{17}$$

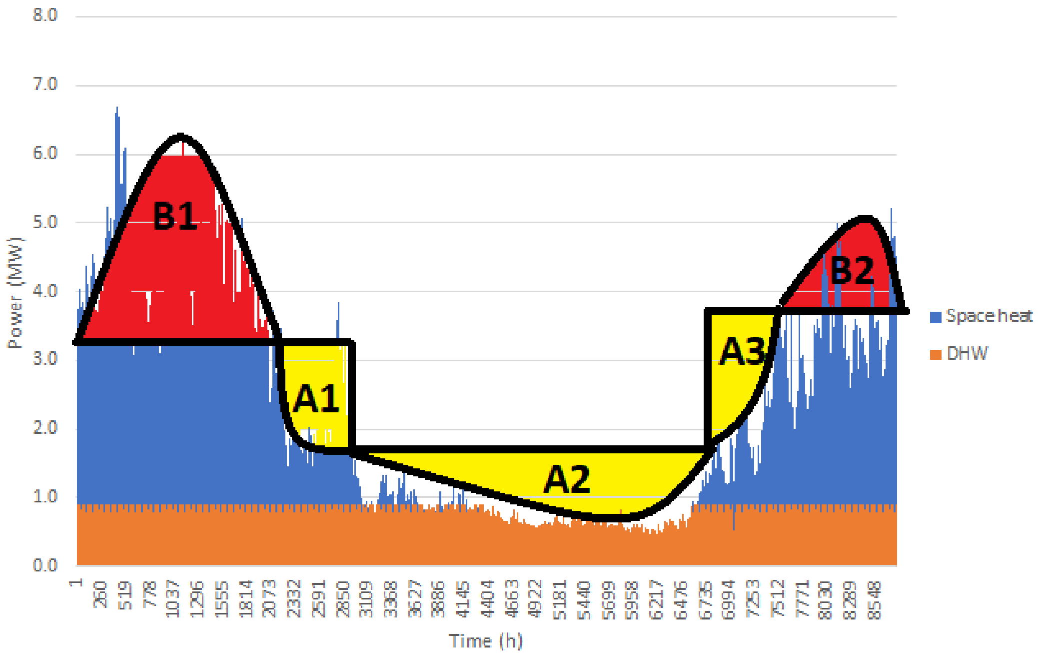


Figure 6-2 Example of a yearly heat demand with a geothermal source as heat supply. The yellow parts can store heat for the red areas, when there is more heat available than demand.

B_1 and B_2 depend on the heat demand and heat supply. For a first estimation, it is assumed that the heat demand for the first two heat strategies, as described in section 5.4, should be used to heat 2,475 homes and the third heat strategy should be used to heat 2,900 homes. With the data from section 4.4, it is possible to make a heat demand curve like in Figure 6-2. The heat supply curve is simply made according to the equations of section 6.4.1.

With the heat demand curve and heat supply curve it is possible to determine the areas B_1 and B_2 and so the estimate the recovery efficiency of the ATES.

All mentioned values in this section can be found in Table 6-3

Table 6-3 Parameters used in yearly energy balance.

Parameters	Value
Peak technology production percentage of LTDH production (%)	0.5
Heat loss in network pipes by 70 °C supply temperature (MW)	0.5
Heat loss in network pipes by 50 °C supply temperature (MW)	0.3
Heat loss in network pipes by 30 °C supply temperature (MW)	0.1
Temperature drop at HEX ATES (°C)	3
Temperature drop at HEX supply set (°C)	2
Heat transfer coefficient of HEX [W/m²K]	1.5
Surface of the upper plate of the HAX [m²]	12.2
Average outside temperature (°C)	10

6.3 Network design

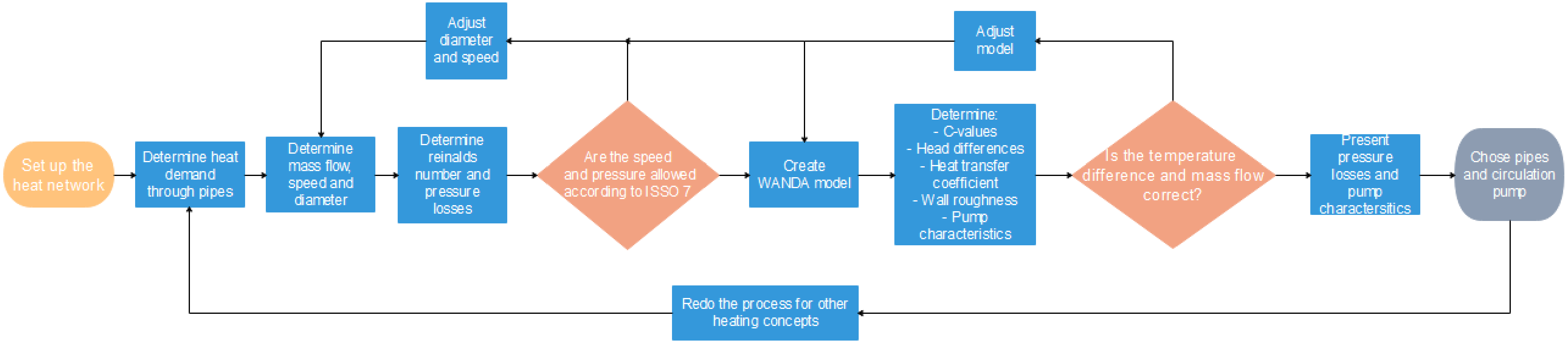


Figure 6-3 Calculation flow chart for the network design.

Calculation flow chart.
The heat transported through the pipes depends on the number of homes in a street. The heat demand is calculated for the worst case scenario. It is possible to determine a first diameter result. If the speed, pressure losses, and diameter are exceeded, adjustments have to be done. If the diameter for the pipes are conform to the ISSO standard, a WANDA model can be made.

To calculate the correct pump characteristics in WANDA, there are certain values that need to be determined. The first results of WANDA can be checked with the first calculated values. If the temperatures or mass flow are incorrect, adjustments need to be made to the WANDA model and to the first calculations. As soon as the results are correct, they can be presented and eventually the pipes and pumps can be selected.

The whole process is repeated for the other heating concepts as described in section 5.3.

WANDA
WANDA is a software which can design and calculate pipelines for flow distribution. The program is developed by Deltares. The heating network in Figure 6-4 is placed in WANDA to calculate and present several losses in the system and to calculate the correct pump characteristics.

Thermaflex
Thermaflex is a supplier for plastic pipes and insulation systems for district heating. They are participants in the WINST project, as mentioned in section 1.1, and can provide specifications about the pipes.

Grundfoss
Grundfoss develops circulation pumps. They have a wide range of pumps and are easy to access for selecting the right circulation pump. The information of Grundfoss will be used to select the circulation pumps.

6.3.1 Network lay-out

The type of network material and size is determined by the heat demand per pipe line. First a network is created. This is based on (Frederiksen & Werner, 2013). The LTGH is based in the center of the district, since the distances between the heat supply plant and each substation are rather short and therefore less heat is lost. For the case in Breda Biesdonk, the LTGH is located in a small park. The network is divided into 4 groups; A in north-west, B in north-east, C in south-west, and D in south-east. This is shown in Figure 6-4. The black lines are the pipes, the white squares are transition points and the white lines show where the pipe is cut off. Pipe numbers 1 are large and decrease step by step to pipe numbers 4.

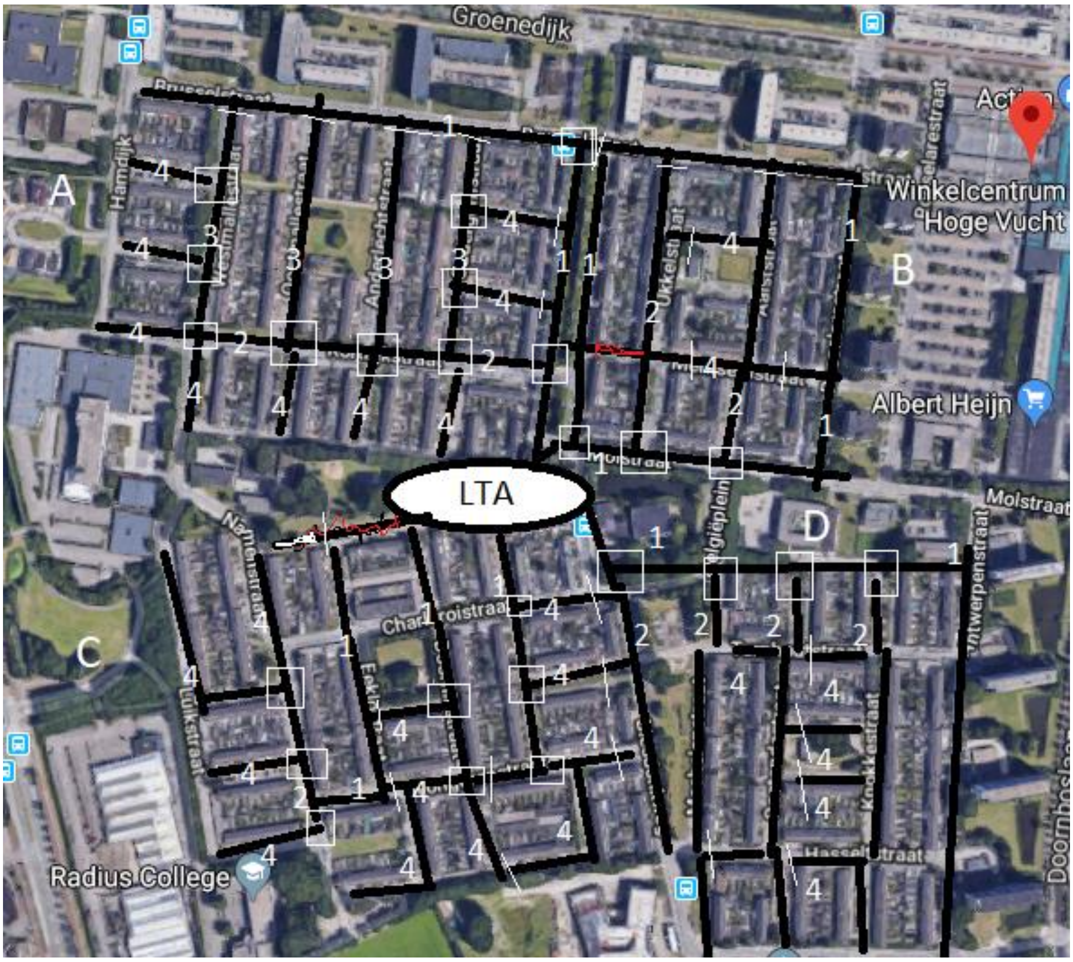


Figure 6-4 Layout of LTDH in Breda Biesdonk.

The number of homes per group in the district and the year heat demand of 2016 is given in Table 6-4.

Table 6-4 Number of homes divided over the four groups in the district.

Type of living	Group A	Group B	Group C	Group D
High-rise buildings	3	2	0	4
Apartments	360	240	0	320
Single livings	150	200	300	100
Heat demand in 2016 according to (Verhaegh, 2018)[3]	5,355	6,358	3,293	4,200

---

[3] The heat usage for the whole year was 18,264 MWh in 2016. In Table 7-1 is the heat demand into a colder year according section 4.4, the usage is 19,206 MWh.

According to (Koenders et al., 2018), an LTGH can supply heat for 2500 – 4500 homes. To make the case-study more realistic for an LTGH, the number of homes in the district is adjusted with the amount of heat an LTGH can supply. Because the heat demand is divided over 4 groups, the heat demand can also be increased by using these groups. Depending on the heat output of the LTGH and the heat demand strategy, the number of groups that must be added can be calculated. The network layouts for the LTDH concepts is given in section 8.2.

6.3.2 Pipe diameters

The pipe diameters are determined by the heat demand of the homes. This is calculated using the following equation.

$$D = \sqrt{\frac{\dot{Q} * 4}{\rho * C_p * \Delta T * \pi * v}} \tag{18}$$

The equation above shows the first estimation of the pipe diameter. The pipe diameters are standardized according to DN numbers. Table 6-5 presents DN numbers from Thermaflex and the related inside diameter, outside diameter, and type of pipe.

Table 6-5 Overview of pipe diameters. Adapted from (Thermaflex, 2017).

DN	160	125	110	90	75	63	50	40	32	25
Inner diameter (mm)	138	102	90	73.6	61.4	51.4	40.8	32.6	26	14.4
Outer diameter (mm)	225	200	200	160	125	200	160	160	125	125
Pipe type	Single	Single	Single	Single	Single	Twin	Twin	Twin	Twin	Twin

The diameter depends also on 2 parameters. The maximum speed in the pipes can be 3 m/s and the pressure drop can be maximum 400 Pascal per meter (Installatietechniek, 2012).

Next to the diameter, the pressure drop is calculated using the Darcy-Weisbach equation.

$$\Delta p = \lambda * \frac{L}{D} * 0.5\rho * v^2 \tag{19}$$

The friction factor depends on the Reynolds number.

$$Re = \frac{v * D * \rho}{\mu} \tag{20}$$

The Reynolds number is bigger than 3500, so the friction factor can be calculated with the Swamee-Jain equation.

$$\frac{1}{\sqrt{\lambda}} = -2log(\frac{\varepsilon}{3.72D} + \frac{5.74}{Re^{0.901}}) \tag{21}$$

Wall roughness for Polybutylene (PB) extrusion pipes is 0.01 mm. PB pipes are used and have the following advantages over traditional steel pipes (van den Groenendaal, 2019).

- Reduce noise disturbance
- Less maintenance and longer lifespan

If the pressure losses are too high, the size of the diameter and speed will be adjusted until the pressure drop and allowed speed is below 400 Pa/m and 3 m/s. Pressure losses for other equipment, like valves and bends, are neglected.

The diameters of the pipes in the network of concept 3 (every house a water-to-water heat pump) are calculated a bit differently. The maximum heat demand is supplied by the condenser side of the heat pump. The heat from the DH is supplied to the evaporator of the heat pump. Therefore, in order to determine the mass flow, the maximum heat demand has to be calculated from the evaporator. This is done by using equation 18. This heat demand should be used in equation 22 for this LTDH concept. The COP is provided in section 6.6.1.

$$\dot{Q}_{evap} = \dot{Q}_{cond} * \frac{COP - 1}{COP} \tag{22}$$

6.3.3 Circulation pump

The power supply of the circulation pump depends on the required volume flow and the pressure loss in the network. The total pressure loss depends on several factors. This calculation can become complex. To simplify this, the computation program WANDA is used.

The aim of this model is to determine the maximum pressure drop over the system with the highest flow. With this outcome, it is possible to determine the maximum power supply, to select a circulation pump (based on the pump and system curve), and the electricity usage per hour by the circulation pumps. The pump is selected with Grundfoss and is explained in Appendix A. The electricity usage is explained in section 6.6.2.

A representation of a part of the WANDA model is given in Figure 6-5. The figure presents the LTGH source with a circulation pump. Through pipes, the flow is divided taking the heat demands into account and returns after valves regulating the flow, through pipes, to the LTGH source. The complete model and explanation of the model can be found in Appendix A.

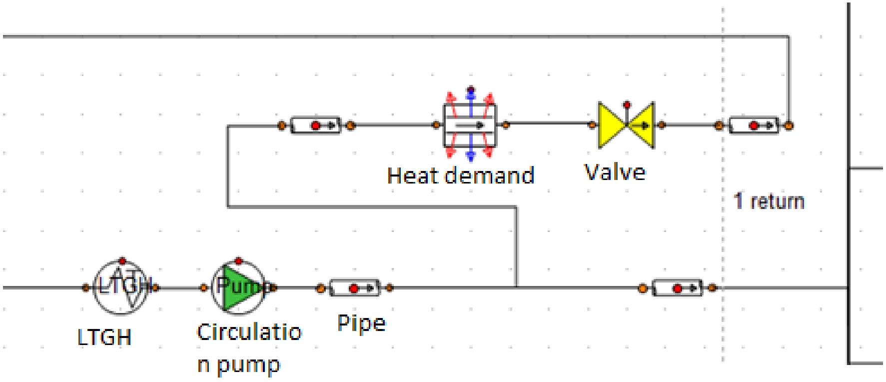


Figure 6-5 Part of the WANDA model.

The calculated head and volume flow will be inserted in the calculation tool from Grundfoss (Grundfoss, n.d.). With this input, the calculation tool selects the right circulation pump for the system.

The type of pumps installed in DH, are centrifugal pumps. These pumps are designed in such a way that they are able to deliver the minimum required pressure at the furthest located living at a certain desired flow rate and efficiency.

The pump curve is a graphical representation of the produced pressure as a function of the mass flow rate. The pressure loss for a closed loop pipe system is related to the total pressure loss and the flow rate. By superimposing the two curves and finding the intersection point, the operating point of the pump can be determined as in Figure 6-6, which is an example of a pump and system curve.

A pump is selected such that the operating point is near the best efficiency point (BEP).

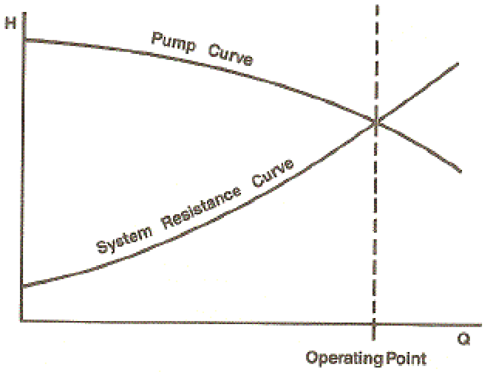


Figure 6-6 Example of a pump and system curve for a fixed speed pump.

6.4 Determination of standard parameters of techniques in LTDH

This section presents how the energy balance is set up. Furthermore, the equations for the energy balance and the dimensions of the storage systems and peak techniques are given.

6.4.1 Heat supply by LTGH

The heat that can be produced by the LTGH source depends on the temperature and the mass flow of the production and injection pipe. This is done by the following equation.

$$\dot{Q}_{LTGH} = \dot{m} * c_p * (T_{production\ well} - T_{injection}) \tag{23}$$

The mass flow is equal to the mass flow of the well pump of the LTGH source. The well pump can produce a maximum volume flow of 150 m^3/h and a minimum flow of 90 m^3/h (de Vrieze, 2018). The temperature at the production well and injection well is 30 ^{o}C and 8 ^{o}C, when a central heat pump is used. When there is no central heat pump, the temperature in the injection well is 20 ^{o}C.

The heat by the LTGH source can be increased with a heat pump. The supply heat in the network can be calculated with the COP of the heat pump and is done by equation 24. More on the COP of a heat pump can be found in section 6.4.1.

$$\dot{Q}_{LTDH} = \frac{COP * \dot{Q}_{LTGH}}{COP - 1} \tag{24}$$

The mass flow in the winter, autumn, and spring of the LTGH source will be 150 m^3/h. During the summer, when the heat demand is extremely less than the heat supply, the LTGH source will reduce the flow to 90 m^3/h.

The available mass flow for the district can be calculated with the temperature difference between the supply and return pipe and the heat flow in the LTDH. Equation 25 is required to determine the mass flows and temperatures in section 6.5

$$\dot{m}_{LTDH\ by\ heat\ pump} = \frac{\dot{Q}_{LTDH}}{cp * (T_{supply} - T_{return})} \tag{25}$$

The outcome of this formula is given in section 7.2.

6.4.2 ATES modelling

The water that flows in or out of the ATES is separated from the DH water by a HEX. The HEX causes a heat drop of 3 °C. So the hot water in the ATES hot well is 3 °C less than the supply temperature in the network. The cold water in the ATES cold well is 3 °C higher than the return temperature in the network. If the ATES supplies heat to the network, the supplied temperature will be 3 °C less than in the ATES hot well. This phenomenon is shown in Figure 6-7. On the left side it can be seen how the ATES works when it needs to supply heat and on the right side it can be seen how the ATES works when it stores heat.

The sizing of the ATES is based on (Drijver et al., 2012; Sommer, 2014). The ATES is installed at 250 meter depth and the maximum mass flow rate is 130 m^3/hour. The supplied power is calculated with equation 26. Since the temperature difference for LTDH concepts 1b and 2b is small, two ATES wells will be installed for these LTDH concepts.

$$\dot{Q}_{ATES} = \dot{m} * cp * (T_{supply\ to\ network} - T_{cold\ water\ towards\ HEX}) \tag{26}$$

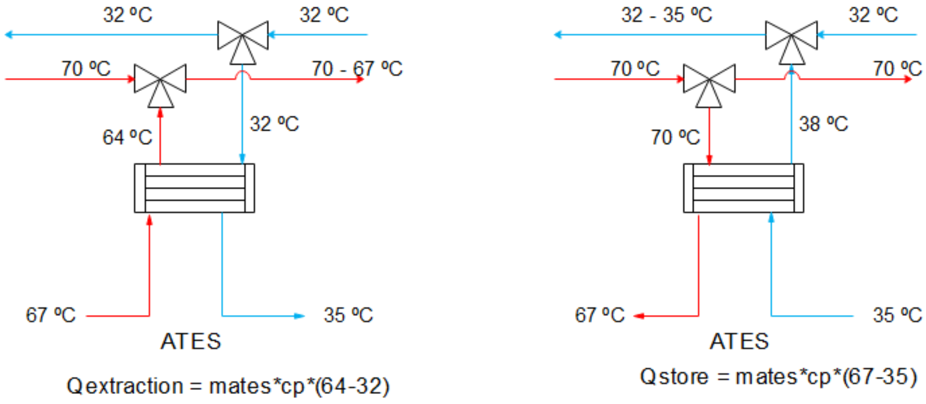


Figure 6-7 Temperatures of the ATES wells and in the district by a supply temperature of 70 °C when the ATES is supplying heat to the network (left) and when the ATES is storing heat (right).

The capacity of the ATES can be determined with the surfaces B_1 and B_2 from Figure 6-2. The amount of heat that needs to be stored are the letters A. However, as explained in section 6.2, the ATES has a recovery efficiency, so the capacity should increase to enough heat. The capacity of the ATES can be calculated with the following equation, where the surfaces B_1 and B_2 are the total energy difference between the LTGH source and the heat demand when the LTGH source cannot meet the total heat demand.

$$Q_{ATES} = \frac{(B_1 + B_2)}{\eta_{recovery}} = A_1 + A_2 + A_3 \tag{27}$$

6.4.3 Water tank modeling

The water tank is directly connected to the LTDH. Therefore, the temperature in the water tank will be increased until it is the same temperature as from the supply side of the LTDH. At the bottom of the tank, the temperature will be the same as the return temperature in the district.

The water tank is designed as follows. The capacity of the tank depends on the temperature difference between the supply and return temperature of the LTDH and it depends on volume of the water tank. It is calculated as follows.

$$Q_{store\ tank} = m * c_p * (T_{supply} - T_{return}) \tag{28}$$

The supplied power is based on the fact that the storage tank can supply that power for a maximum of 5 hours. After that, the temperature in the tank is decreased to a level that the tank cannot supply heat. So the maximum supplied power can be calculated as follows.

$$\dot{Q}_{\max water\ tank} = \frac{Q_{water\ tank}}{5} \tag{29}$$

The first estimated volume of the water tank for this thesis is chosen to be 250 liter, because this is a well-known size for storage tanks. If the outcome of the numerical models shows that the water tank needs to be adjusted, so that the heat concepts from section 5.3.2 can improve according to the KPIs, this will be done by choosing another water tank from the manufacturer datasheet (Huch, 2017).

The LTDH is simulated as one big house. Therefore, in the simulation model, the capacities for daily storage will be multiplied by the number of homes for the numerical model. The output power will also be multiplied by the number of houses and with the simultaneity factor. According to (Installatietechniek, 2015), the simultaneously factor for more than 250 homes is 0.55. The mass flow in the simulation model can be calculated with equation 30.

$$\dot{m}_{water\ tank} = \frac{\dot{Q}_{water\ tank}}{cp * (T_{supply} - T_{return})} \tag{30}$$

The outcome of these calculations can be found in section 7.2.

6.4.4 Heat loss in pipes modeling

As explained in section 6.2, the heat loss, which are caused by the pipes, can be determined by multiplying the length of a pipe with its related heat loss value from Table 6-1. For the complete network, this can become too complex and is therefore simplified as follows.

Figure 6-8 shows a route of heat that must be supplied to a street. The length of the pipes in this route is given in Table 6-6. Using the calculated diameters per LTDH concept and heat demand strategy, as described in section 6.3.2, the hourly heat loss for this piece of network can be determined. For this part of the network, there are 13 routes like this in the network. Because not every route is the same length or has the same diameters, it is assumed that the heat loss in this part of the network, is the heat loss of the route, as given in Figure 6-8, multiplied with 8. The number of parts in the district, n_{parts} in equation 31, depends on the heat demand. The first estimation is 2475 homes, so there are 6 parts.

Figure 6-8 Part A of the proposed layout of the heat pipes for the case district. The yellow line is the trace for the heat loss calculation.

With the calculated diameters, as described in section 6.3.2, the heat loss factors from Table 6-1, the lengths of the pipes in Table 6-6, and equation 31, it is possible to determine the hourly heat loss of the pipes for every LTDH concept and heat demand strategy.

Table 6-6 The length of the pipes in the highlighted trace of Figure 6-8.

Pipe type	Length (m)
1	120
2	280
3	120
4	80

$$\dot{Q}_{loss\ pipes} = \dot{Q}_{loss\ route} * 8 * n_{district\ parts} \tag{31}$$

6.4.5 Peak supply modeling

The peak technologies will be used when the heat supply of all other techniques is not sufficient to meet the heat demand. The power of the peak heat techniques is therefore determined by the energy balance. If the heat supply of all other techniques is fixed, the results of the energy balance will show how large the power must be from the peak techniques. The maximum power that must be supplied by the peak heat techniques is calculated in Chapter 9.

6.4.5 DHW supply

The input data contains the space heat demand and DHW demand. With 70 ^{0}C as supply temperature it is possible to supply the DHW. 50 ^{0}C as supply temperature needs a boost to upgrade the temperature to 60 ^{0}C. The input of the DHW demand can stil be used for the energy balance, but it will differ at the electricity balance.

Drinking water enters a home with 12 ^{0}C and needs to be converted to 60 ^{0}C for DHW use. With a heat exchanger for the 50-30 regime, it is possible to convert the cold water to 45 ^{0}C. Only a boost of 15 ^{0}C is needed. This will be done by the BHP and is explained in section 6.6.1.

6.4.6 Parameters used in model

Table 6-7 presents the parameters used in the numerical model for the energy balance.

Table 6-7 Parameters used in the energy balance.

Model parameter	Value	Unit
First estimated volume water tank	0.25	m^3
Maximum time power supply water tank	5	h
Efficiency 50 ^{0}C ATES	75	%
Efficiency 70 ^{0}C ATES	65	%
Maximum volume flow ATES	130	m^3/h
Depth of ATES installation	250	m
Maximum volume flow LTGH well pump	150	m^3/h
Minimum volume flow LTGH well pump	90	m^3/h
Simultaneously factor	0.55	-

6.5 Hourly energy balance

The energy balance calculates the energy behavior of seasonal storage, daily storage, and peak supply for each hour, for the LTDH concepts with a central heat pump. To simplify the simulation of the energy balance, the LTDH is simulated as one big house. The used MATLAB code can be found in Appendix B.

First, it is important to determine the term "*peak moment*". For the numerical model, there is a peak moment when the heat demand is more than the heat supply of the LTGH and ATES.

The numerical model consists of 3 control schemes. One control scheme is for when there are no peak moments and when there will be no peak moments in the next day. The second control scheme is for when there are no peak moments, but when they will occur within a day. The last control scheme is there for when there are peak moments.

The heat fluxes depend on the mass flows and temperatures in the pipes. The elaboration of the mass and energy balance is given in Appendix B. This appendix shows how the heat fluxes are determined for the numerical model. The related P&IDs are provided in this appendix as well.

Control scheme 1, no peaks occur

The difference between the supply of LTGH and the heat demand and additional losses is calculated for each hour. If supply is higher than demand with additional losses, the ATES will be charged. If the supply is lower than the demand with additional losses, ATES will be discharged.

In summer, the difference between LTGH supply and demand for each hour can be more than the ATES can charge in one hour. This means that too much heat is produced. To prevent the LTGH from producing too much heat, the supply of the LTGH will be reduced in the summer to 60% of the maximum heat production. This is still sufficient to supply the DHW demand by the LTGH.

The equations for this control scheme are given below.

$$\dot{Q}_{ATES(t)} = \dot{Q}_{LTGH(t)} - \dot{Q}_{demand(t)} \tag{32}$$

$$Q_{ATES(t)} = Q_{ATES(t-1)} + \dot{Q}_{ATES(t)} * 1h \tag{33}$$

$$If\ \dot{Q}_{ATES} > 0,\ the\ ATES\ will\ be\ charged$$

Control scheme 2, preparation for a peak moment

Before peak moments occur, the water tank at the houses needs to be charged. This is done by running the ATES at maximum power. The LTGH and the ATES produce more heat than the heat demand, therefore the water tank can be filled. If a peak moment occurs, the water tank is fully charged.

The equations for this control scheme are given below.

$$\dot{Q}_{daily(t)} = \dot{Q}_{LTGH(t)} - \dot{Q}_{demand(t)} + \dot{Q}_{ATESmax} \tag{34}$$

$$Q_{daily(t)} = Q_{daily(t-1)} + \dot{Q}_{daily(t)} * 1h \tag{35}$$

$$Q_{ATES(t)} = Q_{ATES(t-1)} - \dot{Q}_{ATESmax} * 1h \tag{36}$$

Control scheme 3, peak moment

First it will be determined if the peak can be supplied by the water tank. If the water tank has sufficient available heat, this heat will be used. If the water tank does not have sufficient available heat, the external peak source will partially or fully supply the peak. The control scheme for this situation is given in Figure 6-9.

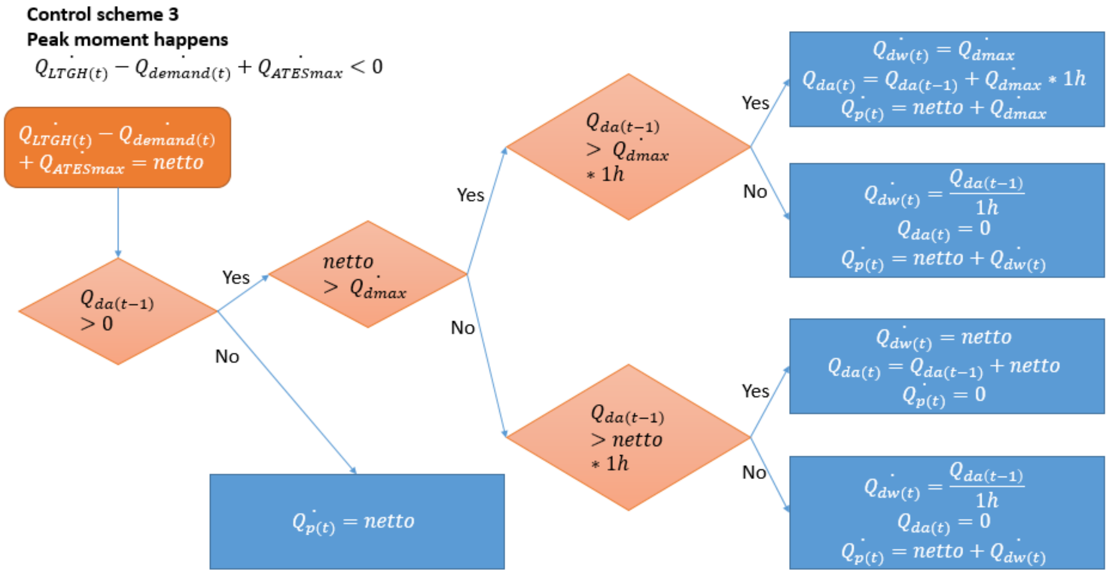


Figure 6-9 Control scheme for the numerical model when a peak occurs. The symbols are described in Table 6-8.

If the heat demand becomes less than the LTGH and ATES supply, control scheme 1 will be executed. Just before a cold moment the model switches to control scheme 2.

LTDH concepts without daily storage tank

The LTDH concepts without a daily storage tank uses control scheme 1. Only when a peak occurs, the peak is supplied by the external peak source.

Table 6-8 Subscript of parameters used in energy balance.

Symbols	Description	Units
$\dot{Q}_{LTGH}$	Heat supply by LTGH	MW
$\dot{Q}_{demand}$	Heat demand by homes	MW
$\dot{Q}_{ATESmax}$	Maximum heat supply by ATES	MW
$\dot{Q}_{ATES}$	Heat supply by ATES	MW
Q_{ATES}	Capacity of ATES	MWh
$netto$	$\dot{Q}_{LTGH} - \dot{Q}_{demand} + \dot{Q}_{ATESmax}$	MW
Q_{da}	Capacity of water tank	MWh
Q_{damax}	Maximum capacity of water tank	MWh
$\dot{Q}_{dmax}$	Maximum heat supply by water tank	MW
$\dot{Q}_{dw}$	Heat supply by water tank	MW
$\dot{Q}_{p}$	Heat supply by peak storage	MW

6.6 Electricity usage

This section presents the equations of the techniques which uses electricity. The electricity consumption of the relevant techniques is calculated for each hour. The sum is the total energy consumption of the network per hour.

6.6.1 Heat pumps

The electricity usage from the heat pumps is defined by the Coefficient of Performance (COP). It is a ratio of useful heating provided to work required. The COP is calculated as follows.

$$COP = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} \tag{37}$$

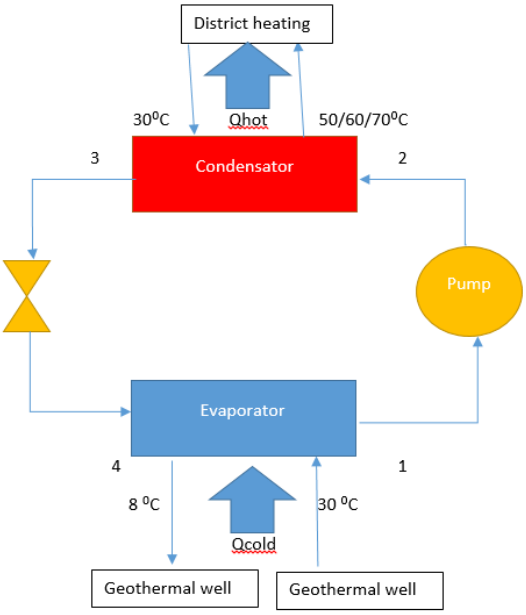


Figure 6-10 Scheme of a heat pump connected to a geothermal well and district heating.

This is the theoretical efficiency of a heat pump. It is the heat produced on the hot side (condenser) divided by the difference in heat at the produced side and at the cold side (evaporator). These heat flows for a heat pump, which uses a geothermal well, are presented in Figure 6-10. However, the actual COP value is lower. It depends on the refrigerant used in the heat pump and operating pressures. The COP values are given by the supplier of a heat pump, but it can be difficult to get these values (de Vrieze, 2018). Therefore, this thesis assumes the COP values with software Coolpack. Furthermore, the formula for the COP can be formulated as the temperatures on the geothermal well and district heating side, instead of the heat at those sides. Therefore, the formula can be written as follows.

$$COP = \eta_{carnot} * \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{38}$$

The scheme of a heat pump is the same as a Carnot cycle. Therefore, the second law of thermodynamics can be used to calculate the temperatures at the condenser and evaporator. Equation 39 determines the difference in heat for a HEX. Equations 41 and 42 presents the average temperature at the condenser and the evaporator. Equation 43 calculates the final electricity usage.

$$dQ = TdS \tag{39}$$

$$\dot{m} * c_p * (T_{outlet} - T_{inlet}) = \dot{m} * c_p * \bar{T} * ln\frac{T_{outlet}}{T_{inlet}} \tag{40}$$

$$T_{hot} = \bar{T}_{condenser} = \frac{T_{supply\,DH} - T_{return\,DH}}{ln\frac{T_{supply\,DH}}{T_{return\,DH}}} \tag{41}$$

$$T_{cold} = \bar{T}_{evaporator} = \frac{T_{production\,well} - T_{injection\,well}}{ln\frac{T_{production\,well}}{T_{injection\,well}}} \tag{42}$$

$$P_{el} = \frac{\dot{Q}}{COP} \tag{43}$$

Water-to-water heat pumps

For the central heat pump, at the LTGH, the temperature at the condenser depends on the supply and return temperature of the LTDH. The temperature at the evaporator depends on the water of the production well and the injection water of the injection well. The last ones are provided by V&SH (de Vrieze, 2018). The values for the calculated COPs can be found Table 6-9.

Table 6-9 COP values for central heat pumps at LTGH.

Supply temperature in LTDH (^{o}C)	50	70
Used refrigerant	R410A	R134a
COP of central heat pump	3.9	3.2

For the decentralized heat pumps, at home level, the temperature at the condenser depends on the supply and return temperature of the heating purposes in the homes. The temperature at the evaporator depends on the supply temperature of the LTDH and how much the heat pump can cool down the water for the return in the LTDH. According to (van Vliet et al., 2016), a supply temperature of 30 ^{o}C and the use of existing radiators will result in a COP for space heating and for DHW of 4.2 and 3.6, with a return temperature of 18 ^{o}C, for the refrigerant R410a.

Air-to-water heat pumps
There are also air – to – water heat pumps. These heat pumps extract the heat from the outside air and convert it into useful heat for a water circulation circuit. The COP therefore relies on the outside temperature. Table 6-10 presents tested COP values of air – to – water heat pumps at different outside temperatures. In here is the temperature to the radiators 55 ^{o}C.

At ambient temperatures below 5 ^{o}C, frost develops on the surface of the evaporator which reduces the performance of the heat pump. The frost layer reduces the rate of heat transfer in the evaporator because it acts as a thermal insulation. Furthermore, the frost layer blocks part of the air flow passage through the evaporator which causes a further reduction of the performance.

To prevent this phenomenon, an electrical resistance is installed in the heat pump. Electricity will go through the resistance when the ambient temperature is below 5 ^{o}C. The power, which uses the resistance, causes a decrease of 10% in the COP (Schmidt & Kristensen, 2014).

Table 6-10 COP values of an air heat pump at several temperature ranges. Adapted from (Ertesvåg, 2011) *and Coolpack. The 10% drop caused by frost formation is included. Used refrigerant is R410a.*

Outside temperature range (^{o}C)	-10 -8.1	-8 -6.1	-6 -4.1	-4 -2.1	-2 -0.1	0 2	2.1 4	4.1 6	6.1 8	8.1 10	10.1 12	12>
COP heat pump (-)	1.9	2.1	2.2	2.4	2.5	2.6	2.7	2.8	3.2	3.3	3.5	3.8

Booster heat pump
As said in section 7.3.7, if the network has a supply temperature below 60 ^{o}C, a BHP is required to prepare the DHW. According to (Kleefkens, 2017), when the supply temperature to the BHP is 45 ^{o}C, the COP is 4.2. The required electricity is calculated with equation 43, where the heat demand is the demand for DHW.

6.6.2 Circulation pumps

The electricity usage of the circulation pump is calculated as follows.

$$P_{el} = \frac{\dot{V} * \Delta p}{\eta} \tag{44}$$

As described in section 6.3, the pressure difference for the circulation pump is mainly caused by friction in the pipes. Equation 19 can be rewritten to a constant, multiplied with the square of the volume flow. It is assumed that the flow is always turbulent and therefor the friction factor is constant.

$$\Delta p = \lambda * \frac{L}{D} * 0.5\rho * (\frac{1}{D^2 \frac{\pi}{4}})^2 * \dot{V}^2 \tag{45}$$

$$\Delta p = C_1 * \dot{V}^2 \tag{46}$$

The volume flow depends on the heat demand. It is assumed that the temperature difference in this equation is constant, so the heat demand is linearly related to the volume flow.

$$\dot{Q}_{demand} = \dot{V} * \rho * c_p * \Delta T \tag{47}$$

$$\dot{Q}_{demand} = C_2 * \dot{V} \tag{48}$$

To combine the rewritten pressure drop and heat demand, the electricity usage is calculated as follows.

$$P_{el} = \frac{C_1}{\eta} * (\frac{\dot{Q}_{demand}}{C_2})^3 \tag{49}$$

Both constants can be determined with the pump choice from the WANDA model from section 6.3.3. It shows what the electricity usage is for the pump at a maximum flow rate, pressure difference, and heat demand.

There is one boundary. The minimum pressure difference must be at least 1 bar. According to ISSO 7.3.3, the pressure difference in a home must be between 0.1 and 0.5 bar, depending on the supply set. Next to that, the minimum pressure difference at the LTGH source must be 0.5 bar (de Vrieze, 2018).

6.6.3 Well pumps

The electricity usage from the well pumps can be calculated with Bernoulli. Bernoulli is a physical law which describes the flow behavior of liquids and gases by means of pressure changes. The Bernoulli equation is as follows.

$$z_1 * g * \rho + \frac{v_1^2}{2} * \rho + P_1 + \frac{P_{pump}}{\dot{V}} = z_2 * g * \rho + \frac{v_2^2}{2} * \rho + P_2 + friction \tag{50}$$

These pressure differences are applicable for the well pumps of the LTGH and the ATES. The electricity consumption can be calculated with equation 51, where the Bernoulli equation is rewritten.

$$P_{el} = \frac{\dot{V}}{\eta} * \left\{ (P_2 - P_1) + \rho * \frac{v^2}{2} + (z_2 - z_1) * \rho * g + \lambda * \frac{(z_2 - z_1)}{D} * 0.5\rho * v^2 \right\} \tag{51}$$

The speed depends on the mass flow through the well. The mass flow depends on the required heat supply. So, the speed through the wells is calculated as follows.

$$v = \frac{\dot{Q}}{A_{well} * C_P * \rho * \Delta T} \tag{52}$$

All the fixed values are presented in Figure 6-11.

What	Well Pump	ATES 50 °C	ATES 60 °C	ATES 70 °C	Unit
P_1	$P_2-\rho g z_1$	$P_2-\rho g z_1$	$P_2-\rho g z_1$	$P_2-\rho g z_1$	Pa
P_2	$1.135*10^5$	$1.135*10^5$	$1.135*10^5$	$1.135*10^5$	Pa
z_1	-750	-250	-250	-250	m
z_2	0	0	0	0	m
c_p	4183	4181	4183	4187	J/kgK
D_{well}	0.2	0.2	0.2	0.2	m
g	9.81	9.81	9.81	9.81	m/s^2
ρ	1005	1021	1017	1023	kg/m^3
λ[4]	0.02	0.02	0.02	0.02	-

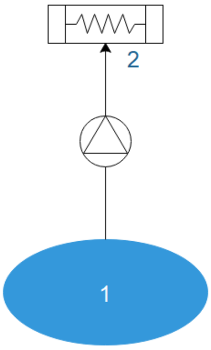


Figure 6-11 Parameters needed to determine the electricity usage of well pumps. Point 1 is in the aquifer and point 2 is just before the water enters the heat exchanger.

6.6.4 Electrical heaters and electrical boiler

These electrical elements convert electricity directly into heat. The heating elements contain an electrical resistance which can convert the current into heat. A small part of the heat is lost to the non-destined environment and therefore this conversion has an efficiency of 95%. The electricity usage can easily be calculated with the following formula.

$$P_{electricity} = \frac{\dot{Q}_{heat}}{\eta} \tag{53}$$

6.6.5 Parameters used in model

Table 6-11 presents the parameters used in the numerical model for the electricity usage.

Table 6-11 Parameters used for electricity usage model.

Model parameter	Value	Unit
COP LTGH 50	3.9	-
COP LTGH 70	3.2	-
COP decentral heat pump space heat	4.2	-
COP decentral heat pump DHW	3.6	-
Depth ATES well	250	m
Depth LTGH well	750	m
Diameter well	0.2	m
Efficiency DHW boiler	95	%
Friction factor in pipes	0.02	-
COP BHP	4.2	-

---

[4] Assumed there is a turbulent flow and a wall roughness of 0.01 mm.

6.7 CO_2 emission

As discussed in section 2.6.2, the LCA analysis is the most performed analysis to evaluate the CO_2 emission of a design. A variation of this method is chosen to evaluate the CO_2 emission, because it provides a conceptual estimation of the CO_2 emission, which is useful enough to see if the peak heat demand can be met in a sustainable way.

The analysis is as follows. The emission during production of heat happens when the LTDH provides heat to the homes. The manufacturing, production, transportation, installation, maintenance and disposal or recycling emissions are neglected, because there are too many variables for that to determine for this scope. This scope only takes into account what the emission is during the production of heat.

According to (Blom, 2010), improving the insulation with small adjustments, like replacing double glass to high efficiency double glass, can lead to a big significant decrease of space heat. Therefore, the CO_2 impact of improving buildings is neglected in this study.

So the emission in this thesis is only caused by the use of electricity and biomass. Regular geothermal sources produce extra CO_2, because natural gas is released from the earth. However, the LTGH source from V&SH is drilled less deep and in a surface where no natural gas is available (Koenders et al., 2018). The emission factor of electricity and biomass are currently 0.649 kg/kWh and 0.093 kg/kWh (Schepers & Scholten, 2016). However, the Netherlands is making a huge energy transition in which the electricity will be generated more sustainably (Nijpels, 2018). That means the emission factor will decrease. The prediction for the emission factor is presented in Table 6-12. The table also presents the amount of total energy that is generated sustainably. These numbers are based on (Energieonderzoek Centrum Nederland et al., 2017; Nijpels, 2018).

Table 6-12 Prediction of the emission factor of the production of electricity in the future in the Netherlands.

Year	**2016 5.8%**	**2020 14%**	**2025 50%**	**2030 66%**	**2040 83%**	**2050 100%**
Emission factor [kg CO_2/kwh]	0.649	0.593	0.344	0.234	0.117	0

6.8 LCOE

This thesis performs a Levelized Cost of Energy (LCOE) analysis to calculate the cost impact of a LTDH. This is a method that clearly shows the total costs of the heat generated and includes most cost items in the calculation. Other methods, such as the Net Present Value, includes the profits. Because a new heat network concerns various stakeholders, it can become unclear who pays which costs and who gets the profits (Wikipedia, n.d.). The LCOE analysis does not take the stakeholders into account and is therefore suitable to give a representation for the total costs

The LCOE calculates the costs per amount of energy produced over a certain time (Wikipedia, n.d.). This is summarized in the following equation.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}} = [\frac{€}{MWh}] \tag{54}$$

The produced energy (Q) is the heat production of the LTGH and related peak sources. The life time (n) is the number of years the systems runs, which is 30 years. The years are expressed in (t) and runs from year 0 to year 30. The interest rate (r) can be estimated to a value of 6%, because a transformation in energy supply can be seen as a risk full project (R. Kumar, 2014). The investment costs (I), Maintenance costs (M), and fuel costs (F) are the total costs which are made in a certain year.

The costs in year 0 are the investment costs (CAPEX). During all the other years the costs exist of operational and maintenance costs (OPEX). The approximate CAPEX and OPEX are presented in Table 6-13.

The fuel costs are the costs for electricity and biomass fuel, which are 0.18 €/kWh and 0.04 €/kWh (ACM, 2018).

Improving the insulation of a home involves investment costs. The details of these costs are given in (Naber et al., 2016). A conceptual estimation can be made for the various conversion of energy labels and is expressed for a fixed price per square meter for a type of home. The values used for this thesis are given in Table 6-13. This thesis assumes that the surface of a single home is 120 m^2 and the surface of an apartment is 80 m^2 (CBS, 2013).

The investment costs of the LTDH consist of the following factors (de Vrieze, 2018; van den Groenendaal, 2019).

- Material costs like pipes, bends and knees.
- Digging costs and paving
- Assembly costs
- Project costs, such as detail engineering, residents communication and traffic control

The determination of these costs is therefore a very detailed process. According to (de Vrieze, 2018; van den Groenendaal, 2019), the CAPEX can be divided in 1/3 of pipe material and 2/3 to engineering, installation and other materials for plastic pipes. For steel pipes, the ratio is 1/6 pipe material and 5/6 other materials and installation. The price for steel pipes is provided by Logstor and given in Table 6-14. The prices are per 12 meter pipe. The material costs of plastic is twice the material costs of steel pipes (van den Groenendaal, 2019).

Table 6-13 Overview of CAPEX and OPEX of aspects in a LTDH network and an all-electric heating concept.

Technology	CAPEX (€)	OPEX / year	Source	Comments
Necessary costs for DH with LTGH				
LTGH	8.400.000 ,-	185.000 ,-	V&SH	Related to drill depth 750 meter
Piping network	See Table 6-14	2% of investment	Werner 2011 & Logstor	
Circulation pump	650 / kW ,-	2% of investment	KSB, 2018	
Improving house insulation	72 ,- / m^2 82 ,- / m^2	-	(Verhaegh, 2018)	Improve flat D->B Improve single house C->B
Storage and peak technologies				
ATES	1500,- / meter depth	-	(Bloemendal, Jaxa-Rozen, & Olsthoorn, 2018)	
Water tank	1800,-	-	Huch leverancier	250 L
Electrical boiler	2000 ,-	-	(CE Delft, 2016)	200 L, 3 kW electricity
Electrical heaters	200 ,- / kW	-	(CE Delft, 2016)	
Water-water heat pump	3000,-	2% of investment	ITHO Daalderop	
Air – water heat pump	7800 ,-	3% of investment	ITHO Daalderop	
Booster heat pump	1500,-	2% of investment	ITHO Daalderop	
Supply set	1650,-	-	Maatregelen EPA-	Maatwerkadvies Bestaande Woningbouw 2013
Increase heat technologies at DH level				
Central heat pump	250 ,- / kW	3% of investment	Weg van gas (blz 43 tabel 9)	Price is per heat pump.
Biomass kettle	1.500 ,- /kW	4% of investment + 0.1206 €/kWh heat	(Sector, 2012)	

Table 6-14 Logstor cost table for steel pipes with PUR insulation.

DN	26	32	40	50	60	75	90	110	125	160	200
Price twin (€/12m)	797	866	953	1141	1497	1895	2309	3436	4855	5920	8903
Price single (€/12m)	414	437	537	569	691	799	1130	1573	1868	2288	2195

Table 6-15 Remaining values for LCOE model.

What	Value	Unit
Price electricity	0.18	€/kWh
Price biomass fuel	0.04	€/kWh
Interest rate	6	%
Surface single home	120	m^2
Surface apartment	80	m^2

6.9 Communicating end results

The numerical models will be calculated for different number of homes in the district, as explained in section 6.3.1. The KPIs, which are calculated with the models, are for the total network. To compare the results, the outcomes of the models are divided by the number of homes in the related network. Then the results of the KPIs are per home. So it is possible to compare the KPIs. This is given in Chapter 10.

For every heat demand scenario, six energy balances are made. With an analysis of electricity usage, CO_2 emission, and, LCOE, it can become unclear what the exact results are. Therefore, the results will be presented as follows.

The presentation of the results of the numerical model, as explained in section 6.5, is as follows. For each heat demand strategy and LTDH concepts with central heat pump, six graphs will be provided. These six graphs are:

1. Power supply by seasonal storage
2. Power by daily storage
3. Power by peak supply
4. Difference between LTGH supply, power by seasonal storage, and heat demand
5. Capacity of the seasonal storage
6. Capacity of the daily storage

These graphs are made for a yearly profile. The results can be found in Chapter 9 and appendix C.

Part 3 Results elaboration

This part presents the results of the performed method. In the first chapter, the number of homes connect to the LTDH is calculated for each heat demand strategy. The two chapters thereafter presents all that is required to calculate the KPIs presented in the last chapter. This part ends with an overview of the savings on CO_2 emission and cost for every LTDH concept and heat demand scenario per home, compared to the reference concept.

7. Results general parameters and yearly energy balance

7.1 Introduction

This chapter presents the results of the conceptual year balance, such as described in section 6.2. The aim of this year balance is to determine the number of homes that can be connected to the LTDH concepts for each heat demand strategy. The first subsection gives the outcomes of the general parameters for the yearly energy balance. These parameters are the power supply by the LTGH source, ATES, and water tank, and the capacity calculations of the ATES and water tank. The subsections after that outline the results of the yearly energy balance for every heat demand strategy.

7.2 Outcomes of general parameters

This subsection provides the parameters of the heat supply by the LTGH source, ATES, and water tank, as per section 6.4. An overview of these outcomes is provided in Table 7-1. In addition, this subsection provides what the general heat loss is at the HEX of the ATES and supply set.

Table 7-1 General outcomes of the power production of the LTGH and ATES for three supply temperatures.

	LTGH power supply to LTDH (MW)	ATES power (MW)	Mass flow after LTGH (kg/s)	Mass flow by ATES (kg/s)	Water tank power (MW)	Water tank capacity (MWh)
Heat supply 70 °C	5.42	4.83	34.1	36.1	2.77	25.15
Heat supply 50 °C	5.14	3.83	68.4	72.2	1.19	10.79
Heat supply 30 °C	1.92	1.2	41.6	72.2	-	-

An LTGH source produces 3.82 MW, with a mass flow in the well pumps of 41.6 kg/s and an extraction and injection temperature of 30 and 8 °C. If the supply temperature in the network is increased to 50 °C and the COP of the heat pump is 3.9, the available thermal power is 5.14 MW, as outlined in section 6.4.1. If the supply temperature in the network is increased to 70 °C and the COP of the heat pump is 3.2, the available thermal power is 5.42 MW. The corresponding mass flows for the LTDH system are 34.1 kg/s and 68.4 kg/s for the supply temperatures of 70 and 50 °C.

If the LTGH source does not use a central heat pump, the injection temperature in the LTGH well is 19 °C. The return temperature in the network is 18 °C and the heat exchanger at the LTGH increases the injection temperature of the well to 19 °C. Therefore, the heat supplied by the LTGH source without central heat pump is 1.92 MW.

As mentioned in section 6.4.2, an ATES well can produce and store 4.83 MW heat, with a mass flow in the well pumps of 36.1 kg/s and the temperature of the hot and cold well is 67 and 35 °C if the supply temperature in the network is 70 °C.

At a supply temperature of 50 °C, the temperatures of the hot and cold well are 47 and 35 °C. Therefore, 1 ATES can produce 1.81 MW. This is insufficient heat for the system and will lead to using the peak source more often than required. That is why 2 ATES wells are chosen for this system. Combined, they can produce 3.83 MW and this will allow for the ATES to increase the mass flow in the system by 72.2 kg/s, if both wells have to supply a maximum.

The capacity and heat supply of the water tank are based on the equations in section 6.4.3. The results of these calculations are provided in Table 7-2. For the capacity of the water tank in a network with a supply temperature of 70 ^{o}C, LTDH concept 2a, it is assumed that the supply temperature to the water tank is 67 ^{o}C (because of the mixture of the ATES production) and that the return temperature is 32 ^{o}C. For a network with a supply temperature of 50 ^{o}C, the supply temperature towards the tank is 47 ^{o}C.

Thus, one water tank can store 10.16 kWh energy and produce 2 kW heat. For 2,475 homes, the total energy storage and heat production is 25.15 MWh and 2.77 MW. For 2,900 homes, the total energy storage and heat production is 29.47 MWh and 3.25 MW. The maximum mass flow in the numerical model in Chapter 9 for the water tank is 18.93 kg/s for 2,475 homes and 22.21 kg/s for 2,900 homes, according to equation 30.

For LTDH concept 2b, where supply temperature is 50 ^{o}C, the supply to the water tank is assumed to be 47 ^{o}C and has the same return temperature as LTDH concept 2a. Therefore, one water tank can store 4.36 kWh energy and produce 0.87 kW of heat. For 2,475 homes, the total energy storage and heat production is 10.79 MWh and 1.19 MW. For 2,900 homes, total energy storage and heat production is 12.64 MWh and 1.39 MW. The maximum mass flow for the numerical model in Chapter 9 for the water tank is 18.98 kg/s for 2,475 homes and 22.17 kg/s for 2,900 homes, as per equation 30.

Table 7-2 Sizing of the water tanks at 70 and 50 ^{o}C as supply temperature in the LTDH.

	One home	2475 homes	2900 homes
Heat supply 70 ^{o}C	2 kW	2.77 MW	3.25 MW
Capacity 70 ^{o}C	10.16 kWh	25.15 MWh	29.47 MWh
Mass flow 70 ^{o}C	0.0137 kg/s	18.93 kg/s	22.21 kg/s
Heat supply 50 ^{o}C	0.87 kW	1.19 MW	1.39 MW
Capacity 50 ^{o}C	4.36 kWh	10.79 MWh	12.64 MWh
Mass flow 50 ^{o}C	0.0139 kg/s	18.98 kg/s	22.17 kg/s

As described in section 6.2, the amount of heat lost is the same for each LTDH concept, as can be seen from Table 7-3.

Table 7-3 Heat loss for yearly energy balance caused by the network pipes and the HEX at the homes and ATES.

	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Energy loss in HEX 2,475 homes (MWh)	793.5	793.5	793.5	793.5	793.5
Energy loss in HEX in 2,900 homes (MWh)	929.8	929.8	929.8	929.8	929.8
Energy loss in HEX ATES (MWh)	6.57	4.97	6.57	4.97	2.17
Energy loss in pipes for 2,475 homes (MWh)	4,380	2,628	4,380	2,628	876
Energy loss in pipes for 2,900 homes (MWh)	5,110	3,066	5,110	3,066	1,022

The heat loss by the HEX of the ATES is relatively small compared to the other losses, as calculated using equation 17. Heat loss with one supply set is 320.6 kWh, according to equation 15 at one home. This means that the heat loss of the HEX for 2,475 and 2,900 homes is 793.5 and 929.8 MWh.

The heat loss in the pipes is calculated according to section 6.2. For one part of the district, the yearly energy loss caused by the heat pipes are 730 kWh, 438 kWh, and 146 kWh when supply temperatures in the network is 70 ^{o}C, 50 ^{o}C, or 30 ^{o}C. Thus, for 2,475 homes the loss caused by the pipes is than 4,380 MWh, 2,628 MWh and 876 MWh and for 2,900 homes loss is 5,110 MWh, 3,066 MWh, and 1,022 MWh.

7.3 Outcome yearly energy balance demand strategy 1

This section shows the results of the yearly energy balance of heating strategy 1. Using the information from section 7.2, it is possible to determine how many homes can be connected to the LTDH concepts with one of the heat demand strategies. To complete the energy balance, the total hours, when 60% percent of the maximum LTGH supply, will be regulated. Table 7-4 provides an overview of the results of the balance, the outcomes of the production side and the outcomes of the loss factors for the first heating strategy. This heat demand is related to 2900 livings.

LTDH concepts 1a and 2a produces 3500 hours in the year 60% of the maximum heat production and LTDH concepts 1b and 2b 3000 hours. This means that there is still sufficient heat available for the demand side and that it is possible to store the overproduction. The yearly energy production from the LTGH sources with the heat pumps is 3,891 and 38,858 MWh for the supply temperatures of 70 and 50 ^{o}C.

Table 7-4 Outcomes of the yearly energy balance for the first heating strategy

	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Hours LTGH in summer mode (h)	3500	3000	3500	3000	0
LTGH energy production (MWh)	39,891	38,858	39,891	38,858	16,819
Peak energy production (MWh)	196	194	196	194	-[5]
Heat demand (MWh)	28,808	28,808	28,808	28,808	28,808
Energy loss by recovery ATES (MWh)	4,155	4,524	4,155	4,524	8,147
Total heat loss according Table 7-3	5,180	3,426	5,180	3,426	1,672

The heat loss caused by the storing time of the ATES is 4,155 and 4,524 MWh for the supply temperatures of 70 and 50 ^{o}C. For concept 3, heat loss is 8,147 MWh.

---

[5] All heat is supplied by the decentralized heat pumps, therefore there is no need for an external heat source.

7.4 Outcome yearly energy balance demand strategy 2

This section shows the results of the yearly energy balance of heating strategy 2. Table 7-5 provides an overview of the results of the balance, the outcomes of the production side and the outcomes of the loss factors for the first heating strategy. This heat demand is related to 2,475 livings.

Table 7-5 Outcomes of the yearly energy balance for the second heating strategy.

	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Hours LTGH in summer mode (h)	4000	4000	4000	4000	0
LTGH energy production (MWh)	38,807	36,802	38,807	36,802	16,819
Peak energy production (MWh)	206	200	206	200	-
Heat demand (MWh)	30,248	30,248	30,248	30,248	30,248
Energy loss by recovery ATES (MWh)	1,336	1,109	1,336	1,109	2,476
Total heat loss according Table 7-3	5,180	3,426	5,180	3,426	1,672

Peak shaving causes an increase in the total yearly heat demand, but lowers the heat loss in the system. Therefore, the LTGH, of the LTDH concepts 1a, 1b, 2a, and 2b produces 4000 hours in the year 60% of the maximum heat production. Consequently, there is still sufficient heat available for the demand side and it remains possible to store the overproduction. Yearly energy production from the LTGH sources with the heat pumps is 38,807 and 38,802 MWh for the supply temperatures of 70 and 50 ^{o}C.

The heat loss which are caused by the storing time of the ATES is 1,336 and 1,109 MWh for the supply temperatures of 70 and 50 ^{o}C. For concept 3, the heat loss is 2,476 MWh.

7.5 Outcome yearly energy balance demand strategy 3

Table 7-6 provides an overview of the results of the balance, the outcomes of the production side and the outcomes of the loss factors for the first heating strategy. This heat demand is for 2,900 livings.

Table 7-6 Outcomes of the yearly energy balance for the third heating strategy

	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Hours LTGH in summer mode (h)	4000	4000	4000	4000	0
LTGH energy production (MWh)	38,807	36,802	38,807	36,802	16,819
Peak energy production (MWh)	200	200	200	200	-
Heat demand (MWh)	30,014	30,014	30,014	30,014	30,014
Energy loss by recovery ATES (MWh)	1,046	882	1,046	882	2,246
Total heat loss according Table 7-3	6,046	4,001	6,046	4,001	1,954

Insulation measures cause a decrease of the total yearly heat demand. Since more homes are connected to this heat demand strategy, the number of homes is increased. With this heat demand strategy, the LTDH concepts 1a,1b,2a, and 2b produces 4000 hours in the year 60% of the maximum heat production. Consequently, there is still sufficient heat available for the demand side and it is possible to store the overproduction. The annual energy production from the LTGH sources with the heat pumps is 38,807 and 38,802 MWh for the supply temperatures of 70 and 50 ^{o}C.

Heat loss caused by the storing time of the ATES is 1,046 and 882 MWh for the supply temperatures of 70 and 50 ^{o}C. For concept 3, heat loss is 2,246 MWh.

8. Results network layout

8.1 Introduction

The aim of this chapter is to present the results of the performed calculations of section 6.3 and the yearly energy balance in section 6.2. The pipe diameters and maximum power supply of the circulation pumps are calculated in this chapter. The calculations were done using Microsoft Excel and WANDA. An overview of the created spreadsheets and the WANDA model can be found in Appendix A.

8.2 Network lay-out and pipe diameters

Connection pipes

The calculations from section 7.2.2 for a single house shows that the connection pipe, for every LTDH concept and heat scenario, has diameter size DN 32. Smaller diameters will lead to higher pressure losses. For high-rise buildings, with 50 apartments, the diameter size of the connection pipes are given in Table 8-1. According to (de Vrieze, 2018), the length of the connection pipes to single livings is 7 meters and for a high-rise building, it is 15 meters. This is excluding the return pipe.

Table 8-1 DN diameter size for high-rise buildings related to the LTDH concepts and heat demand strategies.

Heat demand strategy	1a 70 peak collective	1b 50 peak collective	2a 70 peak decentral	2b 50 peak decentral	3 Decentral heat pumps
Strategy 1: Current heat demand	110	125	110	110	110
Strategy 2: Applying peak shaving	110	125	110	110	110
Strategy 3: Appling insulation improvements	90	125	90	110	90

Number of homes connected to the network and layout

The number of homes that can be connected to the district (and therefore the heat demand) is calculated using the equations in section 6.2. The results are presented in Table 8-2. Heat demands are calculated as described in section 5.4. Using these equations, the total amount of heat demand is different per heat demand strategy.

Table 8-2 Yearly heat demand and homes connected to the LTDH for the heat demand strategies.

Heat demand strategy	Yearly heat demand (MWh)	Number of single homes	Number of apartments	Total number of livings
Strategy 1: Current heat demand	28,808	1200	1275	2475
Strategy 2: Applying peak shaving	30,248	1200	1275	2475
Strategy 3: Applying insulation improvements	30,014	1400	1500	2900

As mentioned in section 6.3.1, the case-district is too small for an LTDH with an LTGH source. That is why the network is adjusted, according to section 6.3.1. The network layout for heat demand strategies 1 and 2 is given in Figure 8-1 and the network layout for heat demand strategy 3 is given in Figure 8-2. The network in Figure 8-1 is divided into 6 parts and the network in Figure 8-2 is divided into 7 parts.

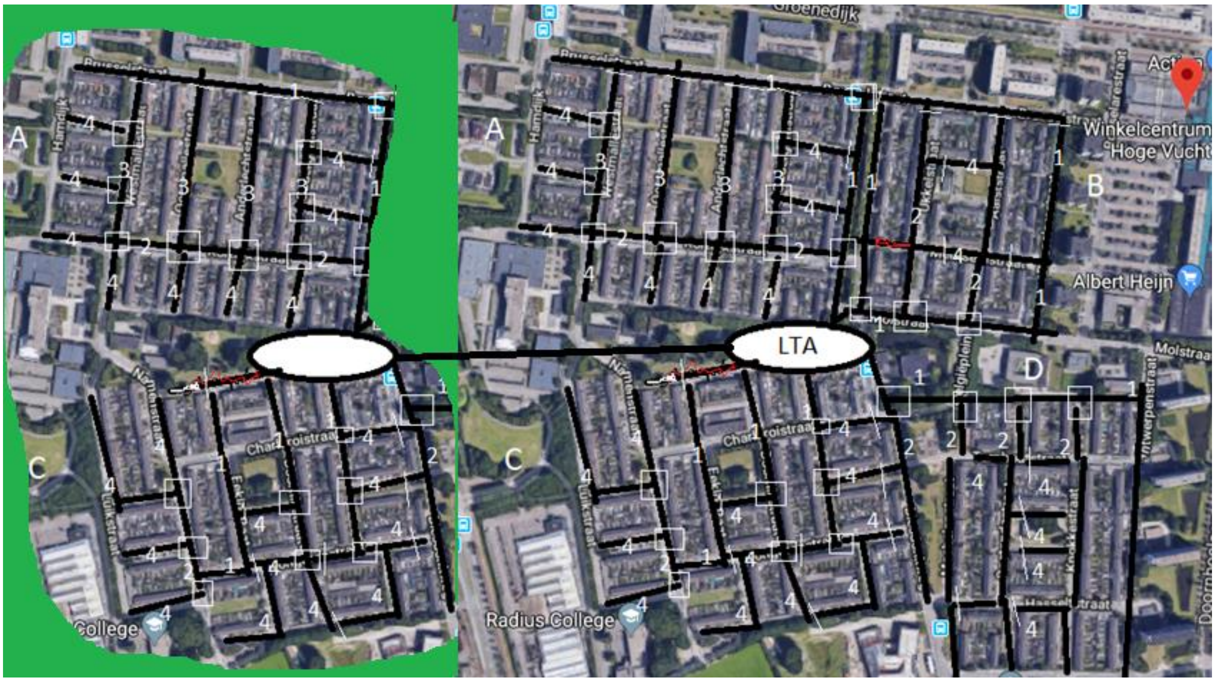


Figure 8-1 Overview network layout for the first two heat demand strategies.

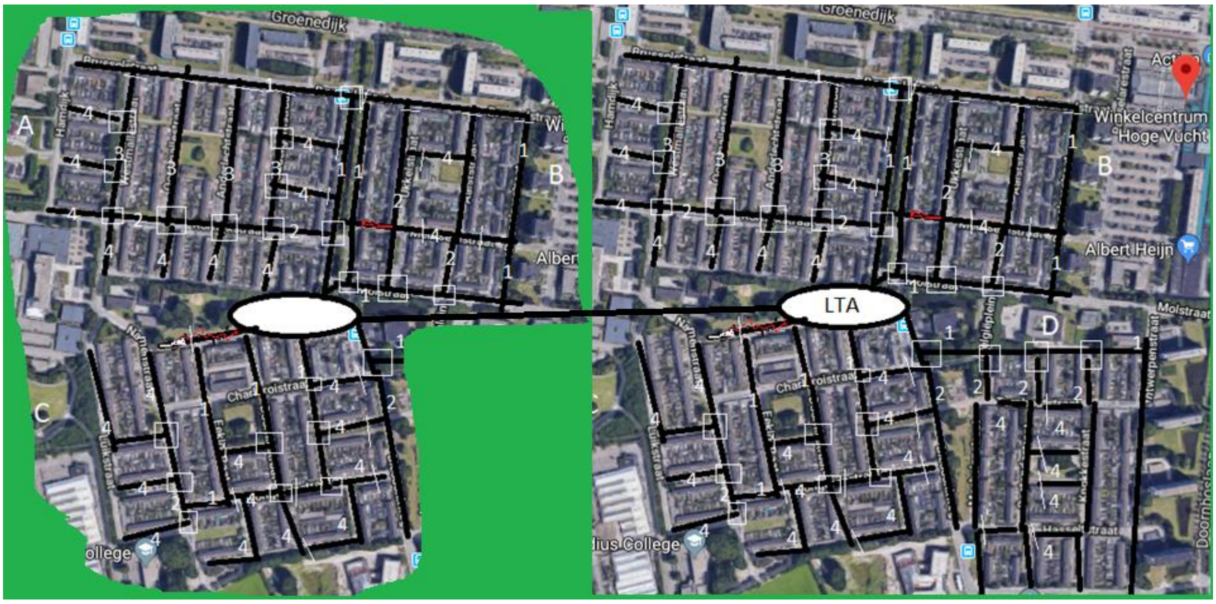


Figure 8-2 Overview network layout for the last heat demand strategy.

Heat and mass flow through the pipes

The heat produced by the LTGH source and ATES sources and the mass flow for in the system is based on equations 23 and 26. The results are given in Table 8-3. Because the low temperature difference in the ATES wells when the temperature is upgraded to 50 ^{0}C, 2 ATES wells will be installed to meet the heat demand.

Table 8-3 Heat production and mass flow production by the LTGH and ATES sources for the LTDH concepts with central heat pumps.

	LTGH (MW)	LTGH (kg/s)	ATES (MW)	ATES (kg/s)
70 supply	5.42	34.1	4.83	36.1
50 supply	5.14	68.4	3.83	72.2

The heat through the pipes in equation 18 is the maximum heat flow in the network. For LTDH concepts 1a and 1b (collective peak supply), the maximum heat flow is equal to the maximum heat demand and the losses in the network. For LTDH concepts 2a and 2b (decentralized peak supply), the maximum heat flow is equal to the maximum heat supply of the LTGH source and the ATES source. The maximum heat and mass flow through the network for the LTDH concepts with a central heat pump are given in Table 8-4. The table also shows how much heat and mass flow through one part of the district. This information is required to determine the inner pipe diameters and to select a circulation pump.

Table 8-4 Maximum heat supply and mass flow in the network for the heat demand strategies and for the LTDH concepts with central heat pumps.

	1a 70 peak collective	1b 50 peak collective	2a 70 peak decentral	2b 50 peak decentral
Heat demand strategy 1: Current heat demand				
Heat in LTDH (MW)	13.47	13.47	10.25	8.76
Heat in one part LTDH (MW)	2.25	2.25	1.71	4.38
Mass flow in LTDH (kg/s)	84.80	179	70.2	140.6
Mass flow in one part LTDH (kg/s)	14.13	25.57	11.7	23.43
Heat demand strategy 2: Peak shaving strategy				
Heat in LTDH (MW)	12.35	12.35	10.25	8.76
Heat in one part LTDH (MW)	2.06	2.06	1.71	4.38
Mass flow in LTDH (kg/s)	77.75	164.14	70.2	140.6
Mass flow in one part LTDH (kg/s)	12.96	27.36	11.7	23.43
Heat demand strategy 3: Insulation improvement				
Heat in LTDH (MW)	13.34	13.34	10.25	8.76
Heat in one part LTDH (MW)	1.91	1.91	1.46	1.25
Mass flow in LTDH (kg/s)	83.98	177.30	70.2	140.6
Mass flow in one part LTDH (kg/s)	12.00	25.33	10.0	20.1

The heat and mass flow through the pipes for LTDH concept 3, with decentralized heat pumps, are calculated according to equations 18 and 22. The results of these calculations are provided in Table 8-5. The table converts the heat demand to one part of the district. This table also provides how much heat and mass flow flows through one part of the district. This information is required to determine the inner pipe diameters and to select a circulation pump.

Table 8-5 Heat and mass flows through the network for LTDH concept 3.

	Maximum power demand (MW)	For one part over the district (MW)	Evaporator heat side (COP 3.8) (MW)	Maximum mass flow in one part of the district (kg/s)
Heating strategy 1	13.47	2.25	1.65	32.5
Heating strategy 2	12.35	2.06	1.49	29.7
Heating strategy 3	13.34	1.91	1.38	27.5

Network pipes dimensioning

The results of the dimensioning of the network pipes are based on the calculations in section 6.3.2 and the mass flows and heat flows in from Table 8-4 and Table 8-5. The figures on the next page present the total length needed for a certain diameter. Figure 8-3, Figure 8-4, and Figure 8-5 present the pipe lengths for all the LTDH heating concepts of the three heat demand strategies. These figures do not include the connection pipes to the homes. These pipes are given in Table 8-6. All these results have an influence on the cost analysis in Chapter 10.

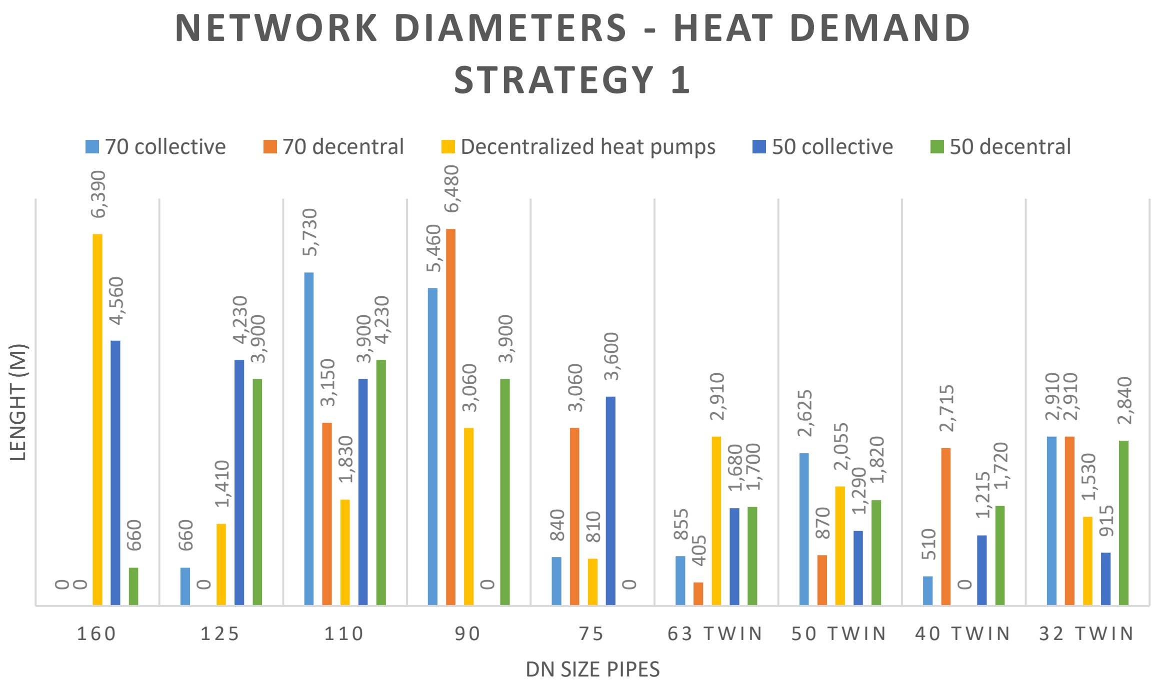


Figure 8-3 Diameters of pipes for the LTDH concepts and heating strategy 1: Current heat demand. This is for 2475 homes

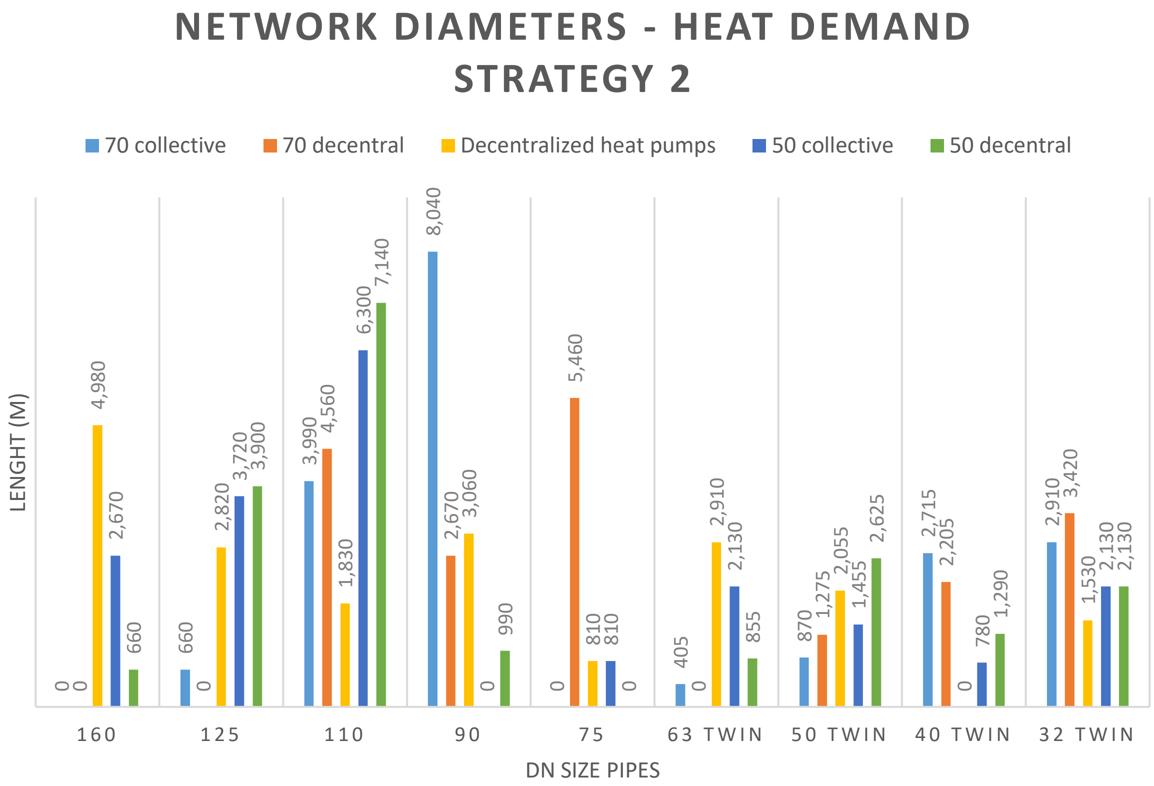


Figure 8-4 Diameters of pipes for the LTDH concepts and heating strategy 2: Applying peak shaving. This is for 2475 homes.

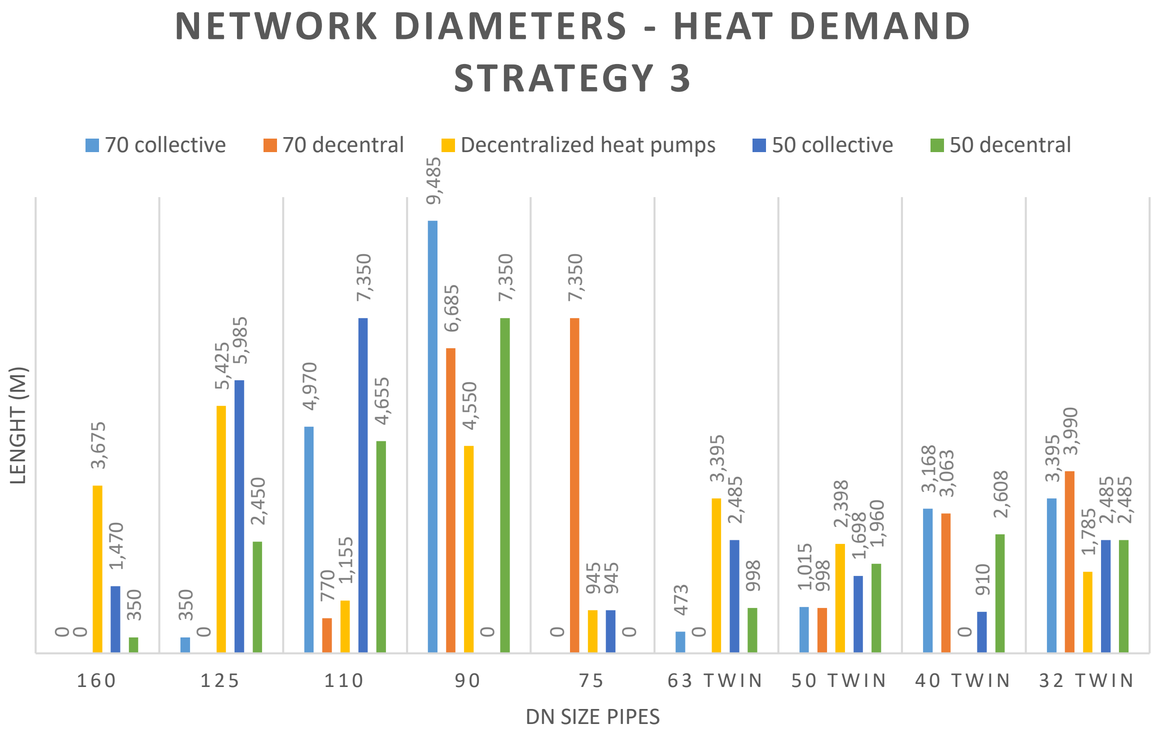


Figure 8-5 Diameters of pipes for the LTDH concepts and heating strategy 3: Insulation improvements. This is for 2,900 homes.

It is visible from the figures above that the diameter of the pipes increases when the supply temperature in the LTDH decreases. This is because the same heat must be transferred, so the flowrate of lower supply temperatures increases. Out of all heat demand strategies, concept 3 has the largest pipe diameters, because the biggest mass flow has to travel through the pipes for this network. The high mass flow occurs because the temperature difference between the supply and return pipes is the smallest for this LTDH concept.

The location of the peak sources also has an influence on the diameter sizes. If the peak heat will be supplied by the network, the diameter increases. For example, as can be seen in Figure 8-3, with 50 ^{0}C supply the collective concept requires 4,560 and 4,230 meters pipe of DN 160 and DN 125, while the decentral concept requires 660 and 2,850 meter of DN 160 and DN 125.

Peak shaving leads to smaller diameters in the network, because the mass flow in the network is lower for every heat concept, as can be seen from Table 8-4 and Table 8-5 . For concept 1a, 2000 meters of DN 110 pipe for the current heat demand can be replaced by DN 90 if peak shaving is applied. This is also the case for 2000 meters of DN 50 pipe, which can be replaced by a DN 40 size, when peak shaving is applied. In general, peak shaving leads to a decrease in pipe diameter and therefor, the costs for producing, installation, and maintenance of the network are lower with the heat demand strategy peak shaving.

Comparing insulation measures with respect to other heat demands is tricky because more homes are connected to this network. In consequence, the length of the pipes is greater than for the other heat demands. However, you can see from Figure 8-5 that insulation does have an effect on the network. It can be seen, for example, that the least meters of DN 160 are required for this heat demand.

The required number of connection pipes has been left out of the figures on the previous page. The number of connection pipe per heat demand strategy is given in Table 8-6. These are required for the LCOE calculation in Chapter 10.

Table 8-6 Total length of connection pipes for the 3 different heat demand strategies.

	Heat demand strategy 1 Current heat demand	Heat demand strategy 2 Peak shaving	Heat demand strategy 3 Insulation measures
Length for high-rise building connection (m)	540	540	660
Length for low-rise building connection (m)	6,825	6,825	8,000

Heat loss in network pipes

Table 8-7 provides the outcomes of the pipe diameters of the route as described in section 6.3.2. The lengths are multiplied with the heat loss values from Table 6-1.

Table 8-8 shows the amount of heat loss for the track, heat loss for a part of the district, and the heat loss for the whole district. The last value is multiplied for a whole year, which is the total energy loss caused by the network pipes.

Table 8-7 Pipe diameter for the route as given in Figure 6-8 for the first heating strategy

Pipe type	Length (m)	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Heat demand strategy 1: Current heat demand						
1	120	DN 125	DN 160	DN 110	DN 125	DN 160
2	280	DN 90	DN 110	DN 90	DN 110	DN 110
3	120	DN 50	DN 63	DN 40	DN 50	DN 63
4	80	DN 32	DN 40	DN 32	DN 32	DN 32
Heat demand strategy 2: Applying peak shaving						
1	120	DN 125	DN 160	DN 110	DN 125	DN 160
2	280	DN 90	DN 110	DN 90	DN 110	DN 110
3	120	DN 40	DN 63	DN 40	DN 50	DN 63
4	80	DN 32	DN 32	DN 32	DN 32	DN 32
Heat demand strategy 3: Improving insulation						
1	120	DN 110	DN 160	DN 110	DN 125	DN 160
2	280	DN 90	DN 110	DN 75	DN 90	DN 90
3	120	DN 40	DN 63	DN 40	DN 50	DN 63
4	80	DN 32	DN 32	DN 32	DN 32	DN 32

In Table 8-7, it can be seen that for concept 1a only pipe 3 changes from DN 50 to DN 40 if an adjusted heat demand strategy is applied. The same applies to pipe number 4 of concept 1b. Finally, pipe number 2 for concept 2b and concept 3 changed from DN 110 to DN 90 if insulation is applied.

Table 8-8 shows that the hourly loss in the network varies from 427 kW to 192 kW for the first heat demand. Adjusting the heat demand strategy has a small influence on the amount of loss in the heat network. With insulation, the loss varies from 407 to 187 kW. However, the energy balance in Chapter 7 mainly refers to orders from MW, so adjusting the heat demand has little influence on the amount of loss in the pipeline network.

The outcomes in the row of Table 8-8 titled ‘Heat loss for the whole district (kW)’ is used in the numerical model of section 6.5 and Chapter 9.

Table 8-8 Outcomes of heat loss caused by the pipes for the first heating strategy.

	Concept 1a Peak collective 70 supply	Concept 1b Peak collective 50 supply	Concept 2a Peak decentral 70 supply	Concept 2b Peak decentral 50 supply	Concept 3 Decentralized heat pumps
Heat demand strategy 1: Current heat demand					
Heat loss for the route (kW)	8.89	6.47	7.95	6.27	3.99
Heat loss for part A of the district (kW)	71.12	51.76	63.6	50.16	31.92
Heat loss for the whole district (kW)	427	311	382	301	192
Heat demand strategy 2: Applying peak shaving					
Heat loss for the route (kW)	8.48	6.56	7.95	6.27	3.99
Heat loss for part A of the district (kW)	67.84	52.48	63.6	50.16	31.92
Heat loss for the whole district (kW)	407	315	382	301	192
Heat demand strategy 3: Improving insulation					
Heat loss for the route (kW)	8.48	6.56	7.64	6.13	3.60
Heat loss for part A of the district (kW)	67.84	52.48	61.12	49.04	31.2
Heat loss for the whole district (kW)	475	367	428	343	218

8.3 Sizing of circulation pump

The results of this section are based on the calculations in section 6.3.3 and on the WANDA model. The WANDA model and related calculations and assumptions are described in Appendix A. Table 8-9 presents the results of the WANDA model. It shows the required head, and volume flow for the circulation pumps for every LTDH concept and heat demand strategy. With these results it is possible to select a pump from Grundfoss, which is required to determine the electricity usage of the circulation pumps. The selected pump with the related electrical power and the efficiency of converting electricity in useful power is given in Table 8-10. The pump selection process can be found in Appendix A.

The circulation pumps are selected for one part of the DH. As shown in section 6.3.1, the district is divided into several parts. Because heating strategies 1 and 2 are applied for 6 parts, all the LTDH networks need 6 circulation pumps. The networks for heat demand strategy 3 needs 7 circulation pumps.

Table 8-9 WANDA results of the circulation pump.

		Concept 1a 70 peak collective	Concept 1b 50 peak collective	Concept 2a 70 peak decentral	Concept 2b 50 peak decentral	Concept 3 Decentral heat pumps
Heat demand strategy 1 current heat demand	[bar] [m3/h]	5.4 55.0	6.5 108.5	4.8 30.7	5.7 56.0	7 110.4
Heat demand strategy 2 Peak shaving	[bar] [m3/h]	5.5 51.4	6.2 98.6	5.8 26.9	6.2 52.7	7.2 90.9
Heat demand strategy 3 Insulation improvement	[bar] [m3/h]	6.8 45.5	5.2 89.7	6.9 23.7	6.5 43.5	7.3 81.6

Table 8-10 Pump selection and related engine power. Adapted from (Grundfoss, n.d.).

		Concept 1a 70 peak collective	Concept 1b 50 peak collective	Concept 2a 70 peak decentral	Concept 2b 50 peak decentral	Concept 3 Decentral heat pumps
Heat demand strategy 1 current heat demand	[-]	CR 45-4	CR 95-4	CR 32-4	CR 45-4	CR 64-4
	[kW]	13.9	26.66	6.13	14.02	16.61
	[%]	62.8	70.1	65.6	62.1	72.1
Heat demand strategy 2 Peak shaving	[-]	CR 45-4	CR 95-3	CR 20-7	CR 45-4	CR 64-4
	[kW]	12.2	23.1	7.5	13.9	23.36
	[%]	64.4	73.6	57.5	65.2	69.2
Heat demand strategy 3 Insulation improvement	[-]	CR 45-6	CR 95-3	CR 15-9	CR 45-4	CR 64-4
	[kW]	13.0	17.33	7.69	11.29	17.1
	[%]	65.9	73.5	58	68.3	72.1

9. Results hourly energy balance

9.1 Introduction

This chapter presents the results of the performed calculations of section 6.5. The chapter is divided into three parts, one for each heat demand strategy.

Per subsection the outcomes of the hourly energy balance are given for each heat concept with a central heat pump. The hourly energy balance includes the following parameters for every LTDH concept, with central heat pump, for a cold period.

- The heat difference between the LTGH supply and demand
- The heat supply by the ATES source
- The heat supply and capacity of the water storage tank
- The heat supply by the peak sources

A negative value means that a heat technique supplies heat to the homes. A positive value for the power graphs for the storage systems means that the storage system is charged with that amount of power.

The results in section 7.2 are the parameters used for the numerical model. The numerical model was written in MATLAB and the code and used parameters in the model can be found in Appendix B. The numerical energy balance of section 6.5 has been elaborated with this data.

In addition to the code, Appendix B also describes how the model works. For each scenario, an assessment is made of the capacity of the water tank and the heat demand. With this information, the model determines how much heat the water tank and the ATES source are filled with – or how much heat is withdrawn – and how much heat must be supplied from the peak source. The hourly energy and mass balances are also provided in Appendix B.

The elaboration of the energy balances are presented as stated in section 6.7. Sections 9.2, 9.3, and 9.4 show the energy balance for the coldest week. The subsections from 9.2 until 9.4 represent the results of two LTDH concepts with the same supply temperature. In Appendix C, where all the outcomes of the energy balances are provided, the graphs of the energy balances can be found for an entire year. The last section of this chapter presents a summary of all the found results.

To properly understand what exactly can be seen in this chapter, Figures 9-1 until Figure 9-4 provide P&IDs of the LTDH concepts. These show the maximum and minimum temperatures and mass flows in a certain pipe and equipment. The calculations were done using these P&IDs.

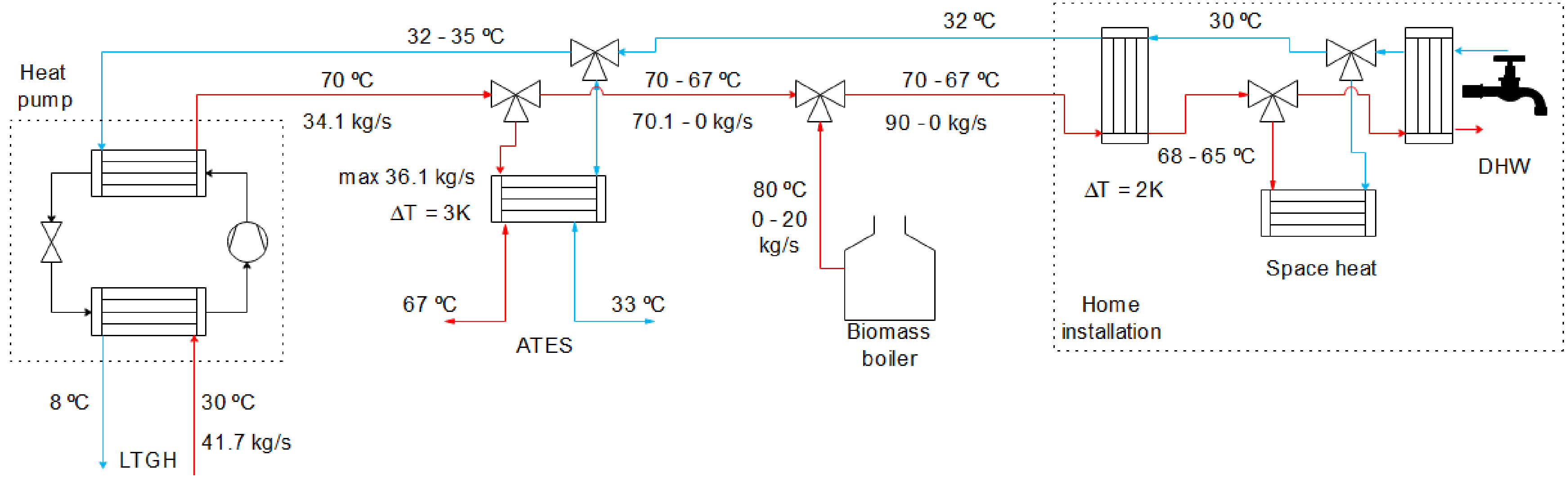


Figure 9-1 P&ID of LTDH concept 1a, supply temperature 70 °C and a central biomass boiler for peak moments.

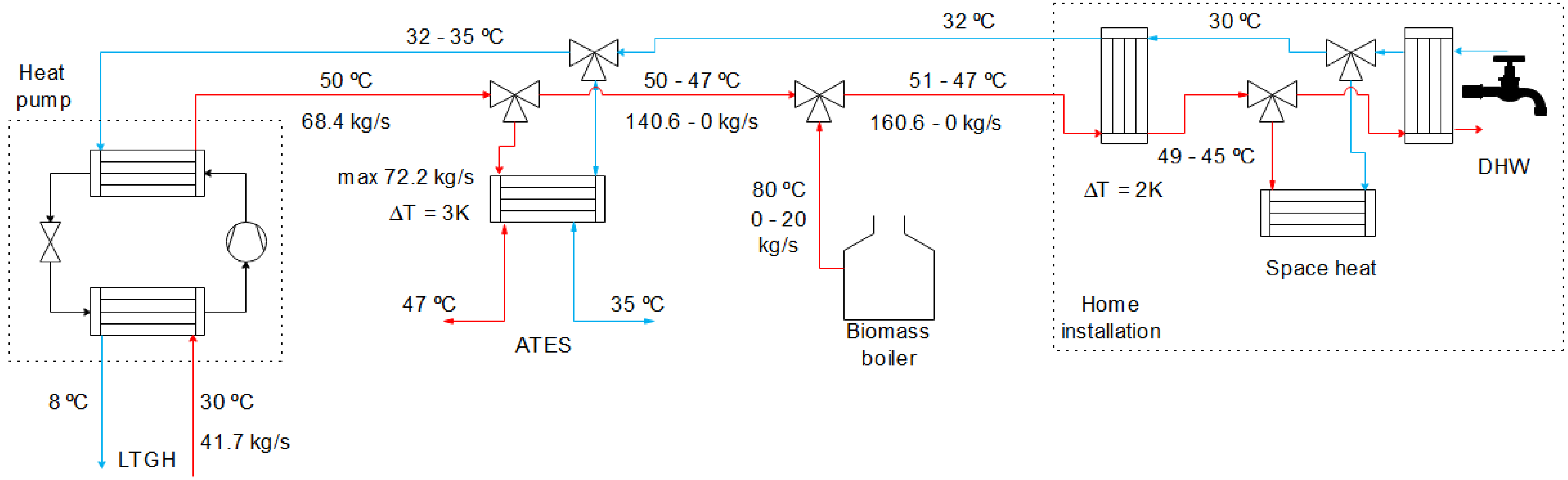


Figure 9-2 P&ID of LTDH concept 1b, supply temperature 50 °C and a central biomass boiler for peak moments.

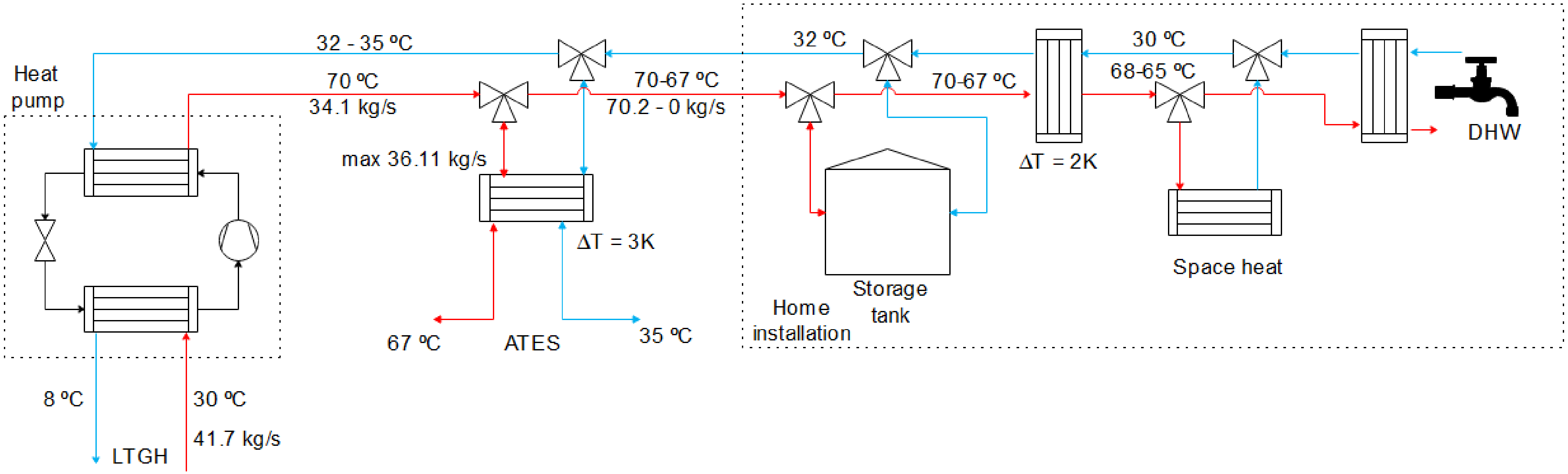


Figure 9-3 P&ID of LTDH concept 2a, supply temperature 70 ºC and a water tank and electrical heaters for peak moments.

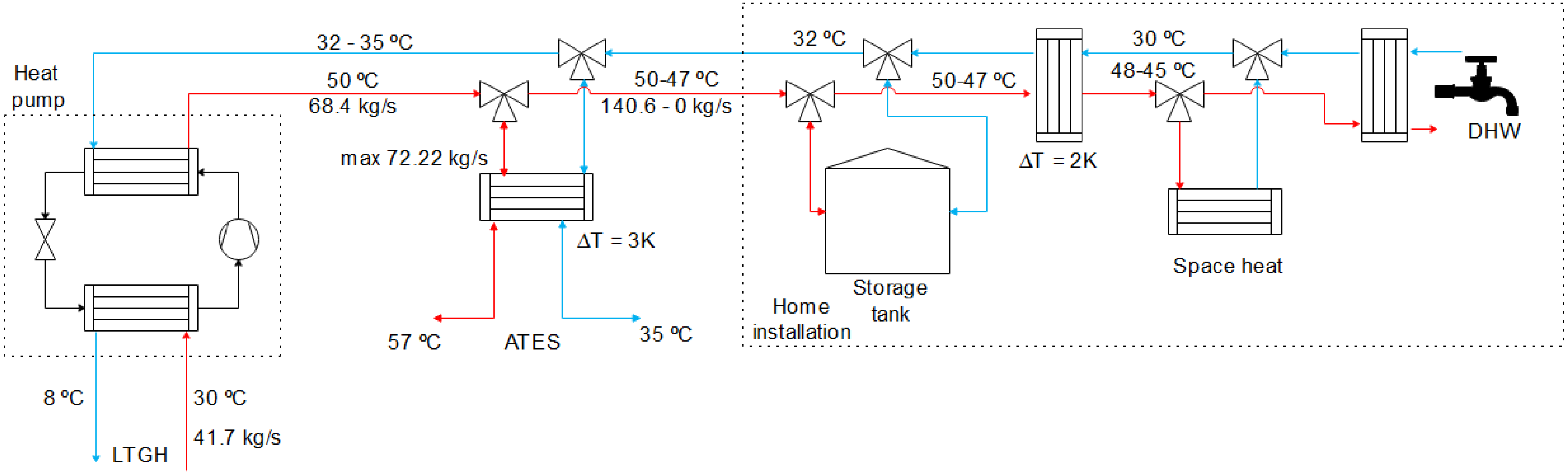


Figure 9-4 P&ID of LTDH concept 2b, supply temperature 50 ºC and a water tank and electrical heaters for peak moments.

9.2 Heat demand strategy 1: Current heat demand

9.2.1 LTDH Concept 1a and 2a: 70 °C supply temperature

Figure 9-5 until Figure 9-11 present the results of the energy balance for the LTDH concepts with 70 °C supply temperature for the coldest two weeks in January (12 until 23 January), with the first heat demand strategy.

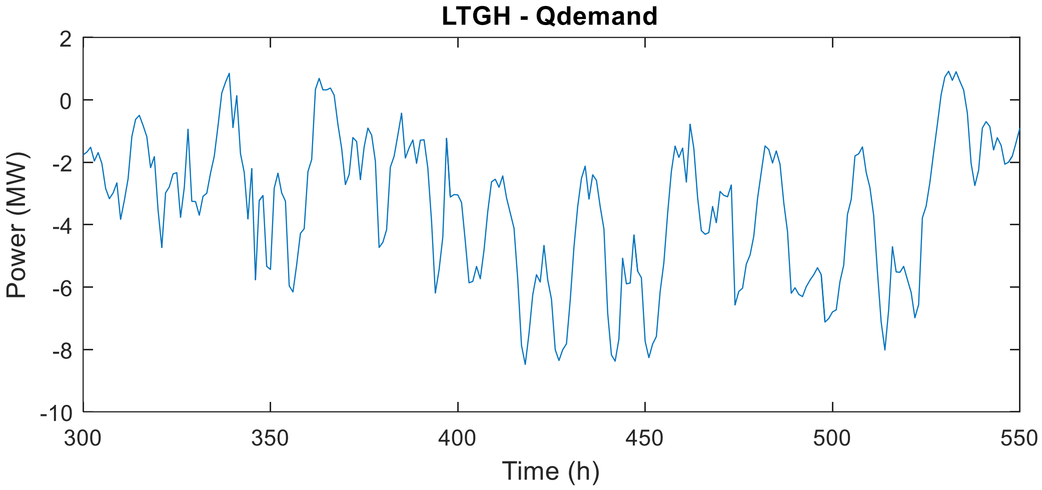


Figure 9-5 Heat difference between the LTGH supply and heat demand during the coldest two weeks for LTDH concept 1a and 2a, using the first heat demand strategy.

Figure 9-5 shows the heat difference between LTGH supply of 70 °C and the heat demand during 10 cold days. Most of the time, the difference is lower than 0 MW. This means that there is more heat demand than heat supplied by the LTGH, so the ATES source and peak sources need to provide extra heat. The largest difference is around 8.5 MW.

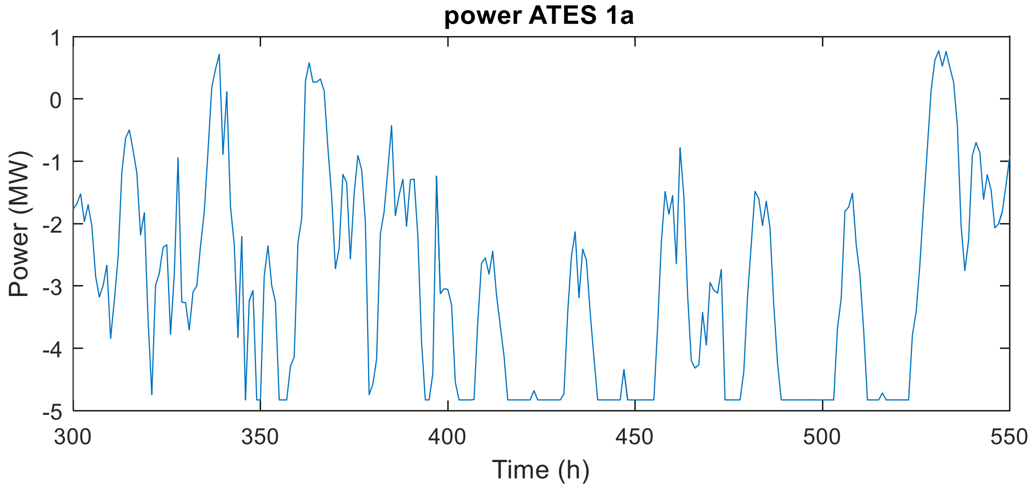


Figure 9-6 ATES supply power by LTDH concept 1a, where the peak heat is supplied by a central biomass boiler. The first heat demand strategy is applied.

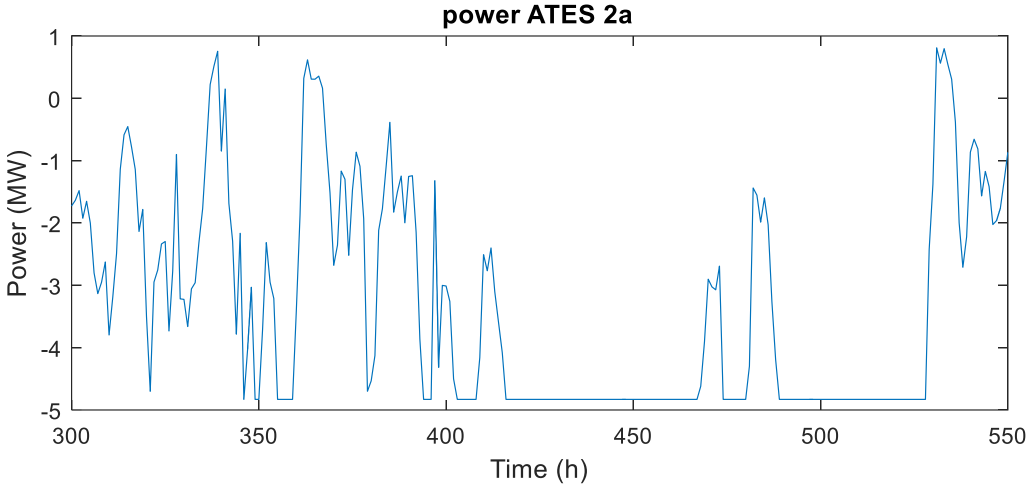


Figure 9-7 ATES supply power by LTDH concept 2a, where the peak heat is supplied at the home. The first heat demand is applied.

Figure 9-6 and Figure 9-7 show the heat supply from the ATES source. The ATES for concept 2a provides more heat between hours 420 and 530, in order to supply heat to the daily storage tank. The total heat supply from the ATES source during these 10 cold days is less for concept 1a.

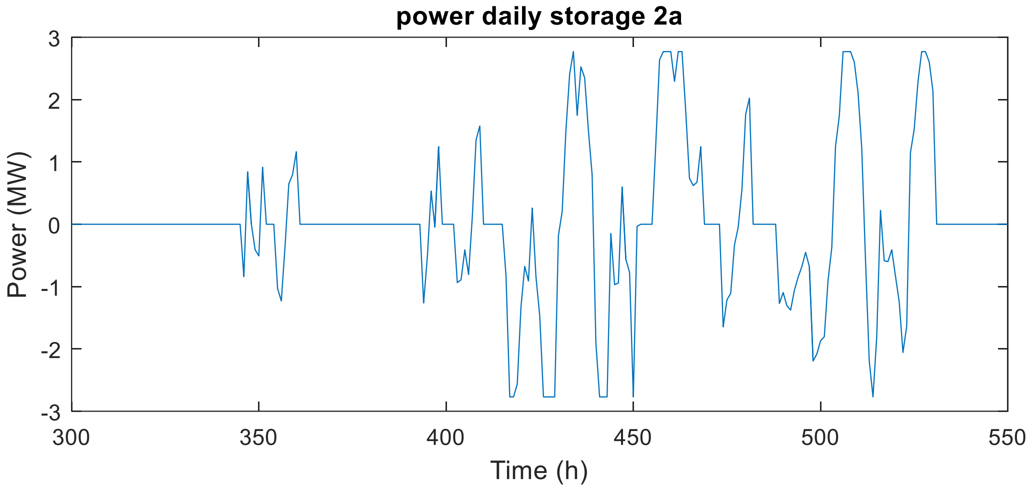


Figure 9-8 Power supply from the daily storage tank for LTDH concept 2a, using the first heat demand strategy.

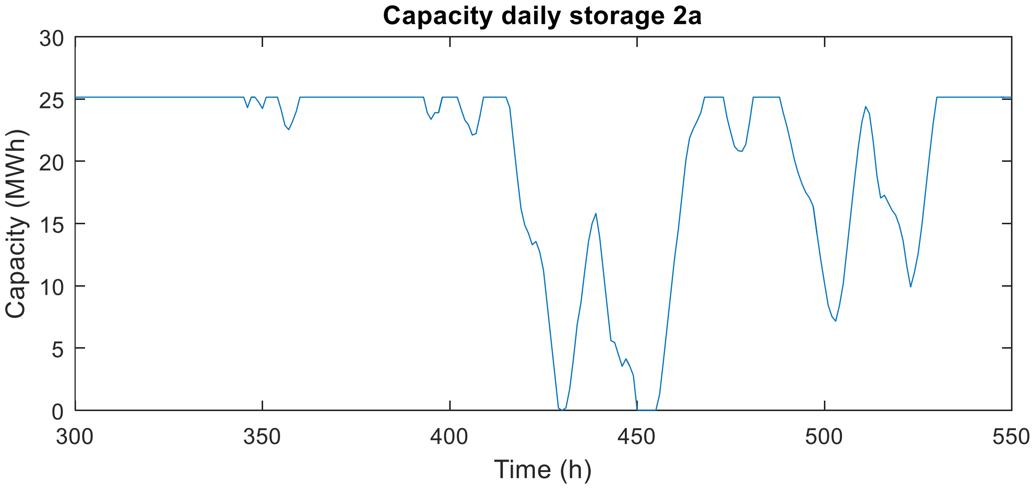


Figure 9-9 Capacity of the daily storage tank for LTDH concept 2a, using the first heat demand strategy.

Figure 9-8 shows the power behavior and Figure 9-9 shows the capacity for the daily storage tank during the 10 cold days. Before hour 400, the storage tank has the maximum capacity available for the peak moment. The storage tank decreases in capacity from 400 until 430. This is when the storage tank supplies the peak. After that, the tank will be heated somewhat to help during the peak between hour 430 and 450. There is still a peak between hours 450 until 455, but this will not be supplied by the daily storage tank as the tank has no capacity.

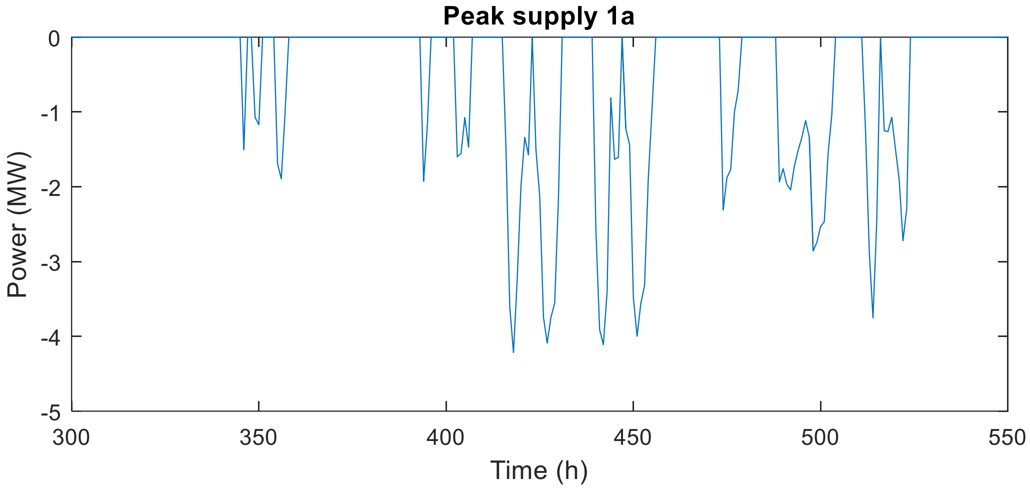


Figure 9-10 Heat supply by the biomass boiler for LTDH concept 1a, using the first heat demand strategy.

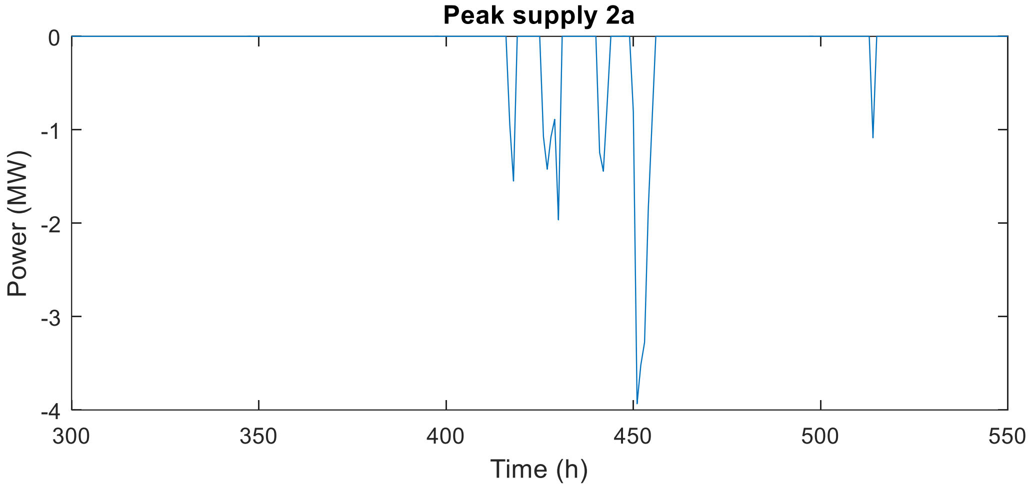


Figure 9-11 Heat supply by the electrical heaters for LTDH concept 2a, using the first heat demand strategy.

Figure 9-10 and Figure 9-11 show the peak supply of the heat concepts during 10 cold days. Concept 2a does not use the peak source until hour 410. Before that, the peak moments are fully covered by the storage tank. Between hours 420 and 460, for both LTDH concepts, heat is supplied by the peak source. However, the peaks are for concept 2a smaller, because a part of the peak is covered by the storage tank. Only the peak around hour 450 is the same for both concepts.

Table 9-1 shows the heat production of the ATES and peak source for the two LTDH concepts during the cold period, which is between 12 January and 23 January. Table 9-2 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

Table 9-1 Overview of the ATES and peak source heat production during a cold period for LTDH concept 1a and 2a and heat demand strategy 1.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is on [h]	Maximum heat production peak source [MW]
1a: Collective	757	151.4	72	4.22
2a: Decentral	842	27.7	17	3.93

Table 9-2 Overview of the ATES and peak source heat production throughout a whole year for LTDH concept 1a and 2a and heat demand strategy 1.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is on [h]	Total heat production peak source [MWh]
1a: Collective	3,786	8,112	135	233
2a: Decentral	3,835	8,681	18	28.7

The tables above reveal how during peak hours and in a year, the ATES produces and stores more heat for the concept with the water tank. In return, the decentral peak supply LTDH concept only requires 17 hours from the external peak source to meet the heat demand. In comparison with the collective peak supply concept, where the peak source supplies heat for 72 hours, the water tank can decrease the peak heavily.

Table 9-3 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1a and 2a and heat demand strategy 1.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1a: Collective	28,808	38,311	233	9,736	33.8
2a: Decentral	28,808	38,716	29	9,936	34.5%

Table 9-3 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 34 %. This is mainly caused by the recovery efficiency of the ATES, which is 30 %.

9.2.2 LTDH Concept 1b and 2b: 50 °C supply temperature

Figure 9-12 until Figure 9-18 presents the results of the energy balance for the LTDH concepts with 50 °C supply temperature for the coldest two weeks in January (12 until 23 January).

Figure 9-12 shows the heat difference between LTGH supply of 50 °C and the heat demand during 10 cold days. Most of the time, the difference is below 0 MW. This means that there is more heat demand than supplied by the LTGH, so the ATES source and peak sources needs to provide extra heat. The largest difference is around 9 MW.

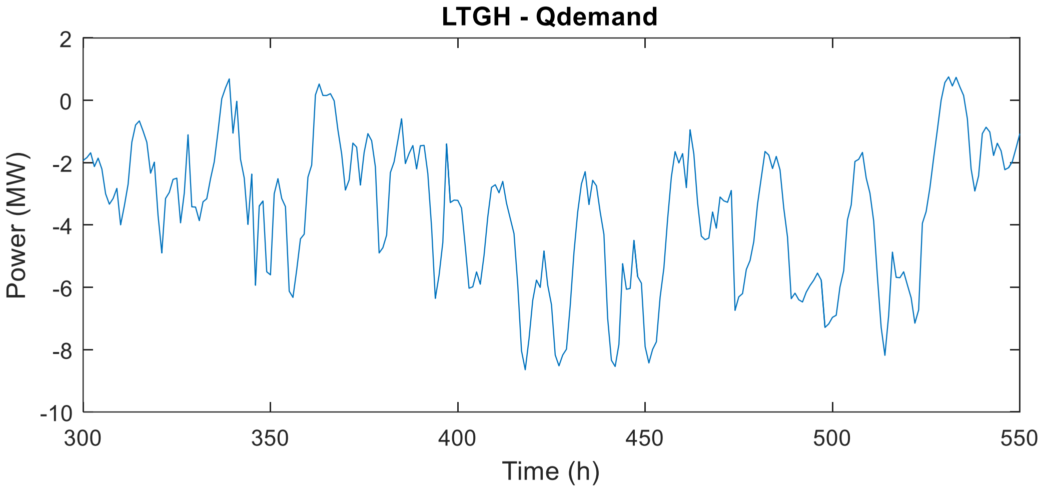


Figure 9-12 Heat difference between the LTGH supply and heat demand strategy 1, during the coldest two weeks for LTDH concept 1b and 2b.

Figure 9-13 and Figure 9-14 show the heat supply from the ATES source. The ATES for concept 2b provides more heat between hours 400 and 520, to supply heat to the daily storage tank. Total heat supply from the ATES source during these 10 cold days is less for concept 1b.

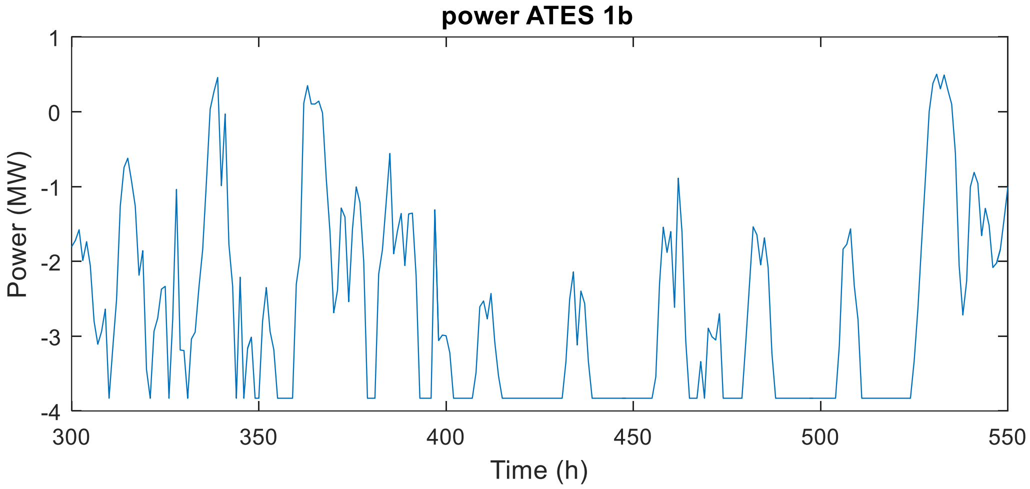


Figure 9-13 ATES supply power for LTDH concept 1b, where the peak is supplied by a central biomass boiler. The first heat demand strategy is applied.

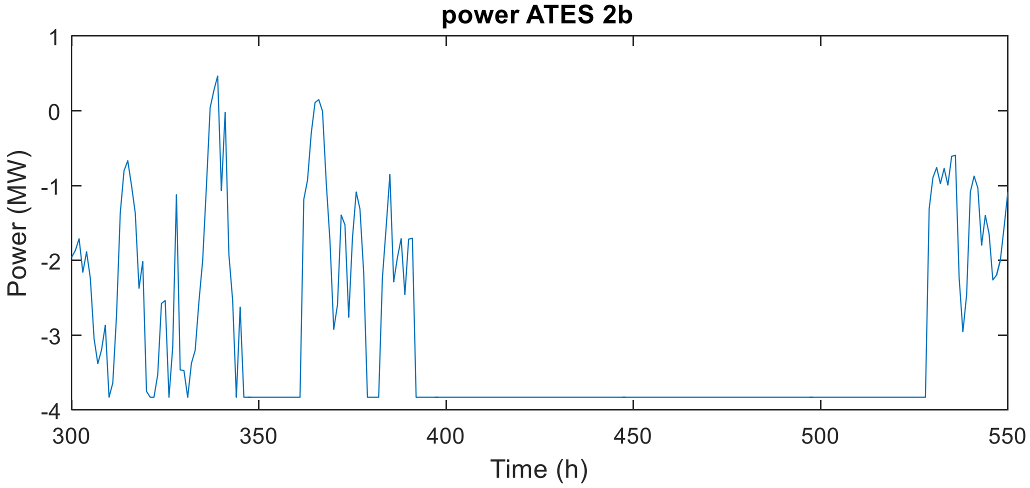


Figure 9-14 ATES supply power for LTDH concept 2b, where the peak is supplied at the home. The first heat demand strategy is applied.

Figure 9-13 and Figure 9-14 show the heat supply from the ATES source. The ATES for concept 2b provides more heat between hours 400 and 520, to supply heat to the daily storage tank. Total heat supply from the ATES source during these 10 cold days is less for concept 1b.

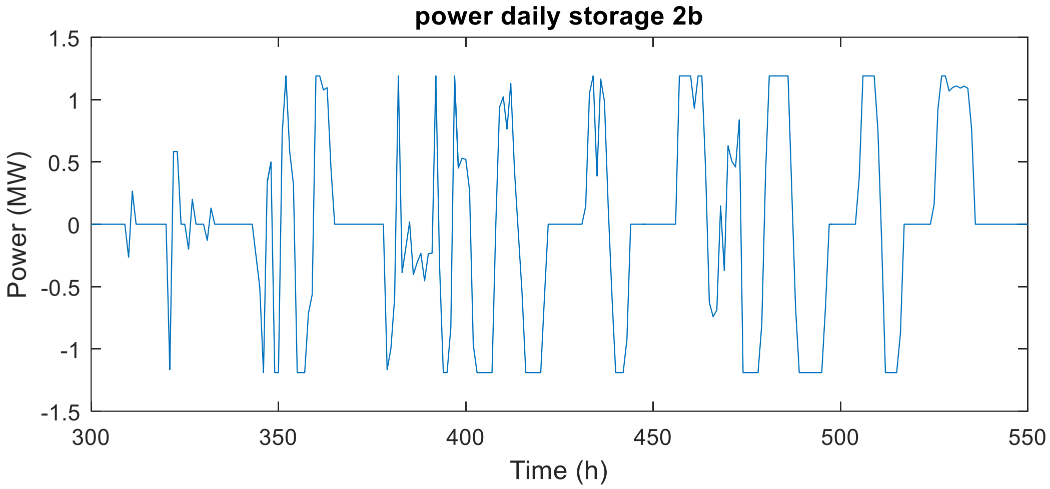


Figure 9-15 Power supply by the daily storage tank for LTDH concept 2b. The first heat demand strategy is applied.

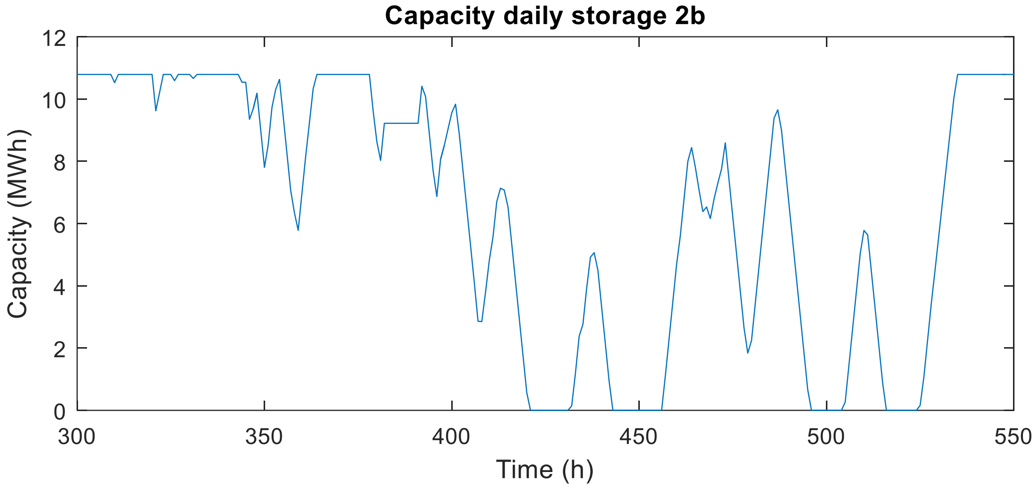


Figure 9-16 Capacity of the daily storage tank for LTDH concept 2b. The first heat demand strategy is applied.

Figure 9-15 shows the power behavior and Figure 9-16 shows the capacity for the daily storage tank during the 10 cold days. Before hour 400, the storage tank provides some heat to the homes and also stores a little heat. At hour 400, a peak occurs and the capacity of the water tank decreases significantly. Between hours 430 and 440, and hours 445 and 460, the water tank is empty and cannot help with supporting the peak. After that, the capacity of the water tank increases, so the water tank can help support the peak sources around hour 500.

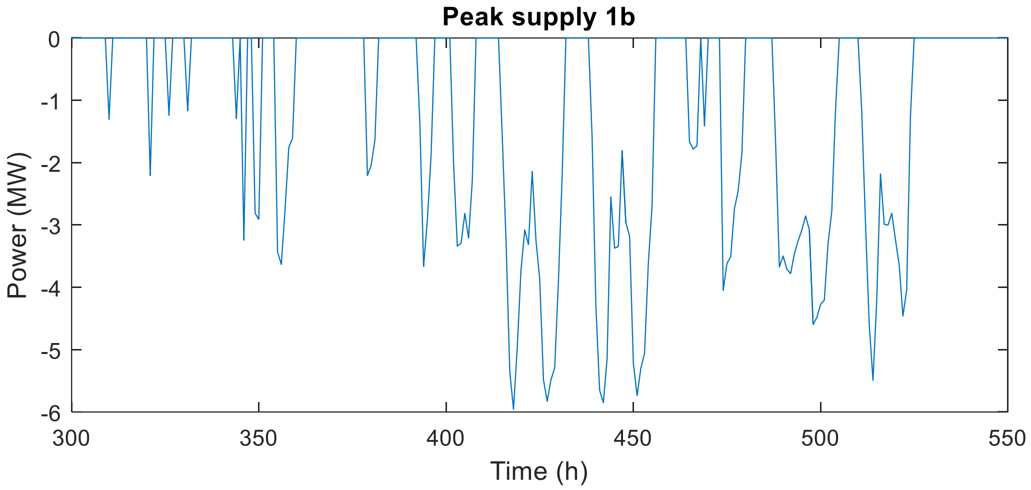


Figure 9-17 Heat supply from the biomass boiler for LTDH concept 1b. The first heat demand strategy is applied.

Figure 9-17 and Figure 9-18 shows the peak supply of the heat concepts during 10 cold days. Concept 2b does not supply the peak between hours 300 and 350, 365 and 385, and 460 and 470. The other moments, both concepts uses the peak sources. However, most of the heat usage of the peak source of concept 2b is less than from concept 1b, because a part of the peak is supplied by the water tank. Only during hours 425, 450, 490, and 520, the peak supply of the peak source is for both LTDH concepts the same.

Table 9-4 shows the heat production of the ATES and peak source for the two LTDH concepts during the cold period, which is between 12 January and 23 January. Table 9-5 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

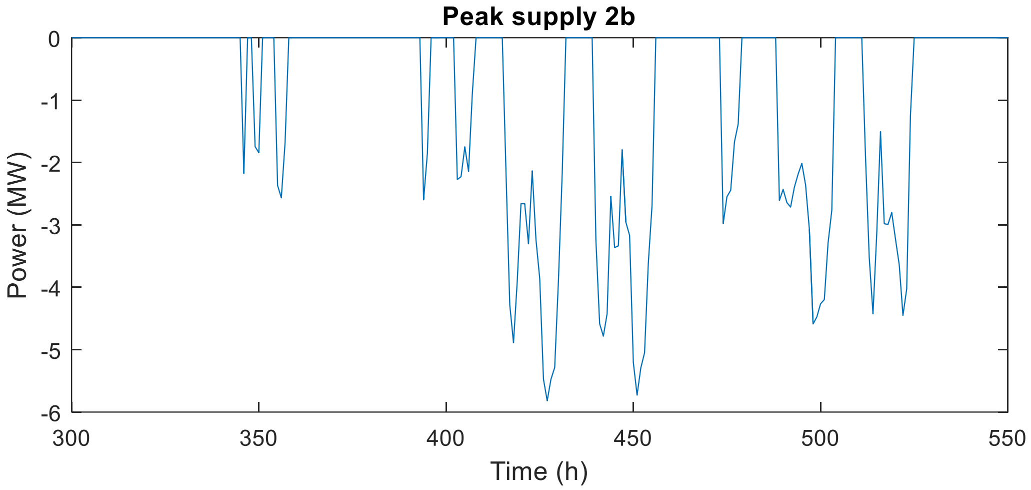


Figure 9-18 Heat supply from the electrical heaters for LTDH concept 2b. The first heat demand strategy is applied.

Table 9-4 Overview of the ATES and peak source heat production during a cold period for LTDH concept 1b and 2b and the first heat demand strategy.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is on [h]	Maximum heat production peak source [MW]
1b: Collective	740	326	101	5.95
2b: Decentral	779	246	78	5.82

Table 9-5 Overview of the ATES and peak source heat production throughout a whole year for LTDH concept 1b and 2b and the first heat demand strategy.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is on [h]	Total heat production peak source [MWh]
1b: Collective	3,959	7,348	295	741
2b: Decentral	4,286	7,609	151	392

The water tank reduces the time when the peak source supplies heat from 101 to 78 hours. For this supply temperature, the peak production is less with a water tank, but not significantly like when the supply temperature is 70 ⁰C. For the whole year, a water tank reduces the heat production with 50%. However, the heat storage and production of the ATES source is a bit higher when a water tank is used.

Table 9-6 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1b and 2b and heat demand strategy 1.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1b: Collective	28,808	36,572	741	8,504	29.5
2b: Decentral	28,808	36,602	392	8,186	28.4

Table 9-6 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 29 %. This is mainly caused by the recovery efficiency of the ATES, which is 25 %.

9.3 Heat demand strategy 2: Peak shaving

The whole process in section 9.2 is also executed for heat demand strategy 2, where the residents preheat their homes so the peak will shave. The related figures and remarks can be found in Appendix C. The most important results are given below.

9.3.1 LTDH Concept 1a and 2a: 70 ⁰C supply temperature

Table 9-7 shows the heat production of the ATES and the peak source for the two LTDH concepts during the cold period. Table 9-8 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

Table 9-7 Overview of the ATES and peak source heat production during a cold period for LTDH concepts 1a and 2a and heat demand strategy 2.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is supplying heat [h]	Maximum heat production peak source [MW]
1a: Collective	930	170	96	3.08
2a: Decentral	976	104	57	2.96

Table 9-8 Overview of the ATES and peak source heat production throughout a whole year for LTDH concepts 1a and 2a and heat demand strategy 2.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is supplying heat [h]	Total heat production peak source [MWh]
1a: Collective	4,657	7,806	117	187
2a: Decentral	4,675	7,853	57	104

The tables above shows that during peak hours and in one year, the ATES produces and stores more heat for the concept with the water tank. In return, the decentral peak supply LTDH concept only requires 57 hours of an external peak source to match the heat demand. In comparison with the collective peak supply concept, where the peak source supplies heat for 96 hours in the cold period and 117 hours in a year, the water tank can decrease the peak with +- 47%.

Table 9-9 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1a and 2a and heat demand strategy 2.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1a: Collective	30,248	39,538	187	9,478	31.3
2a: Decentral	30,248	39,736	104	9,592	31.7

Table 9-9 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 31.5 %. This is mainly caused by the recovery efficiency of the ATES, which is 30 %.

9.3.2 LTDH Concept 1b and 2b: 50 ºC supply temperature

Table 9-10 shows the heat production of the ATES and peak source for the two LTDH concepts during the cold period, with peak shaving applied by the residents. Table 9-11 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

Table 9-10 shows that the water tank of LTDH concept 2b reduces the peak source in 30 hours usage and 51 MWh of energy. The ATES needs to produce 40 MWh energy more to provide the heat to the tank. For longer cold periods, the water tank is not useful. However, over a year, the water tank saves 215 MWh of peak production. In addition, the ATES needs to produce and store 905 MWh and 96 MWh more heat.

Table 9-10 Overview of the ATES and peak source heat production during a cold period for LTDH concepts 1b and 2b and heat demand strategy 2.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is supplying heat [h]	Maximum heat production peak source [MW]
1b: Collective	830	446	158	4.84
2b: Decentral	870	395	128	4.83

Table 9-11 Overview of the ATES and peak source heat production throughout a whole year for LTDH concepts 1b and 2b and heat demand strategy 2.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is supplying heat [h]	Total heat production peak source [MWh]
1b: Collective	4,911	7,740	348	768
2b: Decentral	5,006	7,834	209	553

Table 9-12 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1b and 2b and heat demand strategy 2.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1b: Collective	30,248	37,813	768	8,333	27.5
2b: Decentral	30,248	37,866	553	8,171	27.0

Table 9-12 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 27.3 %. This is mainly caused by the recovery efficiency of the ATES, which is 25 %.

9.4 Heat demand strategy 3: Improve insulation

The whole proces in section 9.2 is also executed for heat demand strategy 3, where the thermal insulation of the buildings is improved. The related figures and remarks can be found in Appendix C. The most important results are given below.

9.4.1 LTDH Concept 1a and 2a: 70 ºC supply temperature

Table 9-13 shows the heat production of the ATES and peak source for the two LTDH concepts during the cold period, which is between 12 January and 23 January. Table 9-14 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

Table 9-13 Overview of the ATES and peak source heat production during a cold period for LTDH concepts 1a and 2a and heat demand strategy 3.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is supplying heat [h]	Maximum heat production peak source [MW]
1a: Collective	788	178	79	4.6
2a: Decentral	889	37.5	20	4.4

Table 9-14 Overview of the ATES and peak source heat production throughout a whole year for LTDH concepts 1a and 2a and heat demand strategy 3.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is supplying heat [h]	Total heat production peak source [MWh]
1a: Collective	4,429	8,086	169	299
2a: Decentral	4,442	8,251	21	38.4

Table 9-13 and Table 9-14 show that during peak hours and in one year, the ATES produces and stores more heat for the concept with the water tank. In return, the decentral peak supply LTDH concept only requires 20 hours of peak source usage to match the heat demand. In comparison with the collective peak supply concept where the peak source supplies heat for 79 hours, the water tank can decrease the peak heavily. Throughout the whole year, the peak source is only on for 21 hours when the insulation improves and the homes use a water tank.

Table 9-15 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1a and 2a and heat demand strategy 3.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1a: Collective	30,014	39,724	299	10,009	33.3
2a: Decentral	30,014	39,724	38	9,749	32.5

Table 9-15 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 33 %. This is mainly caused by the recovery efficiency of the ATES, which is 30 %.

9.4.2 LTDH Concept 1b and 2b: 50 ⁰C supply temperature

Table 9-16 shows the heat production of the ATES and peak source for the two LTDH concepts during the cold period, which is between 12 January and 23 January. Table 9-17 shows the heat production of the ATES and peak source for the two LTDH concepts throughout the whole year.

Table 9-16 Overview of the ATES and peak source heat production during a cold period for LTDH concepts 1b and 2b and heat demand strategy 3.

LTDH concept	Total heat production ATES [MWh]	Total heat production peak source [MWh]	Number of hours when peak source is supplying heat [h]	Maximum heat production peak source [MW]
1b: Collective	731	368	107	6.4
2b: Decentral	807	283	84	6.2

Table 9-17 Overview of the ATES and peak source heat production throughout a whole year for LTDH concepts 1b and 2b and heat demand strategy 3.

LTDH concept	Total heat production ATES [MWh]	Total heat storing ATES source [MWh]	Number of hours when peak source is supplying heat [h]	Total heat production peak source [MWh]
1b: Collective	4,488	7,848	339	897
2b: Decentral	4,834	7,887	166	454

From the tables above can be seen that LTDH concept 2b uses the peak source 23 hours less than concept 1b during 10 cold days. The water tank can barely reduce the peak during 10 cold days. However, throughout a whole year the water tank reduces the peak heat production from 897 MWh to 454 MWh.

Table 9-18 Overview of annual heat production by LTGH and heat loss by the system for LTDH concept 1b and 2b and heat demand strategy 3.

LTDH concept	Heat demand [MWh]	Heat production LTGH + heat pump [MWh]	Heat production peak source [MWh]	Heat losses [MWh]	Relative heat loss compared to demand [%]
1a: Collective	30,014	37,687	897	8,571	28.6
2a: Decentral	30,014	37,757	454	8,198	27.3

Table 9-18 shows the annual heat loss and the share of the heat loss to the heat demand. For both LTDH concepts, the share is around 28 %. This is mainly caused by the recovery efficiency of the ATES, which is 25 %.

9.5 Summary results

The previous section provides the outcomes of the energy balances for the whole networks. Since heat demand strategy 3 heats 2,900 homes and heat demand strategy 1 and 2 2,475 homes, it is difficult to compare the results. To compare the results, the heat consumption of the peak sources and ATES are divided over the number of homes in a district. This is presented in Table 9-19 for heat demand strategy 1. The results for the other two heat demand strategies are presented in

Table *9-20* and Table 9-21.

Table 9-19 Overview of the ATES and peak source heat production per home throughout a whole year and peak weeks for the first heat demand strategy.

LTDH concept	Heat extraction ATES during 10 cold days [kWh]	Heat production peak source at peak moment [kWh]	Total heat extraction ATES [kWh]	Total heat storing ATES source [kWh]	Total heat production peak source [kWh]	Total hours peak source on [h]
1a: Collective 70	305.9	61.2	1,530	3,278	94.1	135
1b: Collective 50	299.0	131.7	1,600	2,969	299.4	259
2a: Decentral 70	340.2	11.2	1,550	3,508	11.6	18
2b: Decentral 50	314.7	99.4	1,732	3,074	158.4	151

Table 9-20 Overview of the ATES and peak source heat production per home throughout a whole year and peak week for the second heat demand strategy.

LTDH concept	Heat extraction ATES during 10 cold days [kWh]	Heat production peak source at peak moment [kWh]	Total heat extraction ATES [kWh]	Total heat storing ATES source [kWh]	Total heat production peak source [kWh]	Total hours peak source on [h]
1a: Collective 70	375.8	68.7	1,882	3,154	75.6	117
1b: Collective 50	335.4	180.2	1,984	3,127	310.3	158
2a: Decentral 70	394.3	42.0	1,889	3,173	42	57
2b: Decentral 50	351.5	159.6	2,023	3,165	223.4	128

Table 9-21 Overview of the ATES and peak source heat production per home throughout a whole year and peak week for the third heat demand strategy.

LTDH concept	Heat extraction ATES during 10 cold days [kWh]	Heat production peak source during 10 cold days [kWh]	Total heat extraction ATES [kWh]	Total heat storing ATES source [kWh]	Total heat production peak source [kWh]	Total hours peak source on [h]
1a: Collective 70	271.7	61.4	1,527	2,788	103.1	169
1b: Collective 50	252.1	126.9	1,548	2,706	309.3	339
2a: Decentral 70	306.6	12.9	1,532	2,845	13.2	21
2b: Decentral 50	278.3	97.6	1,667	2,720	156.6	166

For every heat demand scenario, it is visible that the LTDH with 50 ^{o}C supply temperature needs to provide more heat from the peak source than an LTDH with 70 ^{o}C supply temperature. This is the case during 10 cold days and throughout the whole year. During peak hours, 70 ^{o}C LTDH concepts use more heat from the ATES, but throughout the whole year the 50 ^{o}C LTDH concepts requires more heat from the ATES source. Because an LTGH with a 70 ^{o}C supply temperature produces more heat than an LTGH with 50 ^{o}C supply temperature, heat from the ATES is less needed. This also leads to more storage of the ATES at 70 ^{o}C supply temperature.

For each supply temperature and heat demand strategy, energy production from the peak source is less when a water tank is installed at the homes. This is for a whole year and during 10 cold days. Throughout the whole year, it does not have an influence on the ATES source if a water tank is installed. From the tables above, one can see that when the supply temperature is 70 °C in the network, the peak source is minimally on. The least energy production by the peak source is for concept 2a and heat demand strategy 1, where the electrical heaters need to produce 11.6 kWh in a year for only 18 hours. If the supply temperature is 50 °C, the electrical heaters produce more heat.

Heat demand strategy 2, where the residents use a heavy form of peak shaving, leads to an increase in the use of the peak source, throughout the whole year and during 10 cold days. This applies to each LTDH concept, compared to the first heat demand strategy. Also, the ATES source needs to produce more energy than when residents do not use peak shaving. This can be explained by equation 6. This shows that the average heat demand for 24 hours increases when the average outside temperature is below 5 °C. The only positive impact of peak shaving, is that the maximum peak mostly reduces with 1MW in the whole network, which is 0.4 kW for one home.

Improving the insulation reduces the heat demand significantly. Therefore, the whole network is increased to 2,900 homes. This leads to more pipes in the network and more supply sets, and therefore leads to more heat loss in the total system. This phenomenon can be seen in the results of Table 9-21 compared to the results of Table 9-19. However, the use of the peak source throughout the whole year and during the 10 cold days is so small that it can be neglected. The heat storing and production of the ATES source decreases for each LTDH concept.

10. Results KPIs

10.1 Introduction

This chapter presents the results of the calculated KPIs. The calculations are performed as explained in sections 6.6, 6.7, and 6.8 and the results of Chapters 8 and 9. The parameters, which are used, are from the following tables/equations.

- CO_2 emission from Table 6-12
- Electricity usage from section 6.6
- Used costs from Table 6-13 and Table 6-14

For each heat demand scenario the results of the KPIs are given. Electricity usage during peak hours are presented as well as the total electricity usage, CO_2 emission and costs over 30 years. The used Excel spreadsheets and exact outcomes are given in Appendix D (electricity usage), E (CO_2 emission), and F (LCOE).

Heat demand strategies 1 and 2 are used to heat 2,475 homes. Heat demand strategy 3 is used to heat 2,900 homes. To compare the results of the heat demand strategies, the results in electricity usage, CO_2 emission, and LCOE are converted to usage per home.

10.2 Heat demand strategy 1: Current heat demand

10.2.1 Electricity usage

Figure 10-1 shows the electricity usage during 10 cold days and Table 10-1 shows the total electricity usage of the LTDH concepts and reference concept for heat demand strategy 1.

Table 10-1 Total electricity usage of the heating concepts for one home for heat demand strategy 1.

LTDH concept	Electricity during peak [kWh]	Electricity in a year [kWh]	Electricity over 30 years [MWh]
1a: 70 collective	205.63	6,854	205.6
1b: 50 collective	213.45	6,249	187.5
2a: 70 decentral	247.85	6,853	205.6
2b: 50 decentral	317.18	6,413	317.2
3: Decentral heat pumps	213.04	4,173	125.2
Reference	332.56	5,186	155.6

The difference in the yearly electricity consumption between the two LTDH concepts with 50 ^{o}C supply temperature is 164 kWh and for the LTDH with 70 ^{o}C it is 1 kWh. During the 10 cold days, the difference in electricity consumption is 119.8 kWh and 42.2 kWh for the 50 ^{o}C and 70 ^{o}C supply temperature. The LTDH concepts with 50 ^{o}C supply temperature uses the least electricity in both cases. During peak hours, decentral peak supply LTDH concepts uses the most electricity of all the LTDH concepts. This is because the electrical heaters have to produce a considerable amount of electricity. Electricity usage for collective and decentral peak supply for 70 ^{o}C supply temperature are in one year more or less the same.

During the 10 cold days, electricity usage of the decentralized heat pumps fluctuates somewhat. However, peak electricity usage per home is in an hour only 1.48 kW. Throughout the year, this concept consumes the least electricity per home, 4,173 kWh in a year.

During the 10 cold days, the reference scenario uses the most electricity out of all the concepts, which is 332.56 kWh per home and with a highest peak of 3.48 kW. However, over the whole year, the reference concept uses the second least electricity of all the LTDH concepts.

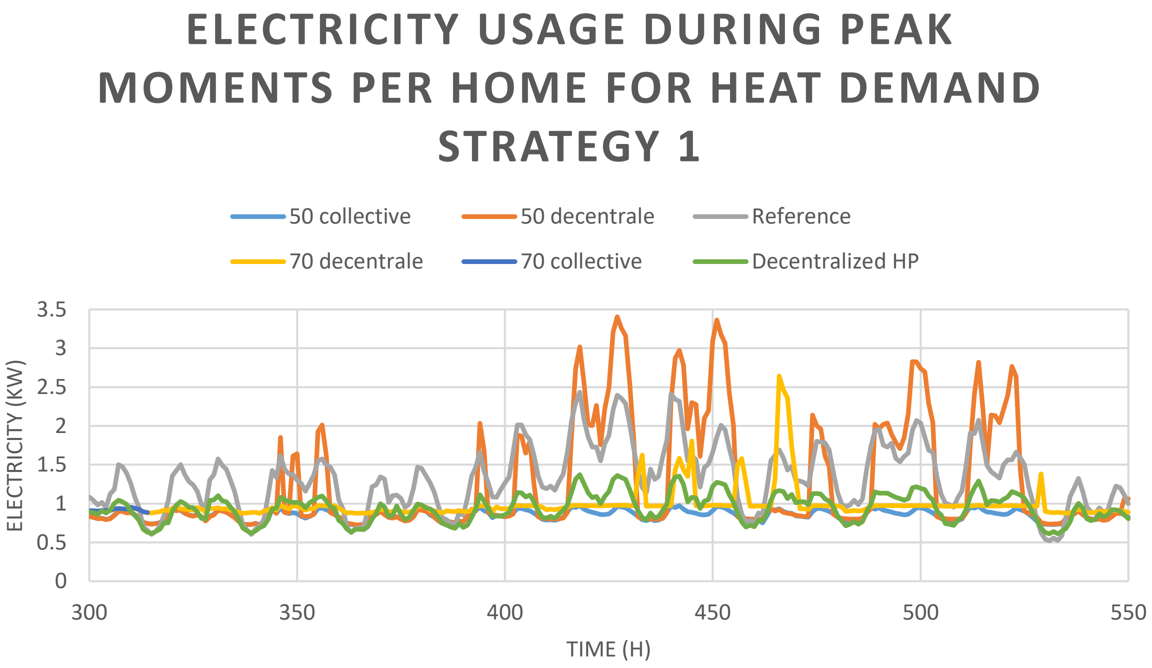


Figure 10-1 Electricity usage of the LTDH concepts during the cold week of the heating concepts for one home, when heat demand strategy 1 is applied.

Table 10-2 and Table 10-3 show the share of electricity consumption per technology for the LTDH concepts per year and during the 10 cold days. Both tables show that 90% of the total electricity usage is used by the collective heat pump and LTGH well pump for LTDH concepts 1 and 2. Moreover, the tables show that there is not a significant difference in the electricity usage between heating the peak at collective or home level. However, during peak hours it makes a difference when the supply temperature in the LTDH is 50 ^{0}C. LTDH concept 2b uses 33% of the total electricity usage for the electrical heaters during the 10 cold days. This is caused, because the water tank cannot supply sufficient heat to the homes.

The largest influence on the electricity usage of LTDH concept 3 are the decentral heat pumps. This is 58.4% throughout the whole year and 75 % during the 10 cold days. The decentral heat pump's consumption is lower than for the collective heat pumps, because the COP of the decentral heat pumps is higher.

Table 10-2 Relative share of electricity usage for each technique throughout the whole year, without influences on the heat demand. The values are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	72.7	0.19	23.7	3.4	-	-	-
1b: 50 collective	62.0	0.46	26.0	3.6	-	7.9	-
2a: 70 decentral	72.7	0.10	23.7	3.3	0.18	-	-
2b: 50 decentral	60.5	0.21	25.3	3.6	2.67	7.95	-
3: Decentral heat pumps	-	0.84	35.1	5.6	-	-	58.4

Table 10-3 Relative electricity usage for each technique during 10 cold days, without influences on the heat demand. The values are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	73.0	0.8	19.8	6.4	-	-	-
1b: 50 collective	62.6	2.1	21.8	6.5	-	7.0	-
2a: 70 decentral	69.3	0.4	18.8	6.8	4.8	-	-
2b: 50 decentral	42.1	0.6	14.7	4.9	33.0	4.7	
3: Decentral heat pumps	-	2.2	19.7	3.1	-	-	75.0

For the LTDH concepts with 50 ^{o}C supply temperature, the influence of the BHP on the total electricity usage is around 7.9% for both concepts. During the peak hours, the share of the BHP decreases. The influence of increasing the temperature to use for DHW is not that much per home.

10.2.2 CO$_2$ emission

Table 10-4 shows the CO$_2$ emission per household for 30 years during the use of the LTDHs and reference concept. The difference between the two network-concepts with 50 ^{o}C is 319 kg over 30 years. CO$_2$ emission for the decentral network is a bit higher, despite the effect of the biomass boiler. The biomass boiler has a bigger impact on the CO$_2$ emission for the 70 ^{o}C supply temperature, because this peak source has to be powered on more frequently than the electrical heaters for this supply temperature. The difference between the two network-concepts with 70 ^{o}C are 304 kg over 30 years. This is less than the 50 ^{o}C, because the peak sources are less needed. The impact of collective or decentral peak supply on the CO$_2$ emission is small.

Heating with a lower supply temperature in the network has a bigger impact on CO$_2$ emissions. When a collective heat pump is used in the LTDH system, 50 ^{o}C as supply temperature emits around 3,800 kg less CO$_2$ compared with 70 ^{o}C. This is lower, because the electricity usage by the 50 ^{o}C network is much lower.

The least CO$_2$ emission is emitted in LTDH concept 3, because it uses the least electricity. The reference concept emits 39.5 tons of CO$_2$ emission per home over 30 years. The emission is only caused by the use of electricity. Since the reference scenario uses the second least electricity, it emits the second least CO$_2$.

Table 10-4 CO$_2$ emission over 30 years per home.

LTDH concept	CO$_2$ emission over 30 years [kg]
1a: 70 collective	52,473
1b: 50 collective	48,503
2a: 70 decentral	52,169
2b: 50 decentral	48,822
Decentralized heat pumps	31,764
Reference	39,484

10.2.3 LCOE

Table 10-5 shows the costs divided per home which are incurred during installation and usage of the network. At every cost aspect, the costs for the collective peak supply LTDH concepts are a bit higher than for a decentral peak supply LTDH concept. This can be explained by the higher costs of the biomass source and the pipes in the network. For 70 °C network, the investment costs for the biomass boiler and pipe network are 6.33 million and 7.78 million euros, and for 50 °C network these investment costs are 8.93 million and 10.8 million euros. The investment costs for a water tank are 4.46 million euros for both concepts and for the heaters it is 0.79 million and 1.16 million euros for the supply temperatures 70 and 50 °C networks. The pipe network respectively costs 7.05 and 9.97 million euros for a decentral peak supply LTDH with 70 and 50 °C supply temperature. These numbers are the total costs, and not spread out over the homes. Moreover, decentral peak supply concepts have lower fuel prices and maintenance costs per year. This results in lower LCOE for decentral peak supply solutions. However, in total the differences are only 0.012 €/kWh for the 70 °C options and 0.021 €/kWh for the 50 °C. Therefore, it might be argues that it does not matter for LCOE to heat decentral or collective.

The investment costs for a 70 °C temperature network are in both cases less than for a 50 °C network. This is because 50 °C networks have higher costs for the pipe network and also needs a BHP for DHW. This also results in higher maintenance costs for a 50 °C network. Despite the fact that the price of fuel for a 50 °C network is less, because of the lower electricity consumption, the total LCOE is less for a 70 °C network.

The lowest LCOE is for LTDH concept 3, where every home has a decentral heat pump. This is mainly caused by the low price of fuel. Even though, the decentral heat pumps needs to be replaced after 15 years, the price of fuel has the most impact on this. The impact of the price of fuel on the total LCOE is given in Table 10-6.

The reference scenario is rather straight forward. The investment cost per household is the investment in and installation of an air heat pump and an electrical boiler. The investment of the heat pump needs to be done twice, since the heat pump has a lifetime of 15 years. The second investment is done in year 15. Since electricity usage is the lowest, the price of fuel is the least for the reference scenario.

Table 10-5 CAPEX, OPEX, price of fuel, and LCOE for the heating concepts per home.

LTDH concept	CAPEX [€]	OPEX [€/year]	Price of fuel [€/year]	LCOE [€/kWh]
1a: 70 collective	11,464	240	1,237	0.198
1b: 50 collective	15,355	338	1,137	0.222
2a: 70 decentral	10,727	161	1,234	0.186
2b: 50 decentral	13,684	187	1,154	0.201
Decentralized heat pumps	[6]12,365	211	751	0.168
Reference	[7]10,300	362	934	0.202

Appendix F outlines the share of the techniques' costs on the total investment costs and operational costs. The most important results is that in general the LTGH, without central heat pump, and network pipes have the biggest impact on all the cost categories. Both techniques have a share between 20 and 30 % for the first 4 LTDH concepts. For the decentralized and reference concepts, the heat pumps have the biggest impact on total costs.

---

[6] This is in year 1. € 2,500 ,- needs be invested again in year 15, to replace the heat pump

[7] This is in year 1. € 7,800 ,- needs be invested again in year 15, to replace the heat pump

Table 10-6 shows what the share is of the costs category. These are relatively similar for each LTDH concept with a central heat pump. The price of fuel, the highest category, fluctuates between 70.4 and 56.6 % share. The investment costs are between 20 and 36 % of the total costs.

For LTDH concept 3, the investment costs have a higher share of the total cost because the resident has to invest twice in a heat pump. The same applies for the reference concept.

Table 10-6 Relative costs per concept split up by cost category for heat demand strategy 1.

LTDH concept	Investment costs	Maintenance costs	Price of fuel
1a: 70 collective	20.6	12.9	66.5
1b: 50 collective	25.2	18.2	56.6
2a: 70 decentral	20.4	9.2	70.4
2b: 50 decentral	25.4	10.4	64.2
3: Decentral heat pumps	33.9	14.5	51.6
Reference	44.4	26.6	29.0

10.3 Heat demand strategy 2: Peak shaving

10.3.1 Electricity usage

Figure 10-2 shows the electricity usage during 10 cold days and Table 10-7 shows the total electricity usage of the LTDH concepts and reference concept for heat demand strategy 1.

Table 10-7 Total electricity usage of the heating concepts for one home for heat demand strategy 2.

LTDH concept	Electricity during peak [kWh]	Electricity in a year [kWh]	Electricity over 30 years [MWh]
1a: 70 collective	239.5	6,886	206.6
1b: 50 collective	217.4	6,430	192.9
2a: 70 decentral	283.3	6,924	207.7
2b: 50 decentral	383.4	6,653	199.6
3: Decentral heat pumps	256.6	4,420	132.6
Reference	414.4	5,624	168.7

The difference in the yearly electricity consumption between the two LTDH concepts with 50 ^{o}C supply temperature is 223 and 38 kWh with 70 ^{o}C supply temperature. During the 10 cold days, the difference in electricity consumption is 166 and 45 kWh for the 50 and 70 ^{o}C supply temperatures. For both scenarios, the decentralized peak supply option uses the most electricity. The big difference for the 50 ^{o}C supply temperature is mainly caused from the use of the electrical heaters. The peak use for concept 2b, is 3.05 kW per home.

The LTDH concepts with 50 ^{o}C supply temperature show lower electricity usage per year than 70 ^{o}C. This is lower due to the fact that the COP of the 50 ^{o}C supply temperature is much higher. The total electricity usage by the LTDH concepts with 70 ^{o}C supply temperature remains constant throughout a year. For 50 ^{o}C, the collective sources uses less electricity.

As can be seen from Figure 10-2, the decentralized heat pumps' electricity usage fluctuates somewhat, with a peak electricity usage of 1.48 kW in an hour. Throughout the year, this concept has the lowest electricity usage per home at 4,420 kWh.

During the 10 cold days, the reference scenario uses the most electricity out of all the concepts, which is 414.4 kWh per home and has a peak of 3 kW at one hour. However, over the whole year, the reference concept uses the second least electricity of all the LTDH concepts. The reason for this is the high COP value when the outside temperature is high.

Therefore, during cold moments, this concept uses the most electricity. During moments when there is a need for space heat, but the outside temperature is above 10 °C, this concept uses the least electricity.

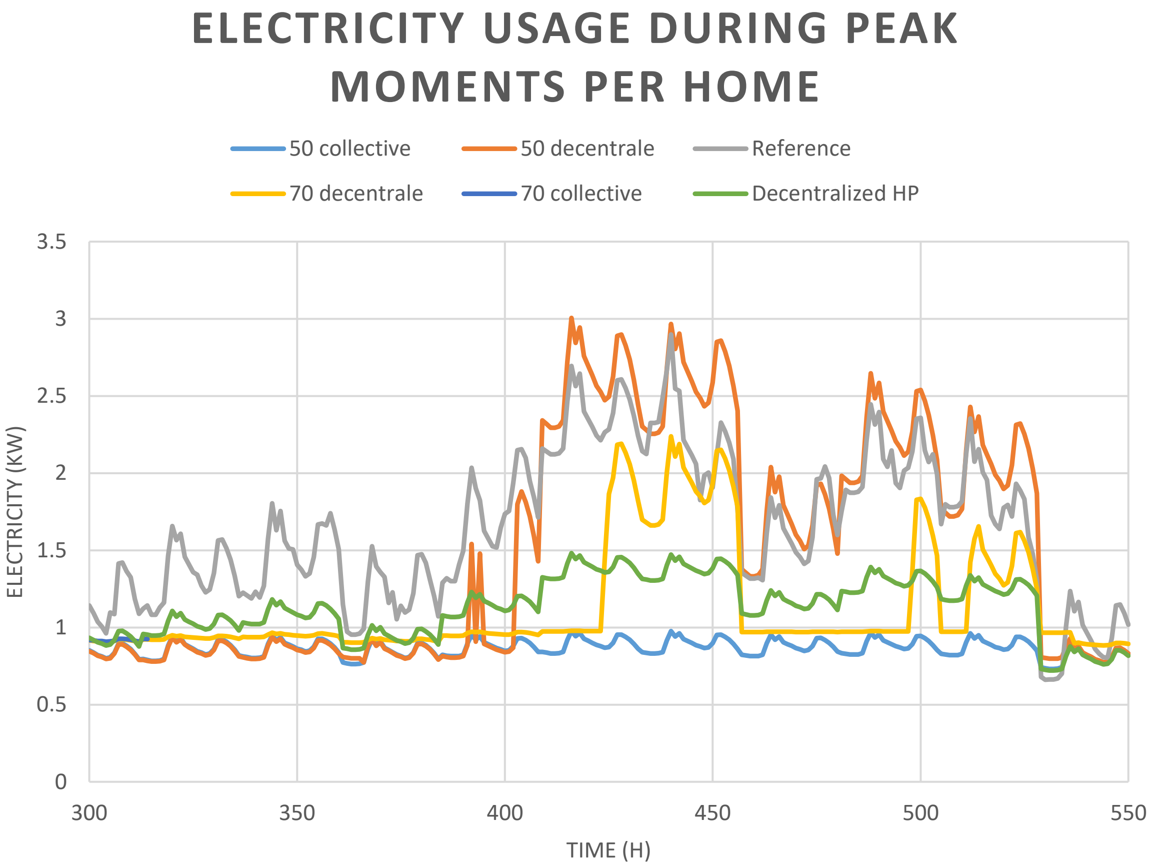


Figure 10-2 Electricity usage during the cold week of the heating concepts for one home, with the peak shaving strategy.

Table 10-8 and The influence of the BHP for 50 °C supply temperature throughout the year is between 7 – 8 %. During peak hours, the relative electricity usage of the BHP becomes less, because of the large usage of electrical heaters.

Table 10-9 show the share of electricity consumption per technology for the LTDH concepts per year and during 10 cold days, when the residents use the peak shave strategy. Both tables show that 90 % of the total electricity usage is used by the LTGH well pump and collective or decentral heat pumps. Only during peak moments LTDH concept 2b needs 43.8 % of the electricity for the electrical heaters. This is because the water tank cannot supply sufficient heat to the homes. Even with peak shaving, the capacity of the water tank is too low. For concept 2a, the electrical heaters require 15.6% of the total electricity usage during the 10 cold days.

Table 10-8 Relative electricity usage per technology throughout the whole year, with the peak shaving strategy. These are parameters are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	72.6	0.24	23.6	3.56	-	-	-
1b: 50 collective	62.6	0.54	25.3	3.86	-	7.7	-
2a: 70 decentral	72.2	0.13	23.5	3.54	0.63	-	-

2b: 50 decentral	60.5	0.27	24.4	7.5	3.53	7.5	-
3: Decentral heat pumps	-	0.72	33.1	5.5	-	-	60.7

The influence of the BHP for 50 °C supply temperature throughout the year is between 7 – 8 %. During peak hours, the relative electricity usage of the BHP becomes less, because of the large usage of electrical heaters.

Table 10-9 Relative electricity usage per technology during 10 cold days, with the peak shaving strategy. These are parameters are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	71.7	1.2	19.4	7.7	-	-	-
1b: 50 collective	61.5	2.7	21.4	7.6	-	6.8	-
2a: 70 decentral	60.6	0.5	16.4	6.8	15.6	-	-
2b: 50 decentral	34.9	0.8	12.1	4.5	43.8	3.9	
3: Decentral heat pumps	-	2.2	16.4	2.7	-	-	78.7

10.3.2 CO_2 emission

Table 10-10 shows the CO_2 emission per home for 30 years for the LTDHs and reference concept, when the residents apply the peak shaving strategy. The emission difference between the collective and decentral concepts, with a central heat pump, is so low that it is neglect able. For the CO_2 emission, it does not make a difference if an LTDH supplies the peak on a collective or decentral level.

The impact of heating with a lower supply temperature in the network does have an influence on CO_2 emission. When an LTDH supplies heat at 50 °C, between 2,050 and 2,750 kg CO_2 emission will be saved. This is lower, because of lower electricity usage in the 50 °C network.

The lowest CO_2 emission lowest for LTDH concept 3, as it uses the least electricity. The reference concept emits 42.8 tons of CO_2 per home in 30 years.

Table 10-10 CO_2 emission over 30 years per home for heat demand strategy 2.

LTDH concept	CO_2 emission over 30 years [kg]
1a: 70 collective	52,657
1b: 50 collective	49,914
2a: 70 decentral	52,712
2b: 50 decentral	50,649
Decentralized heat pumps	33,649
Reference	42,816

10.3.3 LCOE

Table 10-11 shows the costs for each cost category per home, if the residents apply the peak shaving strategy. At every cost aspect, the collective peak supply LTDH concepts cost more than a decentral option. This can be explained by the high costs of the biomass source and the pipes in the network. These costs are 4.51 million and 7.52 million euros for the 70 °C and 7.26 million and 9.45 million euros for the 50 °C network. An investment for the water tanks is 4.46 million euros for both concepts and for the heaters it is 0.592 million and 0.966 million euros for LTDH 1b and 2b. However,

in the total LCOE the difference is only 0.005 €/kWh and 0.014 €/kWh for the 70 and 50 ^{0}C supply temperatures. Therefore, one can argue that it does not matter for the LCOE where the peak heat is supplied.
There is a difference in LCOE for the different supply temperatures. The investment and maintenance costs are lower for a 70 ^{0}C network than for a 50 ^{0}C network. This is because the biomass boiler requires more power and pipe diameters are larger. Despite the fact that lower supply temperatures leads to lower fuel costs, the LCOE is for a 70 ^{0}C network lower than for a 50 ^{0}C network.

LTDH concept 3, in which every home has a decentral heat pump, has the lowest LCOE. This is mainly caused by the low price of fuel. This is the case even when taking into account that the heat pumps have to be replaced after 15 years. The impact of the price of fuel on the total LCOE is given in Table 10-12.

Just like at heat demand strategy 1, the reference scenario is rather straight forward. The resulting investment costs and maintenance costs are the same for the standard heat demand strategy. The maintenance costs are the highest for this concept and have a big impact on the total LCOE. Only concept 1b is more expensive.

Table 10-11 CAPEX, OPEX, price of fuel, and LCOE for the heating concepts per home for heat demand strategy 2.

LTDH concept	CAPEX [€]	OPEX [€/year]	Price of fuel [€/year]	LCOE [€/kWh]
1a: 70 collective	10,622	213	1,243	0.182
1b: 50 collective	14,138	308	1,170	0.205
2a: 70 decentral	10,613	147	1,246	0.177
2b: 50 decentral	13,137	185	1,198	0.191
Decentralized heat pumps	12,457	223	796	0.165
Reference	10,300	362	1,012	0.199

Appendix F provides the relative costs of the techniques on the total investment costs and operational costs. The results are quite similar to the first heating strategy, where the biggest impact on the costs are the LTGH, without central heat pump, and the pipe network. Both are between 20 and 30 % for the LTDHs and have more than 50 % influence on both cost categories.

Table 10-12 shows the relative costs per concept by cost category. These are similar for each LTDH with a central heat pump. When the supply temperature is 70 ^{0}C, investment have a share of approximately 20%, maintenance 10% and fuel 70%. For LTDH with a supply temperature of 50 ^{0}C, the investment have a share of 24 %, the maintenance 15 % and the price of fuel 70 %.

For LTDH concept 3 and the reference concept, the investment costs for both approximately 31 % and the price of fuel 52%. Only the maintenance costs for air-water heat pump are more and therefore have a higher impact on the total costs.

Table 10-12 Relative costs per concept split up by cost category for heat demand strategy 2.

LTDH concept	Investment costs	Maintenance costs	Price of fuel
1a: 70 collective	19.6	11.8	68.6
1b: 50 collective	24.2	15.8	60.0
2a: 70 decentral	20.3	8.4	71.3
2b: 50 decentral	24.0	10.2	65.8
3: Decentral heat pumps	32.8	14.7	52.5
Reference	30.5	18.3	51.2

10.4 Heat demand strategy 3: Improve insulation

10.4.1 Electricity usage

Figure 10-3 shows the electricity usage during 10 cold days and Table 10-13 shows the total electricity usage of the LTDH concepts and reference concept for heat demand strategy 3.

The difference in the yearly electricity consumption between the two LTDH concepts with 50 ^{o}C supply temperature is 161 kWh and for the LTDH with 70 ^{o}C it is 13 kWh. On a yearly basis, it does not matter where the peak is supplied. However, during peak moments the decentralized peak supply option with 50 ^{o}C uses 103 kWh more electricity than the collective option, with peaks of 3.05 kW for decentral and less than 1 kW for collective peak supply.

When the supply temperature is 70 ^{o}C, the difference in peak moments is smaller, namely 6.6 kWh. Less electricity is required in a year when the supply temperature in the network is at 50 ^{o}C, because of the higher COP of the central heat pump.

Table 10-13 Total electricity usage for the heating concepts for one home with heat demand strategy 3.

LTDH concept	Electricity during peak [kWh]	Electricity in a year [kWh]	Electricity over 30 years [MWh]
1a: 70 collective	210.7	5,874	176.2
1b: 50 collective	183.9	5,545	166.4
2a: 70 decentral	216.1	5,887	176.6
2b: 50 decentral	286.9	5,706	171.2
3: Decentral heat pumps	230.1	4,163	124.9
Reference	340.2	4,976	149.3

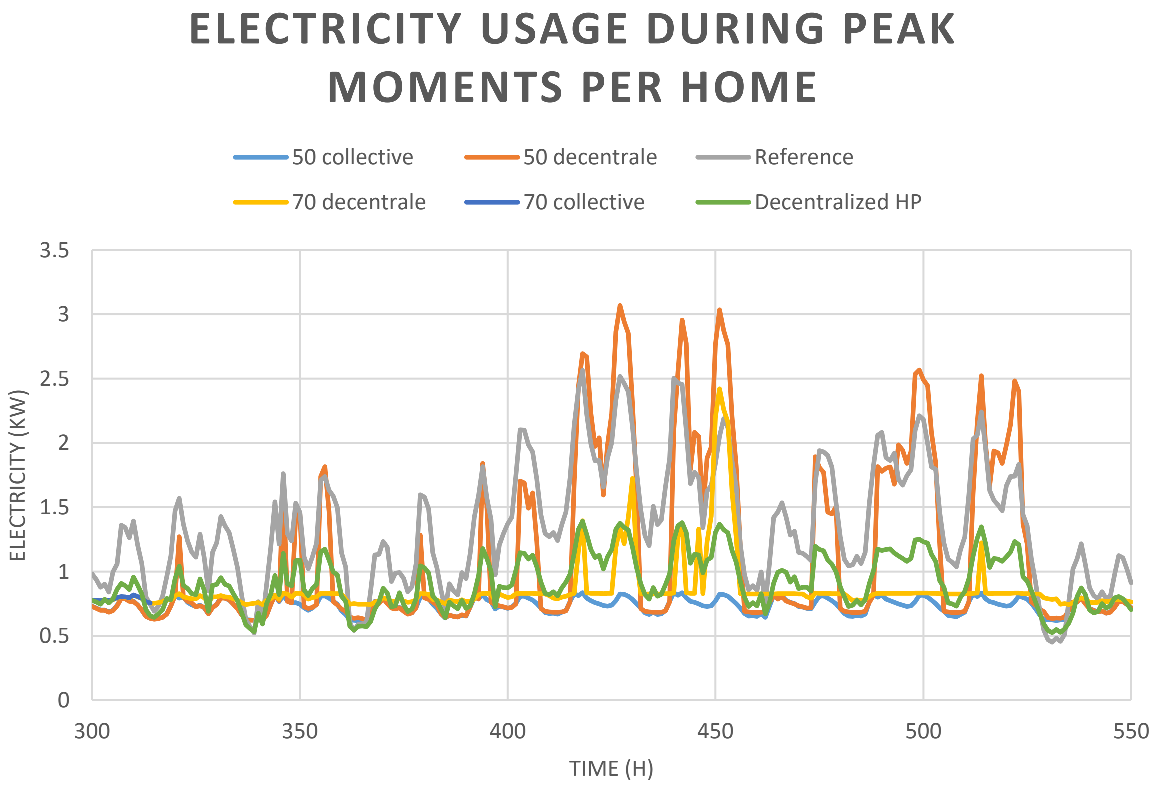


Figure 10-3 Electricity usage during the 10 cold days of the LTDH concepts and reference for one home when extra insulation measures are applied.

During the 10 cold days, electricity usage of the decentralized heat pumps fluctuates somewhat, but the peak electricity usage per home in one hour is 2.05 kWh. Throughout the year, this concept has the lowest electricity usage per home, at 4,163 kWh. Taken together, this heat demand scenario has the lowest electricity usage during peak hours, but also throughout the whole year.

The reference scenario uses the most electricity in the 10 cold days, because the COP is very low. Over the whole year, the average COP is higher which leads to an electricity consumption of 4,976 kWh per home.

Table 10-14 and Table 10-15 show the relative electricity consumption per technology for the LTDH concepts per year and the 10 cold days, with insulation measures. Just like the other heat demand strategies, the LTGH source and collective heat pump requires the most electricity.

Table 10-14 Relative share of the total electricity usage for every technique throughout the whole year, with insulation measures. These are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	72.7	0.21	23.6	3.5	-	-	-
1b: 50 collective	62.0	0.4	25.0	3.7	-	8.9	-
2a: 70 decentral	72.5	0.11	23.6	3.6	0.24	-	-
2b: 50 decentral	60.2	0.2	24.3	3.7	2.9	8.7	-
3: Decentral heat pumps	-	0.6	33.3	5.3	-	-	60.8

Table 10-15 Relative share of the total electricity usage for every technique during 10 cold days, with insulation measures. These are provided in percentages.

LTDH concept	Collective heat pump	Circulation pump	LTGH well pump	ATES pump	Electrical heaters	Booster heat pump	Decentral heat pump
1a: 70 collective	72.7	0.96	19.7	6.7	-	-	-
1b: 50 collective	62.0	1.6	21.6	6.7	-	8.1	-
2a: 70 decentral	67.9	0.47	18.4	7.0	6.3	-	-
2b: 50 decentral	39.8	0.61	13.8	4.8	35.9	5.2	-
3: Decentral heat pumps	-	1.6	17.3	2.7	-	-	78.4

10.4.2 CO_2 emission

Table 10-16 shows the CO_2 emission per home for 30 years for the LTDHs and reference concept, with insulation measures applied. Insulation has a positive impact on the CO_2 emission of an LTDH with LTGH. Compared to heat demand scenario 1, all the networks with a central heat pump saves more than 6,000 kg CO_2 emission.

As with the other heat demand strategies, 50 ^{0}C supply temperature emits less CO_2 than 70 ^{0}C, because less electricity is used. The difference between the collective and decentral peak supply LTDH is marginal.

Table 10-16 CO_2 emission over 30 years per home for heat demand strategy 3.

LTDH concept	CO_2 emission over 30 years [kg]
1a: 70 collective	45,038
1b: 50 collective	43,173
2a: 70 decentral	44,818
2b: 50 decentral	43,340
Decentralized heat pumps	31,693
Reference	37,882

10.4.3 LCOE

Investment costs for this heat demand strategy are higher than the two other strategies. This is because the homes are insulated. According to Table 6-13 and Table 6-15, the price of insulating a single home is € 9,840 and for an apartment € 5,760. Even though, the pipes in the network can decrease, the investment costs is increases a lot with insulation.

Table 10-17 shows the costs divided per home when insulation is applied. At every cost aspect, the cost of collective heating is higher. Decentral heating leads to an LCOE saving of 0.0061 €/kWh and 0.0107 €/kWh when the supply temperatures are 70 and 50 ^{o}C. For every cost aspect, decentral heating has lower costs, so in favor of the LCOE, it is more beneficial to supply the peak at home level instead of using a central biomass boiler.

The investment costs of a 70 ^{o}C temperature network are in both cases less than for a 50 ^{o}C network. This is because a 50 ^{o}C network has higher costs for the network, the peak sources, and also needs a BHP for the DHW. Despite the fact that the price of fuel is lower for a 50 ^{o}C network, a 70 ^{o}C network saves 0.0121 €/kWh and 0.0075 €/kWh for a collective and decentral peak supply option.

The lowest LCOE is for the decentralized heat pumps. This is mainly due to low electricity consumption. While the reference concept also has low electricity consumption, maintenance costs for the all-electric scenario are by far the highest.

Table 10-17 CAPEX, OPEX, price of fuel, and LCOE for the heating concepts per home for heat demand strategy 3.

LTDH concept	Investment [€]	Maintenance [€/year]	Price of fuel [€/year]	LCOE [€/kWh]
1a: 70 collective	18,284	220	1,061	0.197
1b: 50 collective	21,555	304	1,010	0.223
2a: 70 decentral	17,589	131	1,060	0.184
2b: 50 decentral	19,941	166	1,027	0.200
Decentralized heat pumps	19,386	206	749	0.182
Reference	18,030	362	895.68	0.224

Appendix F provides what the relative costs are of the techniques on the total investment costs and operational costs. For the investment costs, insulation has the most influence on total investment costs, which fluctuates between 42 – 47 % of the concepts. The LTGH and pipe network have the highest maintenance costs.

Table 10-18 shows the relative costs per cost category. The biggest impact on the total LCOE is the price of fuel. However, this impact is lower for this heat demand strategy compared to the other two concepts. The share of the investment costs increased between 32.2 and 35.8 % for the LTDH concepts with a central heat pump. For LTDH concept 3 and the reference concept, the investment costs have a higher share, because the resident has to invest twice in the heat pumps.

Table 10-18 Relative costs per category over 30 years for heat demand strategy 3.

LTDH concept	Investment costs	Maintenance costs	Price of fuel
1a: 70 collective	32.2	11.6	56.2
1b: 50 collective	35.4	15.0	49.6
2a: 70 decentral	33.0	7.4	59.6
2b: 50 decentral	35.8	8.9	55.3
3: Decentral heat pumps	43.3	12.2	44.5
Reference	37.9	15.9	45.2

10.5 Summary results

This section presents what the savings are of the 5 LTDH concepts on the KPIs LCOE and CO_2 emission, compared to the reference heating concept. As explained in section 6.9, the reference concept serves as a reference point.

The summary is divided over Figure 10-4, Figure 10-5, and Figure 10-6, where each figure represents a heat demand scenario. Every figure plots the 5 LTDH concepts and the reference concept for a heat demand scenario, with the LCOE on the X-axis and the CO_2 emission on the Y-axis. When a point is positive, it means that LTDH saves on that KPI.

The KPI electricity usage has been left out of the figures. Electricity usage is strongly related to CO_2 emission. To prevent global warming, CO_2 emission is a more important KPI and has the preference to be plotted. The end of this section plots the electricity usage for each LTDH concept.

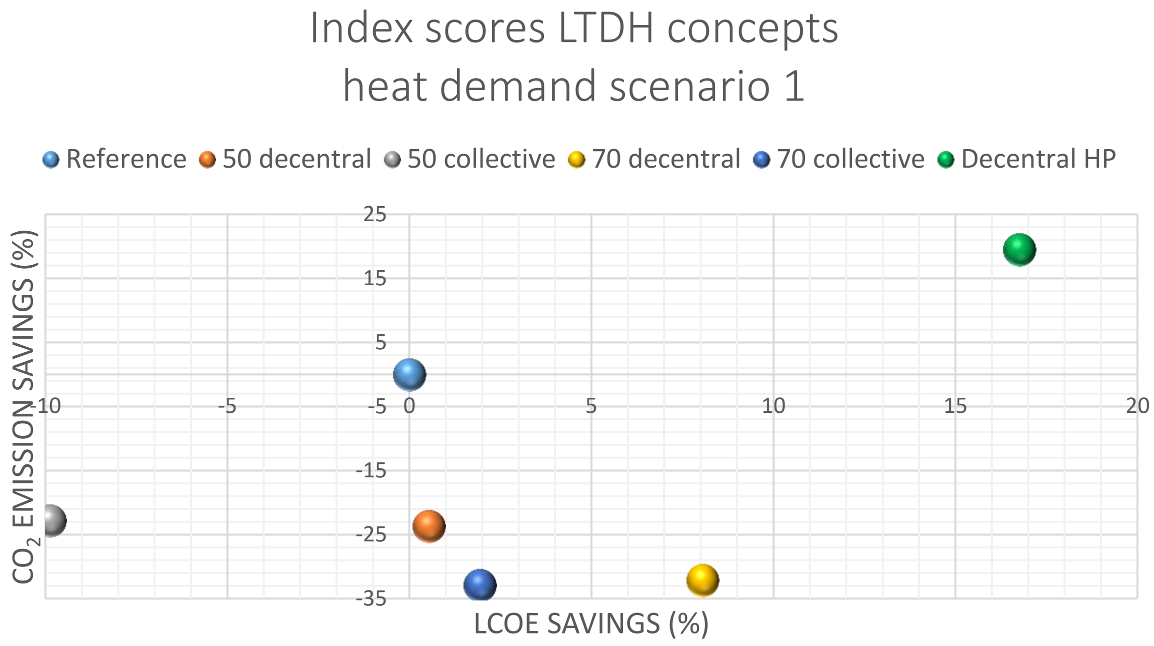


Figure 10-4 Index scores of LTDH concepts for heat demand scenario 1.

Figure 10-4 shows that every LTDH concept with a central heat pump results in more CO_2 emission. The difference between supplying the peak at a central level or at home level does not have a big influence on CO_2 emission. When the supply temperature in the district is 70 ^oC, costs are lower. The decentral peak supply has a small cost advantage. When the supply temperature is 50 ^oC, there will be more costs than in the reference concept. However, the influence on the location of the peak technologies is better for the LCOE when that is done decentrally.
The best LTDH concept for this heat demand scenario is LTDH concept 3, where every home has a decentral heat pump. This saves around 20 % on the CO_2 emission and around 19 % on the LCOE.

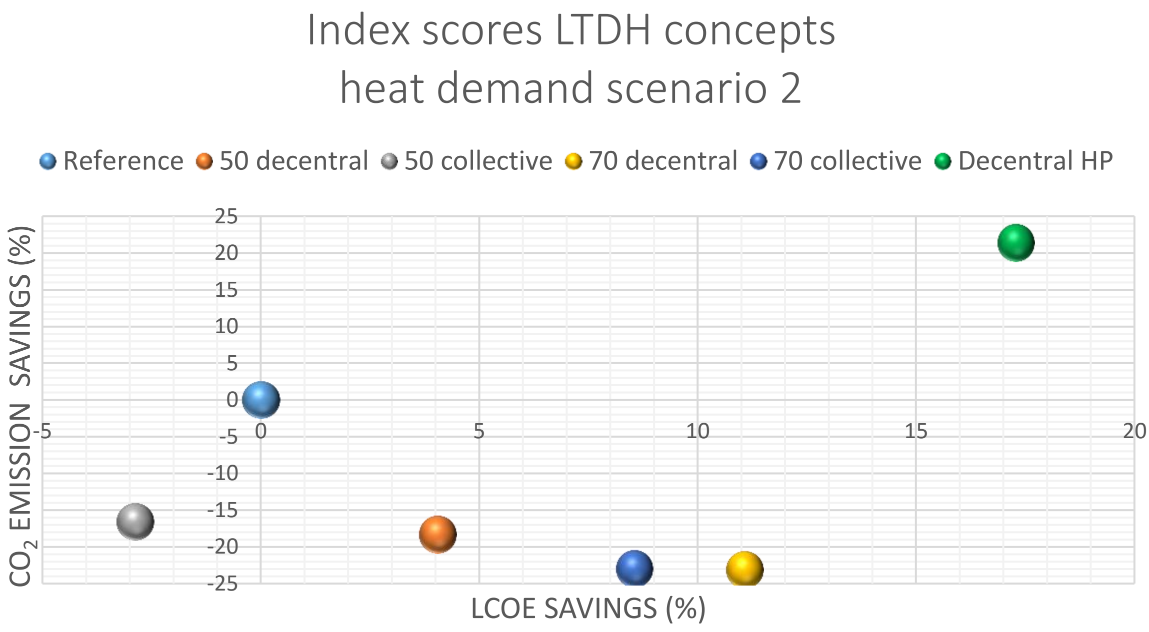


Figure 10-5 Index scores of LTDH concepts for heat demand strategy 2.

Figure 10-5 shows that every LTDH concept with a central heat pump results in more CO_2 emission. The difference between supplying the peak at central level or at home level does not have a big influence on CO_2 emission. Every LTDH saves costs, except concept 1b, where the temperature in the network is 50 ^{o}C and the peak is heated with a biomass boiler. However, this concept scores the best on CO_2 savings of all the LTDH with a central heat pump. When the supply temperature in the district is 70 ^{o}C, more costs are saved. Decentral peak supply has, for both supply temperatures, an advantage by saving more costs. The best LTDH concept for this heat demand scenario is LTDH concept 3, where every home has a decentral heat pump. In this concept network, the savings are around 22 % on the CO_2 emission and around 17 % on LCOE.

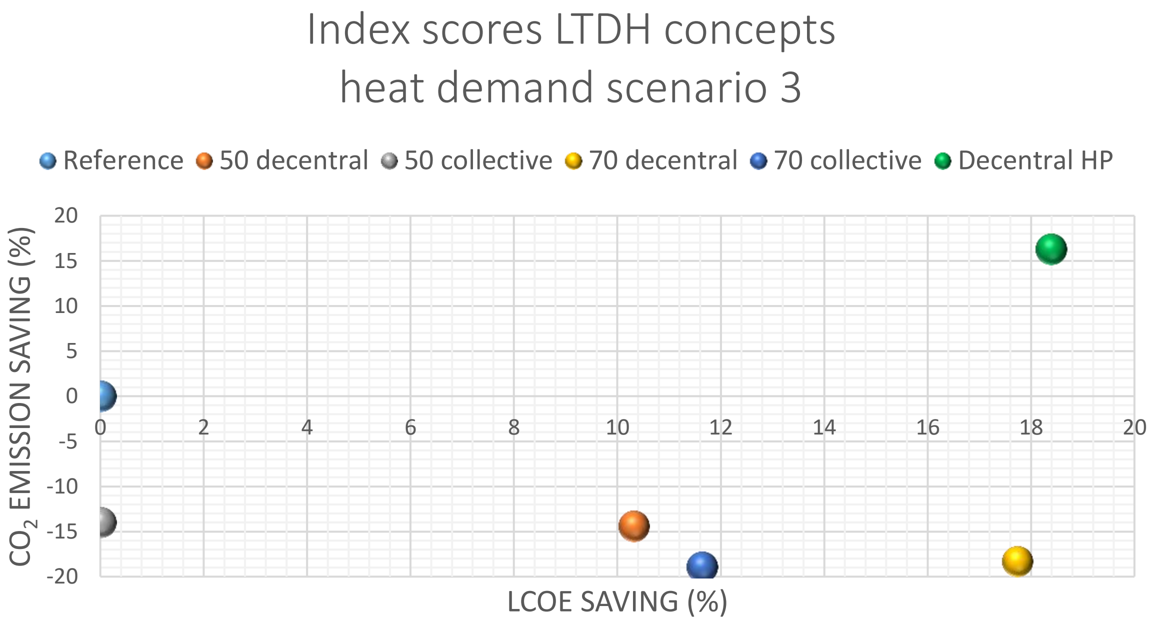


Figure 10-6 Index scores of LTDH concepts for heat demand strategy 3.

Figure 10-6 shows that each LTDH concept with a central heat pump results in more CO_2 emission. The difference between supplying the peak at a central level or at the home level does not have a big influence on CO_2 emission. When the supply temperature is 70 ^oC, more CO_2 will be emitted than with a supply temperature of 50 ^oC. For both supply temperatures, the decentral option saves the most costs. When the supply temperature is 70 ^oC, more costs will be saved than with a supply temperature of 50 ^oC. The best LTDH concept for this heat demand scenario is LTDH concept 3, where every home has a decentral heat pump. This one saves around 22 % on the CO_2 emission and around 17 % on the LCOE.

From the previous three figures, one can see that insulation has the best influence on the KPIs of all the LTDH concepts. The peak shaving strategy results in the worst scores of CO_2 emission savings and the current heat demand strategy results in the worst scores on LCOE savings. However, from Table 10-11 one can see that the lowest LCOE is for this heat demand scenario. So the lowest costs are for LTDH concept 3 when peak shaving is applied. The LCOE is 0.165 € / kWh.

Figure 10-7 shows the electricity savings of the LTDH concepts, when insulation measures are applied, during a cold period and throughout an entire year, compared to the reference concept. From this figure, one can see that each LTDH concept saves electricity during a cold period. LTDH concept 2a, where the supply temperature is 50 ^oC and the peaks are supplied by a biomass boiler, performs the best on this KPI concept. This concept saves 46.8 % of the electricity usage, compared to the reference scenario, which uses 340.2 kWh in 250 cold hours. The best options after that are the LTDH concepts with 70 ^oC supply temperature. Throughout an entire year, only LTDH concept 3 saves electricity. The other concepts consume more electricity than the ‘all-electric’ concept.

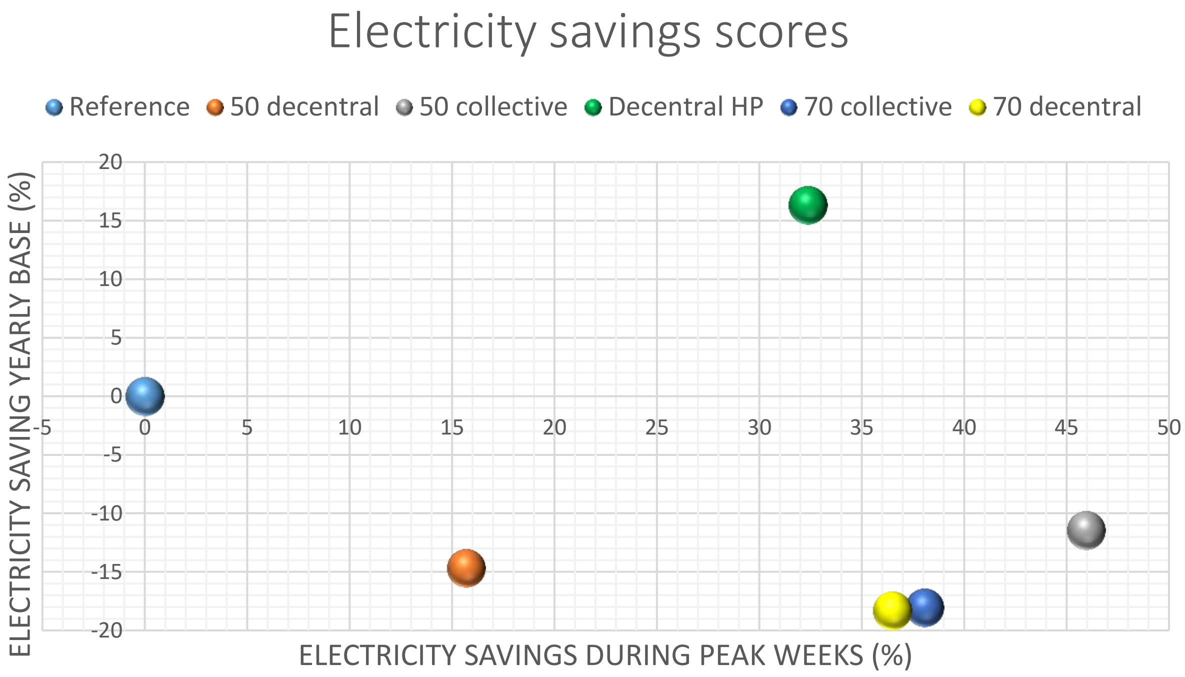


Figure 10-7 Electricity savings for the LTDH concepts compared to the all-electric concept, when insulation measures are applied.

Finally, **Error! Not a valid bookmark self-reference.** shows what the maximum electricity usage is per LTDH concept. This is important to know if the current electricity grid can supply the extra electricity for heat. The tables shows that LTDH concept 1b has the lowest maximum electricity usage and LTDH concept 2b has the highest.

Table 10-19 Maximum electricity usage for heat demand strategy 3.

LTDH concept	1a	1b	2a	2b	3	reference
Electrical power in network (MW)	2.465	2.425	7.022	8.902	4.035	7.439

Comparison to gas

For the summary it is interesting to see what the savings are of a new heating network compared to the current gas network in the Netherlands. The purpose of this is to show why the Netherlands needs to get rid of the gas network for climate change purposes. For this rapid calculation, it is known that 1 m^3 of natural gas costs 82 cents and emits 1.8 kg CO_2 (Pothof, 2019).

It is assumed that 1 1 m^3 of natural gas can provide 35.17 MJ heat. That means that with the current heat demand, which is 28.808 MWh, 2.9 million m3 of gas is needed for heating. In 30 years this equates to 64.3 tons of CO2 emissions per household and 0.084 euros / kWh.

Part 4 Evaluation

This part evaluates the results of this research. The calculation models and most important results are discussed in the first chapter of this part. Thereafter, the conclusions of the present thesis are provided. In this chapter, answers are provided to the research questions from Chapter 1.This part ends with the recommendations, about which future research needs to be done on the field of LTDH and LTGH and how the Netherlands can use this research in releasing LTDH.

11. Discussion

This chapter discusses the designed LTDH concepts from Chapter 5, the developed calculation models from Chapter 6, and the results from Chapter 10. The last section of this chapter discusses what this research contributed on scientific and social area.

11.1 LTDH concepts

This section discusses the designed LTDH concepts from Chapter 5. There are some remarks about the designs. These comments are divided over the ATES, the chosen technologies next to the LTGH, and a few remaining points.

ATES

The ATES of the LTDH concepts stores heat between 30 and 70 ^{o}C. Since it is dictated by law that heat storage is only possible up to 25 ^{o}C, these concepts are currently not possible. Currently, research is being done on the impact of storing higher water temperatures in the subsurface. This can have influence on the subsurface or on the extraction of drinking water. However, a design with a central heat pump is still possible, only the heat pump will be placed after the ATES. So the LTGH can store water at 25 – 30 ^{o}C and the temperature will be increased after the ATES.

Noticeable in Chapter 9 is that the ATES runs often at maximum power in the winter. If the ATES can supply more heat, it is possible to reduce the number of peak moments. So an LTDH concept with multiple ATES sources is also an interesting concept to investigate about what the influences are on the set KPIs.

The location of the ATES is not specified in the LTDH concepts. It is now assumed that it is near the LTGH source, but in reality it could be installed somewhere else. The effect of the location of the ATES in this design is still unclear.

Chosen technologies next to LTGH

The peak heat technologies in Chapter 5 are only a biomass boiler at central level and at home level electrical heaters and decentral heat pump. This was chosen, because these are currently the most relevant. However, in the future it can be interesting to investigate how other heat technologies, such as solar thermal or aqua thermal energy, can be used in an LTDH. The current peak source of a geothermal district heating, a gas boiler, is now only replaced by a biomass boiler. The question which then arises is how sustainable this will be if all the gas boilers are replaced by biomass boilers, because the feedstock of biomass is scarce in the Netherlands.

In terms of storage options, it would also be relevant to look at PCM and TCMs. This research did not include these because PCM is often seen as expensive storage techniques and TCM is still under development. However, these can store and supply more energy than a water tank. This would help a heat network by reducing the use of the peak source. So a similar research with PCM and TCM would be relevant.

Remaining points

Despite the practical research of (Østergaard, 2018), there is still doubt if it is possible that a radiator can produce a return temperature of 30 ^{o}C, when the supply temperature is between 68 and 64 ^{o}C. This large temperature difference results in a low mass flow through the radiators. This research can also be executed with lower temperature differences or a heat curve at the radiators and see how this influences the KPIs. Application of a heat curve would require a decentral hot tap water facility for all scenarios.

Finally, the question can be asked whether it is fair to compare the LTDH concepts with an all-electric scenario. What can be seen in Chapter 10 is that during peak hours an all-electric scenario loads the electricity network the most. The question is whether that extra energy can be handled by the current electricity network. I have the idea that the electricity grid must be enormously upgraded if an all-electric scenario will be the case, which would have an adverse effect on the results of the KPIs of the all-electric scenario.

11.2 Numerical models

In general, the assumptions that are made and numbers that are used were verified with people in the field so these are deemed reasonable and reliable. The correct verification can only be done if such an LTDH will actually be built. However, there are a few remarks about the hourly energy balance from section 6.4 and the results of Chapter 9.

The losses and heat supply in the ATES is calculated very simply. These actually depend on several factors, which can lead to other losses. The same applies if a second ATES is installed. This simplification can be discussed.

The simulation of the water tank is not completely correct. To see what the capacity is in the tank and how much heat can be supplied, the temperature of the water in tank should be known. In the model now it is assumed that it is always 67 ^{0}C for supplying heat. If the tank is used to supply heat, the temperature of the water should decrease and therefore the capacity as well.

The calculation models for the CO_2 emission, electricity usage, and LCOE are straight forward. The only thing that can be doubted with regard to CO_2 emissions, the COP, and the LCOE calculation is whether the correct values have been used. In addition, in this study the CO_2 emissions are only calculated during consumption. This can give a distorted picture. The installation of an LTGH also costs a lot of power and material consumption. To give a better picture an LCA would have been much better in place for this thesis.

11.3 Results

The first thing to mention is that each LTDH and reference scenario emits less CO_2 than the use of gas for heating. According to section 10.5, an average home in this district emits 64.3 tons of CO_2 over 30 years. Every calculated LTDH concept with a specific heat strategy is below 55 tons, so by removing the Netherlands from the gas network, less CO_2 would be emitted during the consumption of heat. Next to that, the CO_2 emission by electricity usage will decrease (or becomes 0) after 30 years because electricity production will become more sustainable.

On another positive note, despite the fact that high peak demands from homes occur less frequently than for greenhouses, an LTDH with LTGH as the main heat source has less costs than heating each home with a single air-heat pump and electrical boiler. So an LTGH can not only be used for heating greenhouses, but also for homes in a dense populated district area.

The price of electricity is a misconception of the results. One may argue that 0.18 cent / kWh is too high assumed. If the electricity price is lower, the savings on the LCOE and share of the fuel price over the total price will shift.

Chapter 10 shows that for every heat demand scenario, LTDH concept 3 saves the most on every KPI. This is mainly due to the lowest electricity consumption. This has a positive influence on both CO_2 emissions and on the LCOE. The investment costs are the lowest for a collective concept with a

biomass source and supply temperature of 70 ^oC, but the consumption of energy is much higher for this scenario, due to the central heat pump and heat losses in the network and ATES.
All concepts with a central heat pump always score lower on CO_2 savings than the reference scenario. This is because decentralized heat pumps can be switched off and therefore have a higher COP on average throughout the year. It can also be seen in Table 10-14 that the COP of the heat pump has a lot of influence on the total consumption. So if it is possible to have a higher COP value for the central heat pump of the LTGH source, the CO_2 emissions may decrease enormously. Another option is to drill a little deeper, so that a higher temperature can be extracted, so that the COP rises or perhaps a heat pump is not required.

Next to that, the electricity usage is for LTDH also higher because there are more heat losses in the network and the ATES. This is caused by the pipes, the heat exchangers in the network and the recovery efficiency of the ATES. All these losses lead to higher CO_2 emissions.

The concept with a central heat pump which saves the most on the LCOE analysis is for every heat demand LTDH concept 2a. This is for every cost aspect. On saving CO_2 emission, concept 1b performs the best of all the concepts with a central heat pump.

Remarkable is that when peak shaving is applied, more CO_2 is emitted for every LTDH concept. It was expected that there would be fewer peaks due to peak shaving and therefore the heaters would have to be deployed less frequently. However, it led to less high peaks, but the number of peaks increased. Especially in concept 2b, where the water tank cannot save sufficient energy, because the low temperature difference.

The LTDH concept which uses the least electricity during peak hours is concept 1b, where the supply temperature is 50 ^oC and the peak is supplied by a biomass boiler. This concept uses a maximum between 0.973 kW and 0.836 kW at one hour, depending on the heat demand strategy.

Concept 2b, where the supply temperature is 50 ^oC and the peak is supplied by a water tank and electrical heaters, uses the most electricity during peak hours. The maximum demand is 3.48 kW electricity for one hour per home, when insulation and peak shaving is not applied. With the use of insulation, the maximum electricity usage decreases to 3.07 kW. This moment occurs in the evening, when the lighting and other appliances are using electricity in the homes. This may lead to overloading on the electricity grid. With LTDH concept 2a, where the supply temperature is 70 ^oC, the electrical heaters are only on between 18 and 21 hours, when no peak shaving is applied. The question is whether the heaters are really needed for those hours or if the residents can heat themselves differently during these few hours in the year, for example by putting on a thicker sweater.

The best heat demand scenario is insulation. Since the heat demand decreases, more homes can be connected to an LTDH with LTGH network. Therefore, the costs, CO_2 emission, and electricity usage are divided over more homes, which leads to a decrease in the use of all these KPIs. Despite the fact that the investment costs increases, the maintenance and fuel costs are reduced a lot, so that the LCOE is reduced by an average of 0.02 € / kWh.

Heat demand strategy peak shaving leads to a reduction of the investment costs because the peak sources need to supply less power and the pipe diameters are smaller. However, this extremely form of peak shaving still reduced the average peak demand with about 1 MW. An interesting heat demand strategy would be a combination of insulation and peak shaving. This maybe leads to the best results for these LTDH concepts.

11.4 Remaining KPIs

This section discusses the remaining KPIs. As explained in section 3.2, there are two KPIs which are not calculated throughout this thesis. However, these are relevant to make it possible to implement LTDH in the Netherlands.

Impact of installation

The water tank of 250 liter takes up a lot of space in a single home of 120 m^2. This will not suit the residents, because the technical room in a home then needs to be bigger which leaves less usable space for the resident. This also applies to the reference scenario (air source heat pumps), the decentral heat pumps and for the concepts with a supply temperature of 50 ^{o}C, which needs a BHP for providing DHW. To reduce the spatial impact of the water tank, it is an option to install the water tank underground. Research into this option needs to be conducted. “Hiding” the decentral heat pump will be more difficult.

Despite the fact that the reference concept scores quite well on the KPIs CO_2 emission and costs savings, there are still other aspects which need to be taken into account, such as resident comfort. An air heat pump can cause a lot of noise, which is considered as undesirable.
In addition, the appearance of an air heat pump is considered as ugly. There are special cabinets on the market to “hide” the look of the air heat pump and reduce the sound. If a residents wants this, the costs will increase by € 750.

For the residents, LTDH concept 1a would take up the least space. In the homes, only a supply set is required to replace the existing gas boiler. However, outside the homes is a biomass plant required. This also emits other substances such as NO_x and particulate matters. This can be considered as unpleasant for the residents which lives close to the biomass plant. There may then be resistance from the municipality, which has already occurred in the Netherlands (Bianchi, 2019). This article shows that people demonstrated against a biomass plant which was placed within one kilometer of their homes.

Reliability

LTDH concept 2b uses the electrical heaters quite often in the winter. For this concept, it can be said that the water tank is not reliable, because it does not supply enough heat. The concepts with a biomass boiler relies on the feedstock of biomass, which is criticized from several angles (Planbureau voor de leefomgeving, 2014). So in terms of reliability, concept 1a, 1b, and 2b can be questioned. As said before, the reference concept loads the electricity network the most during cold moments. It can be questioned if the electricity grid can supply that amount of electricity to the homes.

The most reliable concepts are 2a, where the supply temperature is 70 ^{o}C and every home has a water tank, and 3, where every home have a decentral heat pump. These concepts most often have heat immediately available to the residents.

11.5 Scientific and societal contribution

This research was mainly carried out for V&SH to see how their LTGH source can be implemented in an LTDH and about the possibilities for LTDH in NL. This research showed the influence of a water tank as a storage method for a house, the influence of an ATES, and alternative peak sources in addition to a geothermal source.

First, this study showed that an LTGH source will save the most costs, CO_2, and annual electricity consumption when no central heat pump is used, but the temperature is raised at the homes by a decentral heat pump. The side effects of this are that the peak demand in electricity is greater than at 70 ^{0}C and that the houses have a higher CAPEX and that the heat pump space takes up the houses of the residents.

This research shows that the influence of a water tank can be very relevant if there is a high temperature difference in the network. With a capacity of 250 liters, with the current heat demand, the peaks can already be reduced from 135 to 18 hours per year. At a lower supply temperature in an LTDH, a water tank is a good option if the size of the tank increases. A decentralized option will also lower the total LCOE than with a centralized option.

At a lower supply temperature, it can be seen that CO_2 emissions will decrease because less electricity is required. The LCOE is lower at a higher supply temperature, with a central heat pump, because the CAPEX of higher supply temperatures are a lot lower. This is because a BHP is not required, the pipe diameters are smaller, and the peak sources need less power.

The influences of the heat demand strategies where already known, so it did not contributed on social and scientific field. However, for V&SH it is shown that an LTGH have a better business case when the homes have good insulation measures.
For V&SH, this thesis contributed to see what the impact is of the central heat pump and well pump on the total electricity consumption of the installation. The central heat pump uses more than 60 % in every situation. The central heat pump and well pump together use at least 85%.

12. Conclusion

This thesis chapter provides an answer to the main research question. To answer this main question different sub-questions are established. First, the answers to the sub-questions are presented, followed by the answer to the main question.

12.1 Answering sub questions

What are relevant techniques in LTDH for peak heat demand moments?

This thesis looked into the following heat supply technologies: biomass boiler and electrical heaters. For thermal energy storage, this thesis looked into an ATES and water tank. All these technologies can be used in an LTDH system for meeting the peak heat demand moments. Other technologies, which can be useful as well, can be solar thermal plants and waste heat plants as heat supply technologies and as storage systems PCMs and TCMs, but is not investigated in this research. These can be relevant because these storage systems can store a large amount of energy.

What is a suitable method to design a sustainable LTDH?

This thesis used a morphologic overview to design several LTDH concepts. This method was very useful and made it clear which technologies are available for the design of an LTDH. All suitable options for an LTDH can be compiled in this overview and suitable combinations can be made. Determining the scores for several KPIs, for the different combinations, provides a good comparison for the sustainable LTDH concepts.

What are suitable combinations of techniques in an LTDH?

This thesis investigated the main difference between decentral and collective peak supply. A combination of collective heating is an ATES source for storage and a biomass boiler for supplying extra heat during cold moments. The decentral concepts use, next to the ATES source, a water tank and external heaters or only decentral heat pumps. The combination of a water tank and external heaters is a suitable combination, when the supply temperature is 70 ^{o}C, because the water tank can supply most of the peak demands. With 50 ^{o}C, this combination is not suitable, because the system depends too much on the external heaters.

Does demand side-management have a big influence on LTDH system?

DSM has a big influence on LTDH. The pipe diameters can be reduced if DSM is applied, which reduces the total investment costs. However, when peak shaving is applied, the total electricity usage throughout an entire year will increase and therefore leads to higher CO_2 emissions. Applying insulation measures is the best way of DSM, since the CO_2 emission, electricity usage, and costs decreases for all the LTDH concepts.

How does the system perform during peak moments?

In Chapter 9 and 10 it is shown that with an LTDH system with a biomass boiler as peak source, the electricity network is the least loaded. Other LTDH concepts and the reference concept require more electricity. Concept 2a, which has a supply temperature of 70 ^{o}C and uses a water tank, performs the best. This concept has a lot of available heat in the water tank as well, so the homes can be heated fast.

How dependent is the system of the supply temperature of the LTGH source?

The supply temperature of the LTGH source has an influence on the COP of the heat pumps. Since the heat pumps of the LTGH use most of the total electricity, the electricity usage depends a lot on the supply temperature of the LTGH source. This can be seen in the LCOE and CO_2 emissions as well. If the supply temperature of the LTGH source can be increased, the heat pumps require less electricity which reduces the CO_2 emission and costs for the complete system.

How much electricity, CO_2 emission, and costs can be saved with an LTDH compared to an all-electric heating district?

Chapter 10 shows that the heat demand strategy 'insulation' is the best option for LTDH and is therefore used to answer this question. Table 12-1 shows what the savings are of the electricity, CO_2 emission, and costs of the LTDH concepts compared to the reference concept. A negative value means that the reference scenario saves more on that KPI. The table shows that the LTDH concept 3 saves at every point. After that, most of the savings on the LCOE are done by concept 2a. For the electricity usage during peak hours, concept 1b saves the most.

Table 12-1 Savings of the KPIs for the LTDH concepts compared to the reference concept, when insulation is applied.

	1a: 70 collective	**1b: 50 collective**	**2a: 70 decentral**	**2b: 50 decentral**	**3: decentral heat pumps**
CO2 emission [%]	-18.9	-14.0	-18.3	-14.4	16.3
LCOE [%]	11.6	0	17.7	10.3	18.4
Electricity usage a whole year [%]	-18.0	-11.4	-18.3	-14.4	16.3
Electricity usage during cold days [%]	38.1	45.9	36.5	15.7	32.4

How does this study help in the development of LTDH?

This study shows that the sustainable heating source LTGH can be used in LTDH. Next to that, the thesis shows that a water tank with 70 ^{0}C supply temperature can reduce the peak moments a lot. When the supply temperature is 50 ^{0}C, the water tank does not have enough capacity and therefore will reduce the peak moments a little bit. Finally, it shows that an LTGH requires an ATES for heating a district with only heat demand by homes.

12.2 Answering main question

The main question is as follows.

'What is the best way to meet heat demands, in existing Dutch homes, with LTDH and an LTGH as the main source, based on KPIs?'

The best way to meet the heat demand in existing Dutch homes, with LTDH and an LTGH as main source is an LTGH with decentral heat pump for every single home. This LTDH concept saves 16.3 %, 18.4 %, and 16.3 % on the CO2 emission, LCOE, and electricity usage compared to an all-electric scenario.

13. Recommendations for the future

A study can always be further improved and the same counts for this study. There are several recommendations that can be made related to the LTDH designs and future research.

13.1 Future research

This thesis used fixed values for the water tank (250 liters) and for the ATES (130 m3/h). Both had an influence on the outcomes of the results. It would be interesting to see what the optimal parameters would be for these technologies. With that information, it is possible to design an optimal LTDH.

An optimization study of the designed LTDH concept would be interesting so that the savings in LCOE and CO_2 emission can be improved. This can be done for example to see for LTDH concept 3 what the ideal supply and return temperature would be in the network. Or that only one decentralized heat pump is used for one street instead of one home. For the LTDH concepts with a central heat pump, it would be interesting to see how the efficiencies of the total system will improve if the extraction temperature from the geothermal well is higher and other peak heat technologies are used.

To make the results of this research more reliable, it is important to know what the impact would be on the current electricity grid of the district. For this research, it is unknown whether the grid needs to be adjusted. If the grid must adjust the results for the LCOE will be different.

The CO_2 impact and electricity usage is more for an LTGH design with a central heat pump. This is because the heat pump is also supplying heat in the summer. The concept without a central heat pump and reference concept can turn the heat pumps off when there is no demand for heat. It would be interesting to see how these concepts perform in a district area, with a user which requires heat in the summer, such as an outdoor swimming pool. From this study, it can be predicted that the LTGH with central heat pump concepts have a better influence in saving electricity and CO_2, compared to the all-electric concept.

In saving costs, the LTGH source is a good source for LTDH. Since the Dutch government wants to make more use of geothermal heat (Nijpels, 2018), it would be interesting to compare an LTGH source with a regular geothermal heat for the use in LTDH in the Netherlands. A regular geothermal heat source extracts water with higher temperatures, but also extracts natural gas, which has a negative impact on the climate.

The LCOE analysis shows that the total costs over 30 years can be lower with an LTGH system compared to all-electric. However, some concepts have higher investment costs. It may not be possible to start the investment, because a stakeholder cannot afford these costs. An NPV analysis per stakeholder would be an interesting follow-up research, so it can become clear how the costs are spread out over the stakeholders. With that information, it can become easier for stakeholders to say what their preferred LTDH concept would be.

The LTGH source of V&SH costs less than the reference concept when insulation is applied. However, with a central heat pump, the electricity usage is too much. It would be interesting to investigate how this electricity consumption can decrease and if it is possible to generate electricity for the heat pump. For example, maybe a windmill can produce the required electricity for the heat pump. The electricity grid will be less loaded and therefore the CO_2 emissions can be reduced.

13.2 Recommendations for implementing LTDH and LTGH in Dutch district areas

This research showed that LTDH or all-electric is better for the environment than the current gas network. Also, the costs of both systems are quite clear and have positive results. LTDH is possible, so it should be realized in the Netherlands. However, the energy transition has some problems in the Netherlands.

In 2019, project developers wanted to start building wind farms in Drenthe, a province in the north of the Netherlands (NOS, 2019). The municipality was not happy with this project and started threatening the project developers. They had the feeling that the municipality was not involved in the plans. However, the project developers thought they had involved the municipality.

To prevent something like this example with installing an LTDH and LTGH, the municipality should be involved in the design process. If the costs distribution costs are clear, the municipality can provide their criteria and show what their favorite design would be. In this way, all the stakeholders are well involved and both techniques can be successfully implemented in the Netherlands.

Reference list

ACM. (2018). Warmtetarieven. Retrieved 15 December 2018, from https://www.acm.nl/nl/warmtetarieven

Agemar, T., Weber, J., & Schulz, R. (2014). *Deep Geothermal Energy Production in Germany*. *Energies* (Vol. 7). https://doi.org/10.3390/en7074397

Ahmed, K., Akhondzada, A., Kurnitski, J., & Olesen, B. (2017). Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards. *Sustainable Cities and Society*, *35*(January), 134–144. https://doi.org/10.1016/j.scs.2017.07.010

Airaksinen, M., & Vuolle, M. (2013). Heating energy and peak-power demand in a standard and low energy building. *Energies*, *6*(1), 235–250.

Alva, G., Lin, Y., & Fang, G. (2018). An overview of thermal energy storage systems. *Energy*, *144*, 341–378. https://doi.org/10.1016/j.energy.2017.12.037

Beerink, S., van den Berg, G., Bloemendal, M., & Hartog, N. (2018). Heatstore. Retrieved 2 May 2019, from https://www.kwrwater.nl/en/projecten/heatstore/.

Bianchi, R. (2019). Omwonenden eisen onafhankelijk onderzoek uitstoot toekomstige biomassacentrale in Diemen. Retrieved 5 May 2019, from https://www.nhnieuws.nl/nieuws/242430/omwonenden-eisen-onafhankelijk-onderzoek-uitstoot-toekomstige-biomassacentrale-in-diemen

Bloemendal, M. (2018). *Personal communication with Martin Bloemendaal on October 10, 2018 at TU Delft*. TU Delft.

Bloemendal, M., & Hartog, N. (2018). Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. *Geothermics*, *71*(October 2017), 306–319. https://doi.org/10.1016/j.geothermics.2017.10.009

Bloemendal, M., Jaxa-Rozen, M., & Olsthoorn, T. (2018). Methods for planning of ATES systems. *Applied Energy*, *216*(February), 534–557. https://doi.org/10.1016/j.apenergy.2018.02.068

Blom, I. (2010). *Environmental impacts during the operational phase of residential buildings*. Amsterdam: IOS Press BV.

Cabeza, L. F., Galindo, E., Prieto, C., Barreneche, C., & Inés Fernández, A. (2015). Key performance indicators in thermal energy storage: Survey and assessment. *Renewable Energy*, *83*, 820–827. https://doi.org/https://doi.org/10.1016/j.renene.2015.05.019

CBS. (2013). Twee derde van alle woningen eengezinswoning. Retrieved 20 October 2018, from https://www.cbs.nl/nl-nl/achtergrond/2013/04/twee-derde-van-alle-woningen-eengezinswoning

CE Delft. (2016). Factsheets individuele warmtetechnieken. Retrieved 23 October 2018, from https://www.ce.nl/assets/upload/file/Rapporten/2018/Factsheets warmtetechnieken/Factsheets_compleet.pdf

Danfoss. (n.d.). Ervaar het optimale comfort met AGH warmte-units. Retrieved 16 May 2019, from http://klimaatregling.danfoss.nl/PCMPDF/VBHED110_Danfoss_Orion.pdf

de Vrieze, M. (2018). *Personal communication with Mark de Vrieze on September 30, 2018 at Visser & Smit Hanab*. Papendrecht.

de Wit-Blok, M. (2017, September). Duurzame warmte ’de meerwaarde van (hogetemperatuur)warmteopslag voor warmtenetten. *UNETO-VNI*.

Drijver, B., van Aarssen, M., & Zwart, B. D. (2012). High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. In *Conference proceedings Innostock* (Vol. 2012).

Elzen, B., Geels, F. W., & Green, K. (2004). *System innovation and the transition to sustainability: theory, evidence and policy*. Edward Elgar Publishing.

Energieonderzoek Centrum Nederland, Planbureau voor de leefomgeving, Centraal Bureau voor de Statistiek, & Rijksdienst voor Ondernemend Nederland. (2017). Nationale Energieverkenning 2017.

Erlingsson, T., Jóhannesson, T., Olafsson, E., & Axelsson, G. (2010). Geothermal district heating system in XianYang, Shaanxi, China. In *Proceedings World Geothermal Congress* (pp. 25–29).

Ertesvåg, I. S. (2011). Uncertainties in heat-pump coefficient of performance (COP) and exergy efficiency based on standardized testing, *43*, 1937–1946. https://doi.org/10.1016/j.enbuild.2011.03.039

European Committee for Standardization. (2012). Recommendations for prevention of Legionella growth in installations inside buildings conveying water for human consumption. Retrieved 3 November 2018, from http://www.sis.se/en/construction-materials-and-building/installations-in-buildings/water-supply-systems/sis-cen-tr-163552012

European Parliament. (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. *Official Journal of the European Union Directive*, (October), 1–56. https://doi.org/10.3000/19770677.L_2012.315.eng

Faruqui, A., & Chamberlin, J. H. (1993). Principles and practice of demand-side management. *Palo Alto, CA: Electric Power Research Institute*.

Fitz-Gibbon, C. T. (1990). *Performance indicators* (Vol. 2). Multilingual Matters.

Frederiksen, S., & Werner, S. (2013). *District Heating and Cooling*. Studentlitteratur AB.

Gadd, H., & Werner, S. (2013). Daily heat load variations in Swedish district heating systems. *Applied Energy*, *106*, 47–55. https://doi.org/10.1016/j.apenergy.2013.01.030

Google. (n.d.). Google Maps. Retrieved 20 December 2018, from maps.google.com

Grundfoss. (n.d.). Pump selection. Retrieved 5 April 2019, from https://product-selection.grundfos.com/front-page.html?qcid=465327133

Hirschberg, S., & Wiemer, S. (2015). *Energy from the Earth Energy from the Earth Deep Geothermal as a Resource*. https://doi.org/10.3218/3655-8

Hoge Vucht Biesdonk. (n.d.). Retrieved 12 December 2018, from http://wijkavontuurhogevucht.nl/nieuws/wijk-in-beeld/biesdonk

Huch. (2017). Product catalogue 2017 Innovative storage tanks and container solutions. Retrieved 23 October 2018, from https://huch.com/fileadmin/user_upload/downloads/productcatalogue2017.pdf

Infante Ferreira, C. (2018). *Personal communication with Carlos Infante Ferreira on October 24, 2018 at TU Delft*. TU Delft.

Installatietechniek, K. V. (2012). *ISSO-publicatie 7 Grondleidingen voor warmte- en koudetransport*.

Installatietechniek, K. V. (2015). *ISSO-publicatie 82.1 Energieprestatie woningen*.

Jong Warmtenetwerk. (2018). *Workshop van 'Jong Warmtenetwerk' 30 November 2018*. Utrecht.

Keçebaş, A. (2011). Performance and thermo-economic assessments of geothermal district heating system: A case study in Afyon, Turkey. *Renewable Energy*, *36*(1), 77–83. https://doi.org/https://doi.org/10.1016/j.renene.2010.05.022

Kleefkens, O. (2017). Booster Heat Pump , development of test procedure and calculation methodology in order to estimate the energy performance in various domestic applications.

KNMI. (2017). Uurgegevens van het weer in Nederland.

Koenders, M., Schepers, B., Scholten, T., Willemsen, G., & Zwart, B. de. (2018). *Weg van gas*.

Köfinger, M., Basciotti, D., Schmidt, R. R., Meissner, E., Doczekal, C., & Giovannini, A. (2016). Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies. *Energy*, *110*, 95–104. https://doi.org/https://doi.org/10.1016/j.energy.2015.12.103

Kremer, A. M., Menkveld, M., Matton, R., Segers, R., & Vroom, J. (2017). Monitoring warmte 2015. *ECN*, (April), 66.

Kumar, R. (2014). Chapter 3 - Risks Inherent in Financial Institutions. In R. B. T.-S. of B. and O. F. I. Kumar (Ed.) (pp. 61–93). San Diego: Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-416997-5.00003-8

Laajalehto, T., Kuosa, M., Mäkilä, T., Lampinen, M., & Lahdelma, R. (2014). Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network. *Applied Thermal Engineering*, *69*(1), 86–95. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2014.04.041

Lacirignola, M., & Blanc, I. (2013). Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment, *50*.

Lauenburg, P. (2016). *Temperature optimization in district heating systems*. *Advanced District Heating and Cooling (DHC) Systems*. Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-374-4.00011-2

Lukawski, M. Z., Vilaetis, K., Gkogka, L., & Beckers, K. F. (2013). A proposed hybrid geothermal - natural gas - biomass energy system form Cornell unversity. Technical and economic assessment of retrofitting a low-temperature geothermal district heating system and heat cascading solutions.

Lund, H., Möller, B., Mathiesen, B. V., & Dyrelund, A. (2010). The role of district heating in future renewable energy systems. *Energy*, *35*(3), 1381–1390.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy*, *68*, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

Lundström, L., & Wallin, F. (2016). Heat demand profiles of energy conservation measures in buildings and their impact on a district heating system. *Applied Energy*, *161*, 290–299. https://doi.org/https://doi.org/10.1016/j.apenergy.2015.10.024

Naber, N., Schepers, B., & Rooijers, M. S. F. (2016). Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016 Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – update 2016 De route naar een klimaatneutraal Nederland.

Neels, K. (2018). Transition to sustainable heating at neighbourhood level.

NetbeheerNederland. (n.d.). Energietransitie rekenmodellen. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Rekenmodellen_21_6508ed1a14.pdf

Netherlands Ministry of Economic Affairs. (2016). Energierapport - Transitie naar Duurzaam. *Ministerie van Economische Zaken*, 148. Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2016/01/18/energierapport-transitie-naar-duurzaam

Nijpels, E. (2018). Ontwerp van het Klimaatakkoord Ontwerp van het Klimaatakkoord, (december).

NOS. (2019). Drentse ondernemer windmolenpark krijgt bedreigingen en stopt. Retrieved 20 October 2018, from https://nos.nl/artikel/2277775-drentse-ondernemer-windmolenpark-krijgt-bedreigingen-en-stopt.html

Østergaard, D. S. (2018). *Heating of existing buildings by low-temperature district heating*. DTU.

Østergaard, D., & Svendsen, S. (2017). Space heating with ultra-low-temperature district heating - A case study of four single-family houses from the 1980s. *Energy Procedia*, *116*, 226–235. https://doi.org/10.1016/j.egypro.2017.05.070

Oudes, D., & Stremke, S. (2018). Spatial transition analysis: Spatially explicit and evidence-based targets for sustainable energy transition at the local and regional scale. *Landscape and Urban Planning*, *169*, 1–11.

Planbureau voor de leefomgeving. (2014). Biomassa wensen en grenzen, *24*.

Pothof, I. (2018). *Personal communication with Ivo Pothof on October 17, 2018 at Delft Universitiy of Technology*.

Pothof, I. (2019). Klimaatcijfers op een rijtje. Retrieved 12 June 2019, from https://www.linkedin.com/pulse/klimaatcijfers-op-een-rijtje-ivo-pothof

Powergrove. (n.d.). Demand side management. Retrieved 26 October 2018, from http://www.powerwise.gov.ae/en/research/programmes-projects/demand-side-management.html

Rezaie, B., & Rosen, M. A. (2012). District heating and cooling: Review of technology and potential enhancements. *Applied Energy*, *93*, 2–10.

Rosa, A. D., Li, H., & Svendsen, S. (2011). Method for optimal design of pipes for low-energy district heating , with focus on heat losses, *36*. https://doi.org/10.1016/j.energy.2011.01.024

RTL Nieuws. (2019). Gasexplosie Denhaag was niet opzettelijk: ‘Vermoedelijk gaslek’. *RTL Nieuws*. Retrieved from https://www.rtlnieuws.nl/nieuws/nederland/artikel/4614086/gasexplosie-den-haag-was-niet-opzettelijk-vermoedelijk-gaslek

RVO. (2014). Overzicht afleversets voor warmtelevering. Retrieved 5 January 2019, from https://www.rvo.nl/sites/default/files/2014/11/ENG2014-010 Overzicht afleversets voor warmtelevering %281%29.pdf

Sayegh, M. A., Danielewicz, J., Nannou, T., Miniewicz, M., Jadwiszczak, P., Piekarska, K., & Jouhara, H. (2017). Trends of European research and development in district heating technologies. *Renewable and Sustainable Energy Reviews*, *68*, 1183–1192. https://doi.org/10.1016/j.rser.2016.02.023

Schepers, B., & Scholten, T. (2016). Ketenemissies warmtelevering.

Schmidt, D., & Kallert, A. (2016). *Low temperature district heating for future energy systems, Final report, IEA DHC Annex TS1, ISBN 3-89999-070-6*.

Schmidt, D., Kallert, A., Blesl, M., Svendsen, S., Li, H., Nord, N., & Sipilä, K. (2017). Low Temperature District Heating for Future Energy Systems. *Energy Procedia*, *116*, 26–38. https://doi.org/10.1016/j.egypro.2017.05.052

Schmidt, E. Ø., & Kristensen, M. S. (2014). Optimisation of Defrost Strategy for an Air-to-Water Heat Pump Dynamic Modelling and Experimental Study of Frost Formation on Cross-Flow Heat Exchanger Surface, (June).

Sector, V. P. (2012). Power Generation Biomass for Wind Power, (June).

Sommer, W. (2014). *Modelling and monitoring of Aquifer Thermal Energy Storage*. WUR.

Stremke, S. (2012). Sustainable energy landscape: Implementing energy transition in the physical realm. In *Encyclopedia of Environmental Management, Four Volume Set* (pp. 1–9). CRC Press.

Thermaflex. (2017). Technical data sheet Flexalen ® 600, 1–2.

Ullman, D. G. (1992). *The mechanical design process* (Vol. 2). New York: McGraw-Hill New York.

van Bueren, E., van Bohemen, H., Itard, L., & Visscher, H. (2012). *Sustainable Urban Environments: An Ecosystem Approach*. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-1294-2_12

Van Den Dobbelsteen, A., Broersma, S., & Stremke, S. (2011). Energy potential mapping for energy-producing neighborhoods. *International Journal of Sustainable Building Technology and Urban Development*, *2*(2), 170–176.

van den Groenendaal, T. (2019). *Personal communication with Thomas van den Groenendaal on February 6, 2019 at Thermaflex*. Waalwijk.

van Vliet, E., de Keijzer, J., Slingerland, E., van Tilburg, J., Hofsteenge, W., & Haaksma, V. (2016). *Collectieve warmte naar lage temperatuur*. Utrecht. Retrieved from https://www.ecofys.com/files/files/collectieve-warmte-naar-lage-temperatuur.pdf

Vandeweijer, V. (2013). HTO - Hoge temperatuur opslag in de ondiepe ondergrond Inhoudsopgave.

Verhaegh, N. (2018). Slim van het gas af met lage temperatuur warmte in de bestaande bouw. *DNV-GL*.

Vogtlander, J. (2012). *Lca: a practical guide for students, designers and business managers*.

Werner, S. (2017). International review of district heating and cooling. *Energy*, *137*, 617–631. https://doi.org/10.1016/j.energy.2017.04.045

Wikipedia. (n.d.). Cost of electricity by source. Retrieved 29 October 2018, from https://en.wikipedia.org/wiki/Cost_of_electricity_by_source#cite_note-1

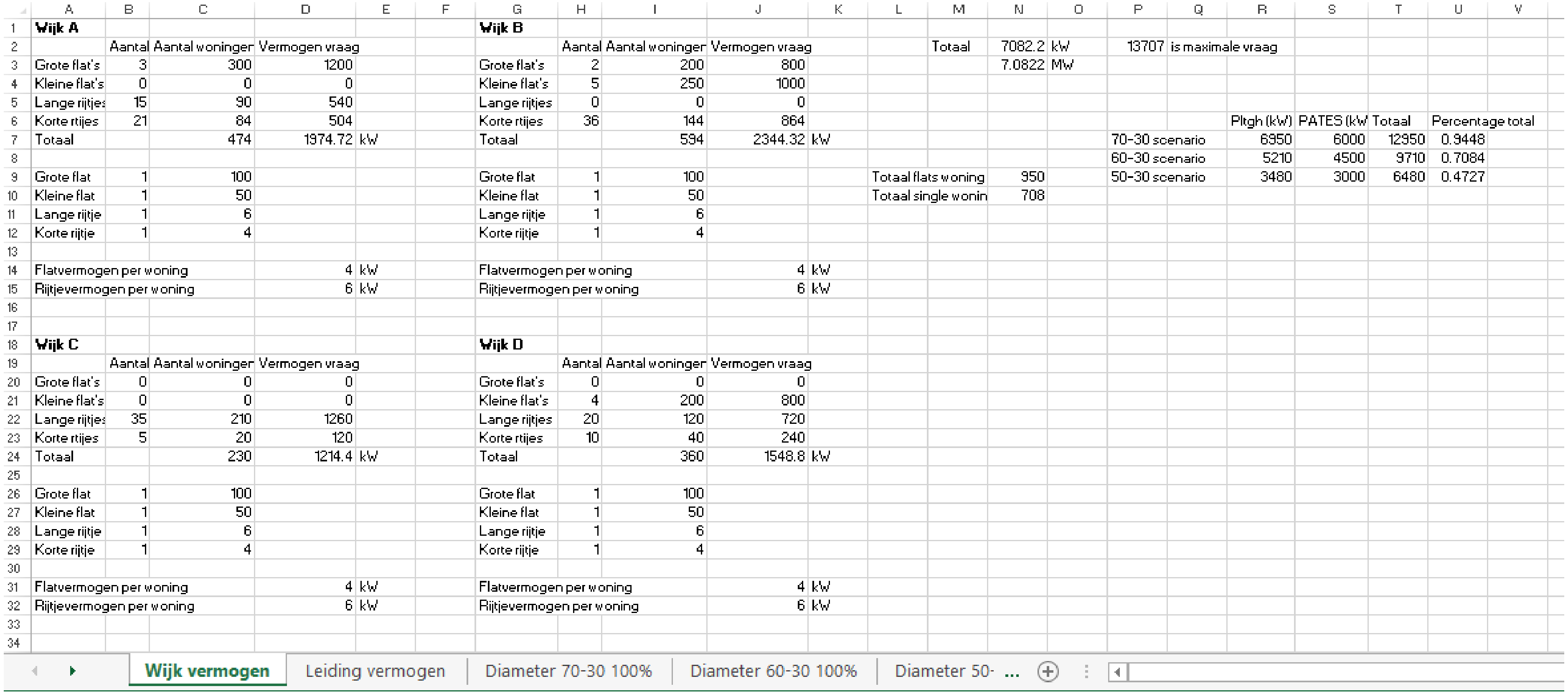
A. Appendix Pipe diameter calculation and pump selection with WANDA

This appendix presents the Excel sheet of the pipe diameter calculations and the WANDA model.

Pipe diameter calculation

These calculations are performed in Microsoft Excel. The next page presents several print screens of the Excel sheet. The model has 2 main tabs; ‘Wijk vermogen’ and ‘Leiding vermogen’. The tab ‘Wijk vermogen’ distributes the heat demand over the homes. If the peak demand is supplied by the network, the heat through the pipes, for the calculations, is the maximum heat demand. If the peak demand is supplied at the homes, the heat through the pipes is the power of LTGH and ATES. The second tab, ‘Leiding vermogen’, divides the heat, which is supplied to the homes, over the pipes, according to the layout of section 6.3.1 and 6.4.4.

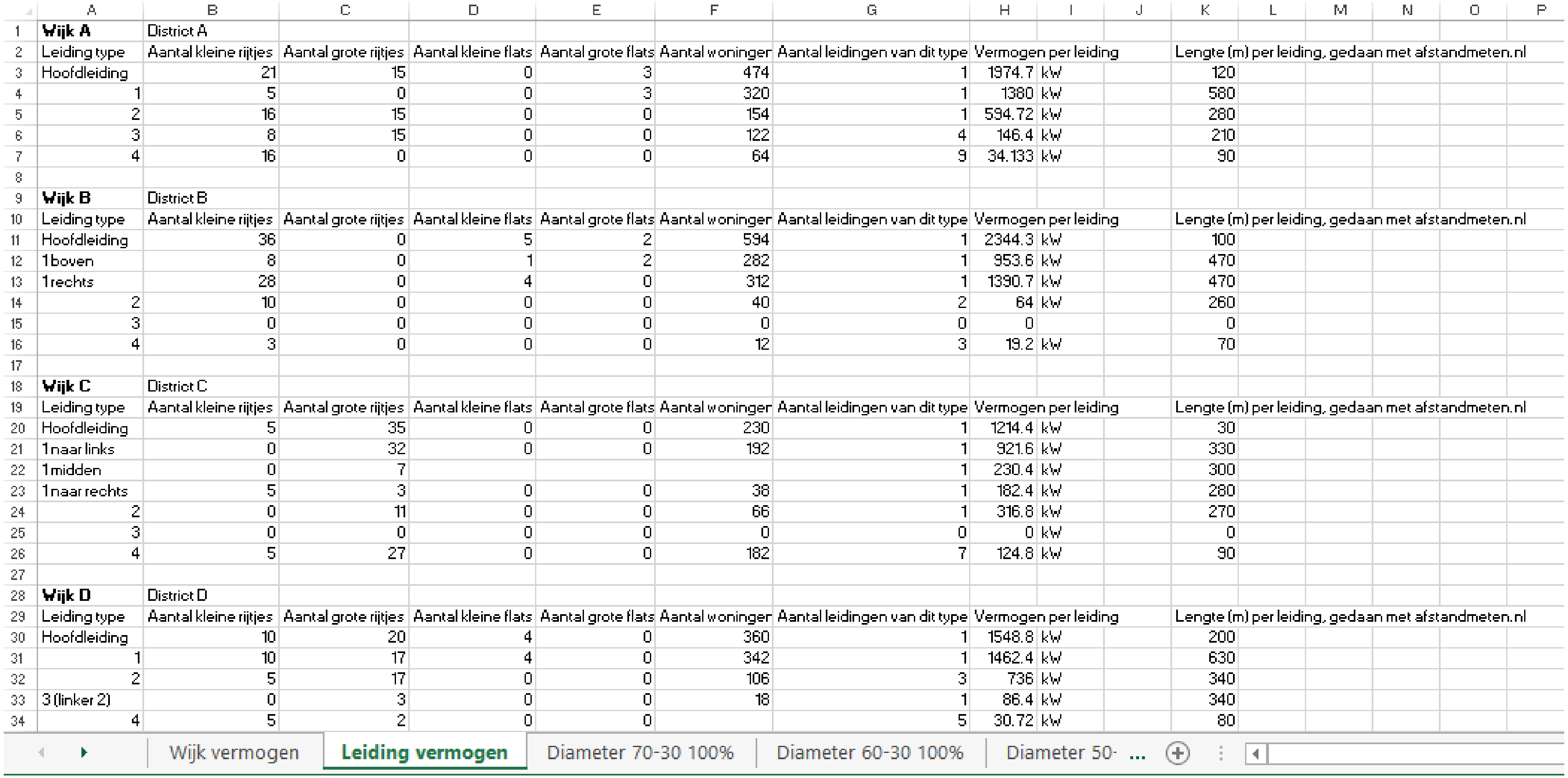
The other tabs calculate the pipe sizes of the several LTDH concepts. Pipe sizes are calculated for the three supply temperatures, where the peak demand is supplied, and if the homes have extra insulation.
The flow through the pipes is determined with the temperature difference and the heat through the pipe from the second tab. With an assumed speed, the inner diameter is calculated. A DN type is selected from the size table from Thermaflex. This is the size that is the closest to the calculated inner diameter. The real speed through the pipes and the pressure drops are calculated with the correct inner diameter. If these parameters are outside the standards according to Dutch Standard ISSO 3, then the diameter will be adjusted.
The print screen shows the diameters, speed, and pressure drops of the LTDH with 70 ^{0}C supply temperature, peak supply by the network, and extra insulation is applied.



	A	B	C	D	E	F	G	H	I	J	K
1	**Wijk A**						**Wijk B**				
2		Aantal	Aantal woninger	Vermogen vraag				Aantal	Aantal woninger	Vermogen vraag	
3	Grote flat's	3	300	1200			Grote flat's	2	200	800	
4	Kleine flat's	0	0	0			Kleine flat's	5	250	1000	
5	Lange rijtjes	15	90	540			Lange rijtjes	0	0	0	
6	Korte rtijes	21	84	504			Korte rtijes	36	144	864	
7	Totaal		474	1974.72	kW		Totaal		594	2344.32	kW
8											
9	Grote flat	1	100				Grote flat	1	100		
10	Kleine flat	1	50				Kleine flat	1	50		
11	Lange rijtje	1	6				Lange rijtje	1	6		
12	Korte rijtje	1	4				Korte rijtje	1	4		
13											
14	Flatvermogen per woning			4	kW		Flatvermogen per woning			4	kW
15	Rijtjevermogen per woning			6	kW		Rijtjevermogen per woning			6	kW
16											
17											
18	**Wijk C**						**Wijk D**				
19		Aantal	Aantal woninger	Vermogen vraag				Aantal	Aantal woninger	Vermogen vraag	
20	Grote flat's	0	0	0			Grote flat's	0	0	0	
21	Kleine flat's	0	0	0			Kleine flat's	4	200	800	
22	Lange rijtjes	35	210	1260			Lange rijtjes	20	120	720	
23	Korte rtijes	5	20	120			Korte rtijes	10	40	240	
24	Totaal		230	1214.4	kW		Totaal		360	1548.8	kW
25											
26	Grote flat	1	100				Grote flat	1	100		
27	Kleine flat	1	50				Kleine flat	1	50		
28	Lange rijtje	1	6				Lange rijtje	1	6		
29	Korte rijtje	1	4				Korte rijtje	1	4		
30											
31	Flatvermogen per woning			4	kW		Flatvermogen per woning			4	kW
32	Rijtjevermogen per woning			6	kW		Rijtjevermogen per woning			6	kW
33											
34											

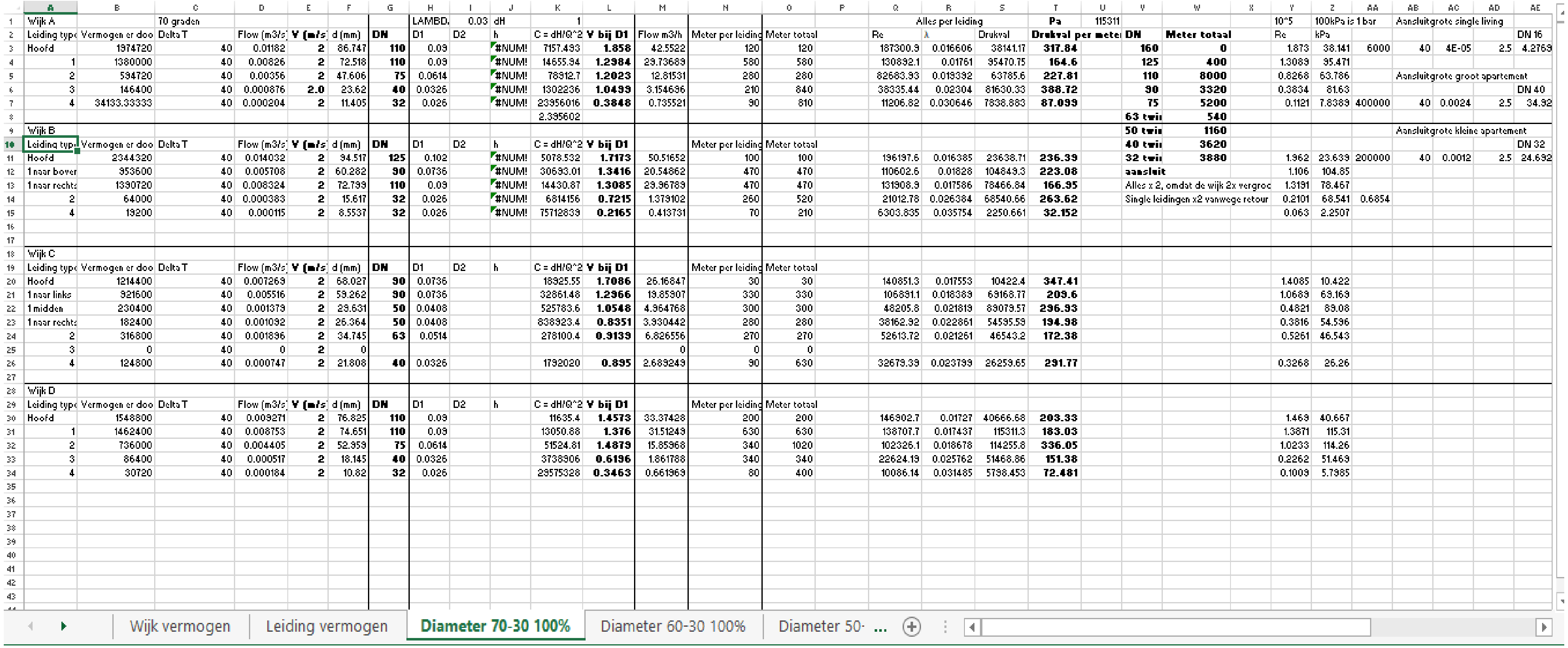
	L	M	N	O	P	Q	R	S	T	U	V
1											
2		Totaal	7082.2	kW	13707	is maximale vraag					
3			7.0822	MW							
4											
5											
6							Pltgh (kW)	PATES (kW	Totaal	Percentage total	
7					70-30 scenario		6950	6000	12950	0.9448	
8					60-30 scenario		5210	4500	9710	0.7084	
9	Totaal flats woning		950		50-30 scenario		3480	3000	6480	0.4727	
10	Totaal single wonin		708								

Figure A-1 Printscreen of the first Excel tab of the pipe diameter calculations.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Wijk A**	District A														
2	Leiding type	Aantal kleine rijtjes	Aantal grote rijtjes	Aantal kleine flats	Aantal grote flats	Aantal woninger	Aantal leidingen van dit type	Vermogen per leiding			Lengte (m) per leiding, gedaan met afstandmeten.nl					
3	Hoofdleiding	21	15	0	3	474	1	1974.7	kW		120					
4	1	5	0	0	3	320	1	1380	kW		580					
5	2	16	15	0	0	154	1	594.72	kW		280					
6	3	8	15	0	0	122	4	146.4	kW		210					
7	4	16	0	0	0	64	9	34.133	kW		90					
8																
9	**Wijk B**	District B														
10	Leiding type	Aantal kleine rijtjes	Aantal grote rijtjes	Aantal kleine flats	Aantal grote flats	Aantal woninger	Aantal leidingen van dit type	Vermogen per leiding			Lengte (m) per leiding, gedaan met afstandmeten.nl					
11	Hoofdleiding	36	0	5	2	594	1	2344.3	kW		100					
12	1 boven	8	0	1	2	282	1	953.6	kW		470					
13	1 rechts	28	0	4	0	312	1	1390.7	kW		470					
14	2	10	0	0	0	40	2	64	kW		260					
15	3	0	0	0	0	0	0	0			0					
16	4	3	0	0	0	12	3	19.2	kW		70					
17																
18	**Wijk C**	District C														
19	Leiding type	Aantal kleine rijtjes	Aantal grote rijtjes	Aantal kleine flats	Aantal grote flats	Aantal woninger	Aantal leidingen van dit type	Vermogen per leiding			Lengte (m) per leiding, gedaan met afstandmeten.nl					
20	Hoofdleiding	5	35	0	0	230	1	1214.4	kW		30					
21	1 naar links	0	32	0	0	192	1	921.6	kW		330					
22	1 midden	0	7				1	230.4	kW		300					
23	1 naar rechts	5	3	0	0	38	1	182.4	kW		280					
24	2	0	11	0	0	66	1	316.8	kW		270					
25	3	0	0	0	0	0	0	0	kW		0					
26	4	5	27	0	0	182	7	124.8	kW		90					
27																
28	**Wijk D**	District D														
29	Leiding type	Aantal kleine rijtjes	Aantal grote rijtjes	Aantal kleine flats	Aantal grote flats	Aantal woninger	Aantal leidingen van dit type	Vermogen per leiding			Lengte (m) per leiding, gedaan met afstandmeten.nl					
30	Hoofdleiding	10	20	4	0	360	1	1548.8	kW		200					
31	1	10	17	4	0	342	1	1462.4	kW		630					
32	2	5	17	0	0	106	3	736	kW		340					
33	3 (linker 2)	0	3	0	0	18	1	86.4	kW		340					
34	4	5	2	0	0		5	30.72	kW		80					

Figure A-2 Printscreen of the second tab of the pipe diameter calculations.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
1	Wijk A		70 graden					LAMBD.	0.03	dH	1						Alles per leiding			**Pa**	115311				10^5	100kPa is 1 bar		Aansluitgrote single living			
2	Leiding typ	Vermogen er doo	Delta T	Flow (m3/s	**V (m/s**	d (mm)	**DN**	D1	D2	h	C = dH/Q^2	**V bij D1**	Flow m3/h	Meter per leiding	Meter totaal		Re	λ	Drukval	**Drukval per mete**		**DN**	**Meter totaal**		Re	kPa					DN 16
3	Hoofd	1974720	40	0.01182	**2**	86.747	**110**	0.09		#NUM!	7157.493	**1.858**	42.5522	120	120		187300.9	0.016606	38141.17	**317.84**		**160**	**0**		1.873	38.141	6000	40	4E-05	2.5	4.2769
4	1	1380000	40	0.00826	**2**	72.518	**110**	0.09		#NUM!	14655.94	**1.2984**	29.73689	580	580		130892.1	0.01761	95470.75	**164.6**		**125**	**400**		1.3089	95.471					
5	2	594720	40	0.00356	**2**	47.606	**75**	0.0614		#NUM!	78912.7	**1.2023**	12.81531	280	280		82683.93	0.019392	63785.6	**227.81**		**110**	**8000**		0.8268	63.786		Aansluitgrote groot apartement			
6	3	146400	40	0.000876	**2.0**	23.62	**40**	0.0326		#NUM!	1302236	**1.0499**	3.154696	210	840		38335.44	0.02304	81630.33	**388.72**		**90**	**3320**		0.3834	81.63					DN 40
7	4	34133.33333	40	0.000204	**2**	11.405	**32**	0.026		#NUM!	23956016	**0.3848**	0.735521	90	810		11206.82	0.030646	7838.883	**87.099**		**75**	**5200**		0.1121	7.8389	400000	40	0.0024	2.5	34.92
8											2.395602											**63 twi**	**540**								
9	Wijk B																					**50 twi**	**1160**					Aansluitgrote kleine apartement			
10	Leiding typ	Vermogen er doo	Delta T	Flow (m3/s	**V (m/s**	d (mm)	**DN**	D1	D2	h	C = dH/Q^2	**V bij D1**		Meter per leiding	Meter totaal							**40 twi**	**3620**								DN 32
11	Hoofd	2344320	40	0.014032	**2**	94.517	**125**	0.102		#NUM!	5078.532	**1.7173**	50.51652	100	100		196197.6	0.016385	23638.71	**236.39**		**32 twi**	**3880**		1.962	23.639	200000	40	0.0012	2.5	24.692
12	1 naar bover	353600	40	0.005708	**2**	60.282	**90**	0.0736		#NUM!	30693.01	**1.3416**	20.54862	470	470		110602.6	0.01828	104849.3	**223.08**		**aansluit**			1.106	104.85					
13	1 naar rechts	1390720	40	0.008324	**2**	72.799	**110**	0.09		#NUM!	14430.87	**1.3085**	29.96789	470	470		131908.9	0.017586	78466.84	**166.95**		Alles x 2, omdat de wijk 2x vergroc			1.3191	78.467					
14	2	64000	40	0.000383	**2**	15.617	**32**	0.026		#NUM!	6814156	**0.7215**	1.379102	260	520		21012.78	0.026384	68540.66	**263.62**		Single leidingen x2 vanwege retour			0.2101	68.541	0.6854				
15	4	19200	40	0.000115	**2**	8.5537	**32**	0.026		#NUM!	75712839	**0.2165**	0.413731	70	210		6303.835	0.035754	2250.661	**32.152**					0.063	2.2507					
16																															
17																															
18	Wijk C																														
19	Leiding typ	Vermogen er doo	Delta T	Flow (m3/s	**V (m/s**	d (mm)	**DN**	D1	D2	h	C = dH/Q^2	**V bij D1**		Meter per leiding	Meter totaal																
20	Hoofd	1214400	40	0.007269	**2**	68.027	**90**	0.0736			18925.55	**1.7086**	26.16847	30	30		140851.3	0.017553	10422.4	**347.41**					1.4085	10.422					
21	1 naar links	921600	40	0.005516	**2**	59.262	**90**	0.0736			32861.48	**1.2966**	19.85907	330	330		106891.1	0.018389	69168.77	**209.6**					1.0689	69.169					
22	1 midden	230400	40	0.001379	**2**	29.631	**50**	0.0408			525783.6	**1.0548**	4.964768	300	300		48205.8	0.021819	89079.57	**296.93**					0.4821	89.08					
23	1 naar rechts	182400	40	0.001092	**2**	26.364	**50**	0.0408			838923.4	**0.8351**	3.930442	280	280		38162.92	0.022861	54595.59	**194.98**					0.3816	54.596					
24	2	316800	40	0.001896	**2**	34.745	**63**	0.0514			278100.4	**0.9139**	6.826556	270	270		52613.72	0.021261	46543.2	**172.38**					0.5261	46.543					
25	3	0	40	0	**2**	0							0	0	0																
26	4	124800	40	0.000747	**2**	21.808	**40**	0.0326			1792020	**0.895**	2.689249	90	630		32679.39	0.023799	26259.65	**291.77**					0.3268	26.26					
27																															
28	Wijk D																														
29	Leiding typ	Vermogen er doo	Delta T	Flow (m3/s	**V (m/s**	d (mm)	**DN**	D1	D2	h	C = dH/Q^2	**V bij D1**		Meter per leiding	Meter totaal																
30	Hoofd	1548800	40	0.009271	**2**	76.825	**110**	0.09			11635.4	**1.4573**	33.37428	200	200		146902.7	0.01727	40666.68	**203.33**					1.469	40.667					
31	1	1462400	40	0.008753	**2**	74.651	**110**	0.09			13050.88	**1.376**	31.51249	630	630		138707.7	0.017437	115311.3	**183.03**					1.3871	115.31					
32	2	736000	40	0.004405	**2**	52.959	**75**	0.0614			51524.81	**1.4879**	15.85968	340	1020		102326.1	0.018678	114255.8	**336.05**					1.0233	114.26					
33	3	86400	40	0.000517	**2**	18.145	**40**	0.0326			3738906	**0.6196**	1.861788	340	340		22624.19	0.025762	51468.86	**151.38**					0.2262	51.469					
34	4	30720	40	0.000184	**2**	10.82	**32**	0.026			29575328	**0.3463**	0.661969	80	400		10086.14	0.031485	5798.453	**72.481**					0.1009	5.7985					

Figure A-3 Printscreen of the third tab of the pipe diameter calculations.

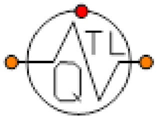
WANDA model

The WANDA model is developed to select a circulation pump. This section explains first the components in WANDA, how the model is arranged, and how input parameters are calculated or assumed.

Components in WANDA

To understand how to model in WANDA and how to insert the digital network of an LTDH in WANDA, it is required to understand what the components are in WANDA. The following sections describe for each component what the component is, what the component does, and an explanation of which parameters there are and how to determine those.

LTGH source

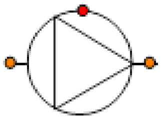


This is the heat production source. In WANDA, this is the component which gives the amount of heat that is available to supply through the network. The parameters which need to be filled in for this component are listed in Table A-1.

Table A-1 Explanation input parameters for component LTGH source in WANDA

Parameter	Description	Calculation / value	Unit
C-value	Head loss coefficient	Pressure drop LTGH/volume flow^2	s^2/m^5
Initial downstr temperature	Supply temperature in the district	Given by the heat concept, in section 5.3	° C

Circulation pump

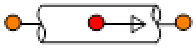


The circulation pump is located after the LTGH source. In WANDA, this is the component which supplies the produced heat to the pipes and heat demands. The parameters which need to be filled in for this component are listed in Table A-2. The component calculates the pump speed and the electrical power required to generate the mass flow.

Table A-2 Explanation input parameters for component 'circulation pump' in WANDA

Parameter	Description	Calculation / value	Unit
QHE_table	Pump curve	Given by a selected heat pump	
Rated speed	The operation speed of the pump	Given by a selected heat pump	rpm
Initial mass flow	The mass flow produced by the pump	Given by the heat concept, in section 7.2.	kg/h

Pipes

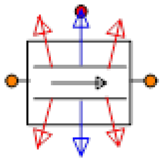


The calculated diameters and certain lengths are entered in this component. In WANDA, this is the component that connects the circulation pump with the heat demand. The parameters which need to be filled in for this component are listed in Table A-3. The component calculates the pressure drop and the temperature drop in the pipe.

Table A-3 Explanation input parameters for component 'pipe' in WANDA

Parameter	Description	Calculation / value	Unit
Inner diameter	The inside diameter of the pipe	Given by the heat concept	mm
Wall roughness	The roughness of the inner material of the pipe	Assumed to be 0.01 mm	mm
Length	The length of a pipe	Given in section 8.2	m
Heat transfer table			
Ground coverage	The depth of the pipe	1.5	m
Thermal conductivity ground	-	1.6	W/mK
Distance between centre of pipes	-		m
Ambient temperature	-	- 10	° C

Heat demand

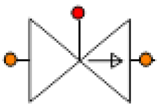


The heat demand for a street is entered into this component. In WANDA, this component indicates the heat demand of a specific street. The parameters which need to be filled in for this component are listed in Table A-4. The component calculates the pressure drop and the temperature drop in the street. These answers can be used to check if the pressure and temperature drop are according to the design requirements.

Table A-4 Explanation input parameters for component 'heat demand' in WANDA

Parameter	Description	Calculation / value	Unit
C-value	Head loss coefficient	Pressure drop LTGH/volume flow^2	s^2/m^5
Constant heat demand	The maximum heat demand for an hour	Given by the data from section 4.4	kW

Valve



The valves are placed after the heat demand and control the flow rate that is sent back to the LTGH source. The parameters which need to be filled in for this component are listed in Table A-5.

Table A-5 Explanation input parameters for component 'Valve' in WANDA

Parameter	Description	Calculation / value	Unit
Inner diameter	Inner diameter of the pipe	Calculated as described in the previous section	mm
Initial mass flow rate	The mass flow rate through the pipe	Calculated as described in the previous section	kg/h
Initial position	How far the valve is open	25	%

WANDA model explanation

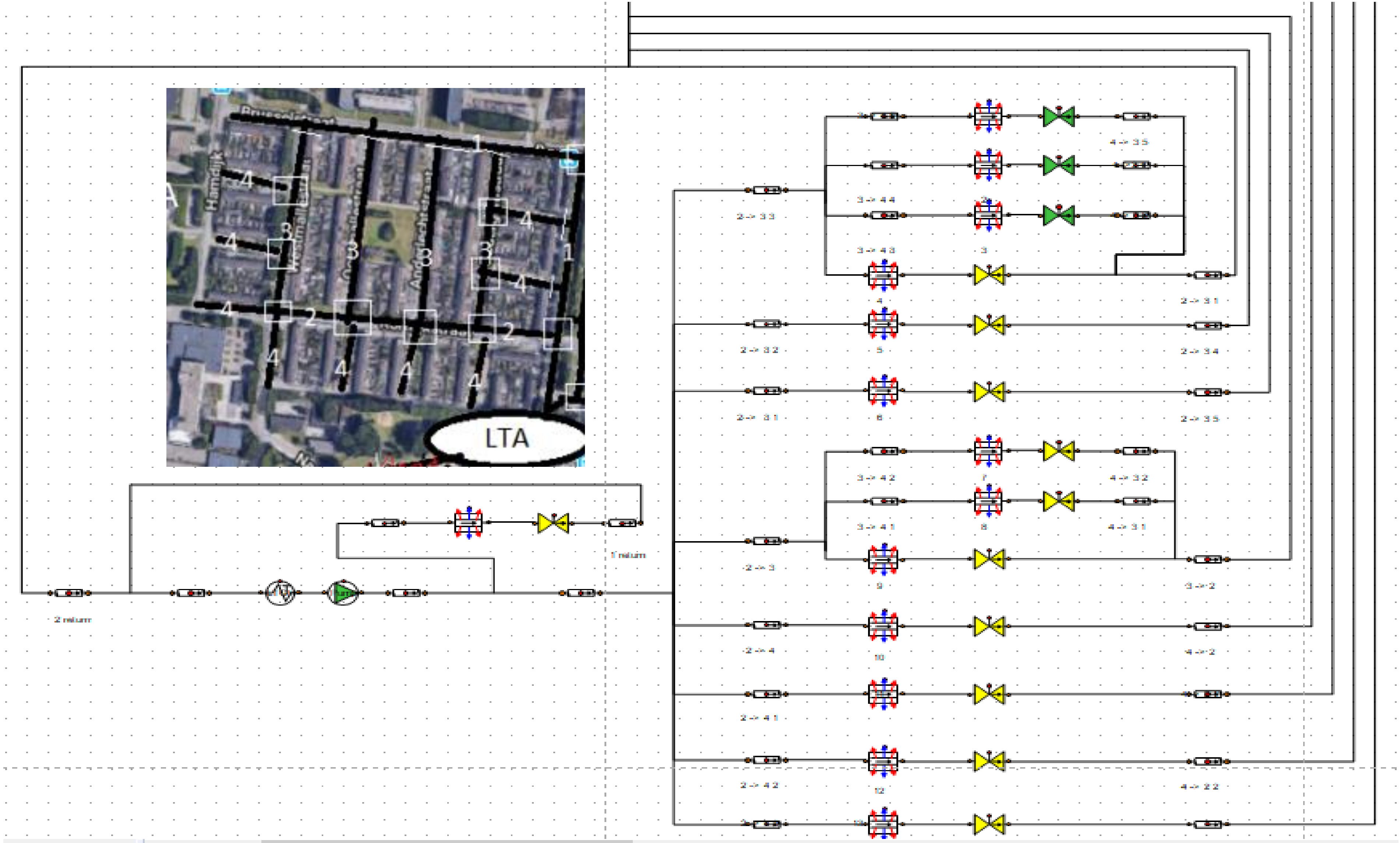


Figure A-4 Printscreen of the WANDA model.

The figure on the previous page is a screenshot of the complete WANDA model and how the pipes can be placed in the district. As explained in section 7.2.1, the district is divided over 4 parts. The WANDA model is only simulated for 1 part, otherwise the whole model would be too complex.

From the LTGH source and the circulation pump, the heat is distributed over the pipe numbers 1 and 2. Pipe 1 distributes the heat among 3 flats. These flats are in the WANDA model presented as one heat component. From pipe number 2, the heat is distributed among the pipes 3 and 4. The heat components, which are related to these pipes, are presenting a street of 20 houses (for pipe 3) and a street of 10 houses (pipe 4). The valves after the heat components regulate the flow through the street.

Head loss coefficient calculation

An important input parameter for the WANDA model is the head loss coefficient. It is the constant value of the Darby-Weibach equation, where is assumed that the flow is in the turbulent regime. With this coefficient, WANDA can calculate the required head for the circulation pump. The head loss coefficient is calculated as follows.

$$C = \frac{\Delta H}{\dot{m}^2} \tag{55}$$

The head is for every heat component and for the LTGH source 5.1 meters. The mass flow is divided over the streets. Table 0-6 presents the calculated head loss coefficient for the components in WANDA.

Table A-6 Head loss coefficient for the components in WANDA.

Concept	1 70-30 peak collective	2 60-30 peak collective	3 50-30 peak collective	4 70-30 peak decentral	5 60-30 peak decentral	6 50-30 peak decentral
Without insulation improvement						
LTGH	23,362	13,141	5,840	73,781	39,062	21,889
High-rise building	74,745	42,044	18,686	236,058	124,976	70,032
Long street	4,250,500	2,390,906	1,062,625	13,423,774	7,106,922	3,982,489
Short street	7.819E7	4.398E7	1.955E7	2.47E8	1.31E8	7.33E7
With insulation improvement						
LTGH	32,335	18,188	8,084	118,377	56,766	34,270
High-rise building	103,453	58,192	25,863	378,738	181,619	109,642
Long street	6,641,405	3,735,791	1,660,351	2.431E7	1.166E7	7,038,691
Short street	1.218E8	6.872E7	3.054E7	4.473E8	2.145E8	1.295E8

Assumptions in model

In the model, a number of parameters are assumed or calculated with a quick calculation. It is about the following parameters.

Thermal conductivity of the ground

The thermal conductivity is a property of a material which measures its ability to conduct heat. It is assumed that the thermal conductivity of the ground is 1.6 W/mK.

Heat transfer coefficient and heat conductivity coefficient

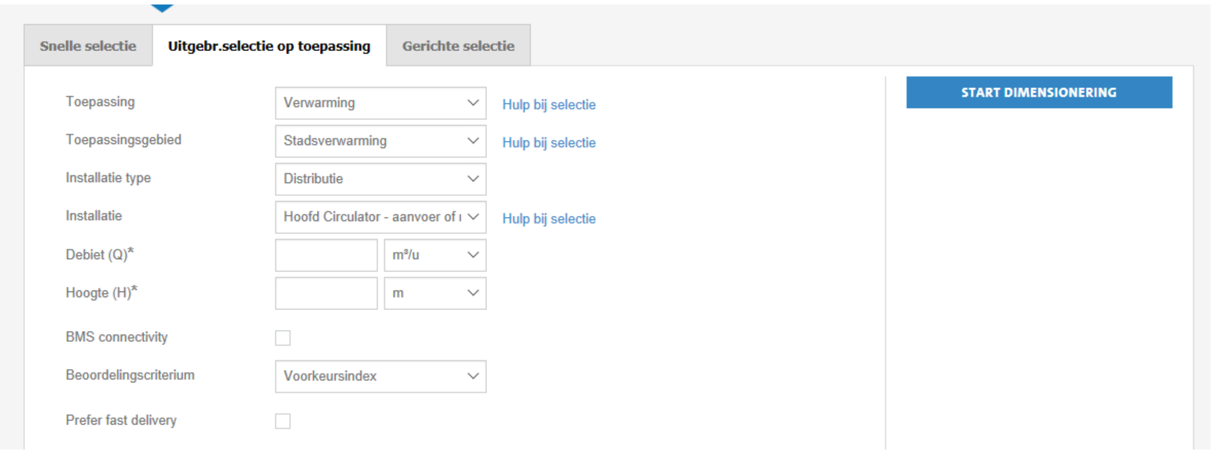
The heat transfer coefficient is the proportionality constant between the heat flux and the temperature difference. This constant depends on the heat conductivity coefficient. WANDA assumes that the most dominant factor for heat loss is between the inner diameter and the outer diameter of the pipe, where the insulation is placed. The heat transfer coefficient is calculated as follows.

$$h = \frac{2\lambda}{D_2 * \ln\frac{D_2}{D_1}} \tag{56}$$

Here is h the heat transfer coefficient, λ is the heat conductivity coefficient, D_2 the outer diameter and D_1 the inner diameter. The outer and inner diameter is provided by Thermaflex. The heat conductivity coefficient of PUR is 0.026 W/m^2 K.

Pump selection in Grundfoss

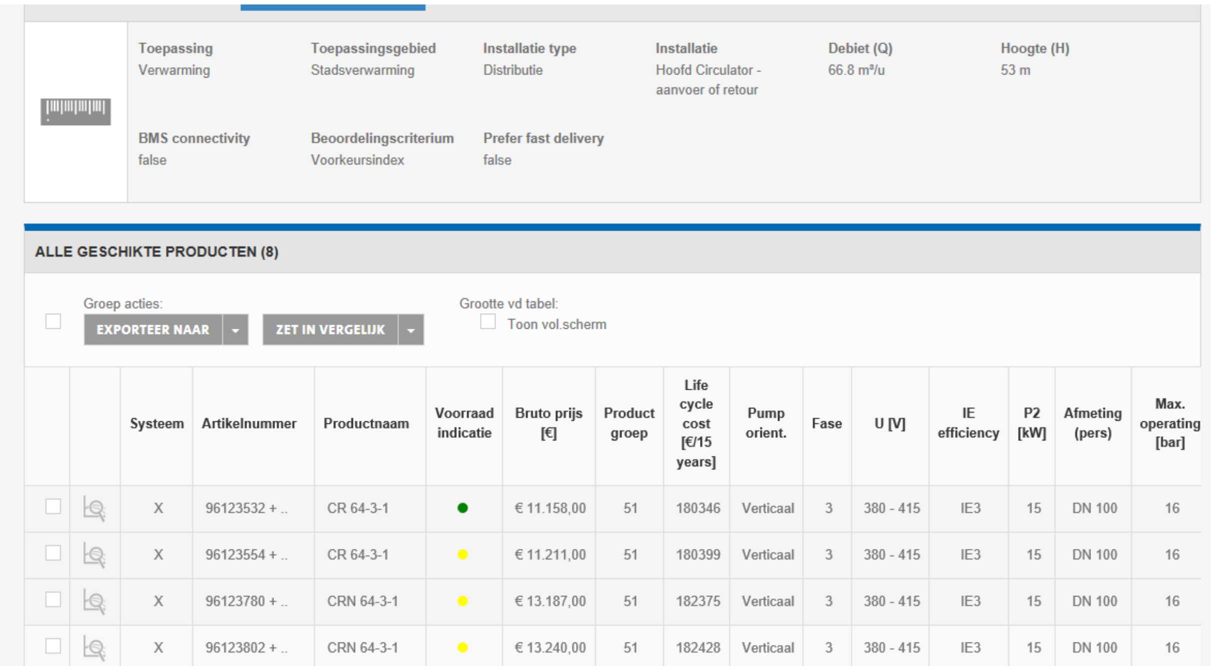
First, the designer must indicate, in the selection tool, that the circulation pump is required for the distribution of DH water and what the flow rate and head are. This is presented in the figure below.



Toepassing: Verwarming
Toepassingsgebied: Stadsverwarming
Installatie type: Distributie
Installatie: Hoofd Circulator - aanvoer of r
Debiet (Q)*: m³/u
Hoogte (H)*: m
BMS connectivity: ☐
Beoordelingscriterium: Voorkeursindex
Prefer fast delivery: ☐

Figure A-5 Printscreen of the first step for the selection tool in Grundfoss.

The tool then calculates a number of suitable pumps. These are arranged by which pump is closest to the BEP. This pump is selected. The figure below shows what the selection looks like.



Toepassing: Verwarming
Toepassingsgebied: Stadsverwarming
Installatie type: Distributie
Installatie: Hoofd Circulator - aanvoer of retour
Debiet (Q): 66.8 m³/u
Hoogte (H): 53 m
BMS connectivity: false
Beoordelingscriterium: Voorkeursindex
Prefer fast delivery: false

ALLE GESCHIKTE PRODUCTEN (8)

Groep acties:

Grootte vd tabel: ☐ Toon vol.scherm

☐		Systeem	Artikelnummer	Productnaam	Voorraad indicatie	Bruto prijs [€]	Product groep	Life cycle cost [€/15 years]	Pump orient.	Fase	U [V]	IE efficiency	P2 [kW]	Afmeting (pers)	Max. operating [bar]
☐		X	96123532 + ..	CR 64-3-1	●	€ 11.158,00	51	180346	Verticaal	3	380 - 415	IE3	15	DN 100	16
☐		X	96123554 + ..	CR 64-3-1	●	€ 11.211,00	51	180399	Verticaal	3	380 - 415	IE3	15	DN 100	16
☐		X	96123780 + ..	CRN 64-3-1	●	€ 13.187,00	51	182375	Verticaal	3	380 - 415	IE3	15	DN 100	16
☐		X	96123802 + ..	CRN 64-3-1	●	€ 13.240,00	51	182428	Verticaal	3	380 - 415	IE3	15	DN 100	16

Figure A-6 Printscreen of the available pumps for the selected requirements.

If a pump is selected, Grundfoss provides a Q-H table and a pump curve of the pump. An example is provided in the figure on the next page.

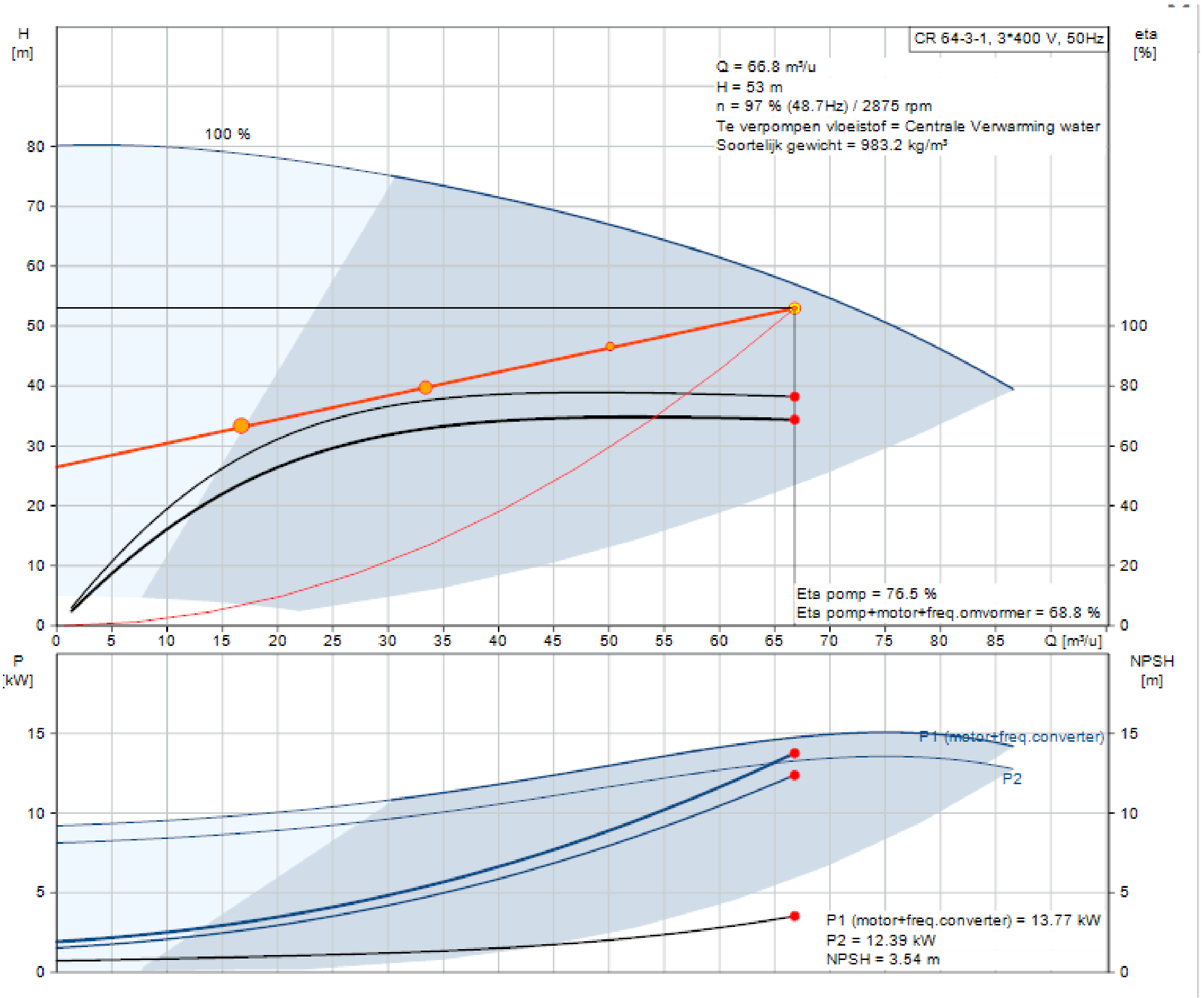


Figure A-7 Printscreen of a Q-H table and pump curve of a pump and required head and flow rate.

B. Appendix Matlab script and energy balance

The MATLAB script exists out of 3 scripts.

- MAIN
- PARAMETERS
- DATA

MAIN
The energy balance, according to section 6.5, is set up in the script MAIN. First, the required data is called up from the scripts PARAMETERS and DATA. Then vectors are created that needs to be filled. Then the computation begins. This is the energy balance, calculated per hour and fills in the vectors. Finally, graphs are made of the results.

PARAMETERS
This script is the parameters that are required for the MAIN script. These can be adjusted according to the different LTDH concepts from Chapter 5. As it is filled in this Appendix, it is for the 50 ^{0}C supply temperature network with a daily storage tank. The storage tank can be left out by filling in 0 for the power and capacity of the storage tank.

DATA
The DATA script is the hourly data of the different heat demand strategies from section 5.4. Both space heat and DHW are in the data. Only an image is shown below. The entire vector consists of 8784 rows, which would make the appendix too long. Figure B-1 shows the data used in heat demand strategy 3.

Main

```
%% Energy balance in LTDH with a low-temperature geothermal heat as base
source
% This script provides the energy status per hour of the daily storage,
seasonal storage and peak supply.
% Author: Sebastiaan Knepper

%% DATA
% Getting data from PARAMETERS file
[Qt_v, Qt_b, Qt_b_summer, Q_s_max, Q_ss, Q_d_max, Q_ds, n_s, t_s_summer,
t_e_summer, mwatermax, Tltgh, Tates, Twater, Tat_ltgh, mates3] =
PARAMETERS(DATA);

%% INITILIAZE
% Making vectors of the seasonal storage, daily storage and peak supply
T = length(Qt_v); %
A = zeros(T, 1); % hourly difference between LTGH and demand
Q_s = zeros(T, 1); % capacity seasonal storage at time t
Q_d = zeros(T, 1); % capacity daily storage at time t
Q_p = zeros(T, 1); % peak supply at time t
Q_sw = zeros(T, 1); % power seasonal storage at time t
Q_dw = zeros (T, 1); % power daily storage at time t
Qltgh = zeros (T,1); % Qltgh bepaling
D = zeros(T,1); % vector to present heat surplus by LTGH
md = zeros (T,1); % massflow demand
md1 = zeros (T,1); % 1e itteratie mass flow
mates1 = zeros (T,1); %1e itteratie ATES flow
mates2 = zeros (T,1); % daadwerkelijke ATES flow
mwater = zeros (T,1); % Flow van Watertank
mwater1 = zeros (T,1); % 1e itteratie watertank flow
mbefore = zeros (T,1); % massflow after ATES
mLTGH = zeros (T,1); % mass flow LTGH
T2 = zeros(T,1); %temperature after ATES
T3 = zeros(T,1); % temperature after Watertank
T4 = zeros(T,1); % available temperature in house
T5 = zeros(T,1); % Return temperature
cp = 4.18/1000;
Treturnh = 30;
Treturnn = 32;

% At t = 0 the storages are 50% filled
Q_d(1) = 0.5*Q_d_max;
Q_s(1) = 0.5*Q_s_max;
Q_sw(1) = 0;
Q_dw(1) = 0;
T_plot = 0:(T+1);

%% COMPUTATION

for t = 2:T

    netto = Qt_b(t) - Qt_v(t);
    Q_d(t) = Q_d(t-1);
    Q_s(t) = Q_s(t-1);
    D(t) = 0;
    mLTGH(t) = Qt_b(t)/(cp*(Tltgh-Treturnn));
    Qltgh(t) = Qt_b(t);
    T5(t) = 32;

if netto > 0 && Q_d(t) >= Q_d_max
```

```
    T2(t) = Tltgh;
    T3(t) = T2(t);
    T4(t) = T3(t) - 2;
    md(t) = Qt_v(t)/(cp*(T4(t)-30));
    mates2(t) = mLTGH(t) - md(t);
    T5(t) = (md(t)*(32+273)+mates2(t)*(38+273))/(md(t)+mates2(t)) - 273;
    Qltgh(t) = mLTGH(t)*cp*(Tltgh - T5(t));
    Q_sw(t) = mates2(t)*cp*(Tat_ltgh-35);
    Q_s(t) = Q_s(t-1) + Q_sw(t);
    Q_d(t) = Q_d_max;
    Q_dw(t) = 0;
        if Q_s(t) >= Q_s_max
            Q_s(t) = Q_s_max;
            Q_sw(t) = 0;
            D(t) = netto;
        end
end

if netto < 0 && netto > -1*Q_ss
    if Q_d(t) >= Q_d_max
        mates1(t) = netto/(cp*(Tates-33));
        T2(t) = ((Tates+273)*mates1(t)*-1+(Tltgh+273)*mLTGH(t))/(mLTGH(t) -
mates1(t))-273;
        md(t) = Qt_v(t)/(cp*(T2(t)-2-30));
        mates2(t) = mLTGH(t) - md(t);
        Q_sw(t) = mates2(t)*cp*(Tat_ltgh-35);
        Q_s(t) = Q_s(t-1) + Q_sw(t);
        T3(t) = T2(t);
        T4(t) = T3(t) - 2;
    else
        if Q_d(t-1) + Q_ss + netto > Q_d_max
            if Q_ds < Q_ss + netto;
            mwater1(t) = (Q_d(t) - Q_d(t-1))/(cp*(Tat_ltgh-32));
            md1(t) = Qt_v(t)/(cp*(Tat_ltgh-30));
            mates1(t) = mwater1(t) + md1(t) - mLTGH(t);
            T2(t) =
((Tltgh+273)*mLTGH(t)+(Tates+273)*mates1(t))/(mLTGH(t)+mates1(t))-273;
            T3(t) = T2(t);
            T4(t) = T3(t) - 2;
            mates2(t) = -(mLTGH(t)*(Tltgh-T2(t)))/(T2(t)-Tates);
            md(t) = Qt_v(t)/(cp*(T4(t)-30));
            mwater(t) = mLTGH(t) - mates2(t) - md(t);
            Q_dw(t) = mwater(t)*cp*(T3(t)-32);
            Q_sw(t) = mates2(t)*cp*(Tat_ltgh-30);
            Q_s(t) = Q_s(t-1) + Q_sw(t);
            else
                T2(t) = Tat_ltgh;
                T3(t) = T2(t);
                T4(t) = T3(t) - 2;
                md(t) = Qt_v(t)/(cp*(T4(t)-30));
                mates2(t) = -mates3;
                mwater(t) = mLTGH(t) - mates2(t) - md(t);
                  Q_dw(t) = Q_d_max-Q_d(t-1);
                  Q_d(t) = Q_d_max;
                  Q_sw(t) = netto - Q_dw(t);
                  Q_s(t) = Q_s(t-1) + Q_sw(t);
            end
        else
            Q_sw(t) = -Q_ss;
            Q_s(t) = Q_s(t-1) - Q_ss;
            mates2(t) = -mates3;
```

```
            T2(t) = Tat_ltgh;
            T3(t) = T2(t);
            T4(t) = T3(t) - 2;
            md(t) = Qt_v(t)/(cp*(T4(t)-30));
            mwater(t) = mLTGH(t) - mates2(t) - md(t);
            if mwater(t)*cp*(T2(t)-32) <= Q_ds
                Q_dw(t) = mwater(t)*cp*(T2(t)-32);
                Q_d(t) = Q_d(t-1) + Q_dw(t);
            else
                Q_dw(t) = Q_ds;
                Q_d(t) = Q_d(t-1) + Q_dw(t);
            end
        end
    end

    if Q_s(t-1) >= Q_s_max
        Q_s(t) = Q_s(t-1)*n_s - Q_sw(t);
    end
end

% TANK OPLADEN

if netto > 0 && Q_d(t-1) < Q_d_max
    if netto > Q_ds
            T2(t) = Tltgh;
            T3(t) = T2(t);
            T4(t) = T3(t) - 2;
        if Q_d(t-1) + Q_ds < Q_d_max
            Q_dw(t) = Q_ds;
            Q_d(t) = Q_d(t-1) + Q_dw(t);
            % ATES OPSLAG BEPALEN
            mwater(t) = Q_ds/(cp*(T2(t)-3-30));
            md(t) = Qt_v(t)/(cp*(T2(t)-2-30));
            mates2(t) = mLTGH(t) - md(t) - mwater(t);
            Q_sw(t) = mates2(t)*cp*(Tltgh-3-30);
            Q_s(t) = Q_s(t-1) + Q_sw(t);
        else
            Q_d(t) = Q_d_max;
            Q_dw(t) = Q_d_max-Q_d(t-1);
            % ATES OPSLAG BEPALEN
            mwater(t) = Q_dw(t)/(cp*(T2(t)-30));
            md(t) = Qt_v(t)/(cp*(T2(t)-2-30));
            mates2(t) = mLTGH(t) - md(t) - mwater(t);
            Q_sw(t) = mates2(t)*cp*(Tat_ltgh-30);
            Q_s(t) = Q_s(t-1) + Q_sw(t);
        end
    else
        if Q_d(t-1) + Q_ds < Q_d_max
            md1(t) = Qt_v(t)/(cp*(Tat_ltgh-2-30));
            mwater(t) = mwatermax;
            mates1(t) = mwater(t) + md1(t) - mLTGH(t);
            T2(t) =
(mLTGH(t)*(Tltgh+273)+(Tates+273)*mates1(t))/(mates1(t)+mLTGH(t)) - 273;
            mates2(t) = -1*mLTGH(t)*(Tltgh-T2(t))/(T2(t)-Tates);
            T3(t) = T2(t);
            T4(t) = T3(t) - 2;
            md(t) = mLTGH(t) - mates2(t) - mwater(t);
            Q_dw(t) = mwater(t)*cp*(T3(t) - 32);
            Q_d(t) = Q_d(t-1) + Q_dw(t);
            Q_sw(t) = mates2(t)*cp*(Tates-33);
            Q_s(t) = Q_s(t-1) + Q_sw(t);
```

```
        else
            T2(t) = Tltgh;
            T3(t) = T2(t);
            T4(t) = T3(t) - 2;
            Q_d(t) = Q_d_max;
            Q_dw(t) = Q_d_max - Q_d(t-1);
            mwater(t) = Q_dw(t)/(cp*(T2(t)-3-30));
            md(t) = Qt_v(t)/(cp*(T2(t)-2-30));
            mates2(t) = mLTGH(t) - md(t) - mwater(t);
            Q_sw(t) = mates2(t)*cp*(Tltgh-3-30);
            Q_s(t) = Q_s(t-1) + Q_sw(t);
        end
    end

        if Q_s(t) >= Q_s_max
            Q_s(t) = Q_s_max;
            Q_sw(t) = 0;
            D(t) = netto;
        end

end

% TANK ONTLADEN

if netto < 0 && netto < - Q_ss
    if Q_d(t-1) <= 0
        Q_sw(t) = Q_ss * -1;
        Q_s(t) = Q_s(t-1) + Q_sw(t);
        Q_dw(t) = 0;
        Q_d(t) = 0;
        mates2(t) = -mates3;
        mwater(t) = 0;
        md(t) = Qt_v(t)/(cp*(Twater-30));
        T2(t) = Tat_ltgh;
        T3(t) = T2(t);
        T4(t) = T3(t)-2;
        Q_p(t) = netto - Q_sw(t) - Q_dw(t) - 2*(mLTGH(t) - mates2(t) -
mwater(t))*cp;
    else
        if netto + Q_ss < - Q_ds
            if Q_d(t-1) - Q_ds > 0
                Q_dw(t) = -Q_ds;
                Q_d(t) = Q_d(t-1) + Q_dw(t);
                Q_sw(t) = -Q_ss;
                Q_s(t) = Q_s(t-1) + Q_sw(t);
                mwater(t) = -mwatermax;
                mates2(t) = -mates3;
                T2(t) = Tat_ltgh;
                T3(t) = ((Tat_ltgh+273)*(-mates2(t)+ mLTGH(t)) -
(Twater+273)*mwater(t)) / (mLTGH(t) - mates2(t) - mwater(t)) - 273;
                T4(t) = T3(t) - 2;
                md(t) = Qt_v(t)/((T4(t)-30)*cp);
                Q_p(t) = netto - Q_sw(t) - Q_dw(t) - 2*(mLTGH(t) -
mates2(t) - mwater(t))*cp;
            else
                Q_d(t) = 0;
                Q_sw(t) = -Q_ss;
                Q_s(t) = Q_s(t-1) + Q_sw(t);
                Q_dw(t) = -Q_d(t-1);
                mwater(t) = Q_dw(t) / (cp*(Tates+1-30));
                mates2(t) = Q_sw(t) / (cp*(Tates-33));
```

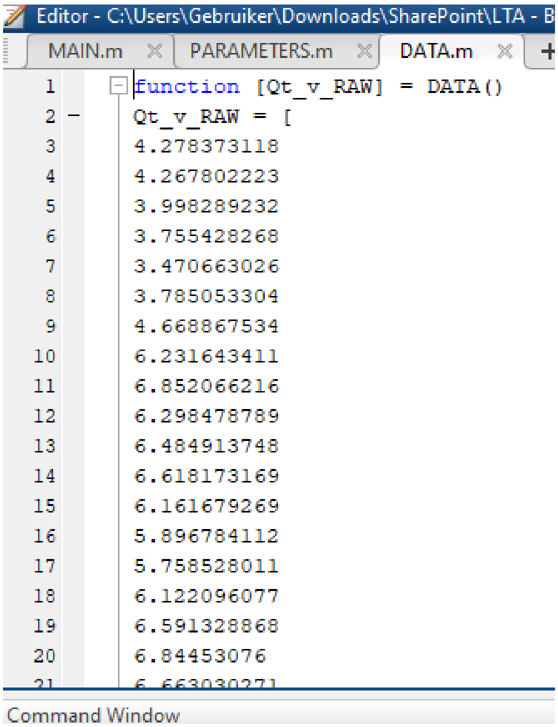
```
                T2(t) = Tat_ltgh;
                T3(t) = ((Tat_ltgh)*(-mates2(t)+mLTGH(t))+ (Twater+273)*-
mwater(t)) / (mLTGH(t) - mates2(t) - mwater(t)) - 273;
                T4(t) = T3(t) - 2;
                md(t) = Qt_v(t)/((T4(t)-30)*cp);
                Q_p(t) = netto - Q_sw(t) - Q_dw(t) - 2*(mLTGH(t) -
mates2(t) - mwater(t))*cp;
            end
        else
            if Q_d(t-1) + netto + Q_ss > 0
                Q_p(t) = 0;
                Q_sw(t) = -Q_ss;
                Q_s(t) = Q_s(t-1) + Q_sw(t);
                mwater1(t) = (netto + Q_ss) / (cp*(Tltgh-30));
                mates2(t) = -mates3;
                T2(t) = Tat_ltgh;
                T3(t) = ((Tat_ltgh+273)*(-mates2(t)+mLTGH(t))+
(Twater+273)*-mwater1(t))/(mLTGH(t) - mates2(t) - mwater1(t)) - 273;
                T4(t) = T3(t) - 2;
                md(t) = Qt_v(t)/(cp*(T3(t) - 2 - 30));
                mwater(t) = mLTGH(t) - mates2(t) - md(t);
                Q_dw(t) = mwater(t)*cp*(Tat_ltgh-32);
                Q_d(t) = Q_d(t-1) + Q_dw(t);
            else
                Q_d(t) = 0;
                Q_dw(t) = -Q_d(t-1);
                Q_sw(t) = -Q_ss;
                Q_s(t) = Q_s(t-1) + Q_sw(t);
                mwater(t) = Q_dw(t) / (cp*(Tat_ltgh-32));
                mates2(t) = Q_sw(t) / (cp*(Tates-33));
                T2(t) = Tat_ltgh;
                T3(t) = ((Tat_ltgh+273)*(-mates2(t)+mLTGH(t))+
(Twater+273)*-mwater1(t)) / (mLTGH(t) - mates2(t) - mwater(t)) - 273;
                T4(t) = T3(t) - 2;
                Q_p(t) = netto - Q_sw(t) - Q_dw(t) - 2*(mLTGH(t) -
mates2(t) - mwater(t))*cp;
            end
        end
    end

    if Q_s(t-1) >= Q_s_max
        Q_s(t) = Q_s(t-1)*n_s - Q_sw(t);
    end

end

    for t = t_s_summer:t_e_summer
        Qt_b(t) = Qt_b_summer;
    end

end

%% PLOT RESULTS

day_start = 300;    %408; %start of coldest day and week
day_end = 432+24; %end of coldest day
week_end = 550; %end of coldest week


figure(1) % daily storage
```

```
plot(Q_d)
xlim([day_start week_end])
title('Capacity daily storage 2b')
xlabel('Time (h)')
ylabel('Capacity (MWh)')

figure(2) % seasonal storage
plot(Q_s)
% xlim([day_start week_end])
title('Capacity ATES 2b')
xlabel('Time (h)')
ylabel('Capacity (MWh)')

figure (3) % peak supply
plot(Q_p)
xlim([day_start week_end])
title('Peak supply 2b')
xlabel('Time (h)')
ylabel('Power (MW)')

figure (4) % difference between supply and demand
plot(Qt_b - Qt_v)
xlim([day_start week_end])
title('LTGH - Qdemand')
xlabel('Time (h)')
ylabel('Power (MW)')

figure (5) % power daily storage
plot(Q_dw)
xlim([day_start week_end])
title('power daily storage 2b')
xlabel('Time (h)')
ylabel('Power (MW)')

figure (6) % power seasonal storage
plot(Q_sw)
xlim([day_start week_end])
title('power ATES 2b')
xlabel('Time (h)')
ylabel('Power (MW)')

%% Export results to excel

% Excel = table(Qltgh,Qt_v,Qltgh -
Qt_v,Q_d,Q_dw,Q_s,Q_sw,Q_p,D,T2,T3,T4,mates2,mwater,md,mLTGH-mates2,mLTGH-
mates2-mwater);
% filename = 'Results_energy_balance.xlsx';
% writetable(Excel,filename)
```

PARAMETERS

```
function [Qt_v, Qt_b, Qt_b_summer, Q_s_max, Q_ss, Q_d_max, Q_ds, n_s,
t_s_summer, t_e_summer, mwatermax, Tltgh, Tates, Twater, Tat_ltgh, mates3]
= PARAMETERS(Qt_v_RAW)

% Adjustable values per concept
Qlossp = 0.343; % heat losses by pipes [MW]. Provided in table 8-8
Qt_ltgh = 5.14; % production by the LTGH source [MW]
Qt_b_summer = 5.14*0.6; % production by the LTGH source in spring [MW]
Q_s_max = 7500; % maximum in seasonal storage [MWh]
Q_ss = 3.83; % seasonal storage discharge / charge per hour [MW]. Provided
in table 8-3
Q_d_max = 12.64; % maximum in daily storage [MWh] . Provided in table 7-2
Q_ds = 1.39; % daily storage discharge / charge per hour [MW]. Provided in
table 7-2
n_s = 0.7; % Recovery efficiency of seasonal storage after full capacity
[%]
t_s_summer = 3000; % time when LTGH switches to summer production [h]
t_e_summer = 6000; % time when LTGH switches to normal production [h]

mwatermax = 22.15; % mass flow by water tank. Provided in section 7.2
Tltgh = 50;
Tates = 44;
Twater = 47;
Tat_ltgh = 47;
mates3 = 36.1*2; % maximale ATES flow provided in table 8-3

% vectors for heat demand and ltgh supply
T = length(Qt_v_RAW);
Qt_v = Qt_v_RAW; % heat demand [MW]
Qt_b = Qt_ltgh*ones(T, 1) - Qlossp; % LTGH supply [MW]
End
```

DATA



```
function [Qt_v_RAW] = DATA()
Qt_v_RAW = [
4.278373118
4.267802223
3.998289232
3.755428268
3.470663026
3.785053304
4.668867534
6.231643411
6.852066216
6.298478789
6.484913748
6.618173169
6.161679269
5.896784112
5.758528011
6.122096077
6.591328868
6.84453076
```

Figure B-1 Data used for the Matlab scripts

Energy balance

As explained in section 6.5, there are 3 situations for the energy balance, which are listed below. For each scenario, a P&ID, a mass balance, and an energy balance are given.

1. No peak occurs
2. A peak will occur soon
3. Peak is happening

Scenario 1a: $Q_{LTGH} > Q_{demand}$, no peak occurs

P&ID example

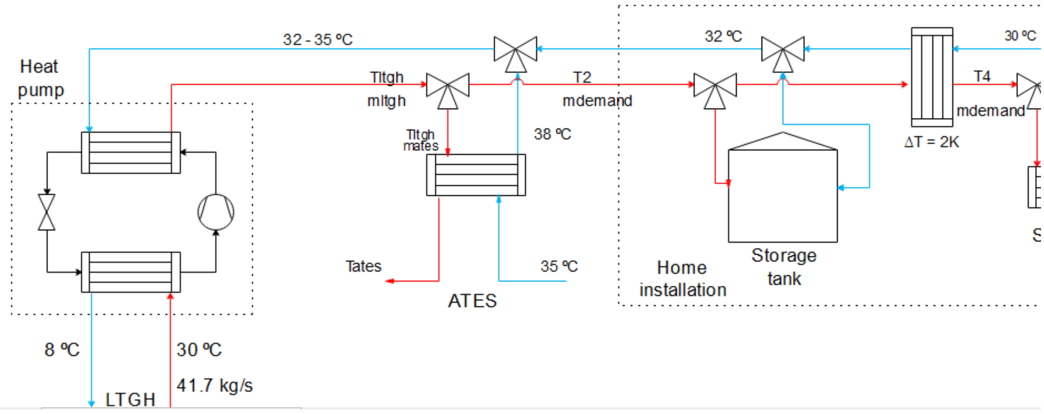


Figure B-2 P&ID of scenario 1a.

Mass balance

$$\dot{m}_{demand\ side} = \frac{\dot{Q}_{demand\ side}}{cp * (T_2 - 2 - 30)}$$

$$\dot{m}_{ATES} = \dot{m}_{LTGH} - \dot{m}_{demand\ side}$$

$$T_{return} = \frac{\dot{m}_{demand\ side} * (32 + 273) + \dot{m}_{ATES} * (38 + 273)}{\dot{m}_{demand\ side} + \dot{m}_{ATES}}$$

Energy balance

$$\dot{Q}_{ATES} = \dot{m}_{ATES} * cp * (T_{ltgh} - 38)$$
$$\dot{Q}_{LTGH} = \dot{m}_{LTGH} * cp * (T_{ltgh} - T_{return})$$

Scenario 1b: $Q_{LTGH} < Q_{demand}$, no peak occurs

P&ID

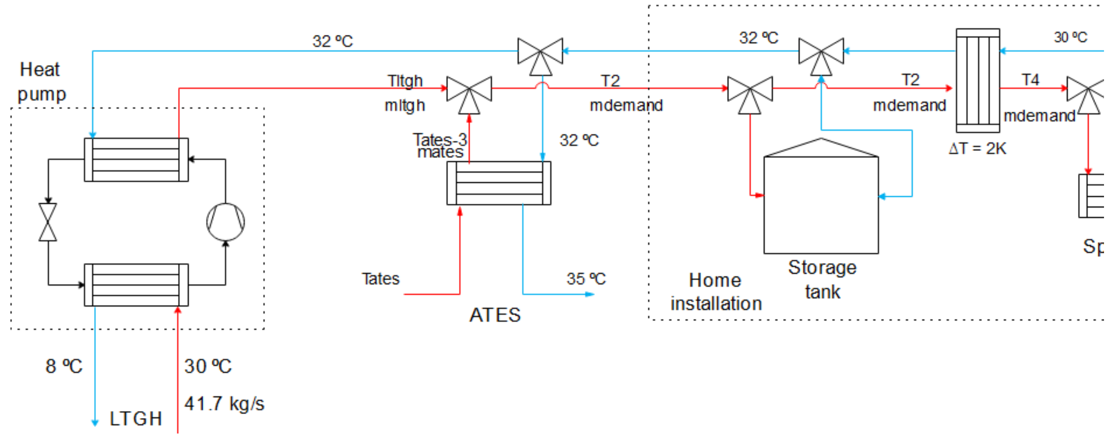


Figure B-3 P&ID of scenario 1b.

Mass balance

$$\dot{Q}_{demand} = \dot{Q}_{LTGH} + \dot{Q}_{ATES} - \dot{Q}_{loss\ pipes}$$

$$\dot{m}_{ATES\ 1} = \frac{\dot{Q}_{demand} - \dot{Q}_{LTGH}}{cp * (T_{ATES} - 3 - 32)}$$

1^{e} iteration

$$T_2 * (\dot{m}_{ATES\ 1} + \dot{m}_{LTGH}) = T_{ATES} * \dot{m}_{ATES} + T_{LTGH} * \dot{m}_{LTGH}$$

$$\dot{m}_{demand\ side} = \frac{\dot{Q}_{demand\ side}}{cp * (T_3 - 2 - 30)}$$

$$\dot{m}_{ATES\ 2} = \dot{m}_{demand\ side} - \dot{m}_{LTGH}$$

Energy balance

$$\dot{Q}_{ATES} = \dot{m}_{ATES\ 2} * cp * (T_{ATES} - 35)$$

Scenario 2: peak will occur soon

P&ID

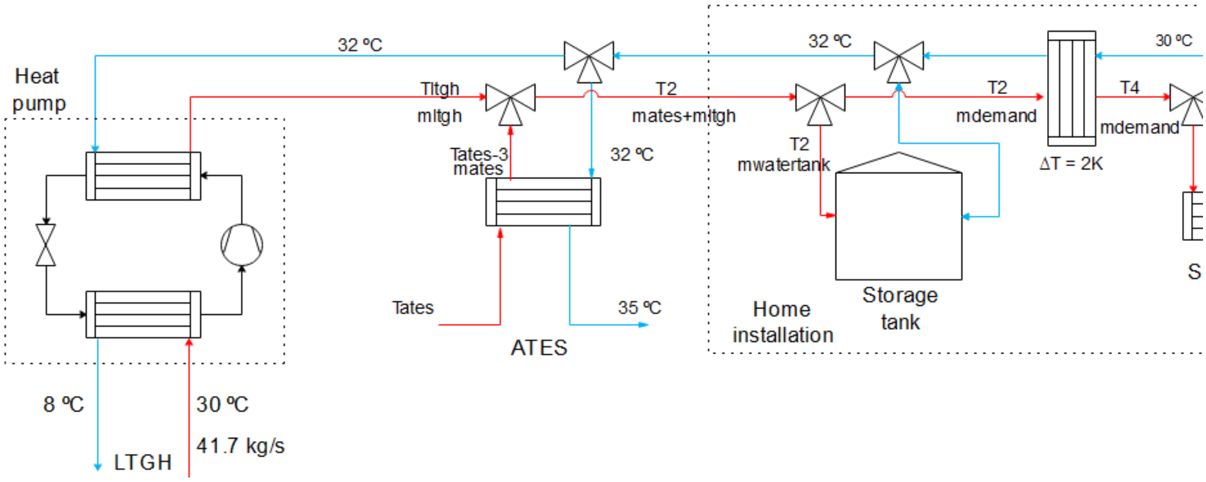


Figure B-4 P&ID of scenario 2.

Mass balance

$$T_2 * (\dot{m}_{ATES} + \dot{m}_{LTGH}) = T_{ATES} * \dot{m}_{ATES} + T_{LTGH} * \dot{m}_{LTGH}$$

$$\dot{m}_{demand\ side} = \frac{\dot{Q}_{demand\ side}}{cp * (T_3 - 2 - 30)}$$

$$\dot{m}_{ATES} = maximaal = 130\frac{m3}{h} = 36.11\ kg/s$$

$$\dot{m}_{water\ tank} = \dot{m}_{LTGH} + \dot{m}_{ATES} - \dot{m}_{demand\ side}$$

$$T_{watertank} * (\dot{m}_{ATES} + \dot{m}_{LTGH} - \dot{m}_{demand\ side}) = T_{ATES} * \dot{m}_{ATES} + T_{LTGH} * \dot{m}_{LTGH}$$

Energy balance

$$\dot{Q}_{ATES\ supply} = \dot{m}_{ATES} * cp * (T_{ates} - 3 - 32)$$

$$\dot{Q}_{watertank\ receive} = \dot{m}_{watertank} * cp * (T_2 - 30)$$

Remarks

If the LTGH can supply the heat demand and the maximum power to the water tank, then the mass flow of the ATES is 0.

Scenario 3: Peak occurs

P&ID

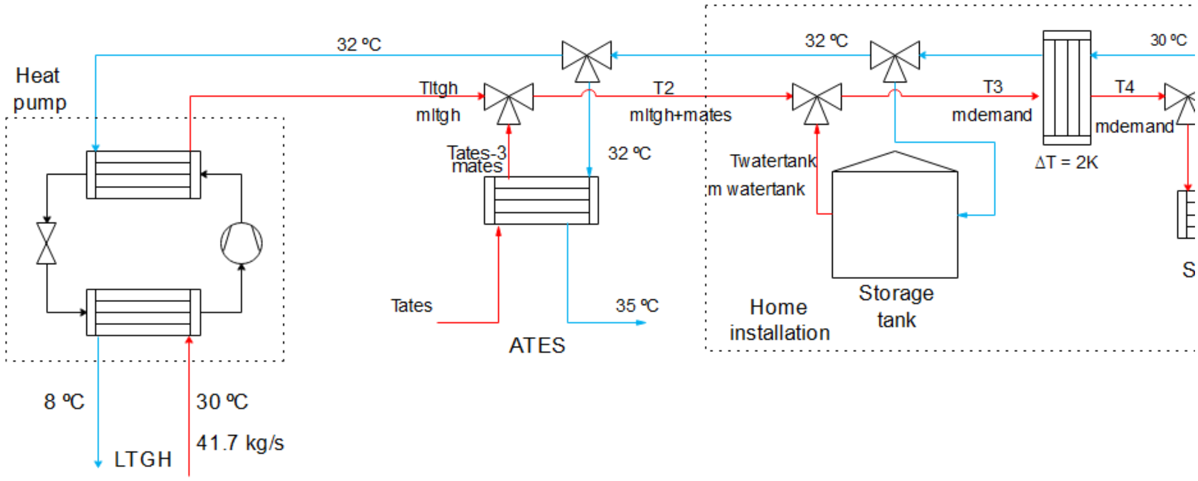


Figure B-5 P&ID of scenario 3.

Mass balance

$$\dot{Q}_{demand} = \dot{Q}_{LTGH} + \dot{Q}_{ATES} + \dot{Q}_{watertank} - \dot{Q}_{loss}$$

$$\dot{m}_{watertank\ 1} = \frac{\dot{Q}_{demand} - \dot{Q}_{LTGH} - \dot{Q}_{ATES}}{cp * (T_{ates} - 3 - 32)}$$

$$T_3 * (\dot{m}_2 + \dot{m}_{water\ tank}) = T_2 * \dot{m}_2 + T_{supply\ from\ water\ tank} * \dot{m}_{water\ tank1}$$

$$T_4 = T_3 - 2$$

$$\dot{m}_{demand\ side} = \frac{\dot{Q}_{demand\ side}}{cp * (T_4 - 30)}$$

$$\dot{m}_{ATES} = maximaal = 130 \frac{m3}{h} = 36.11\ kg/s$$

$$\dot{m}_{water\ tank\ 2} = \dot{m}_{demand\ side} - \dot{m}_{LTGH} - \dot{m}_{ATES}$$

Energy balance

$$\dot{Q}_{water\ tank} = \dot{m}_{water\ tank\ 2} * cp * (T_3 - 32)$$

Remarks

If the water tank is empty, an external peak source provides extra heat

C. Appendix Results energy balance

This appendix presents the results of the numerical model from Appendix B. FIRST BLABLABLA. After that, for every heat demand scenario is the outcomes of the energy balances provided. The outcomes are the following.

- NETTO – the difference between LTGH supply and heat demand
- Power seasonal storage – the heat supply from or in the ATES
- Seasonal storage – the capacity of the ATES
- Peak supply – the heat supplied by the peak source
- Power daily storage – the supply from or in the water tank
- Daily storage – the capacity of the water tank

A negative number in the NETTO graphs means that there is not enough available heat from the LTGH sources and a positive number is that there is a surplus of heat by the LTGH source. A negative number in the POWER graphs means that the amount of heat supplied to the network. A positive number means that the storage is being charged. The layout of the pages is as follows.

Heat demand strategy 2

LTDH Concept 1a and 2a: 70 ^{o}C supply temperature

Figure C-1 until Figure C-7 presents the results of the energy balance for the LTDH concepts with 70 ^{o}C supply temperature for the coldest two weeks in January (12 until 23 January). In this section, the heat demand strategy is the application of peak shaving by the residents.

Figure C-1 shows the heat difference between the heat of the LTGH, with 70 ^{o}C as supply temperature in the network, and the heat demand, when the residents use the peak shaving strategy, during 10 cold days. The heat difference is always below 0 MW, which means that there is more heat demand than supplied by the LTGH. This means that the ATES and / or peak sources need to provide extra heat. Remarkably, Figure C-1 is that there is not a heavy peak at a certain hour. The heat difference is quite the same for periods of 24 hour. The largest difference is around 7.5 MW.

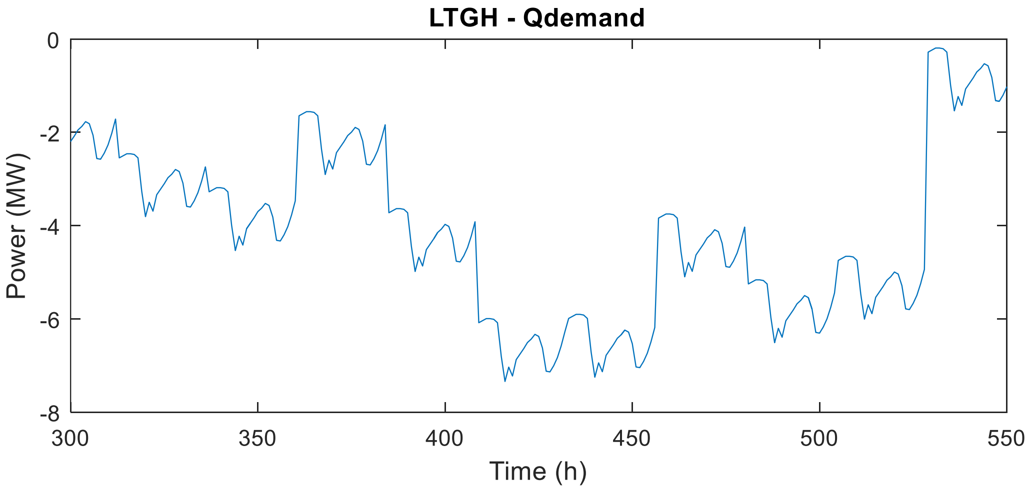


Figure C-1 Heat difference between the LTGH supply and heat demand strategy 2, during the coldest two weeks for LTDH concept 1a and 2a.

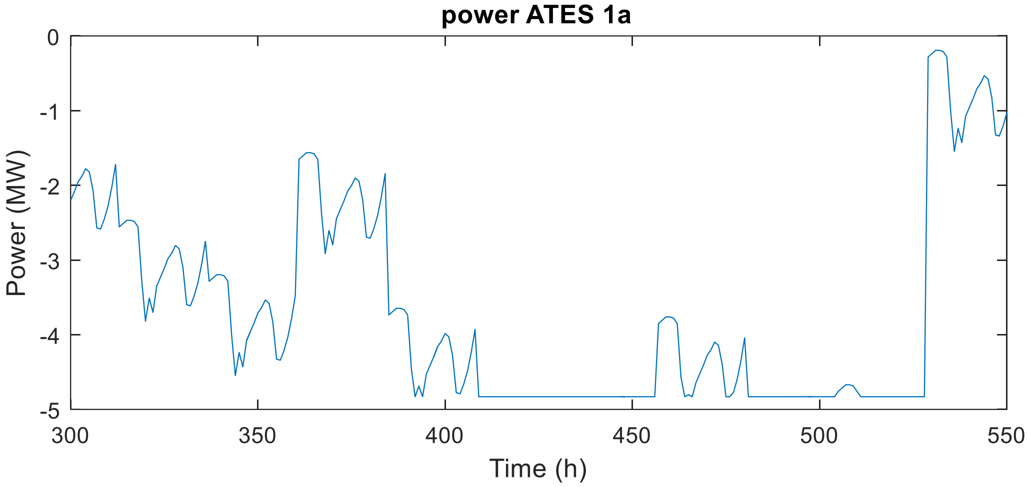


Figure C-2 ATES supply power by LTDH concept 1a and heat demand strategy 2.

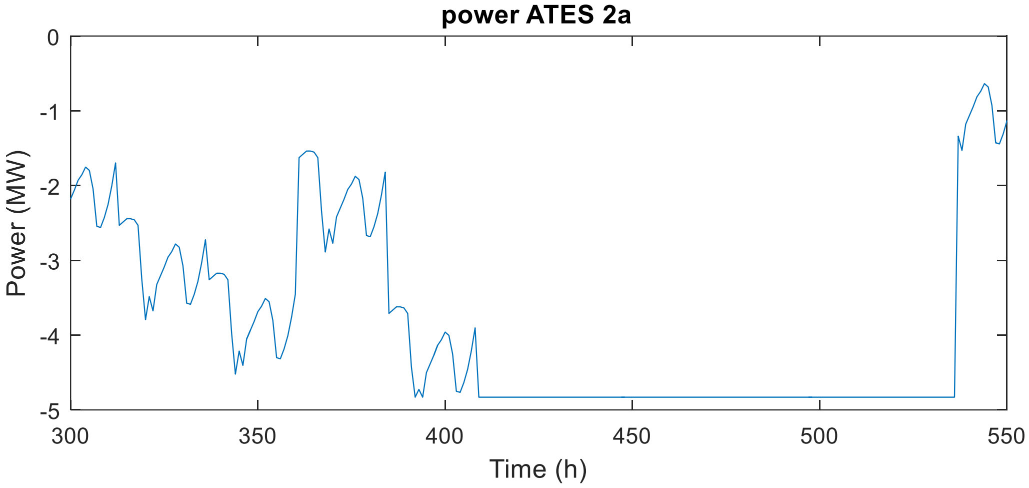


Figure C-3 ATES supply power by LTDH concept 2a and heat demand strategy 2.

Figure C-2 and Figure C-3 show the heat supply from the ATES source. The ATES for LTDH concept 2a provides more heat between the hours 460 and 480, in order to supply heat to the storage tank. The total heat supply by the ATES source during these 10 cold days is less for LTDH concept 1a, which is achieved in the last few hours.

Figure C-4 shows the power supply and storage and Figure C-5 shows the capacity for the storage tank during the 10 cold days. The storage tank supplies heat to the homes after hour 400. Before that, no peak occurred. The storage tank supplies heat for 30 hours. After that, the storage tank is empty. In hour 455, there is no more peak, and so the storage tank is filled. At hour 480, a peak occurs, and the storage tank is needed. After hour 530, the peak is over and the tank is filled up again.

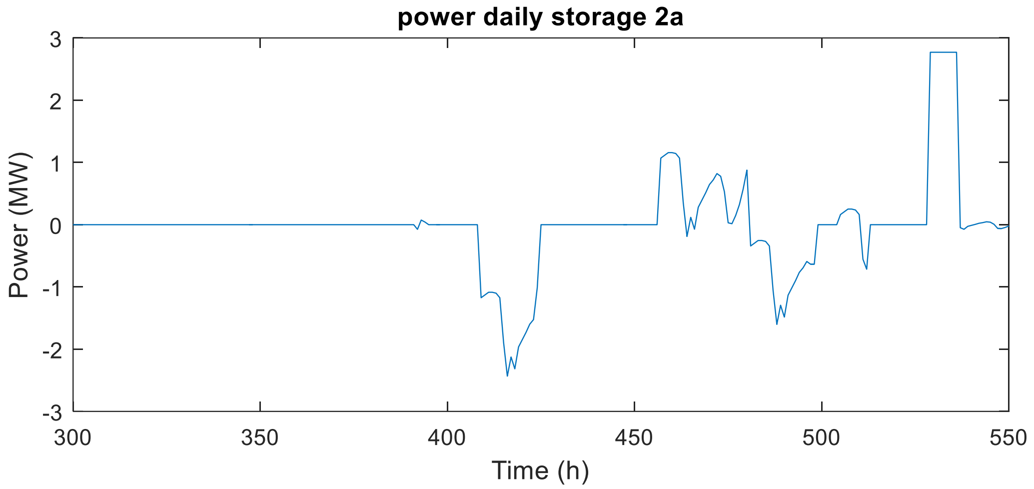


Figure C-4 Power supply from the storage tank for LTDH concept 2a and heat demand strategy 2.

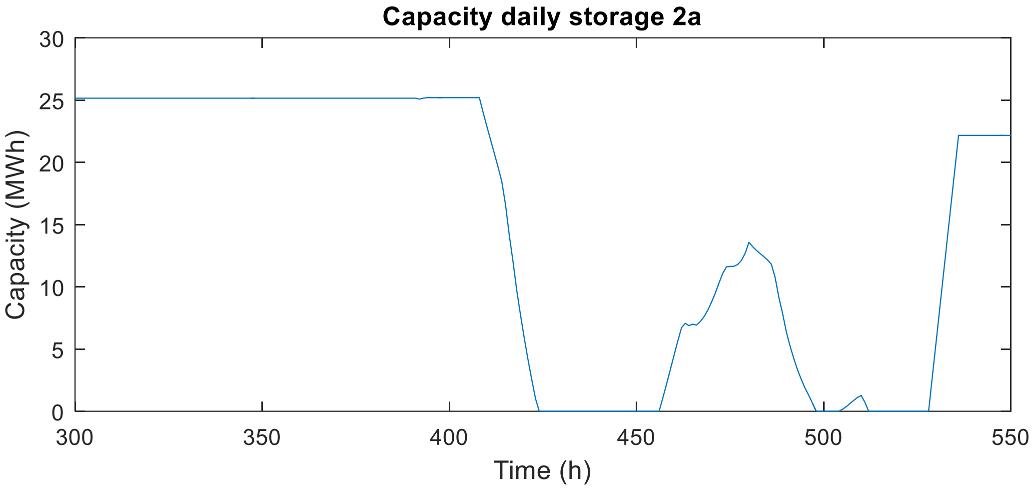


Figure C-5 Capacity of the daily storage tank for LTDH concept 2a and heat demand strategy 2.

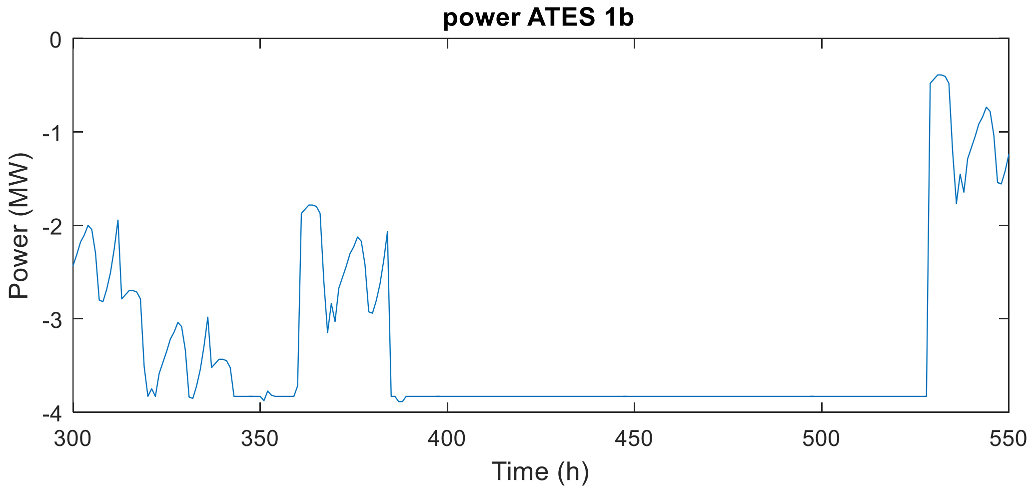


Figure C-6 and Figure C-7 show the peak supply of the heat concepts during 10 cold days. The figures show that between hours 430 and 455, and 490 and 530, peak supply is the same for both heating concepts. The first peaks, between hours 380 and 430, LTDH concept 2a does not require the electrical heaters, because the water tank can supply the peak demand. This also happens between hours 470 and 490.

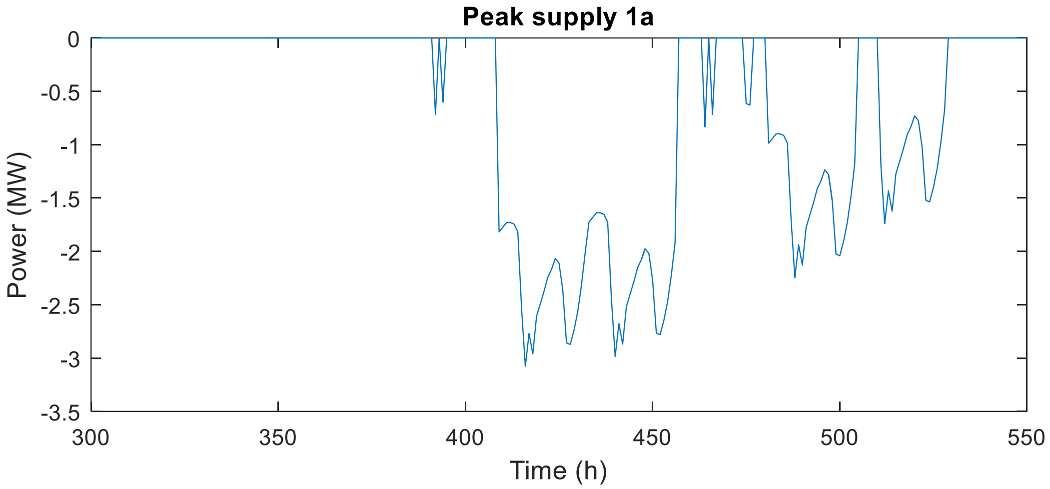


Figure C-6 Heat supply from the biomass boiler for LTDH concept 1a and heat demand strategy 2.

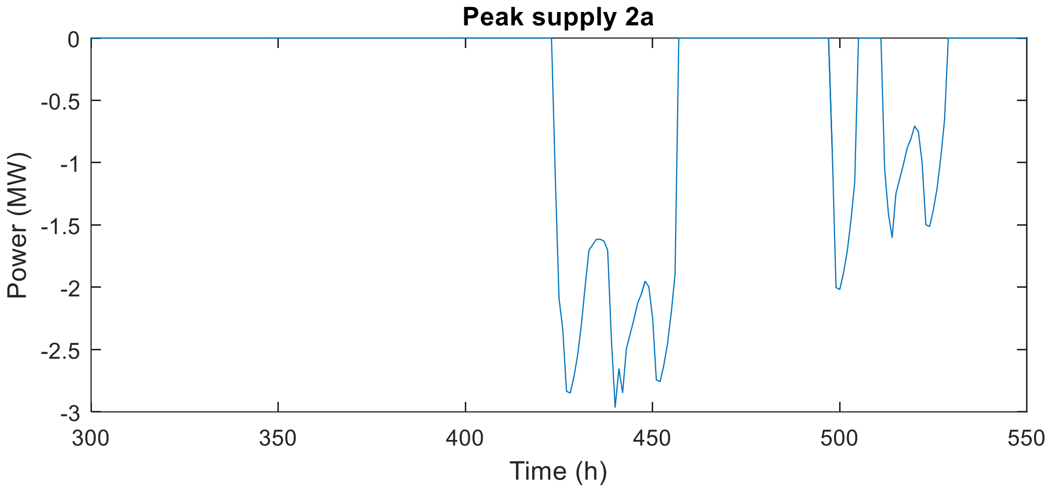


Figure C-7 Heat supply from the electrical heaters for LTDH concept 2a and heat demand strategy 2.

LTDH Concept 1b and 2b: 50 °C supply temperature

Figure C-8 until Figure C-14 presents the results of the energy balance for the LTDH concepts with 50 °C supply temperature for the coldest two weeks in January (12 until 23 January). In this section, the heat demand strategy is the application of peak shaving by the residents.

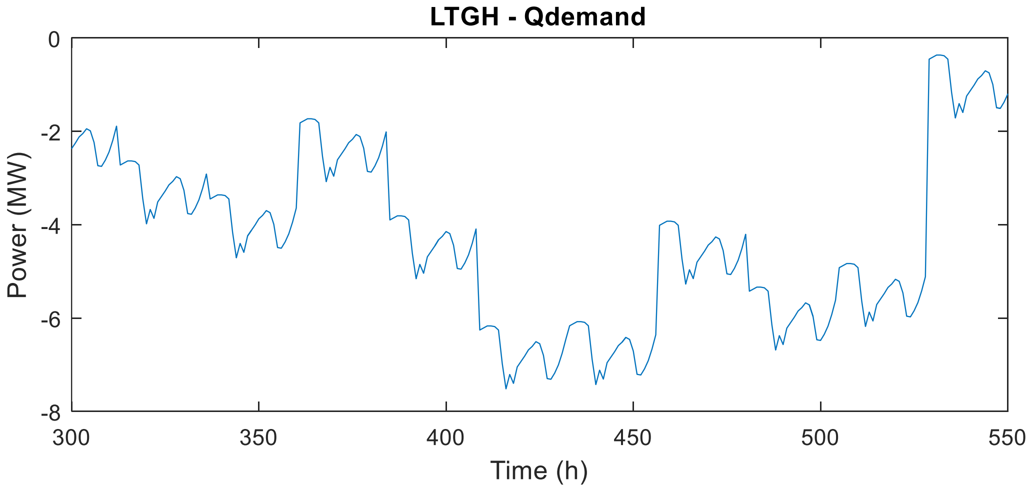


Figure C-8 Heat difference between the LTGH supply and heat demand strategy 2 during the coldest two weeks for LTDH concept 1b and 2b.

Figure C-8 shows the heat difference between the heat of the LTGH, with 50 °C as supply temperature in the network, and the heat demand, when the residents use the peak shaving strategy, during 10 cold days. The heat difference is always below 0 MW which means that there is more heat demand than supplied by the LTGH. This means that the ATES and / or peak sources need to provide extra heat. Moreover, the figure shows that there is not a heavy peak at a certain hour. The heat difference stays relatively constant during a period of 24 hours. The little difference which occurs within 24 hours is caused by the demand for DHW. The largest difference is around 7.8 MW.

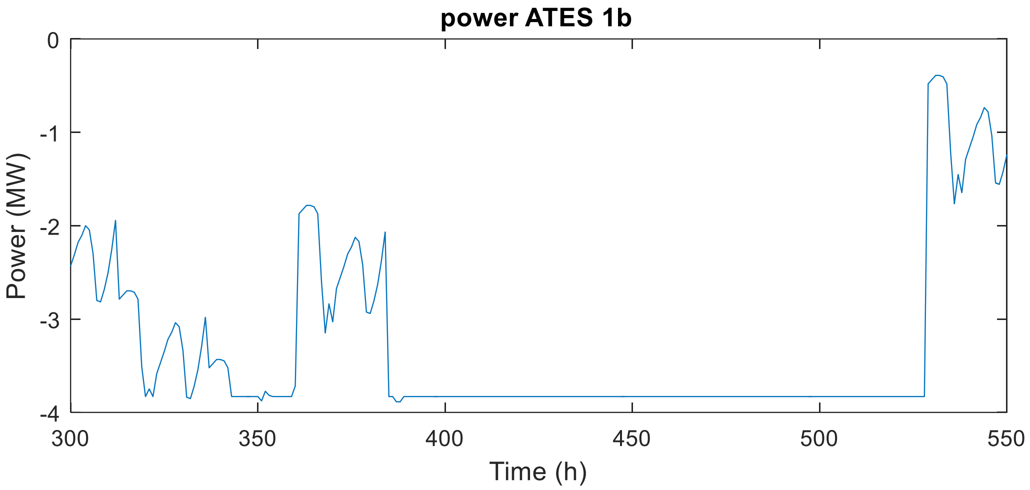


Figure C-9 ATES supply power for LTDH concept 1b and heat demand strategy 2.

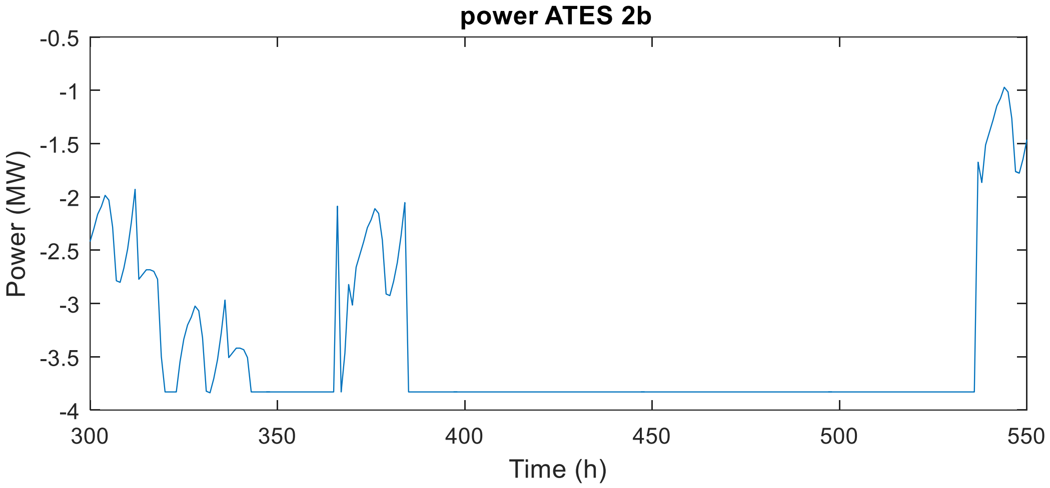


Figure C-10 ATES supply power for LTDH concept 1b and heat demand strategy 2.

Figure C-9 and Figure C-10 show heat supply from the ATES source. For both LTDH concepts, the ATES provides almost the same amount of heat. Between hours 360 and 380, the ATES for LTDH concept 2b provides a little bit more heat, because the storage tank will be charged. Both concepts are supplying for more than 130 hours in a straight row maximum heat to the networks.

Figure C-11 shows the power behavior and Figure C-12 shows the capacity of the storage tank during the 10 cold days. These figures show that the water tank only has an influence on the heat supply between hours 345 and 355, and between hours 390 until 405. In those hours, the water tank can provide the complete peak, or part of the peak. After hour 405, the water tank is empty and will not be charged.

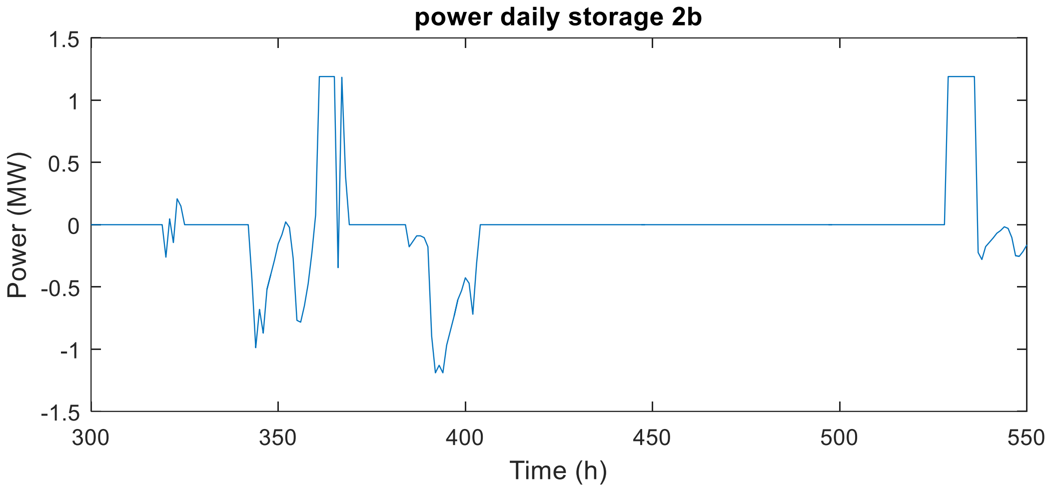


Figure C-11 Power supply from the storage tank for LTDH concept 2b and heat demand strategy 2.

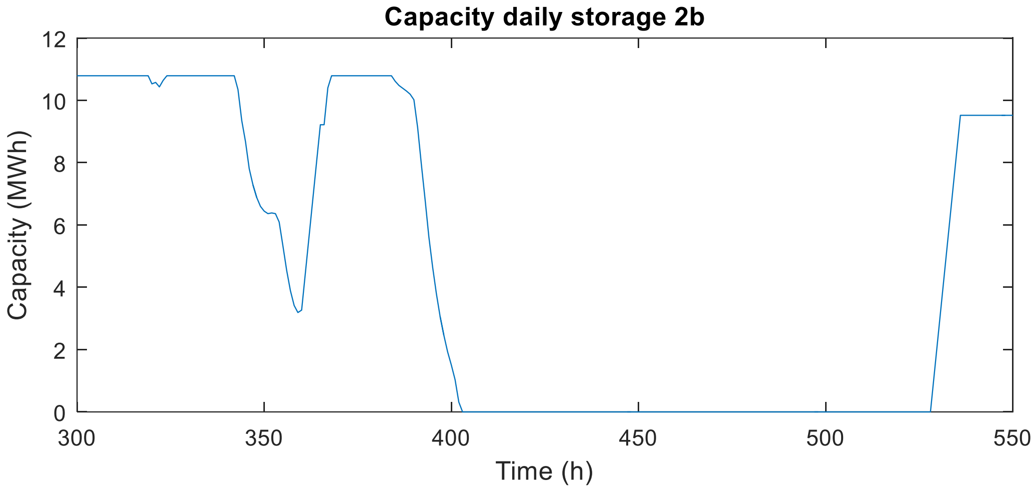


Figure C-12 Capacity of the storage tank for LTDH concept 2b and heat demand strategy 2.

Figure C-20 and Figure C-21 show the peak supply of the heat concepts during 10 cold days. The peaks in the first hours are for LTDH concept 2b supplied by the water tank. After that, both LTDH concepts require the same amount of heat.

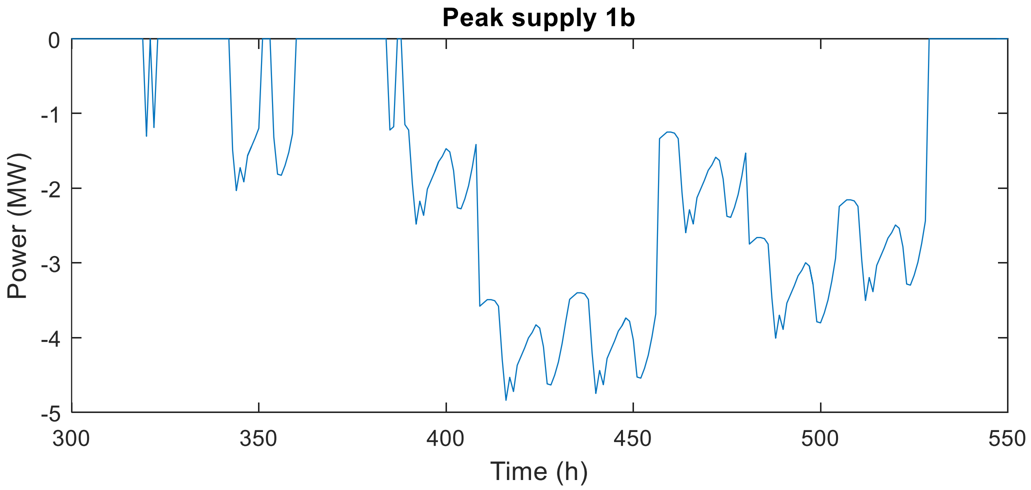


Figure C-13 Heat supply from the biomass boiler for LTDH concept 1b and heat demand strategy 2.

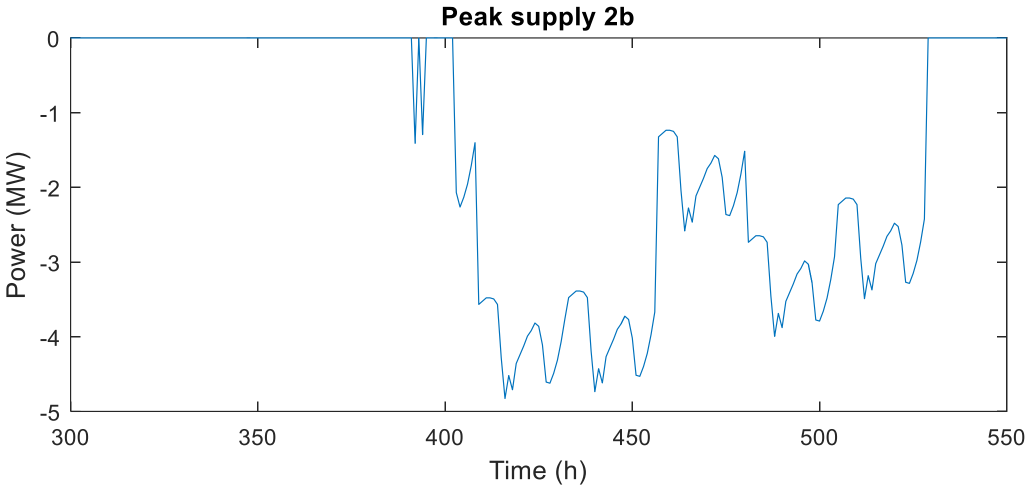


Figure C-14 Heat supply from the electrical heaters for LTDH concept 2b and heat demand strategy 2.

Heat demand strategy 3

LTDH concept 1a and 2a: 70 °C supply temperature

Figure C-15 until Figure C-21 presents the results of the energy balance for the LTDH concepts with 70 °C supply temperature for the coldest two weeks in January (12 until 23 January). In this section, the heat demand strategy is to improve the insulation layer of the buildings. This makes it possible to connect 2,900 homes to the network, instead of 2,475 homes.

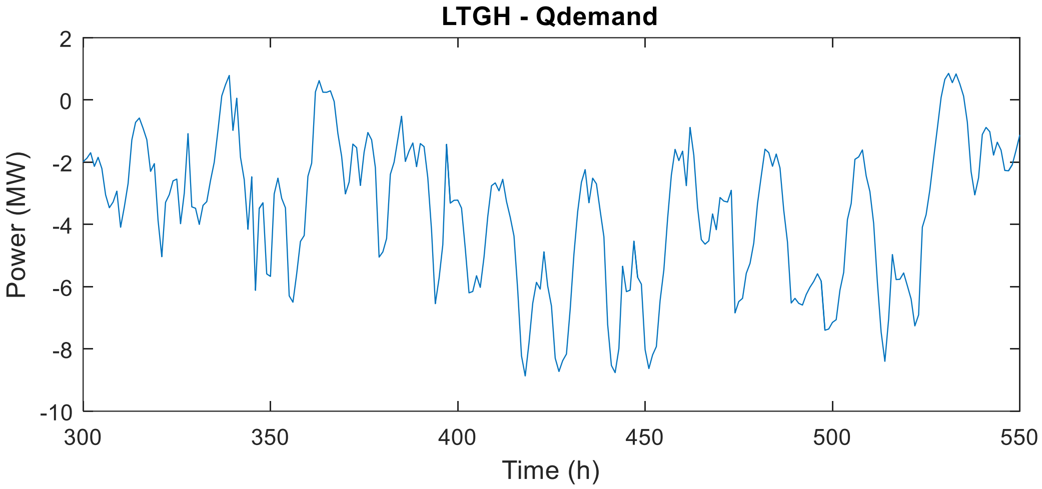


Figure C-15 Heat difference between the LTGH and heat demand during the coldest two weeks for LTDH concept 1a and 2a and heat strategy 3.

Figure C-15 shows the heat difference between the heat of the LTGH, with 70 °C as the supply temperature in the network, and the heat demand, when the homes have better insulation measures, during 10 cold days. The heat difference is mostly below 0 MW which means that there is more heat demand than is supplied by the LTGH. This means that the ATES and / or peak sources need to provide extra heat. The largest difference is around 8.2 MW.

Figure C-16 and Figure C-17 show the heat supply by the ATES source. The ATES for concept 2a provides more heat to the network between hours 420 and 520, because it supplies the storage tank for heat. The total heat supply by the ATES source during these 10 cold days is less for LTDH concept 1a.

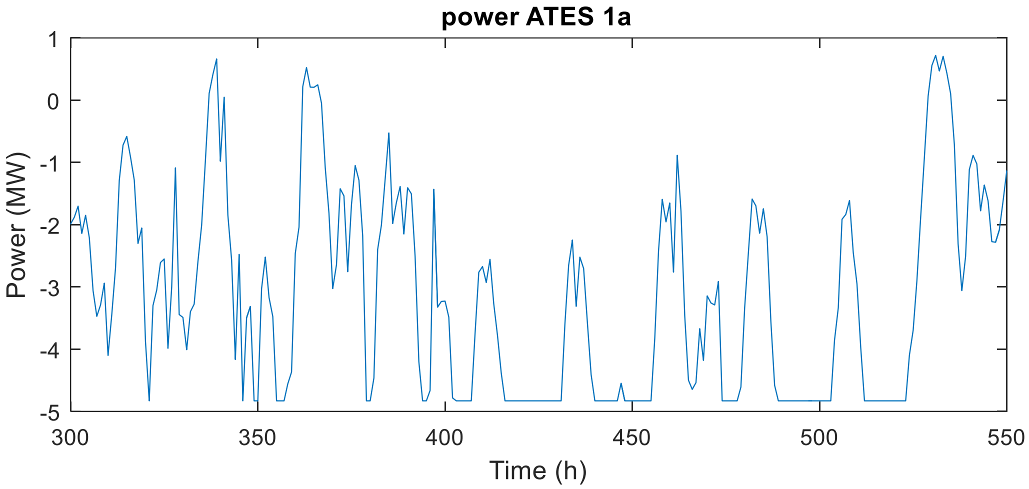


Figure C-16 ATES supply power for LTDH concept 1a and heat demand strategy 3.

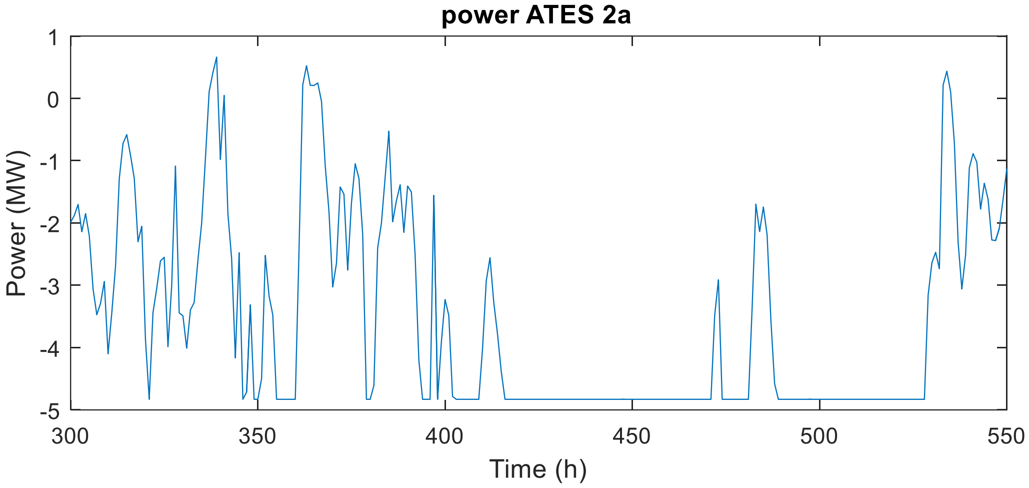


Figure C-17 ATES supply power for LTDH concept 2a and heat demand strategy 3.

Figure C-18 shows the power behavior and Figure C-19 shows the capacity for the storage tank during 10 cold days and heat demand strategy 3. Before hour 400, the storage tank has the maximum capacity available for the peak moment. The storage tank decreases in capacity from 400 until 430. This is when the storage tank supplies the peak. After that, the tank will be heated for a little bit to help during the peak between hour 430 and 450. There is until a peak between hours 450 until 455, but this will not be supplied by the daily storage tank because the tank has no capacity.

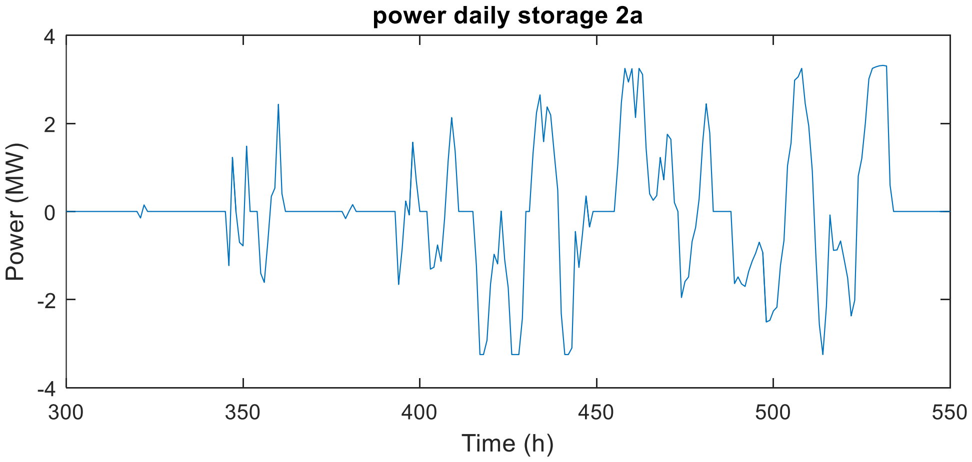


Figure C-18 Power supply of the storage tank for LTDH concept 2a and heat demand strategy 3.

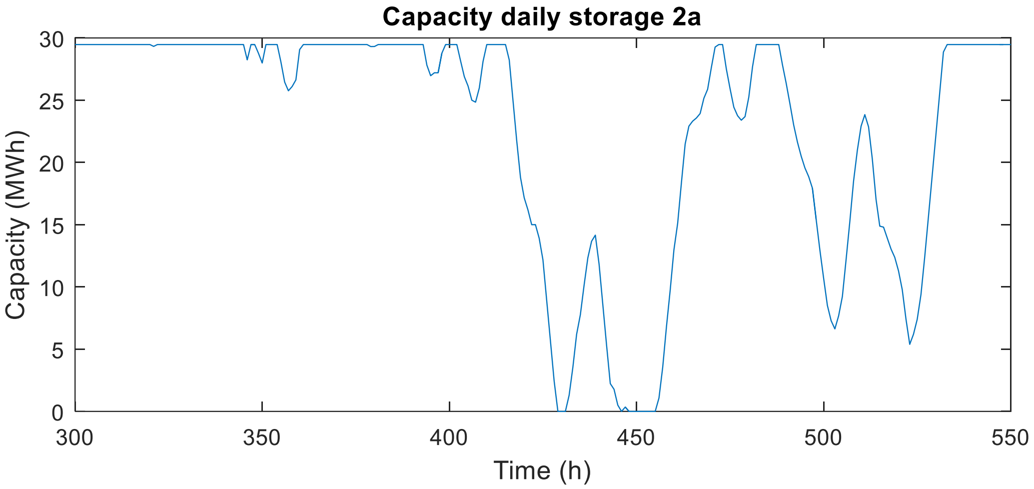


Figure C-19 Capacity of the storage tank for LTDH concept 2a and heat demand strategy 3.

Figure C-20 and Figure C-21 show the peak supply of the heat concepts during 10 cold days. Concept 2a does not use the peak source until hour 410. Before that, the peak moments are fully covered by the storage tank. Between hours 420 and 460, both LTDH concepts supplies the peak by the peak source.

However, the peaks are smaller for concept 2a, because a part of the peak is covered by the storage tank. Only the peak around hour 450 is for both concepts the same. These results are quite similar to the first heat demand strategy.

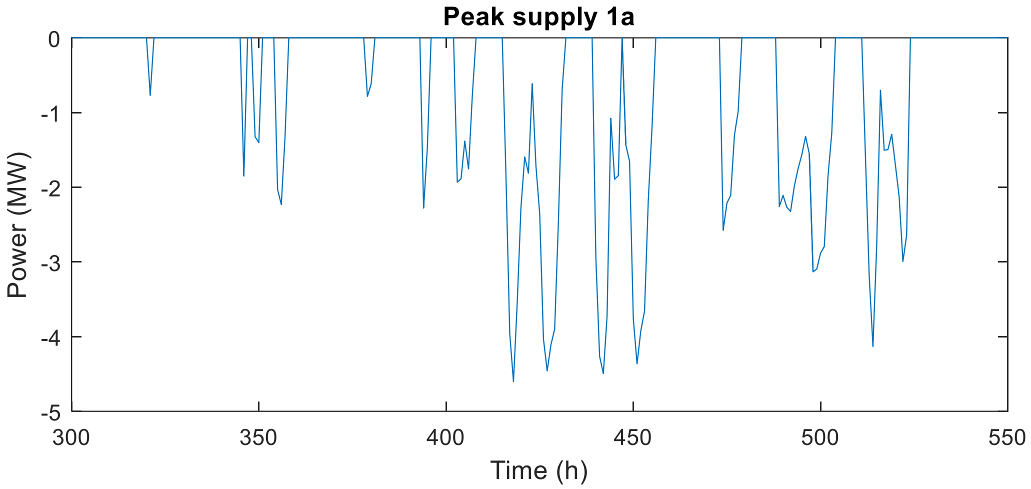


Figure C-20 Heat supply from the biomass boiler for LTDH concept 1a and heat demand strategy 3.

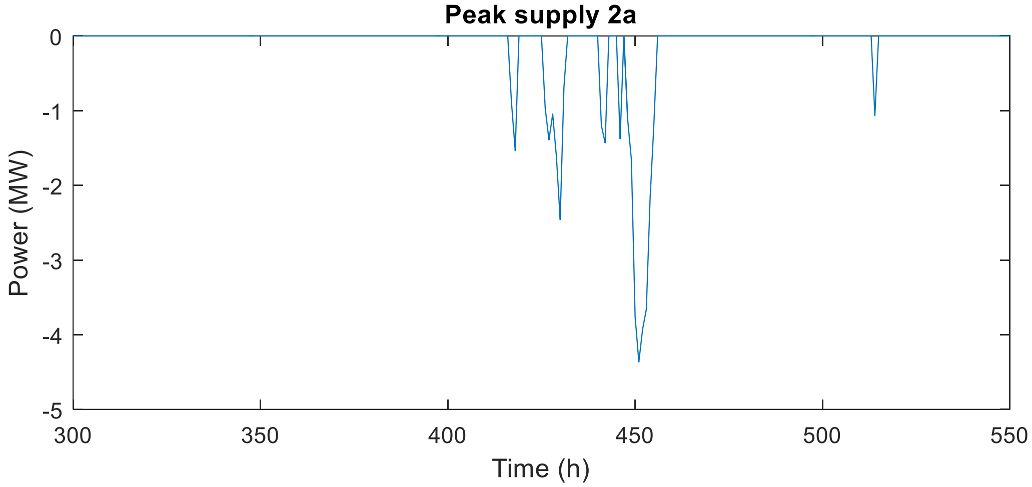


Figure C-21 Heat supply from the electrical heaters for LTDH concept 2a and heat demand strategy 3.

LTDH concept 1b and 2b: 50 ^{o}C supply temperature

Figure C-22 until Figure C-28 present the result of the energy balance for LTDH concepts with 50 ^{o}C supply temperature and heat demand scenario 3, where the insulation of the homes is improved, for the coldest two weeks in January (12 until 23 January).

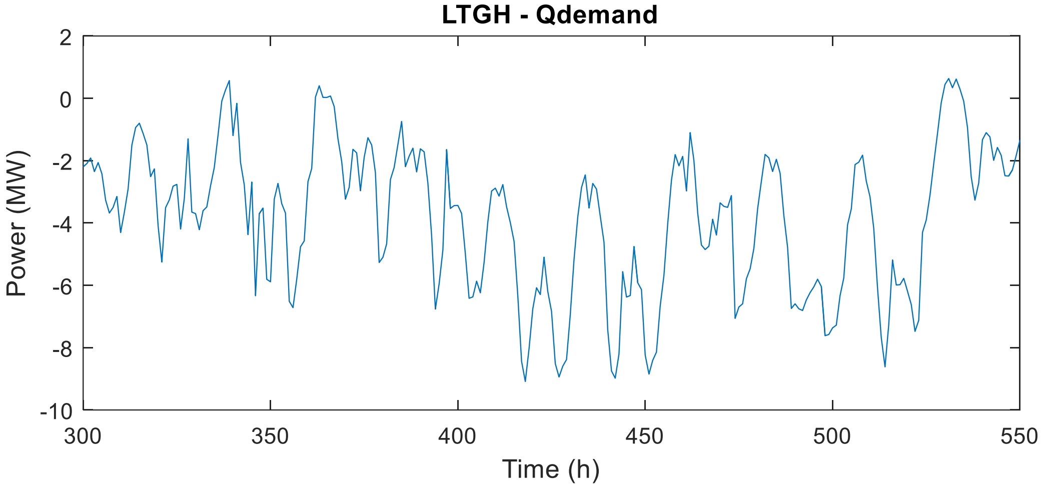


Figure C-22 Heat difference between the LTGH and heat demand during the coldest two weeks for LTDH concept 1b and 2b and heat demand strategy 3.

Figure C-22 shows the heat difference between the heat of the LTGH, with 50 ^{o}C as supply temperature in the network, and the heat demand, when the homes have better insulation, during 10 cold days. Mostly, the heat difference is below 0 MW which means that there is more heat demand than is supplied by the LTGH. This means that the ATES and / or peak sources need to provide extra heat. The largest difference is around 9.2 MW.

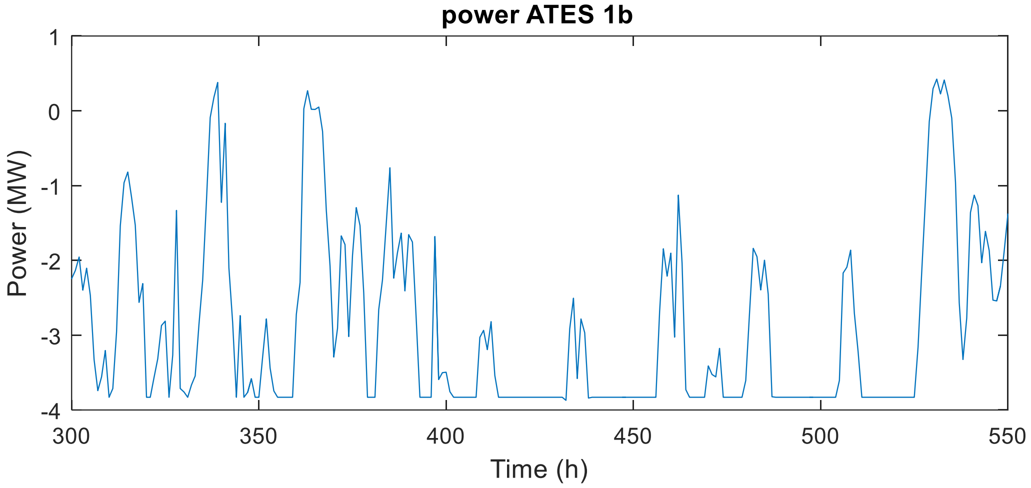


Figure C-23 ATES supply power for LTDH concept 1b and heat demand strategy 3.

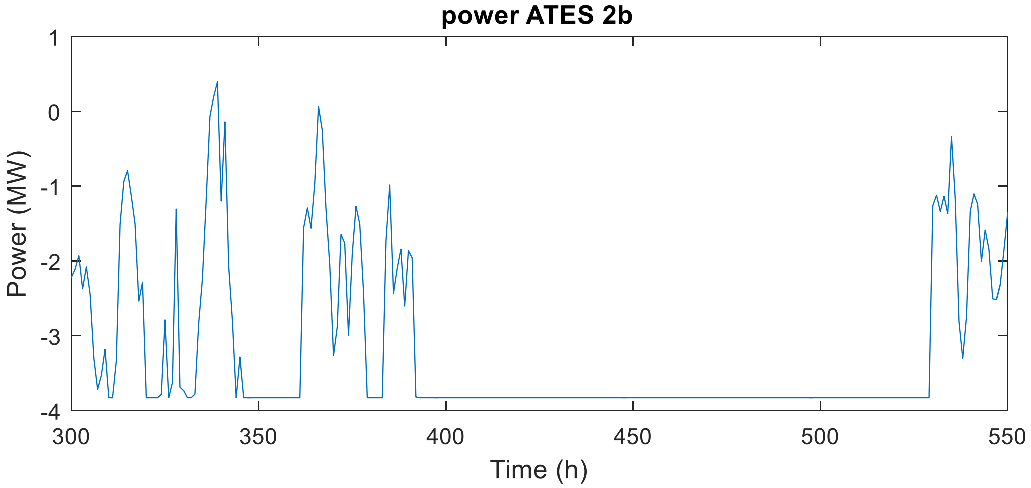


Figure C-24 ATES supply power for LTDH concept 2b and heat demand strategy 3.

Figure C-23 and Figure C-24 show the heat supplied by the ATES source. The ATES for concept 2b provides more heat between hours 390 and 530, in order to supply heat to the storage tank. The total heat supply from the ATES source during these 10 cold days is less for concept 1b.

Figure C-25 shows the power behavior and Figure C-26 shows the capacity of the storage tank during the 10 cold days. Before hour 350, the storage tank provides some heat to the system. A small peak occurs around hour 355, where the peak source supplies heat for a short period. After that, the tank will be charged for the peak moments around hour 400. Between the hours 400 and 530, the tank often fluctuates between supplying heat and storing heat. There are moments when the tank cannot supply heat, because the tank has no capacity.

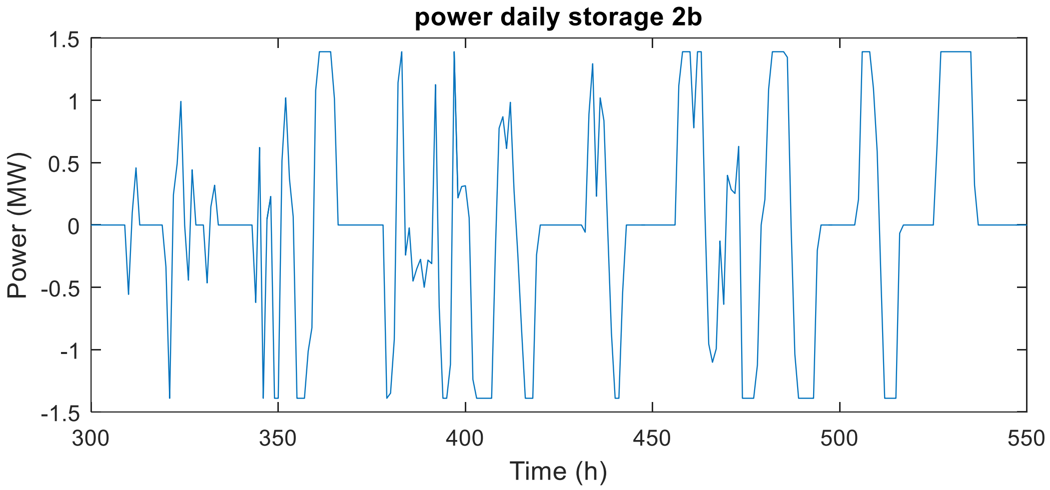


Figure C-25 Power supply from the storage tank for LTDH concept 2b and heat demand strategy 3.

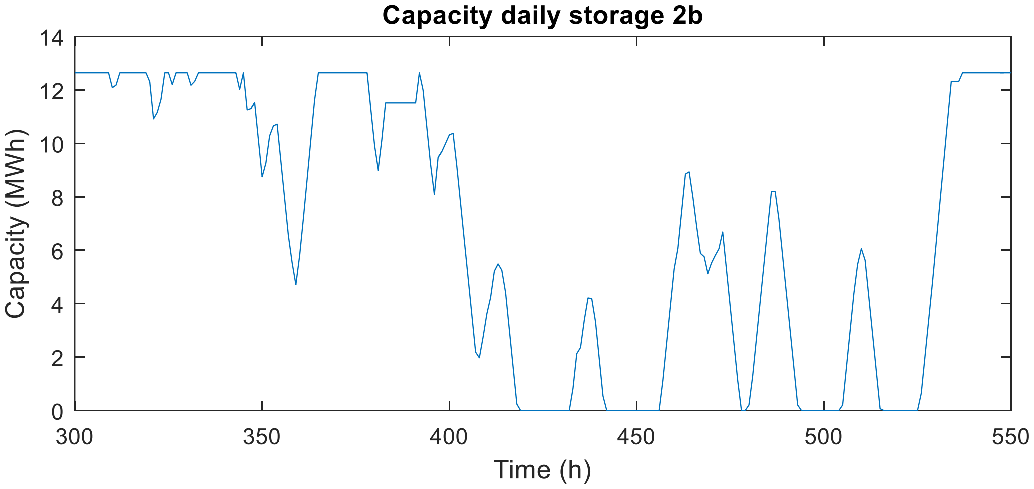


Figure C-26 Capacity of the storage tank for LTDH concept 2b and heat demand strategy 3.

Figure C-27 and Figure C-28 show the peak supply of the heat concepts during 10 cold days. The figures show that LTDH concept 1b uses the peak source more often than 2b and, when both concepts need to use the peak source, the peak source of LTDH concept 1b consumes more heat. Only between hours 425 and 430, 445 and 455, and 490 and 530, both concepts supply the same amount of peak heat, because the water tank of concept 2b has no capacity anymore.

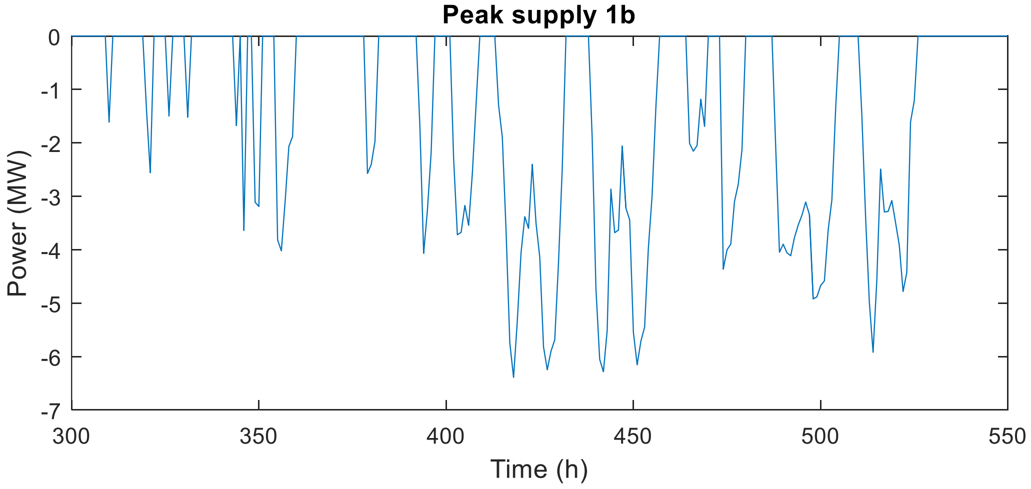


Figure C-27 Heat supply from the biomass boiler for LTDH concept 1b and heat demand strategy 3.

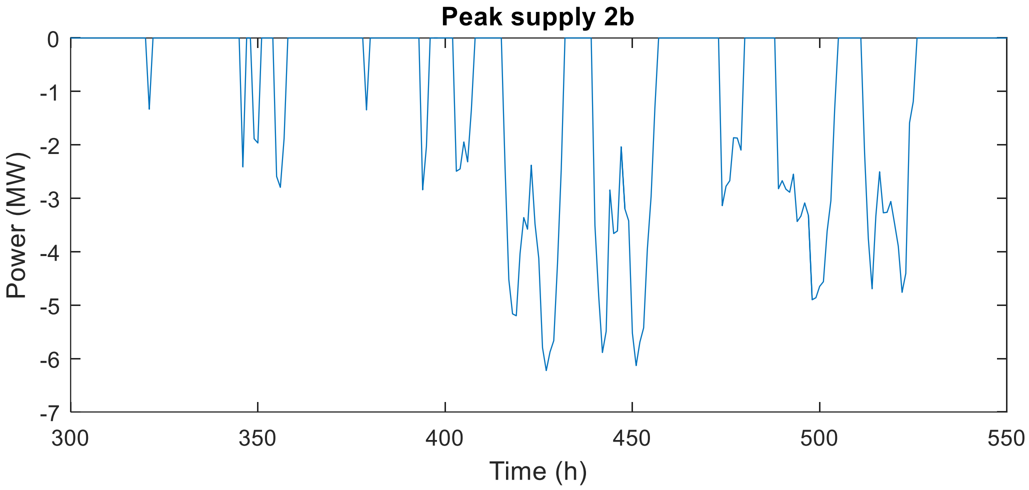


Figure C-28 Heat supply from the electrical heaters for LTDH concept 2b and heat demand strategy 3.

Yearly energy balances

The graphs on the next pages are sorted as follows.

Peak supply in homes

The NETTO graph is shown in the left-hand column at the top. This is the difference between the heat demand and heat supply of LTGH. Below that is the graph of the hourly power consumption of the seasonal storage. Lastly, the capacity of the seasonal storage is given.

The peak supply graph is shown in the right-hand column at the top. Below that is the graph of the hourly power consumption of the daily storage given. Lastly, the capacity of the daily storage is presented.

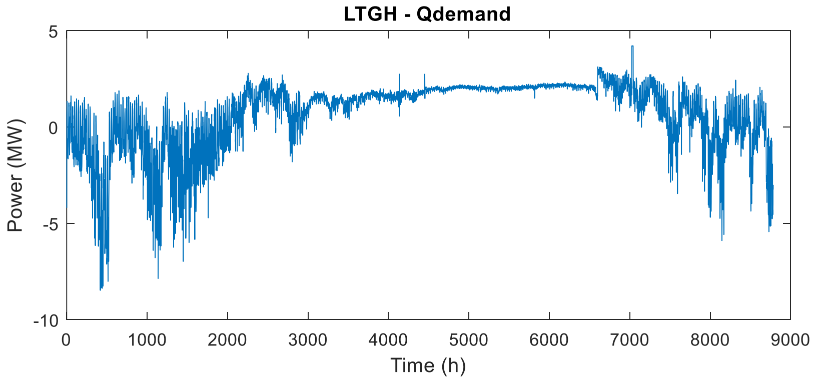
Peak supply by the net

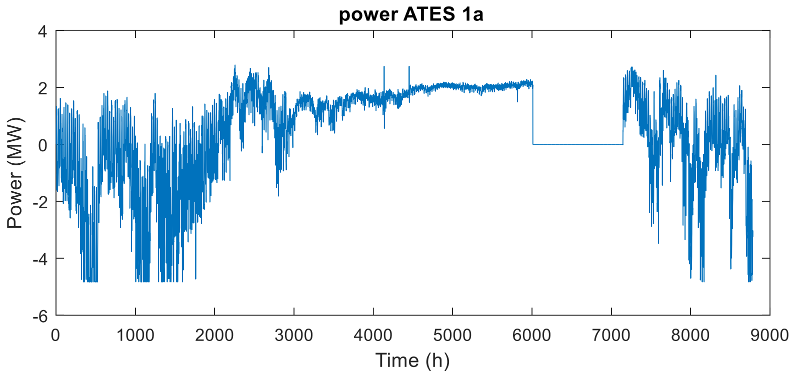
The NETTO graph is shown in the left-hand column at the top. Below that is the peak supply graph shown.

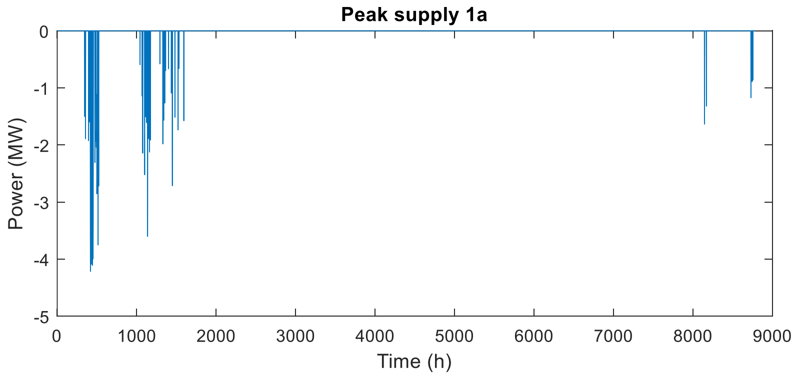
The hourly power consumption of the seasonal storage is shown in the right-hand column at the top. Below that is the capacity of the seasonal storage given.

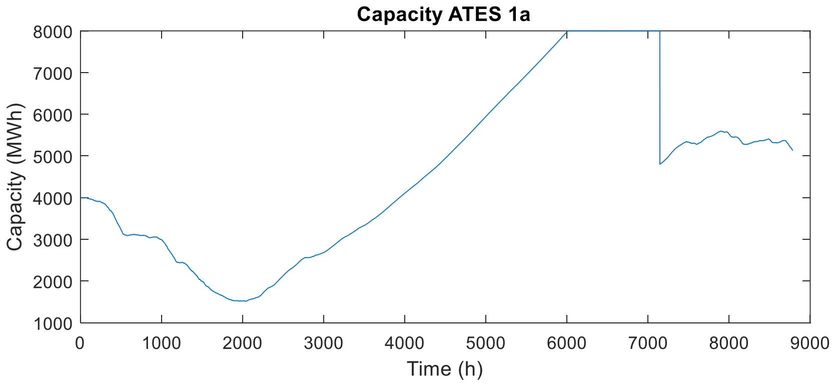
Heat demand strategy 1: Maintain current heating strategy

LTDH concept 1a: 70 ºC, peak supply from the biomass boiler

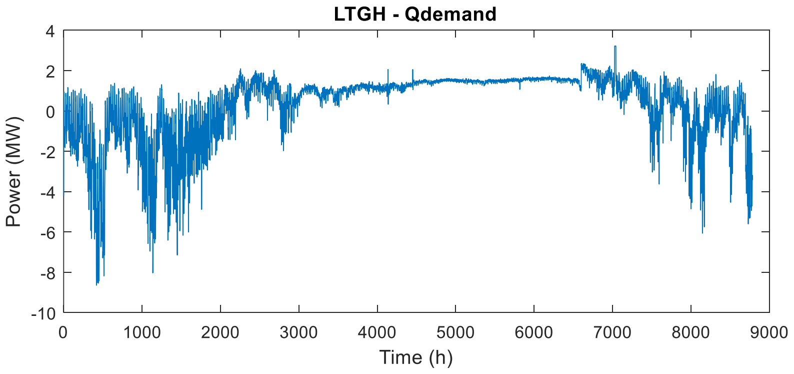


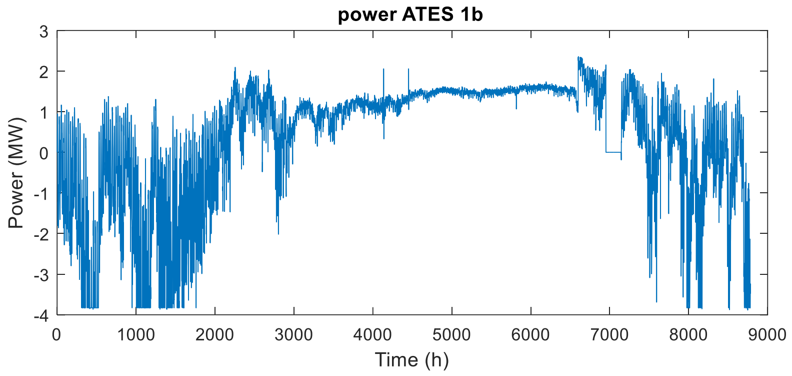


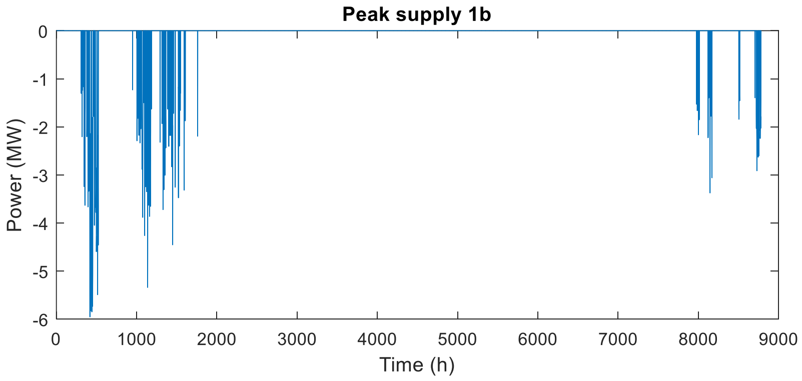


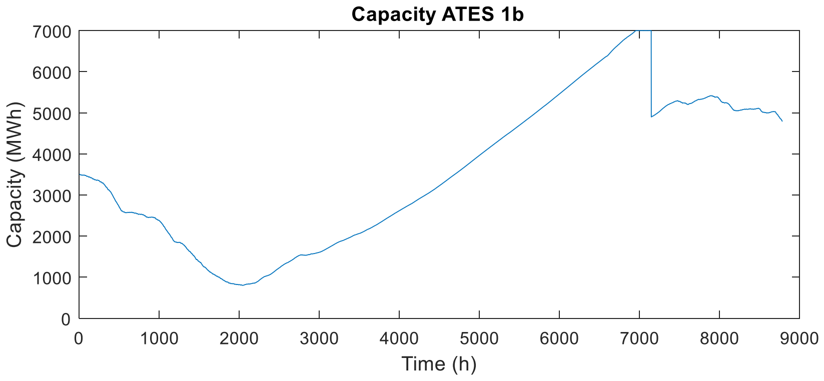


LTDH concept 1b: 50 ºC, peak supply from the biomass boiler

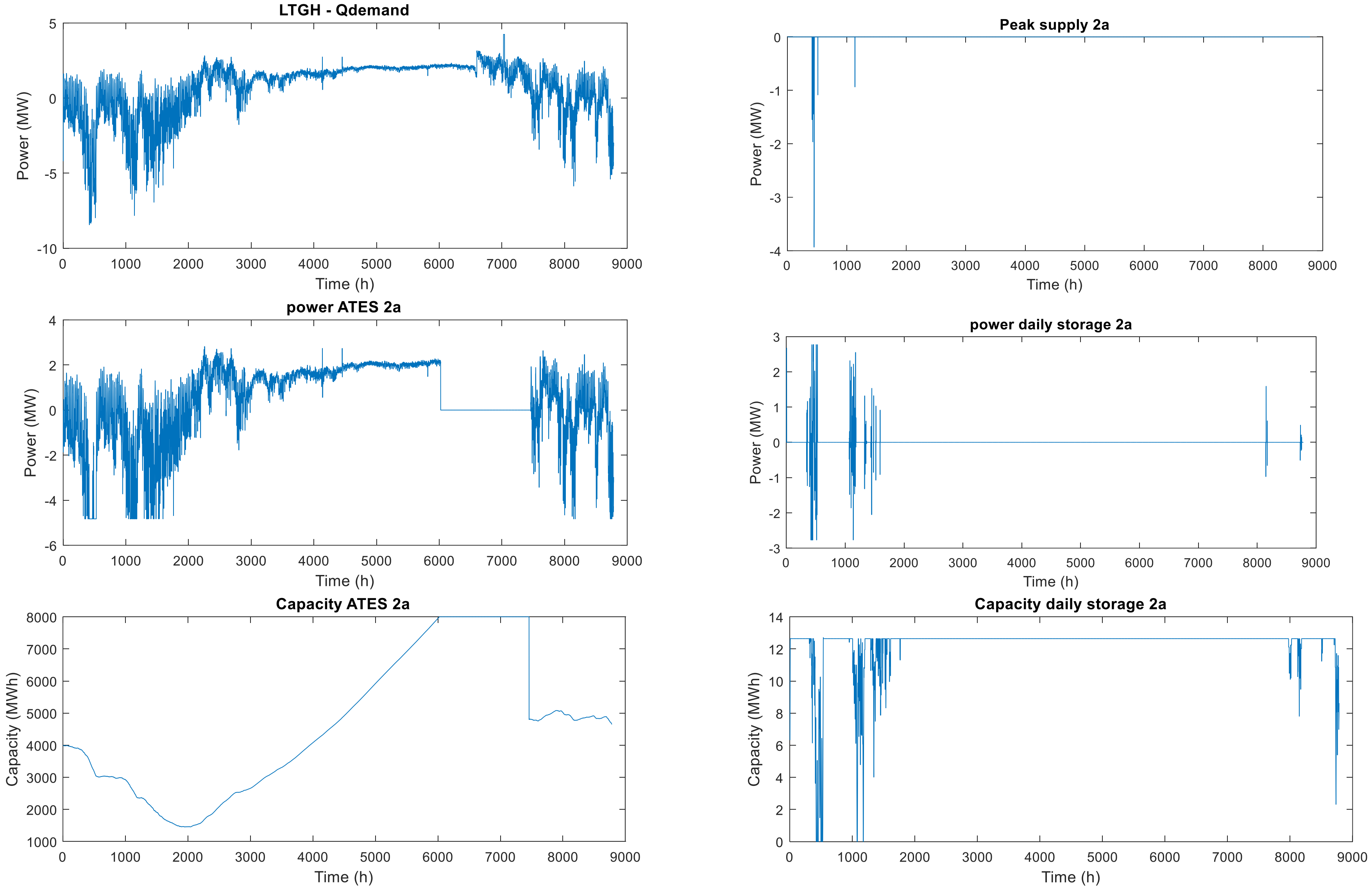

LTGH - Qdemand


power ATES 1b

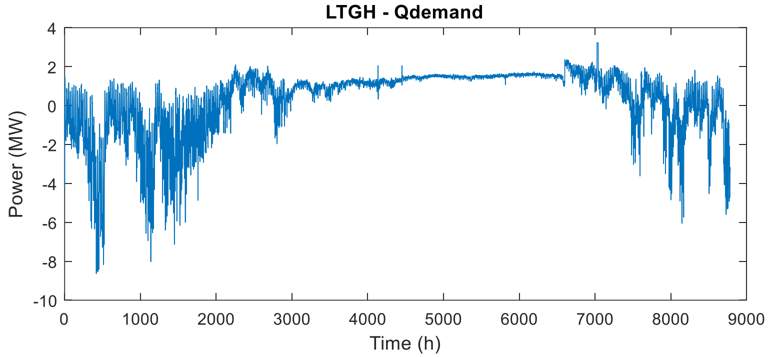

Peak supply 1b

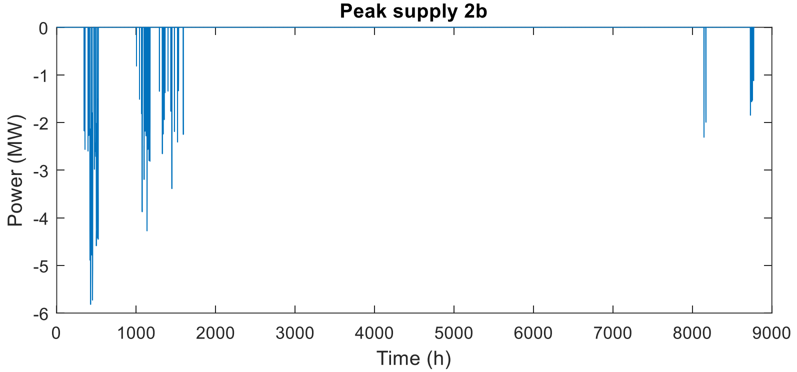

Capacity ATES 1b

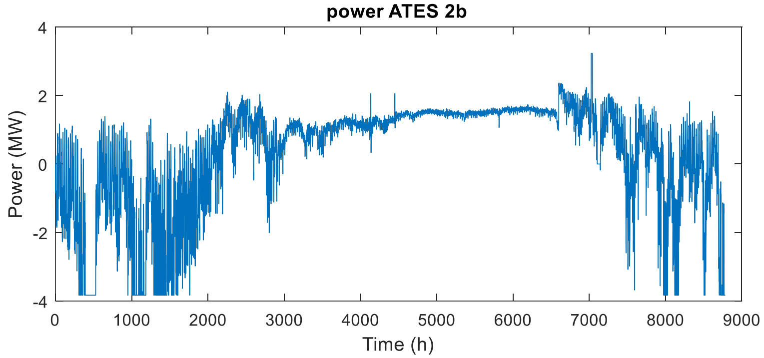
LTDH concept 2a: 70 ºC, peak supply from electrical heaters and water tank

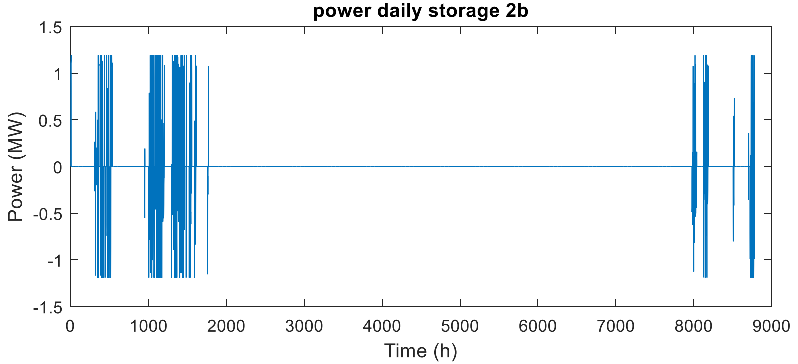


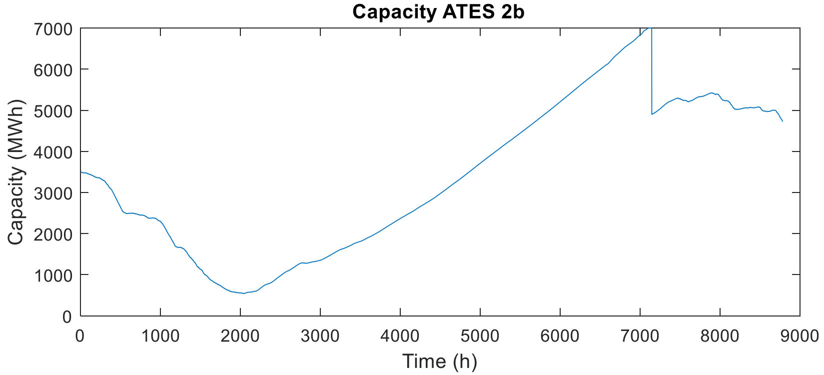
LTDH concept 2b: 50 ⁰C, peak supply from electrical heaters and water tank

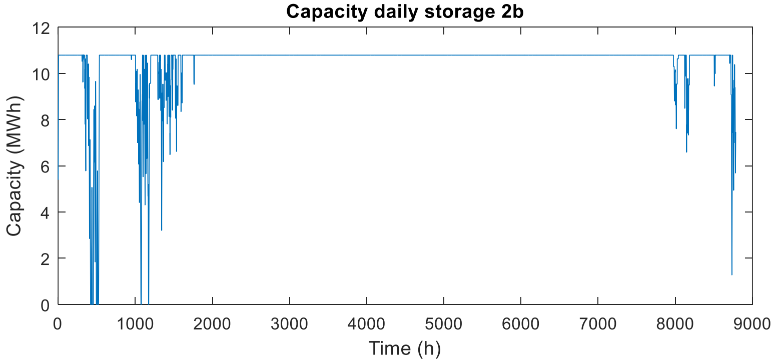






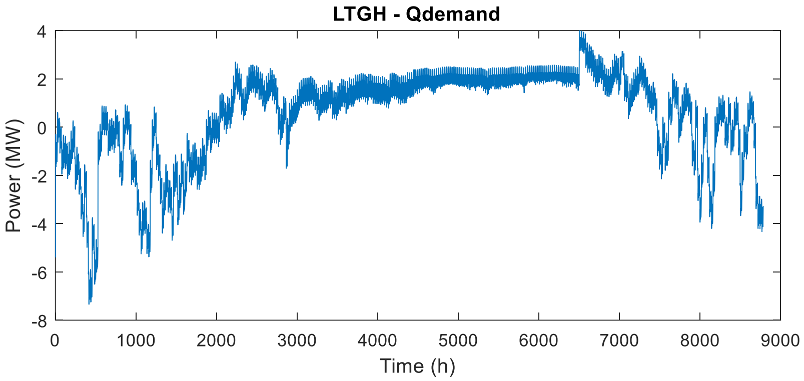


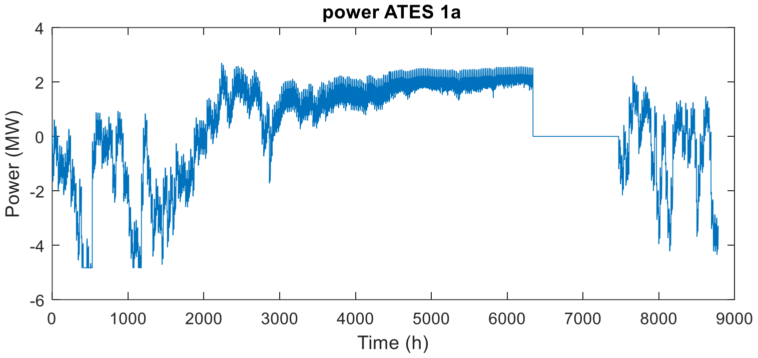


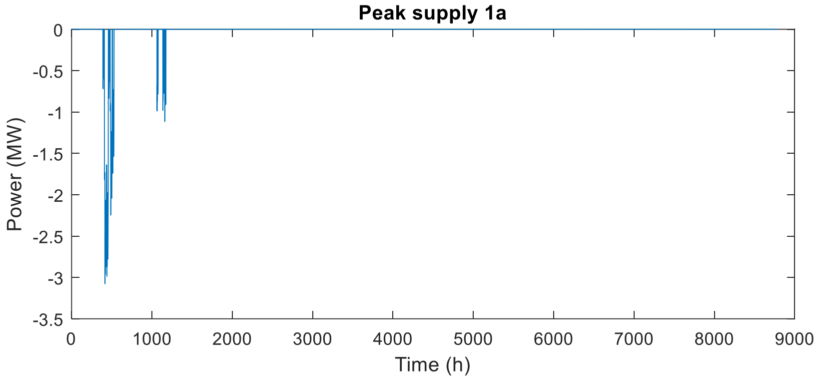


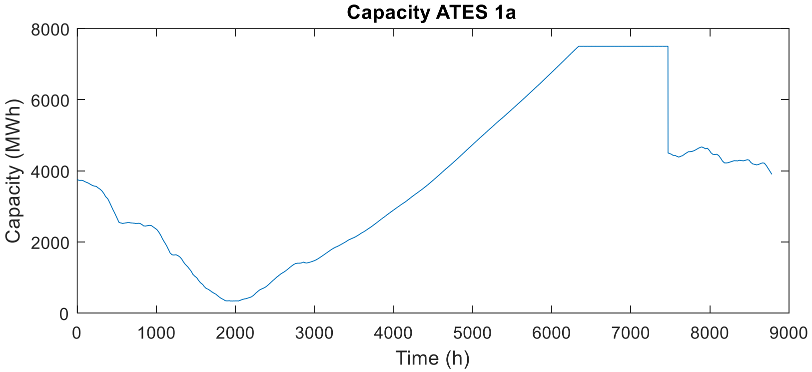
Heat demand strategy 2: Peak shaving

LTDH concept 1a: 70 ºC, peak supply from the biomass boiler

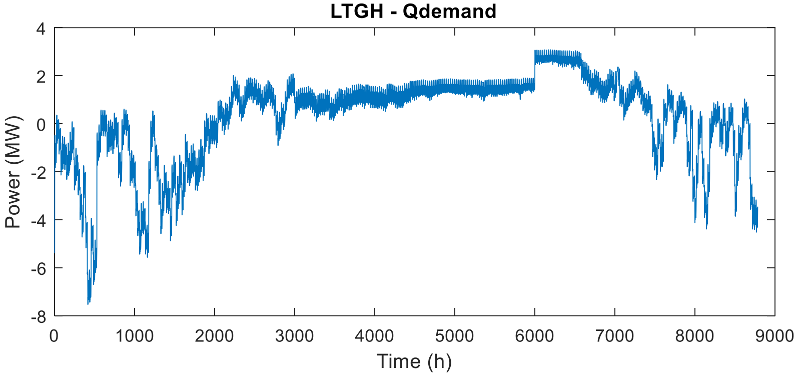

LTGH - Qdemand

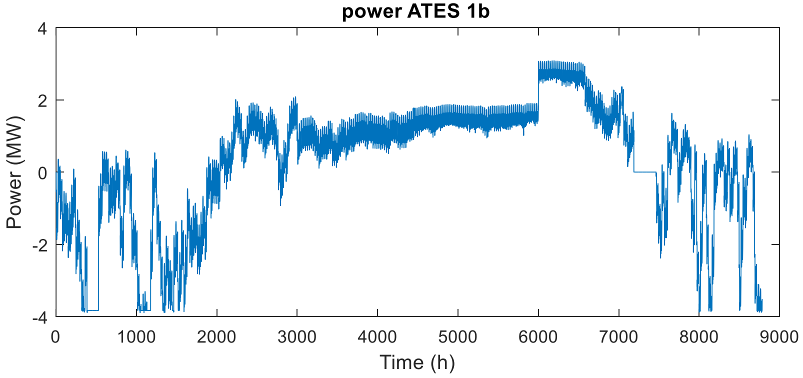

power ATES 1a

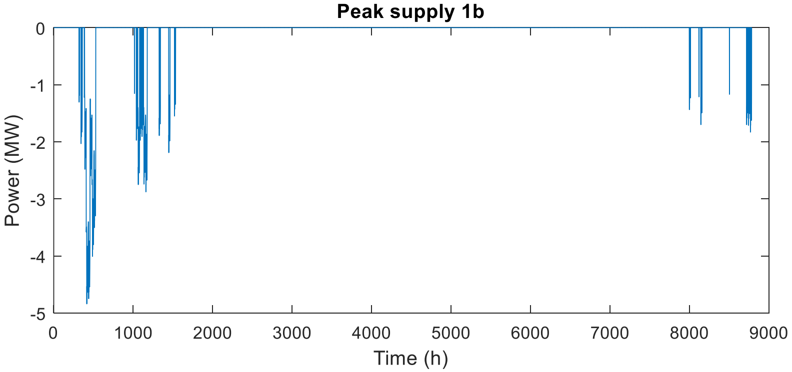

Peak supply 1a

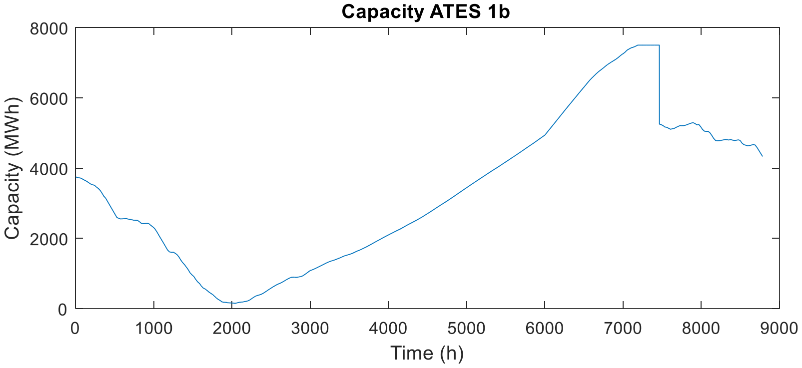

Capacity ATES 1a

LTDH concept 1b: 50 ºC, peak supply from the biomass boiler

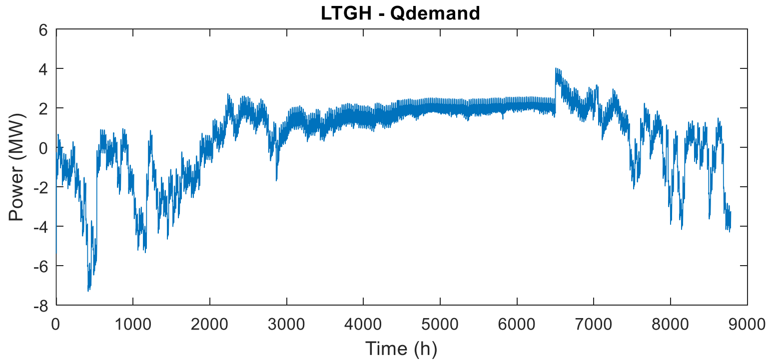


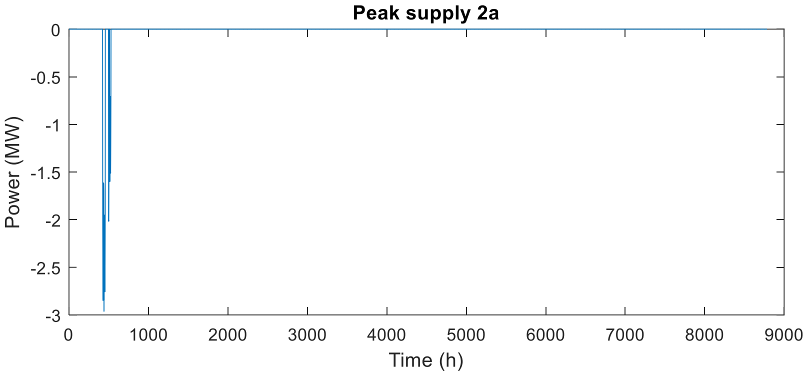


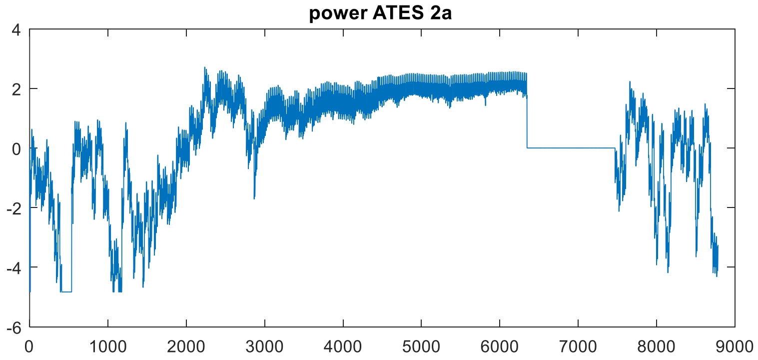


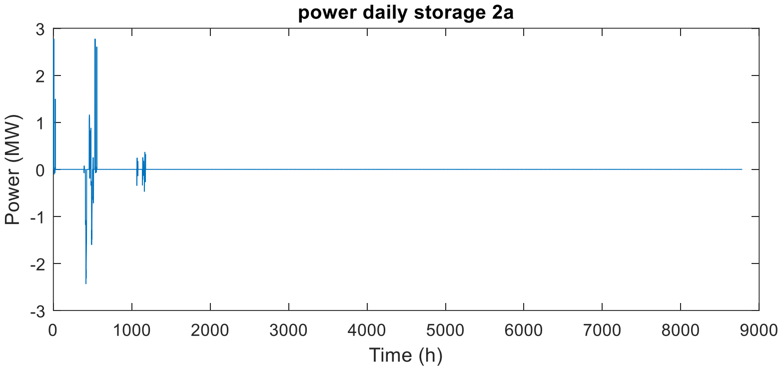


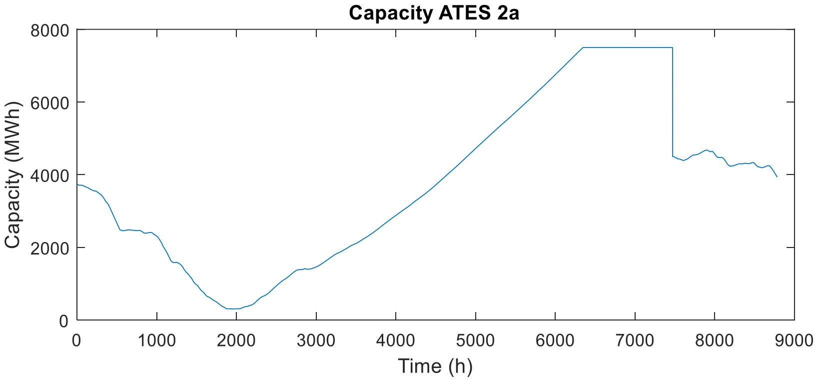
LTDH concept 2a: 70 ºC, peak supply from electrical heaters and water tank

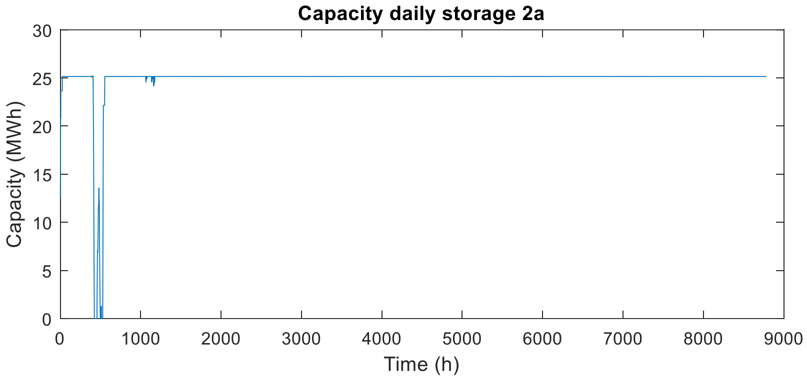

LTGH - Qdemand


Peak supply 2a


power ATES 2a

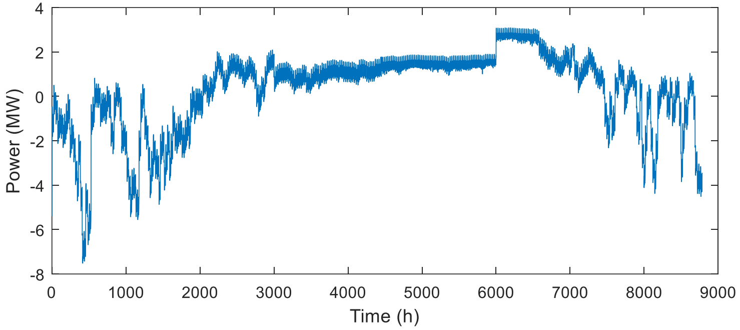

power daily storage 2a


Capacity ATES 2a

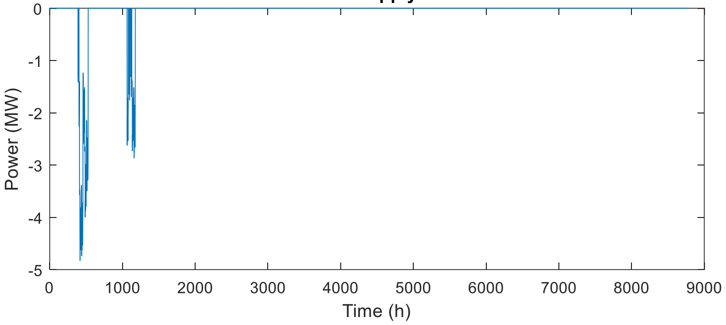

Capacity daily storage 2a

LTDH concept 2b: 50 ºC, peak supply from electrical heaters and water tank

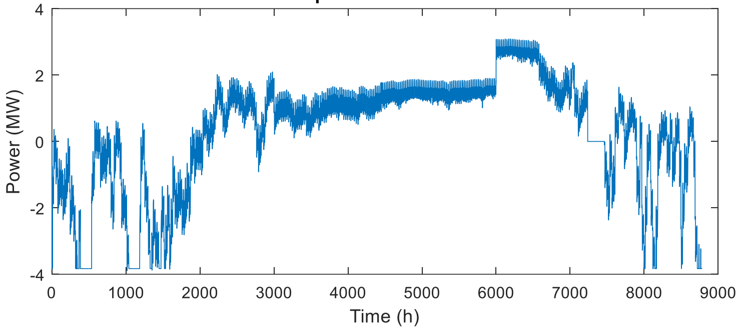
LTGH - Qdemand



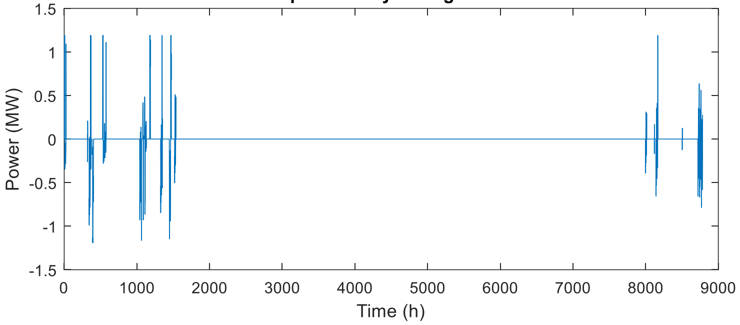
Peak supply 2b



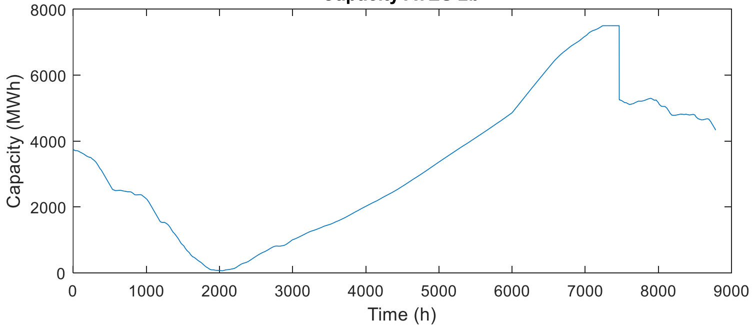
power ATES 2b



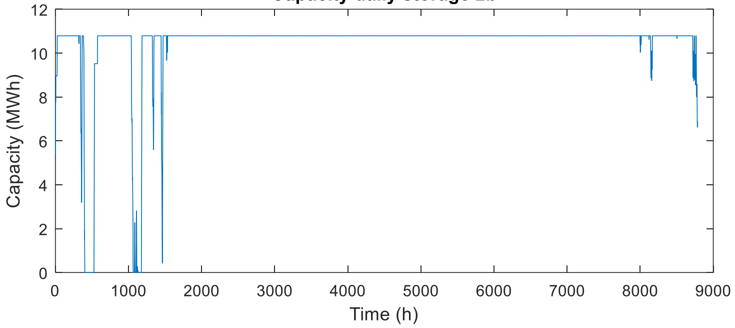
power daily storage 2b



Capacity ATES 2b

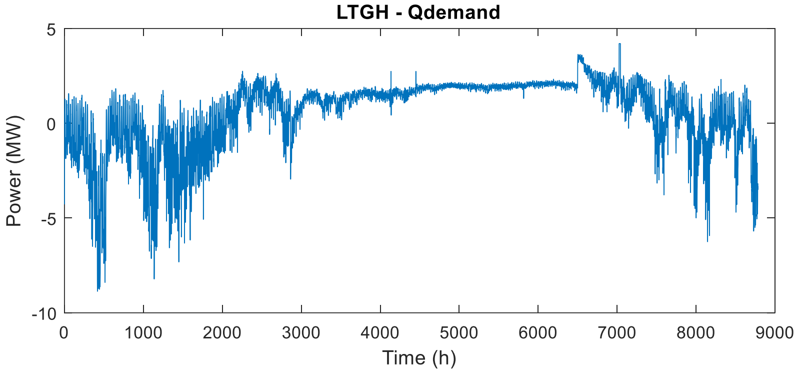


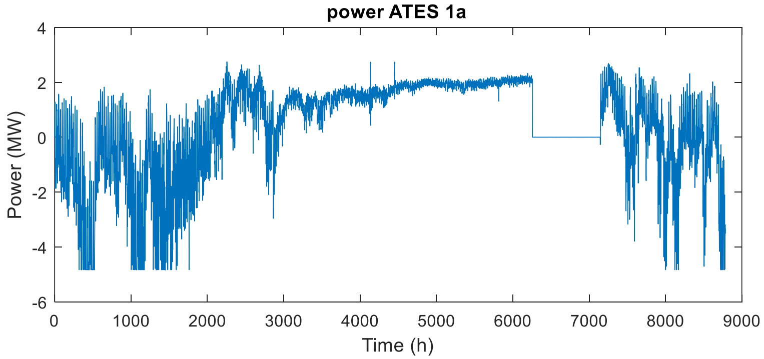
Capacity daily storage 2b

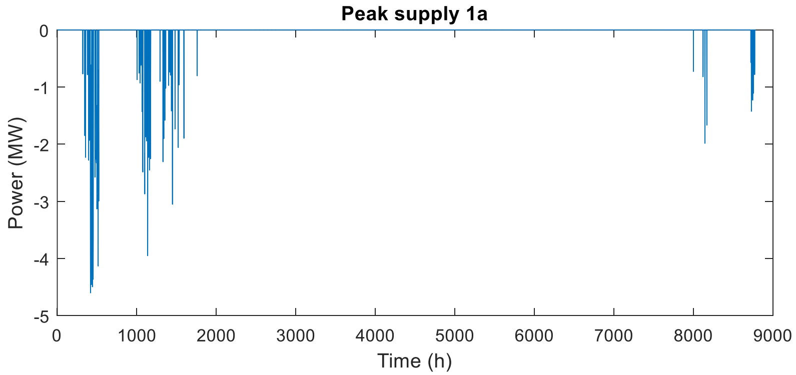


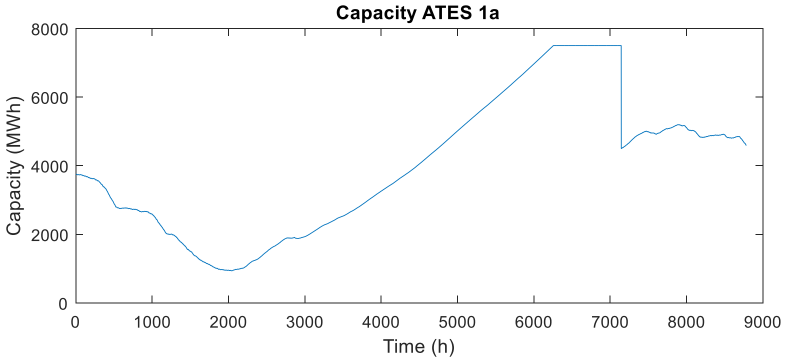
Heat demand strategy 3: Thermal insulation measures applied

LTDH concept 1a: 70 ⁰C, peak supply from the biomass boiler

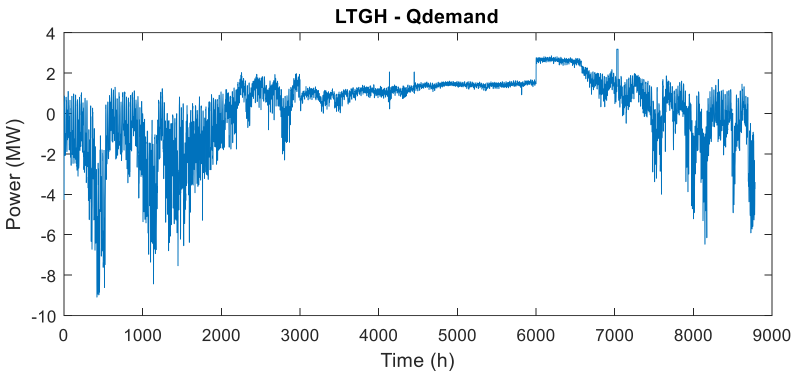

LTGH - Qdemand

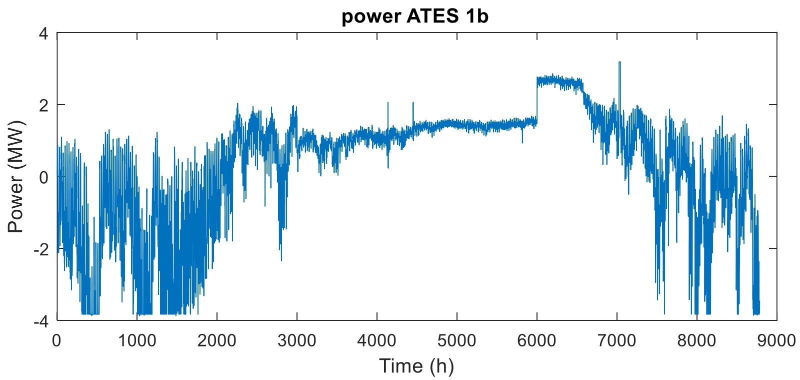

power ATES 1a

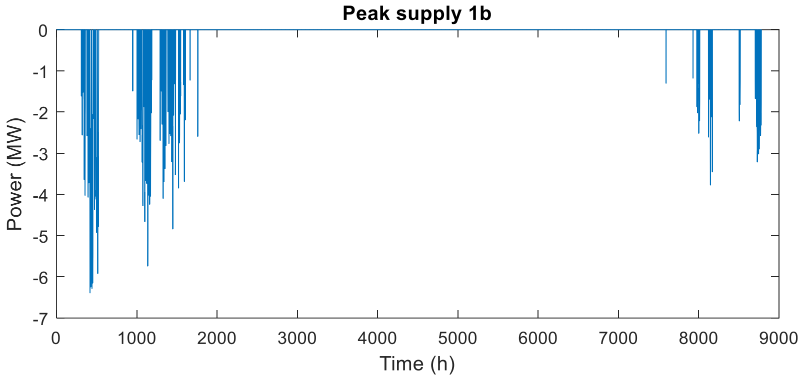

Peak supply 1a

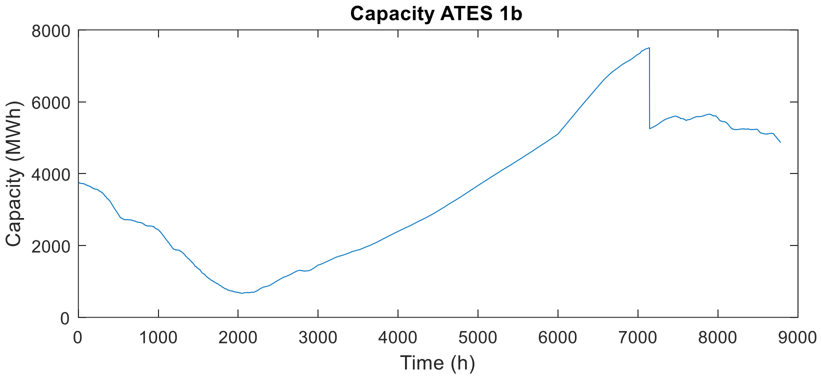

Capacity ATES 1a

LTDH concept 1b: 50 ºC, peak supply from the biomass boiler

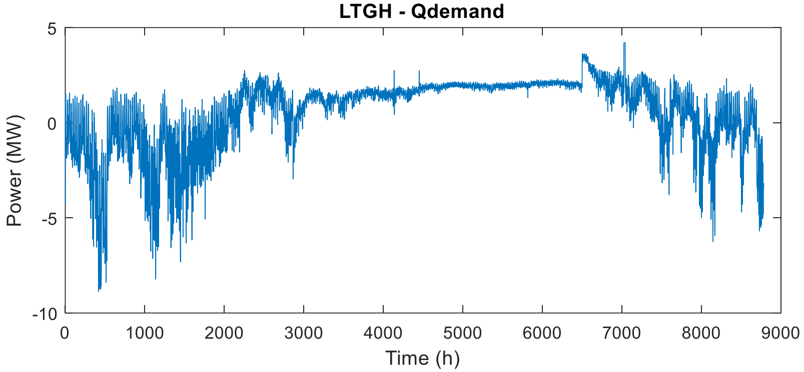


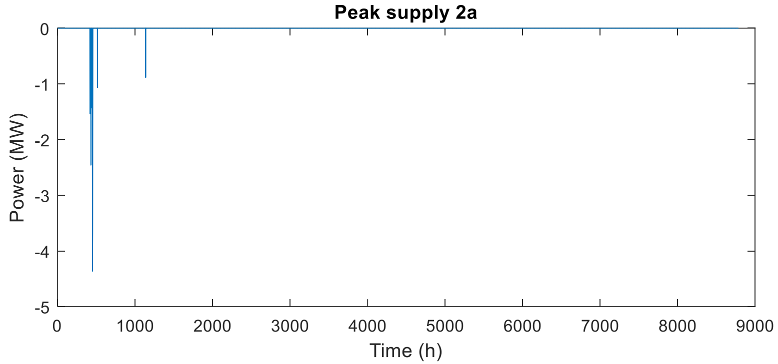


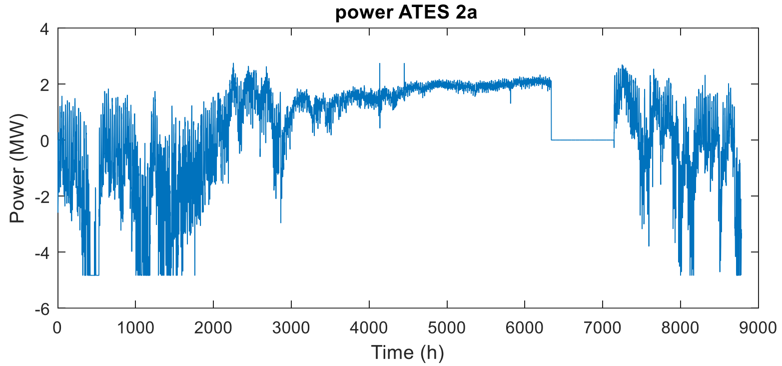


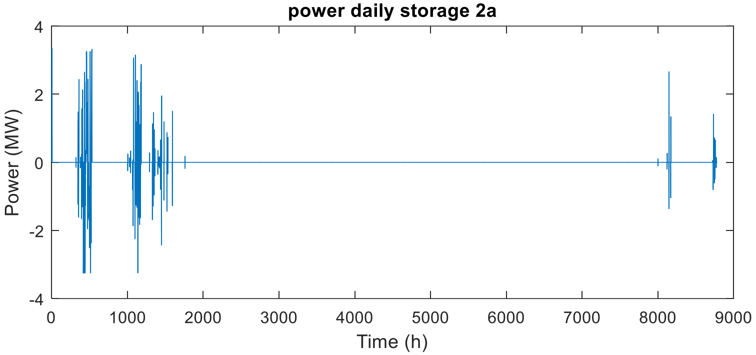


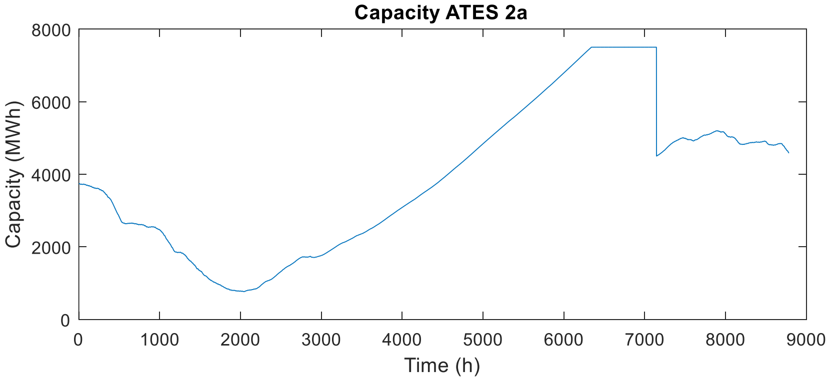
LTDH concept 2a: 70 ºC, peak supply from electrical heaters and water tank

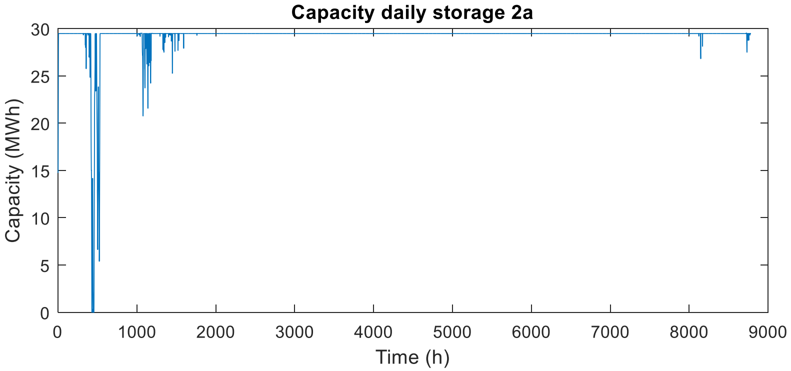

LTGH - Qdemand


Peak supply 2a

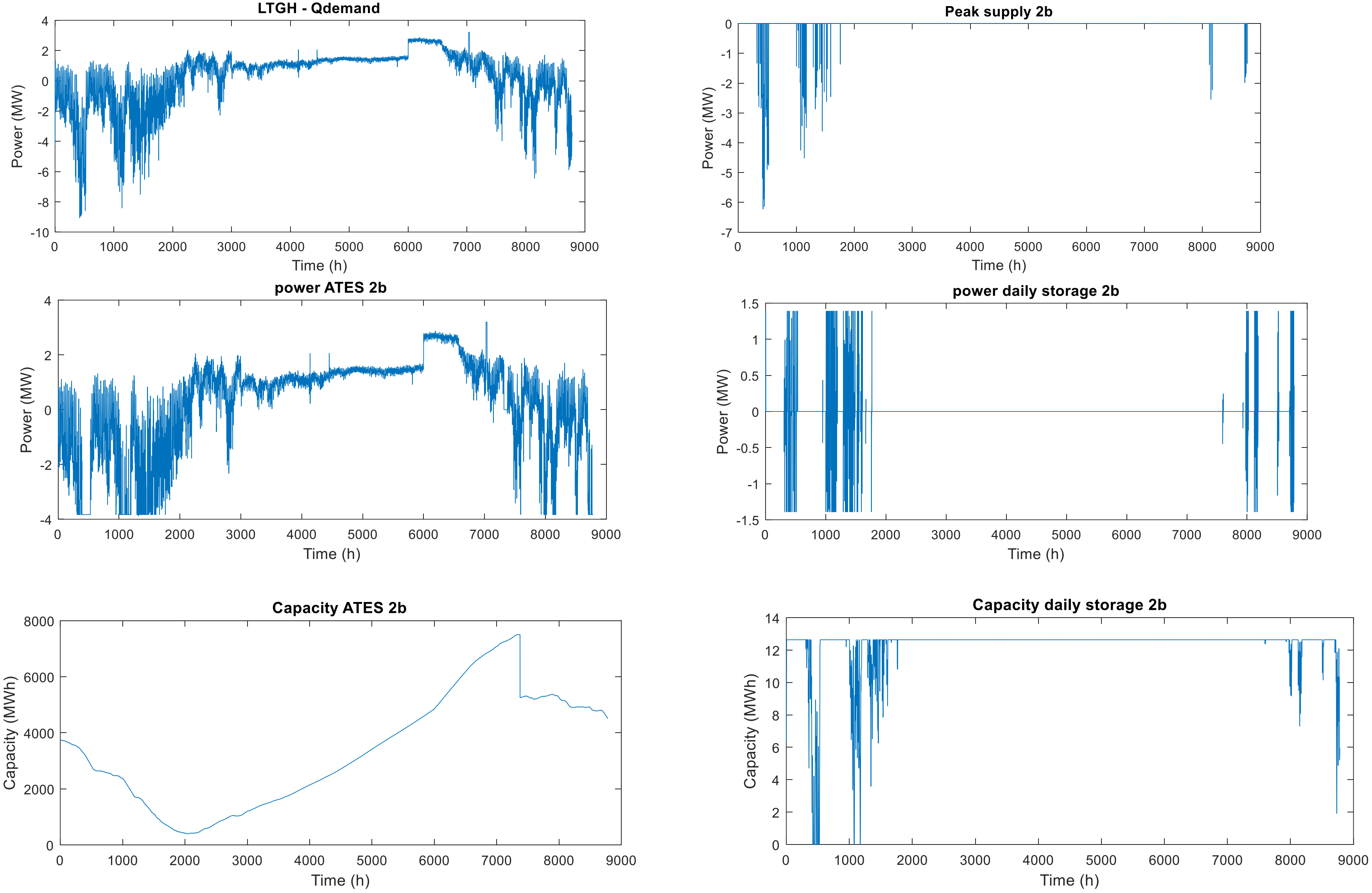

power ATES 2a


power daily storage 2a


Capacity ATES 2a


Capacity daily storage 2a

LTDH concept 2b: 50 ºC, peak supply from electrical heaters and water tank



D. Appendix Electricity usage

This appendix presents the calculation tool and the results of the performed calculations in Chapters 6.4 and 10. The electricity usage is calculated with Microsoft Excel. Print screens of the sheets used for LTDH concept 1a, using the first heat demand strategy, are presented in the next pages. The sheet calculates electricity usage as follows.

Circulation pump

The electricity usage of the circulation pump is calculated with equation 29, which is repeated below.

$$P_{el} = \frac{\dot{V} * \Delta p}{\eta}$$

$$P_{el} = \frac{C_1}{\eta} * (\frac{\dot{Q}_{demand}}{C_2})^3$$

C1 and C2 are determined with the required flow rate and required pressure for the maximum heat demand.

$$C_1 = \frac{\dot{V}^2}{\Delta p}$$

$$C_2 = \frac{\dot{V}}{\dot{Q}_{demand}}$$

Figure D-1 presents the screenshot of the used Excel sheet. Cell C7 and cell C12 determines the constants. After that, the hourly volume flow is calculated in column G for one circulation pump. The pressure difference is calculated in column I, where the minimum pressure difference has to be 1 bar. The lasts columns calculate the hourly electricity usage of one circulation pump and all the circulation pumps.

ATES and well pump

The pump power of the ATES and well pump are calculated with equation 51, the Bernoulli equation. In Figure D-2 and Figure D-3 is the first column the fixed values for this equation. The columns after that calculate the hourly pressure difference, mass flow, and the speed in the wells. With that, the hourly electricity usage of the pump is calculated.

Air – to – water heat pump

For the air – to –water heat pump is a little Matlab script written to determine the hourly COP of the heat pump, which is related to the outside temperature. The sheet next to the script, in

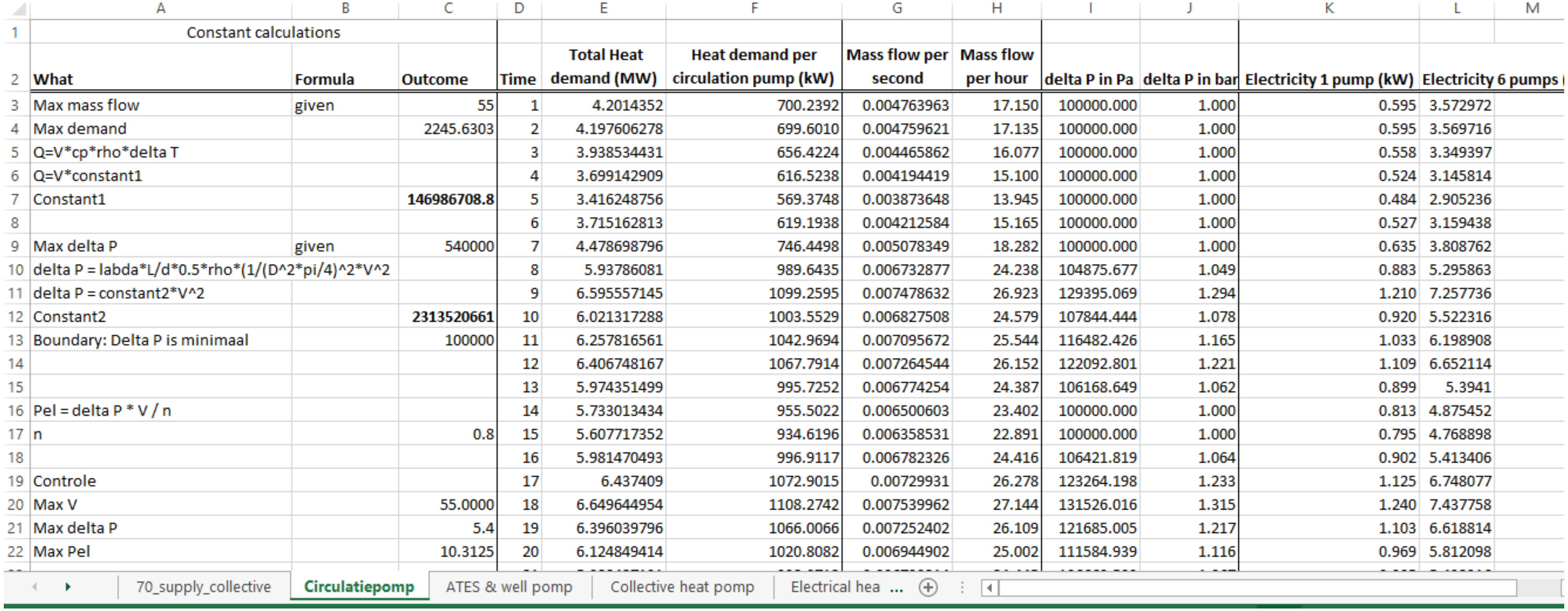
Figure D-4, presents the hourly electricity usage of the heat pump and the electric boiler. This is calculated according to equation 51.

Remaining heat pumps

The remaining heat pumps are the collective heat pump at the LTGH source, the decentral heat pumps, and the BHP. These are calculated with the COP values from Table 6-10 and equation 43. The electricity usage is calculated in Figure D-5.

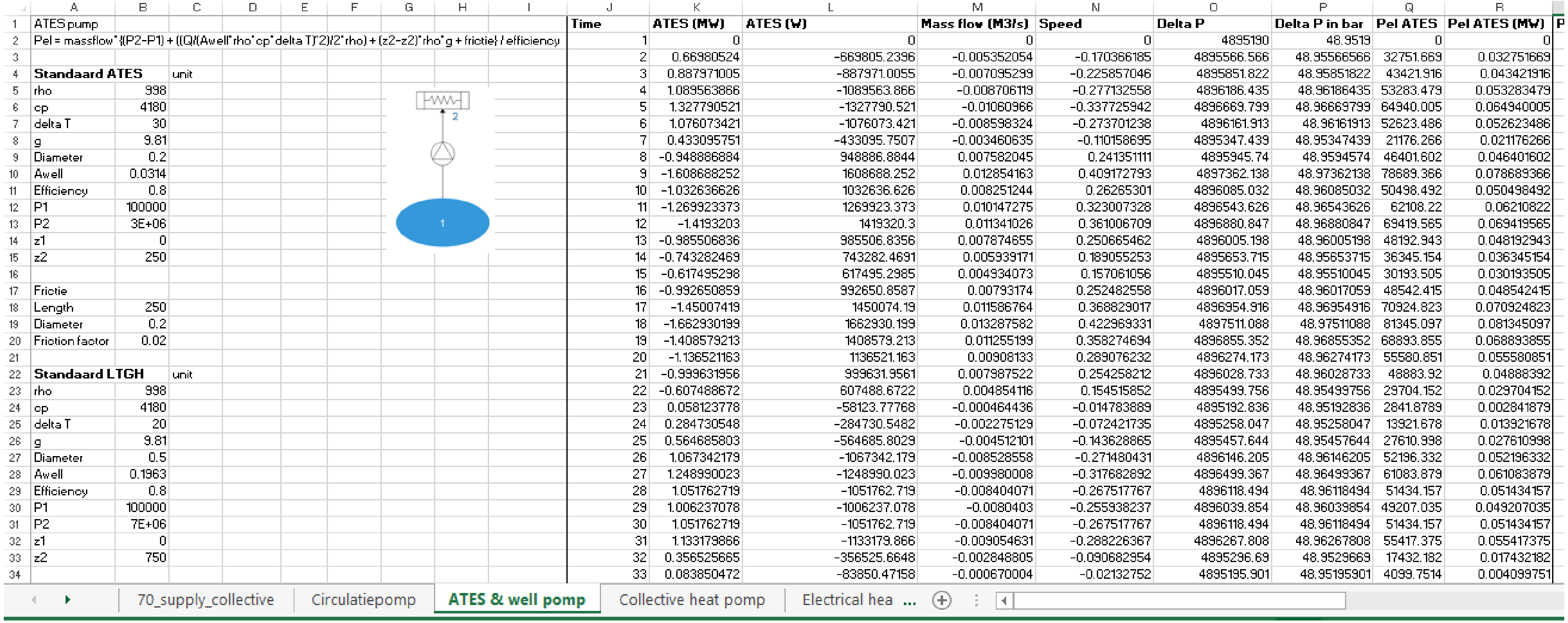
Total electricity usage

The total electricity usage is the sum of the hourly electricity consumption of every device. This is calculated in the last sheet, in Figure D-5.



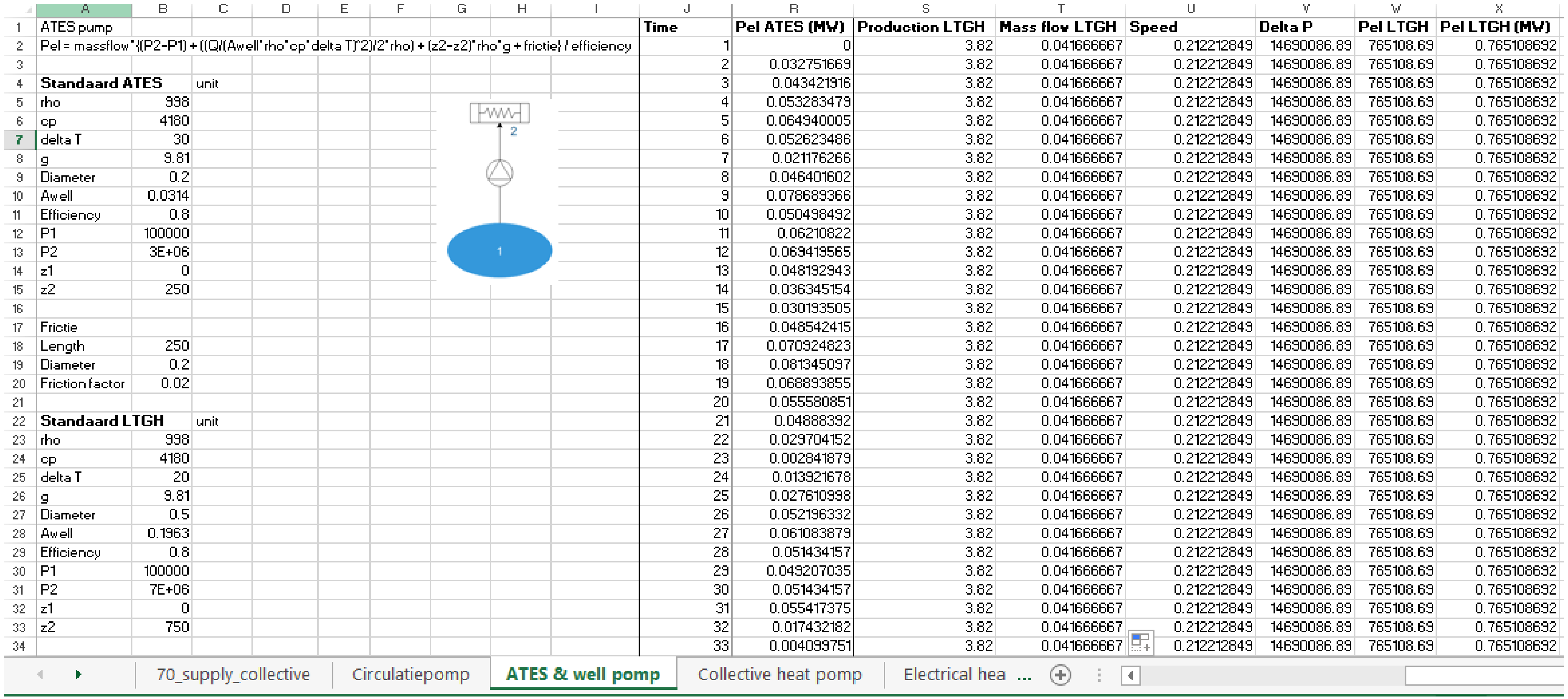
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Constant calculations												
2	**What**	**Formula**	**Outcome**	**Time**	**Total Heat demand (MW)**	**Heat demand per circulation pump (kW)**	**Mass flow per second**	**Mass flow per hour**	**delta P in Pa**	**delta P in bar**	**Electricity 1 pump (kW)**	**Electricity 6 pumps**	
3	Max mass flow	given	55	1	4.2014352	700.2392	0.004763963	17.150	100000.000	1.000	0.595	3.572972	
4	Max demand		2245.6303	2	4.197606278	699.6010	0.004759621	17.135	100000.000	1.000	0.595	3.569716	
5	Q=V*cp*rho*delta T			3	3.938534431	656.4224	0.004465862	16.077	100000.000	1.000	0.558	3.349397	
6	Q=V*constant1			4	3.699142909	616.5238	0.004194419	15.100	100000.000	1.000	0.524	3.145814	
7	Constant1		**146986708.8**	5	3.416248756	569.3748	0.003873648	13.945	100000.000	1.000	0.484	2.905236	
8				6	3.715162813	619.1938	0.004212584	15.165	100000.000	1.000	0.527	3.159438	
9	Max delta P	given	540000	7	4.478698796	746.4498	0.005078349	18.282	100000.000	1.000	0.635	3.808762	
10	delta P = labda*L/d*0.5*rho*(1/(D^2*pi/4)^2*V^2			8	5.93786081	989.6435	0.006732877	24.238	104875.677	1.049	0.883	5.295863	
11	delta P = constant2*V^2			9	6.595557145	1099.2595	0.007478632	26.923	129395.069	1.294	1.210	7.257736	
12	Constant2		**2313520661**	10	6.021317288	1003.5529	0.006827508	24.579	107844.444	1.078	0.920	5.522316	
13	Boundary: Delta P is minimaal		100000	11	6.257816561	1042.9694	0.007095672	25.544	116482.426	1.165	1.033	6.198908	
14				12	6.406748167	1067.7914	0.007264544	26.152	122092.801	1.221	1.109	6.652114	
15				13	5.974351499	995.7252	0.006774254	24.387	106168.649	1.062	0.899	5.3941	
16	Pel = delta P * V / n			14	5.733013434	955.5022	0.006500603	23.402	100000.000	1.000	0.813	4.875452	
17	n		0.8	15	5.607717352	934.6196	0.006358531	22.891	100000.000	1.000	0.795	4.768898	
18				16	5.981470493	996.9117	0.006782326	24.416	106421.819	1.064	0.902	5.413406	
19	Controle			17	6.437409	1072.9015	0.00729931	26.278	123264.198	1.233	1.125	6.748077	
20	Max V		55.0000	18	6.649644954	1108.2742	0.007539962	27.144	131526.016	1.315	1.240	7.437758	
21	Max delta P		5.4	19	6.396039796	1066.0066	0.007252402	26.109	121685.005	1.217	1.103	6.618814	
22	Max Pel		10.3125	20	6.124849414	1020.8082	0.006944902	25.002	111584.939	1.116	0.969	5.812098	

Figure D-1 Calculation sheet of the circulation pump.



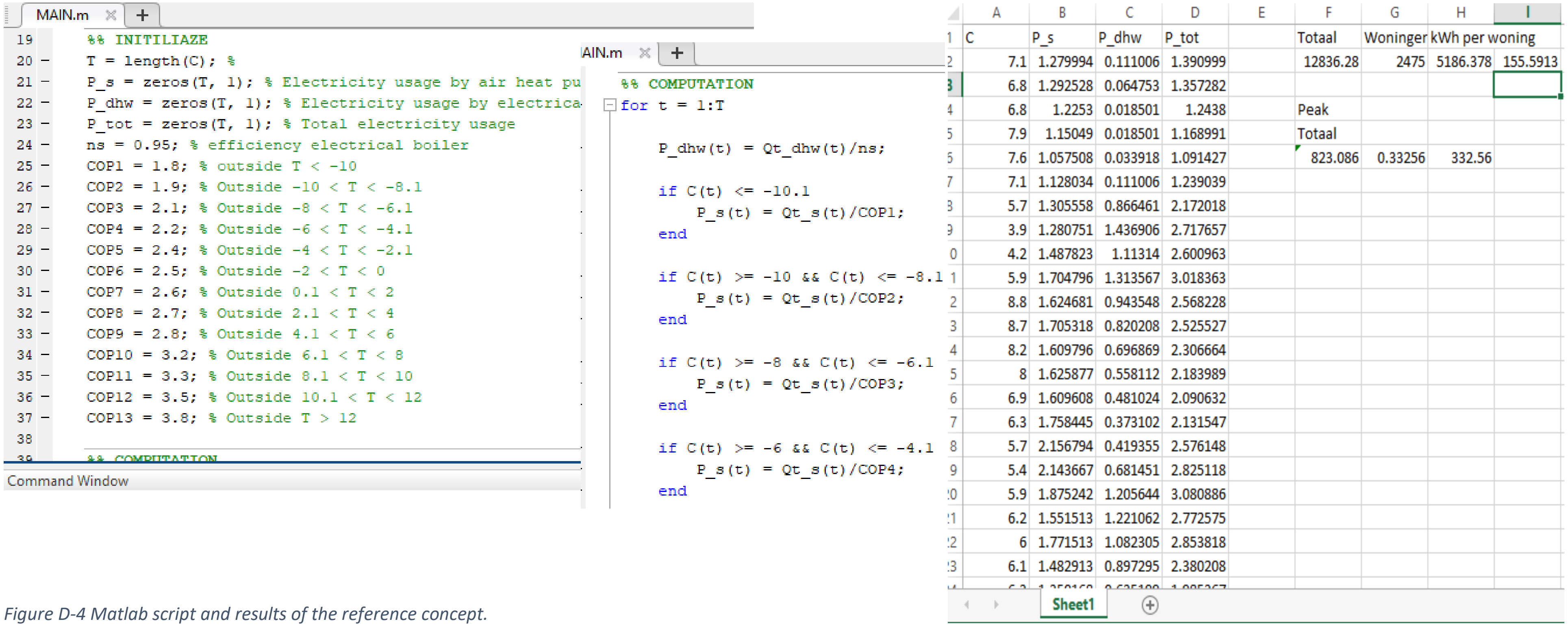
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	ATES pump									**Time**	**ATES (MW)**	**ATES (W)**	**Mass flow (M3/s)**	**Speed**	**Delta P**	**Delta P in bar**	**Pel ATES**	**Pel ATES (MW)**
2	Pel = massflow*{(P2-P1) + ((Q/(Awell*rho*cp*delta T)^2)/2*rho) + (z2-z2)*rho*g + frictie} / efficiency									1	0	0	0	0	4895190	48.9519	0	0
3										2	0.66980524	-669805.2396	-0.005352054	-0.170366185	4895566.566	48.95566566	32751.669	0.032751669
4	**Standaard ATES**		unit							3	0.887971005	-887971.0055	-0.007095299	-0.225857046	4895851.822	48.95851822	43421.916	0.043421916
5	rho	998								4	1.089563866	-1089563.866	-0.008706119	-0.277132558	4896186.435	48.96186435	53283.479	0.053283479
6	cp	4180								5	1.327790521	-1327790.521	-0.01060966	-0.337725942	4896669.799	48.96669799	64940.005	0.064940005
7	delta T	30								6	1.076073421	-1076073.421	-0.008598324	-0.273701238	4896161.913	48.96161913	52623.486	0.052623486
8	g	9.81								7	0.433095751	-433095.7507	-0.003460635	-0.110158695	4895347.439	48.95347439	21176.266	0.021176266
9	Diameter	0.2								8	-0.948886884	948886.8844	0.007582045	0.241351111	4895945.74	48.9594574	46401.602	0.046401602
10	Awell	0.0314								9	-1.608688252	1608688.252	0.012854163	0.409172793	4897362.138	48.97362138	78689.366	0.078689366
11	Efficiency	0.8								10	-1.032636626	1032636.626	0.008251244	0.26265301	4896085.032	48.96085032	50498.492	0.050498492
12	P1	100000								11	-1.269923373	1269923.373	0.010147275	0.323007328	4896543.626	48.96543626	62108.22	0.06210822
13	P2	3E+06								12	-1.4193203	1419320.3	0.011341026	0.361006709	4896880.847	48.96880847	69419.565	0.069419565
14	z1	0								13	-0.985506836	985506.8356	0.007874655	0.250665462	4896005.198	48.96005198	48192.943	0.048192943
15	z2	250								14	-0.743282469	743282.4691	0.005939171	0.189055253	4895653.715	48.95653715	36345.154	0.036345154
16										15	-0.617495298	617495.2985	0.004934073	0.157061056	4895510.045	48.95510045	30193.505	0.030193505
17	Frictie									16	-0.992650859	992650.8587	0.00793174	0.252482558	4896017.059	48.96017059	48542.415	0.048542415
18	Length	250								17	-1.45007419	1450074.19	0.011586764	0.368829017	4896954.916	48.96954916	70924.823	0.070924823
19	Diameter	0.2								18	-1.662930199	1662930.199	0.013287582	0.422969331	4897511.088	48.97511088	81345.097	0.081345097
20	Friction factor	0.02								19	-1.408579213	1408579.213	0.011255199	0.358274694	4896855.352	48.96855352	68893.855	0.068893855
21										20	-1.136521163	1136521.163	0.00908133	0.289076232	4896274.173	48.96274173	55580.851	0.055580851
22	**Standaard LTGH**		unit							21	-0.999631956	999631.9561	0.007987522	0.254258212	4896028.733	48.96028733	48883.92	0.04888392
23	rho	998								22	-0.607488672	607488.6722	0.004854116	0.154515852	4895499.756	48.95499756	29704.152	0.029704152
24	cp	4180								23	0.058123778	-58123.77768	-0.000464436	-0.014783889	4895192.836	48.95192836	2841.8789	0.002841879
25	delta T	20								24	0.284730548	-284730.5482	-0.002275129	-0.072421735	4895258.047	48.95258047	13921.678	0.013921678
26	g	9.81								25	0.564685803	-564685.8029	-0.004512101	-0.143628865	4895457.644	48.95457644	27610.998	0.027610998
27	Diameter	0.5								26	1.067342179	-1067342.179	-0.008528558	-0.271480431	4896146.205	48.96146205	52196.332	0.052196332
28	Awell	0.1963								27	1.248990023	-1248990.023	-0.009980008	-0.317682892	4896499.367	48.96499367	61083.879	0.061083879
29	Efficiency	0.8								28	1.051762719	-1051762.719	-0.008404071	-0.267517767	4896118.494	48.96118494	51434.157	0.051434157
30	P1	100000								29	1.006237078	-1006237.078	-0.0080403	-0.255938237	4896039.854	48.96039854	49207.035	0.049207035
31	P2	7E+06								30	1.051762719	-1051762.719	-0.008404071	-0.267517767	4896118.494	48.96118494	51434.157	0.051434157
32	z1	0								31	1.133179866	-1133179.866	-0.009054631	-0.288226367	4896267.808	48.96267808	55417.375	0.055417375
33	z2	750								32	0.356525665	-356525.6648	-0.002848805	-0.090682954	4895296.69	48.9529669	17432.182	0.017432182
34										33	0.083850472	-83850.47158	-0.000670004	-0.02132752	4895195.901	48.95195901	4099.7514	0.004099751

Figure D-2 Calculation sheet of the ATES well pump.



	A	B	C	J	R	S	T	U	V	W	X
1	ATES pump			**Time**	**Pel ATES (MW)**	**Production LTGH**	**Mass flow LTGH**	**Speed**	**Delta P**	**Pel LTGH**	**Pel LTGH (MW)**
2	Pel = massflow*{(P2-P1) + ((Q/(Awell*rho*cp*delta T)^2)/2*rho) + (z2-z2)*rho*g + frictie} / efficiency			1	0	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
3				2	0.032751669	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
4	**Standaard ATES**		unit	3	0.043421916	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
5	rho	998		4	0.053283479	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
6	cp	4180		5	0.064940005	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
7	delta T	30		6	0.052623486	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
8	g	9.81		7	0.021176266	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
9	Diameter	0.2		8	0.046401602	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
10	Awell	0.0314		9	0.078689366	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
11	Efficiency	0.8		10	0.050498492	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
12	P1	100000		11	0.06210822	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
13	P2	3E+06		12	0.069419565	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
14	z1	0		13	0.048192943	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
15	z2	250		14	0.036345154	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
16				15	0.030193505	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
17	Frictie			16	0.048542415	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
18	Length	250		17	0.070924823	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
19	Diameter	0.2		18	0.081345097	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
20	Friction factor	0.02		19	0.068893855	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
21				20	0.055580851	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
22	**Standaard LTGH**		unit	21	0.04888392	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
23	rho	998		22	0.029704152	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
24	cp	4180		23	0.002841879	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
25	delta T	20		24	0.013921678	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
26	g	9.81		25	0.027610998	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
27	Diameter	0.5		26	0.052196332	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
28	Awell	0.1963		27	0.061083879	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
29	Efficiency	0.8		28	0.051434157	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
30	P1	100000		29	0.049207035	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
31	P2	7E+06		30	0.051434157	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
32	z1	0		31	0.055417375	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
33	z2	750		32	0.017432182	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692
34				33	0.004099751	3.82	0.041666667	0.212212849	14690086.89	765108.69	0.765108692

Figure D-3 Calculation sheet of the LTGH well pump.

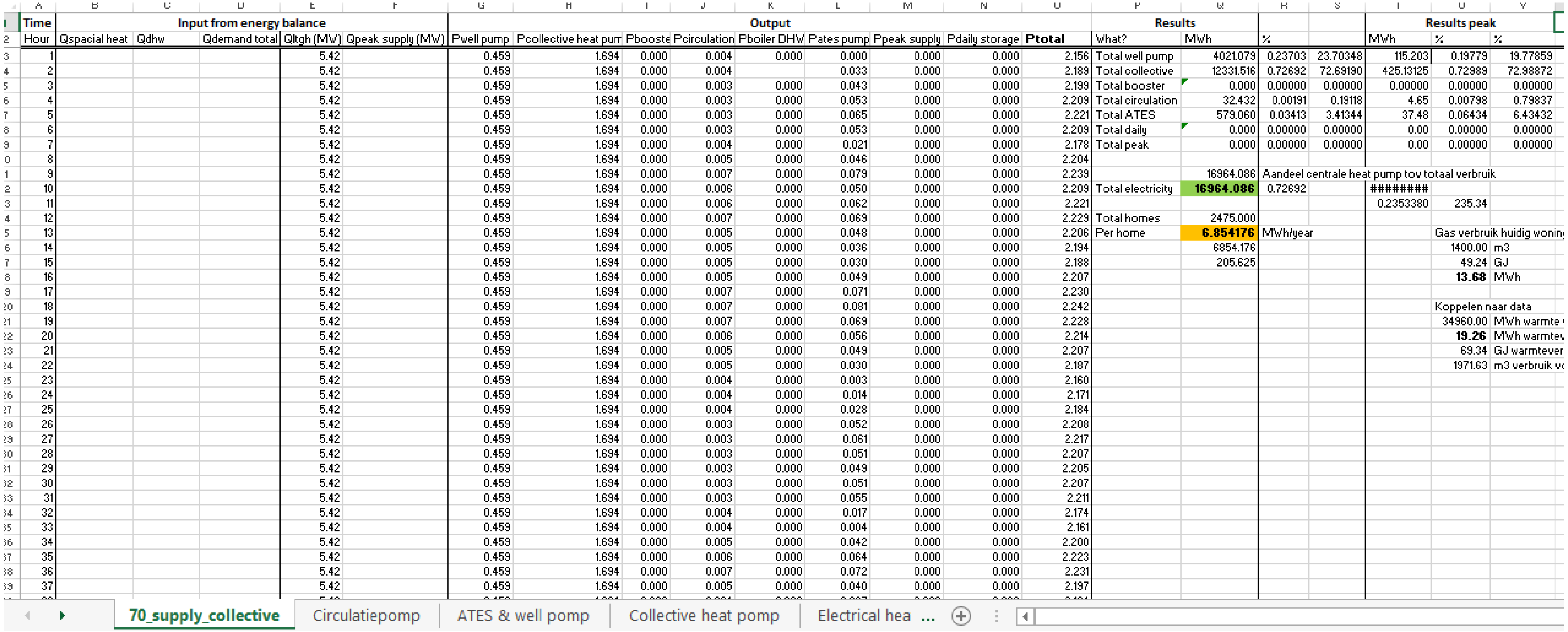


```
%% INITILIAZE
T = length(C); %
P_s = zeros(T, 1); % Electricity usage by air heat pu
P_dhw = zeros(T, 1); % Electricity usage by electrica
P_tot = zeros(T, 1); % Total electricity usage
ns = 0.95; % efficiency electrical boiler
COP1 = 1.8; % outside T < -10
COP2 = 1.9; % Outside -10 < T < -8.1
COP3 = 2.1; % Outside -8 < T < -6.1
COP4 = 2.2; % Outside -6 < T < -4.1
COP5 = 2.4; % Outside -4 < T < -2.1
COP6 = 2.5; % Outside -2 < T < 0
COP7 = 2.6; % Outside 0.1 < T < 2
COP8 = 2.7; % Outside 2.1 < T < 4
COP9 = 2.8; % Outside 4.1 < T < 6
COP10 = 3.2; % Outside 6.1 < T < 8
COP11 = 3.3; % Outside 8.1 < T < 10
COP12 = 3.5; % Outside 10.1 < T < 12
COP13 = 3.8; % Outside T > 12

%% COMPUTATION
```

```
%% COMPUTATION
for t = 1:T

    P_dhw(t) = Qt_dhw(t)/ns;

    if C(t) <= -10.1
        P_s(t) = Qt_s(t)/COP1;
    end

    if C(t) >= -10 && C(t) <= -8.1
        P_s(t) = Qt_s(t)/COP2;
    end

    if C(t) >= -8 && C(t) <= -6.1
        P_s(t) = Qt_s(t)/COP3;
    end

    if C(t) >= -6 && C(t) <= -4.1
        P_s(t) = Qt_s(t)/COP4;
    end
```

A	B	C	D	E	F	G	H	I
C	P_s	P_dhw	P_tot		Totaal	Woninger	kWh per woning	
7.1	1.279994	0.111006	1.390999		12836.28	2475	5186.378	155.5913
6.8	1.292528	0.064753	1.357282					
6.8	1.2253	0.018501	1.2438		Peak			
7.9	1.15049	0.018501	1.168991		Totaal			
7.6	1.057508	0.033918	1.091427		823.086	0.33256	332.56	
7.1	1.128034	0.111006	1.239039					
5.7	1.305558	0.866461	2.172018					
3.9	1.280751	1.436906	2.717657					
4.2	1.487823	1.11314	2.600963					
5.9	1.704796	1.313567	3.018363					
8.8	1.624681	0.943548	2.568228					
8.7	1.705318	0.820208	2.525527					
8.2	1.609796	0.696869	2.306664					
8	1.625877	0.558112	2.183989					
6.9	1.609608	0.481024	2.090632					
6.3	1.758445	0.373102	2.131547					
5.7	2.156794	0.419355	2.576148					
5.4	2.143667	0.681451	2.825118					
5.9	1.875242	1.205644	3.080886					
6.2	1.551513	1.221062	2.772575					
6	1.771513	1.082305	2.853818					
6.1	1.482913	0.897295	2.380208					

Figure D-4 Matlab script and results of the reference concept.



Time	Input from energy balance					Output									Results				Results peak		
Hour	Qspacial heat	Qdhw	Qdemand total	Qltgh (MW)	Qpeak supply (MW)	Pwell pump	Pcollective heat pum	Pbooste	Pcirculation	Pboiler DHW	Pates pump	Ppeak supply	Pdaily storage	**Ptotal**	What?	MWh	%		MWh	%	%
1				5.42		0.459	1.694	0.000	0.004	0.000	0.000	0.000	0.000	2.156	Total well pump	4021.079	0.23703	23.70348	115.203	0.19779	19.77859
2				5.42		0.459	1.694	0.000	0.004		0.033	0.000	0.000	2.189	Total collective	12331.516	0.72692	72.69190	425.13125	0.72989	72.98872
3				5.42		0.459	1.694	0.000	0.003	0.000	0.043	0.000	0.000	2.199	Total booster	0.000	0.00000	0.00000	0.00000	0.00000	0.00000
4				5.42		0.459	1.694	0.000	0.003	0.000	0.053	0.000	0.000	2.209	Total circulation	32.432	0.00191	0.19118	4.65	0.00798	0.79837
5				5.42		0.459	1.694	0.000	0.003	0.000	0.065	0.000	0.000	2.221	Total ATES	579.060	0.03413	3.41344	37.48	0.06434	6.43432
6				5.42		0.459	1.694	0.000	0.003	0.000	0.053	0.000	0.000	2.209	Total daily	0.000	0.00000	0.00000	0.00	0.00000	0.00000
7				5.42		0.459	1.694	0.000	0.004	0.000	0.021	0.000	0.000	2.178	Total peak	0.000	0.00000	0.00000	0.00	0.00000	0.00000
8				5.42		0.459	1.694	0.000	0.005	0.000	0.046	0.000	0.000	2.204							
9				5.42		0.459	1.694	0.000	0.007	0.000	0.079	0.000	0.000	2.239		16964.086	Aandeel centrale heat pump tov totaal verbruik				
10				5.42		0.459	1.694	0.000	0.006	0.000	0.050	0.000	0.000	2.209	Total electricity	**16964.086**	0.72692		########		
11				5.42		0.459	1.694	0.000	0.006	0.000	0.062	0.000	0.000	2.221					0.2353380	235.34	
12				5.42		0.459	1.694	0.000	0.007	0.000	0.069	0.000	0.000	2.229	Total homes	2475.000					
13				5.42		0.459	1.694	0.000	0.005	0.000	0.048	0.000	0.000	2.206	Per home	**6.854176**	MWh/year			Gas verbruik huidig wonin	
14				5.42		0.459	1.694	0.000	0.005	0.000	0.036	0.000	0.000	2.194		6854.176				1400.00	m3
15				5.42		0.459	1.694	0.000	0.005	0.000	0.030	0.000	0.000	2.188		205.625				49.24	GJ
16				5.42		0.459	1.694	0.000	0.005	0.000	0.049	0.000	0.000	2.207						**13.68**	MWh
17				5.42		0.459	1.694	0.000	0.007	0.000	0.071	0.000	0.000	2.230							
18				5.42		0.459	1.694	0.000	0.007	0.000	0.081	0.000	0.000	2.242						Koppelen naar data	
19				5.42		0.459	1.694	0.000	0.007	0.000	0.069	0.000	0.000	2.228						34960.00	MWh warmte
20				5.42		0.459	1.694	0.000	0.006	0.000	0.056	0.000	0.000	2.214						**19.26**	MWh warmtev
21				5.42		0.459	1.694	0.000	0.005	0.000	0.049	0.000	0.000	2.207						69.34	GJ warmtever
22				5.42		0.459	1.694	0.000	0.005	0.000	0.030	0.000	0.000	2.187						1971.63	m3 verbruik v
23				5.42		0.459	1.694	0.000	0.004	0.000	0.003	0.000	0.000	2.160							
24				5.42		0.459	1.694	0.000	0.004	0.000	0.014	0.000	0.000	2.171							
25				5.42		0.459	1.694	0.000	0.004	0.000	0.028	0.000	0.000	2.184							
26				5.42		0.459	1.694	0.000	0.003	0.000	0.052	0.000	0.000	2.208							
27				5.42		0.459	1.694	0.000	0.003	0.000	0.061	0.000	0.000	2.217							
28				5.42		0.459	1.694	0.000	0.003	0.000	0.051	0.000	0.000	2.207							
29				5.42		0.459	1.694	0.000	0.003	0.000	0.049	0.000	0.000	2.205							
30				5.42		0.459	1.694	0.000	0.003	0.000	0.051	0.000	0.000	2.207							
31				5.42		0.459	1.694	0.000	0.003	0.000	0.055	0.000	0.000	2.211							
32				5.42		0.459	1.694	0.000	0.004	0.000	0.017	0.000	0.000	2.174							
33				5.42		0.459	1.694	0.000	0.004	0.000	0.004	0.000	0.000	2.161							
34				5.42		0.459	1.694	0.000	0.005	0.000	0.042	0.000	0.000	2.200							
35				5.42		0.459	1.694	0.000	0.006	0.000	0.064	0.000	0.000	2.223							
36				5.42		0.459	1.694	0.000	0.007	0.000	0.072	0.000	0.000	2.231							
37				5.42		0.459	1.694	0.000	0.005	0.000	0.040	0.000	0.000	2.197							

Figure D-5 Calculation sheet of the total electricity usage.

E. Appendix CO_2 emissions

This appendix presents the calculation tool and the results of the performed calculations in Chapters 6.7 and 10. The CO_2 emissions are calculated with Microsoft Excel. A print screen of the sheet used is presented in Figure E-1. This sheet is for the first heat demand strategy.

The spreadsheet calculates as follows. The first columns provide the emission factors of electricity and biomass usage per kWh per year. The columns after presents the electricity and biomass usage per LTDH concept per year per home. This usage is multiplied with the emission factors, so the total CO_2 emission is calculated per year. The sum of the emission for each year is the total CO_2 emission per home. These are given in row 3, columns R till W.
Table E-1, Table E-2, and Table E-3 show how much CO_2 is emitted per 5 years in kilograms. This is divided over the electricity consumption and biomass consumption. The end of the table shows the total amount of CO_2 emitted in 30 years.

Table E-1 CO_2 emissions per household, using heat demand strategy 1.

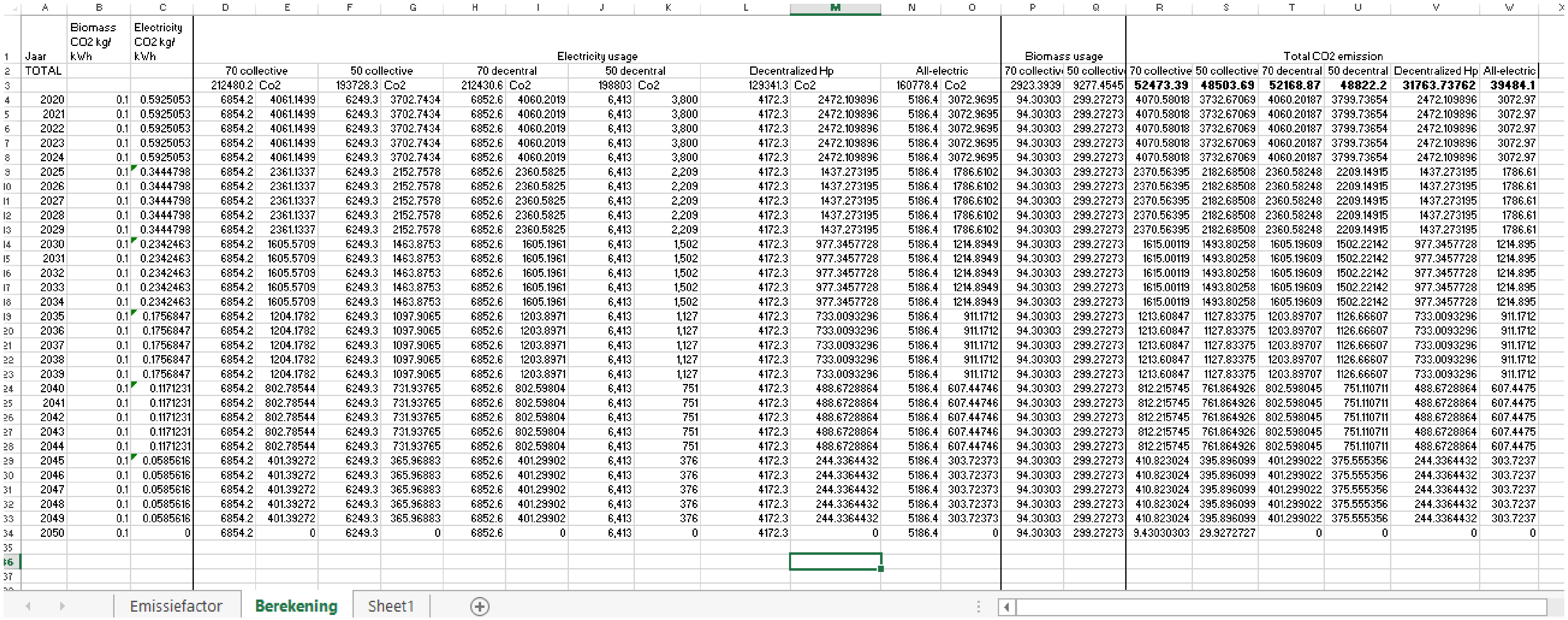
LTDH concept	1a		1b		2a		2b		3		Reference	
Year	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio
2020-2024 [kg]	20305.7	47.2	18513.7	149.6	20301.0	0.0	18998.7	0.0	12360.5	0.0	15364.8	0.0
2025-2029 [kg]	11805.7	47.2	10763.8	149.6	11802.9	0.0	11045.7	0.0	7186.4	0.0	8933.1	0.0
2030-2034 [kg]	8027.9	47.2	7319.4	149.6	8026.0	0.0	7511.1	0.0	4886.7	0.0	6074.5	0.0
2035-2039 [kg]	6020.9	47.2	5489.5	149.6	6019.5	0.0	5633.3	0.0	3665.0	0.0	4555.9	0.0
2040-2044 [kg]	4013.9	47.2	3659.7	149.6	4013.0	0.0	3755.6	0.0	2443.4	0.0	3037.2	0.0
2045-2049 [kg]	2007.0	47.2	1829.8	149.6	2006.5	0.0	1877.8	0.0	1221.7	0.0	1518.6	0.0
2050 [kg]	0.0	9.4	0.0	29.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (tons)	**52.47**		**48.50**		**52.17**		**48.82**		**31.76**		**39.48**	

Table E-2 CO_2 emissions per household, using heat demand strategy 2.

LTDH concept	1a		1b		2a		2b		3		Reference	
Year	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio
2020-2024 [kg]	20400.0	37.8	19049.0	155.2	20512.5	0.0	19709.7	0.0	13094.4	0.0	16661.2	0.0
2025-2029 [kg]	11860.4	37.8	11075.0	155.2	11925.9	0.0	11459.1	0.0	7613.0	0.0	9686.8	0.0
2030-2034 [kg]	8065.1	37.8	7531.0	155.2	8109.6	0.0	7792.2	0.0	5176.8	0.0	6587.0	0.0
2035-2039 [kg]	6048.8	37.8	5648.3	155.2	6082.2	0.0	5844.2	0.0	3882.6	0.0	4940.3	0.0
2040-2044 [kg]	4032.5	37.8	3765.5	155.2	4054.8	0.0	3896.1	0.0	2588.4	0.0	3293.5	0.0
2045-2049 [kg]	2016.3	37.8	1882.8	155.2	2027.4	0.0	1948.1	0.0	1294.2	0.0	1646.8	0.0
2050 [kg]	0.0	7.6	0.0	31.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (tons)	**52.66**		**49.91**		**52.71**		**50.65**		**33.65**		**42.82**	

Table E-3 CO_2 emissions per household, using heat demand strategy 3.

LTDH concept	**1a**		**1b**		**2a**		**2b**		**3**		**Reference**	
Year	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio	E	Bio
2020-2024 [kg]	17401.9	51.6	16427.2	154.7	17440.4	0.0	16904.2	0.0	12333.0	0.0	14741.5	0.0
2025-2029 [kg]	10117.4	51.6	9550.7	154.7	10139.8	0.0	9828.0	0.0	7170.3	0.0	8570.7	0.0
2030-2034 [kg]	6879.8	51.6	6494.5	154.7	6895.0	0.0	6683.0	0.0	4875.8	0.0	5828.0	0.0
2035-2039 [kg]	5159.9	51.6	4870.9	154.7	5171.3	0.0	5012.3	0.0	3656.9	0.0	4371.0	0.0
2040-2044 [kg]	3439.9	51.6	3247.2	154.7	3447.5	0.0	3341.5	0.0	2437.9	0.0	2914.0	0.0
2045-2049 [kg]	1720.0	51.6	1623.6	154.7	1723.8	0.0	1670.8	0.0	1219.0	0.0	1457.0	0.0
2050 [kg]	0.0	10.3	0.0	30.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (tons)	**45.04**		**43.17**		**44.82**		**43.44**		**31.69**		**37.88**	



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	Jaar	Biomass CO2 kg/ kWh	Electricity CO2 kg/ kWh	Electricity usage												Biomass usage		Total CO2 emission					
2	TOTAL			70 collective		50 collective		70 decentral		50 decentral		Decentralized Hp		All-electric		70 collectiv	50 collectiv	70 collective	50 collective	70 decentral	50 decentral	Decentralized Hp	All-electric
3				212480.2	Co2	193728.3	Co2	212430.6	Co2	198803	Co2	129341.3	Co2	160778.4	Co2	2923.3939	9277.4545	**52473.39**	**48503.69**	**52168.87**	**48822.2**	**31763.73762**	**39484.1**
4	2020	0.1	0.5925053	6854.2	4061.1499	6249.3	3702.7434	6852.6	4060.2019	6,413	3,800	4172.3	2472.109896	5186.4	3072.9695	94.30303	299.27273	4070.58018	3732.67069	4060.20187	3799.73654	2472.109896	3072.97
5	2021	0.1	0.5925053	6854.2	4061.1499	6249.3	3702.7434	6852.6	4060.2019	6,413	3,800	4172.3	2472.109896	5186.4	3072.9695	94.30303	299.27273	4070.58018	3732.67069	4060.20187	3799.73654	2472.109896	3072.97
6	2022	0.1	0.5925053	6854.2	4061.1499	6249.3	3702.7434	6852.6	4060.2019	6,413	3,800	4172.3	2472.109896	5186.4	3072.9695	94.30303	299.27273	4070.58018	3732.67069	4060.20187	3799.73654	2472.109896	3072.97
7	2023	0.1	0.5925053	6854.2	4061.1499	6249.3	3702.7434	6852.6	4060.2019	6,413	3,800	4172.3	2472.109896	5186.4	3072.9695	94.30303	299.27273	4070.58018	3732.67069	4060.20187	3799.73654	2472.109896	3072.97
8	2024	0.1	0.5925053	6854.2	4061.1499	6249.3	3702.7434	6852.6	4060.2019	6,413	3,800	4172.3	2472.109896	5186.4	3072.9695	94.30303	299.27273	4070.58018	3732.67069	4060.20187	3799.73654	2472.109896	3072.97
9	2025	0.1	0.3444798	6854.2	2361.1337	6249.3	2152.7578	6852.6	2360.5825	6,413	2,209	4172.3	1437.273195	5186.4	1786.6102	94.30303	299.27273	2370.56395	2182.68508	2360.58248	2209.14915	1437.273195	1786.61
10	2026	0.1	0.3444798	6854.2	2361.1337	6249.3	2152.7578	6852.6	2360.5825	6,413	2,209	4172.3	1437.273195	5186.4	1786.6102	94.30303	299.27273	2370.56395	2182.68508	2360.58248	2209.14915	1437.273195	1786.61
11	2027	0.1	0.3444798	6854.2	2361.1337	6249.3	2152.7578	6852.6	2360.5825	6,413	2,209	4172.3	1437.273195	5186.4	1786.6102	94.30303	299.27273	2370.56395	2182.68508	2360.58248	2209.14915	1437.273195	1786.61
12	2028	0.1	0.3444798	6854.2	2361.1337	6249.3	2152.7578	6852.6	2360.5825	6,413	2,209	4172.3	1437.273195	5186.4	1786.6102	94.30303	299.27273	2370.56395	2182.68508	2360.58248	2209.14915	1437.273195	1786.61
13	2029	0.1	0.3444798	6854.2	2361.1337	6249.3	2152.7578	6852.6	2360.5825	6,413	2,209	4172.3	1437.273195	5186.4	1786.6102	94.30303	299.27273	2370.56395	2182.68508	2360.58248	2209.14915	1437.273195	1786.61
14	2030	0.1	0.2342463	6854.2	1605.5709	6249.3	1463.8753	6852.6	1605.1961	6,413	1,502	4172.3	977.3457728	5186.4	1214.8949	94.30303	299.27273	1615.00119	1493.80258	1605.19609	1502.22142	977.3457728	1214.895
15	2031	0.1	0.2342463	6854.2	1605.5709	6249.3	1463.8753	6852.6	1605.1961	6,413	1,502	4172.3	977.3457728	5186.4	1214.8949	94.30303	299.27273	1615.00119	1493.80258	1605.19609	1502.22142	977.3457728	1214.895
16	2032	0.1	0.2342463	6854.2	1605.5709	6249.3	1463.8753	6852.6	1605.1961	6,413	1,502	4172.3	977.3457728	5186.4	1214.8949	94.30303	299.27273	1615.00119	1493.80258	1605.19609	1502.22142	977.3457728	1214.895
17	2033	0.1	0.2342463	6854.2	1605.5709	6249.3	1463.8753	6852.6	1605.1961	6,413	1,502	4172.3	977.3457728	5186.4	1214.8949	94.30303	299.27273	1615.00119	1493.80258	1605.19609	1502.22142	977.3457728	1214.895
18	2034	0.1	0.2342463	6854.2	1605.5709	6249.3	1463.8753	6852.6	1605.1961	6,413	1,502	4172.3	977.3457728	5186.4	1214.8949	94.30303	299.27273	1615.00119	1493.80258	1605.19609	1502.22142	977.3457728	1214.895
19	2035	0.1	0.1756847	6854.2	1204.1782	6249.3	1097.9065	6852.6	1203.8971	6,413	1,127	4172.3	733.0093296	5186.4	911.1712	94.30303	299.27273	1213.60847	1127.83375	1203.89707	1126.66607	733.0093296	911.1712
20	2036	0.1	0.1756847	6854.2	1204.1782	6249.3	1097.9065	6852.6	1203.8971	6,413	1,127	4172.3	733.0093296	5186.4	911.1712	94.30303	299.27273	1213.60847	1127.83375	1203.89707	1126.66607	733.0093296	911.1712
21	2037	0.1	0.1756847	6854.2	1204.1782	6249.3	1097.9065	6852.6	1203.8971	6,413	1,127	4172.3	733.0093296	5186.4	911.1712	94.30303	299.27273	1213.60847	1127.83375	1203.89707	1126.66607	733.0093296	911.1712
22	2038	0.1	0.1756847	6854.2	1204.1782	6249.3	1097.9065	6852.6	1203.8971	6,413	1,127	4172.3	733.0093296	5186.4	911.1712	94.30303	299.27273	1213.60847	1127.83375	1203.89707	1126.66607	733.0093296	911.1712
23	2039	0.1	0.1756847	6854.2	1204.1782	6249.3	1097.9065	6852.6	1203.8971	6,413	1,127	4172.3	733.0093296	5186.4	911.1712	94.30303	299.27273	1213.60847	1127.83375	1203.89707	1126.66607	733.0093296	911.1712
24	2040	0.1	0.1171231	6854.2	802.78544	6249.3	731.93765	6852.6	802.59804	6,413	751	4172.3	488.6728864	5186.4	607.44746	94.30303	299.27273	812.215745	761.864926	802.598045	751.110711	488.6728864	607.4475
25	2041	0.1	0.1171231	6854.2	802.78544	6249.3	731.93765	6852.6	802.59804	6,413	751	4172.3	488.6728864	5186.4	607.44746	94.30303	299.27273	812.215745	761.864926	802.598045	751.110711	488.6728864	607.4475
26	2042	0.1	0.1171231	6854.2	802.78544	6249.3	731.93765	6852.6	802.59804	6,413	751	4172.3	488.6728864	5186.4	607.44746	94.30303	299.27273	812.215745	761.864926	802.598045	751.110711	488.6728864	607.4475
27	2043	0.1	0.1171231	6854.2	802.78544	6249.3	731.93765	6852.6	802.59804	6,413	751	4172.3	488.6728864	5186.4	607.44746	94.30303	299.27273	812.215745	761.864926	802.598045	751.110711	488.6728864	607.4475
28	2044	0.1	0.1171231	6854.2	802.78544	6249.3	731.93765	6852.6	802.59804	6,413	751	4172.3	488.6728864	5186.4	607.44746	94.30303	299.27273	812.215745	761.864926	802.598045	751.110711	488.6728864	607.4475
29	2045	0.1	0.0585616	6854.2	401.39272	6249.3	365.96883	6852.6	401.29902	6,413	376	4172.3	244.3364432	5186.4	303.72373	94.30303	299.27273	410.823024	395.896099	401.299022	375.555356	244.3364432	303.7237
30	2046	0.1	0.0585616	6854.2	401.39272	6249.3	365.96883	6852.6	401.29902	6,413	376	4172.3	244.3364432	5186.4	303.72373	94.30303	299.27273	410.823024	395.896099	401.299022	375.555356	244.3364432	303.7237
31	2047	0.1	0.0585616	6854.2	401.39272	6249.3	365.96883	6852.6	401.29902	6,413	376	4172.3	244.3364432	5186.4	303.72373	94.30303	299.27273	410.823024	395.896099	401.299022	375.555356	244.3364432	303.7237
32	2048	0.1	0.0585616	6854.2	401.39272	6249.3	365.96883	6852.6	401.29902	6,413	376	4172.3	244.3364432	5186.4	303.72373	94.30303	299.27273	410.823024	395.896099	401.299022	375.555356	244.3364432	303.7237
33	2049	0.1	0.0585616	6854.2	401.39272	6249.3	365.96883	6852.6	401.29902	6,413	376	4172.3	244.3364432	5186.4	303.72373	94.30303	299.27273	410.823024	395.896099	401.299022	375.555356	244.3364432	303.7237
34	2050	0.1	0	6854.2	0	6249.3	0	6852.6	0	6,413	0	4172.3	0	5186.4	0	94.30303	299.27273	9.43030303	29.9272727	0	0	0	0

Figure E-1 Spreadsheet of the CO_2 emissions calculations. This sheet is for the first heat demand strategy.

F. Appendix LCOE

This appendix presents the calculation tool and the results of the performed calculations in Chapters 6.8 and 10.

The LCOE is calculated with Microsoft Excel. A print screen of the LCOE calculation sheet of LTDH concept 1a with heat demand strategy 1 is shown in Figure F-1.

The sheet works as follows. The investment costs (It) are given in the first columns. Column C shows the price of an equipment per unit. Column D shows how many units are required for the equipment. The total investment costs per equipment are given in Column E. The maintenance costs (Mt) are given in column G. The interest rate (r), the required heat (Ht), and the fuel costs (Ft) heat are given in columns I, K, and L. The price of electricity per used kWh (cell I8) and biomass (cell I9) is multiplied with the used electricity and biomass throughout a year for the total network to determine the Ft. With this information, the LCOE can be calculated. This is done for every year. In cell O33 is the LCOE given.

Table F-1 until Table F-10 shows the investment costs, operational costs per year and costs of fuel per year for each LTDH concept. This is done for each heat demand strategy.

Table F-1 Investment costs for heat demand strategy 1

LTDH concept	LTGH source	Collective heat pump	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	8,400,000	1,355,000	375,000	48,000	4,083,750	0	0	6,330,000	7,782,038
1b: 50 collective	8,400,000	1,285,000	750,000	48,000	4,083,750	0	3,712,500	8,925,000	10,800,050
2a: 70 decentral	8,400,000	1,355,000	375,000	48,000	4,083,750	4,455,000	0	786,000	7,047,143
2b: 50 decentral	8,400,000	1,285,000	750,000	48,000	4,083,750	4,455,000	3,712,500	1,164,000	9,968,475
Decentralized heat pumps	8,400,000	0	375,000	48,000	4,083,750	0	7,425,000	0	10,272,046
Reference	0	0	0	0	0	6,187,500	19,305,000	0	0

Table F-2 Fuel price for heat demand strategy 1.

LTDH concept	1a: 70 collective	1b: 50 collective	2a: 70 decentral	2b: 50 decentral	3: Decentral heat pumps	Reference
Electricity	3,053,457	2,783,930	3,053,012	2,856,992	1,859,072	2,310,363
Biomass	9,320	29,640	0	0	0	0

Table F-3 Maintenance for heat demand strategy 1.

LTDH concept	LTGH source	Heat pumps	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	185,000	27,100	7,500	480	0	0	0	217,860	155,641
1b: 50 collective	185,000	25,700	15,000	480	0	0	37,125	356,670	216,000
2a: 70 decentral	185,000	27,100	7,500	480	0	0	0	15,720	140,943
2b: 50 decentral	185,000	25,700	15,000	480	0	0	37,125	23,280	199,370
Decentralized heat pumps	185,000	0	15,000	480	0	0	148,500	0	205,441
Reference	0	0	0	0	0	123,750	772,200	0	0

Table F-4 Investment costs for heat demand strategy 2

LTDH concept	LTGH source	Heat pumps	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	8,400,000	1,355,000	375,000	48,000	4,083,750	0	0	4,512,000	7,515,157
1b: 50 collective	8,400,000	1,285,000	750,000	48,000	4,083,750	0	3,712,500	7,260,000	9,452,891
2a: 70 decentral	8,400,000	1,355,000	375,000	48,000	4,083,750	4,455,000	0	592,000	6,957,562
2b: 50 decentral	8,400,000	1,285,000	750,000	48,000	4,083,750	4,455,000	3,712,500	966,000	8,813,520
Decentralized heat pumps	8,400,000	0	750,000	48,000	4,083,750	0	7,425,000	0	10,123,996
Reference	0	0	0	0	0	6,187,500	19,305,000	0	0

Table F-5 Fuel costs for heat demand strategy 2

LTDH concept	1a: 70 collective	1b: 50 collective	2a: 70 decentral	2b: 50 decentral	3: Decentral heat pumps	Reference
Electricity	3,067,713	2,864,565	3,084,642	2,963,912	1,969,110	2,505,492
Biomass	7,480	30,720	0	0	0	0

Table F-6 Maintenance costs for heat demand strategy 2

LTDH concept	LTGH source	Heat pumps	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	185,000	27,100	7,500	480	0	0	0	157,800	150,303
1b: 50 collective	185,000	25,700	15,000	480	0	0	37,125	309,960	189,060
2a: 70 decentral	185,000	27,100	7,500	480	0	0	0	11,840	139,151
2b: 50 decentral	185,000	25,700	15,000	480	0	0	37,125	19,320	176,270
Decentralized heat pumps	185,000	0	15,000	480	0	0	148,500	0	202,480
Reference	0	0	0	0	0	123,750	772,200	0	0

For the 3rd heat demand strategy, the thermal insulation of the buildings is improved. The used numbers in the calculation for the LCOE is provided in Table F-7

Table F-7 Investment costs of thermal insulation improvements.

	Price per m2	Surface of one home	Number of homes	Total costs
Low-rise building	82	120	1400	13,776,000
High-rise building	72	80	1500	8,640,000

Table F-8 Investment costs for heat demand strategy 3.

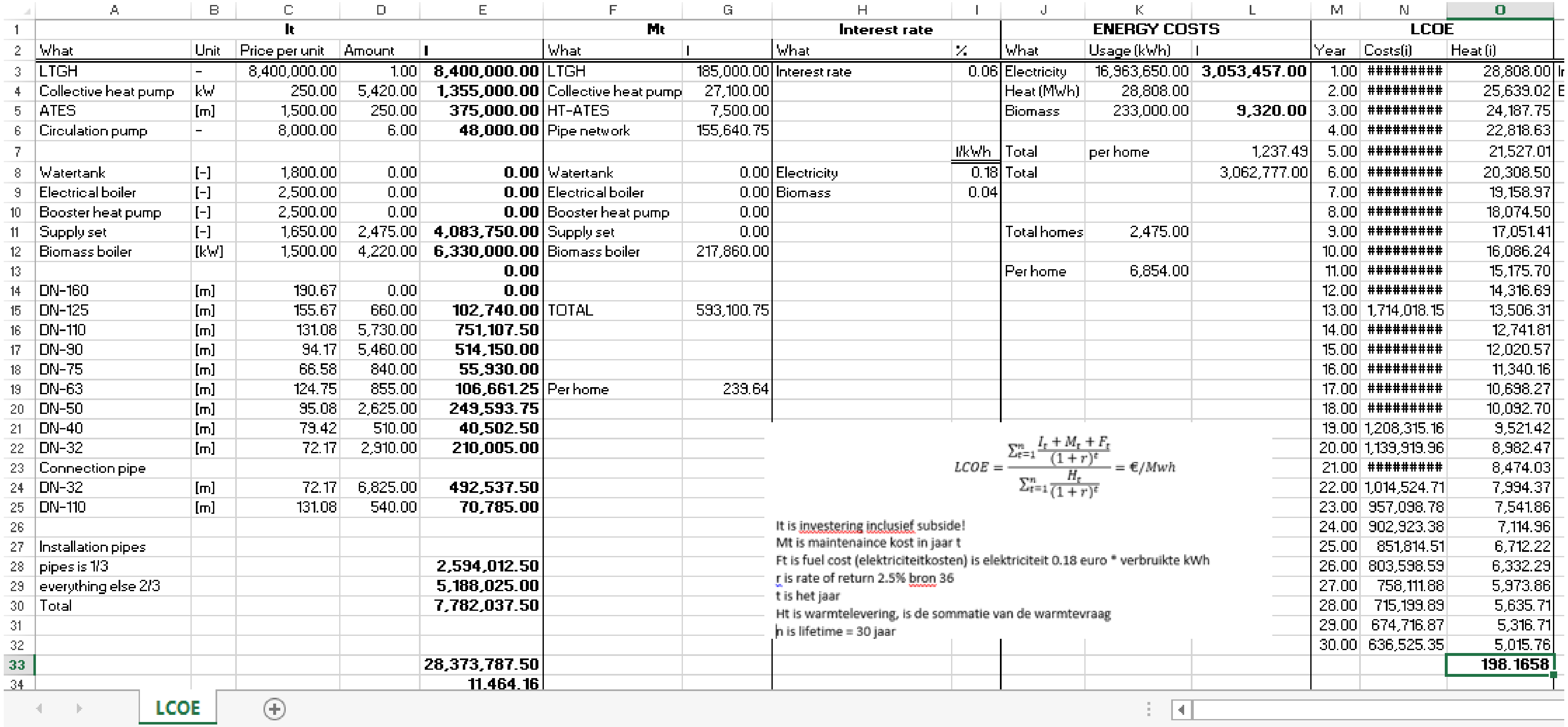
LTDH concept	LTGH source	Heat pumps	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	8,400,000	1,355,000	375,000	56,000	4,785,000	0	0	6,900,000	8,737,635
1b: 50 collective	8,400,000	1,285,000	750,000	56,000	4,785,000	0	4,350,000	9,600,000	10,868,203
2a: 70 decentral	8,400,000	1,355,000	375,000	56,000	4,785,000	5,220,000	0	880,000	7,521,674
2b: 50 decentral	8,400,000	1,285,000	750,000	56,000	4,785,000	5,220,000	4,350,000	1,240,000	9,327,132
Decentralized heat pumps	8,400,000	0	750,000	56,000	4,785,000	0	8,700,000	0	11,110,936
Reference	0	0	0	0	0	7,250,000	22,620,000	0	0

Table F-9 Fuel costs for heat demand strategy 3.

LTDH concept	1a: 70 collective	1b: 50 collective	2a: 70 decentral	2b: 50 decentral	3: Decentral heat pumps	Reference
Electricity	3,066,228	2,894,490	3,073,014	2,978,532	2,173,086	2,597,472
Biomass	11,960	35,880	0	0	0	0

Table F-10 Maintenance costs for heat demand strategy 3.

LTDH concept	LTGH source	Heat pumps	ATES	Circulation pump	Supply set	Water tank	BHP	Heaters / biomass	Network pipes
1a: 70 collective	185,000	27,100	7,500	560	0	0	0	242,880	174,753
1b: 50 collective	185,000	25,700	15,000	560	0	0	43,500	395,640	217,364
2a: 70 decentral	185,000	27,100	7,500	560	0	0	0	17,600	150,433
2b: 50 decentral	185,000	25,700	15,000	560	0	0	43,500	24,800	186,543
Decentralized heat pumps	185,000	0	15,000	560	0	0	174,000	0	222,219
Reference	0	0	0	0	0	145,000	904,800	0	0



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**It**					**Mt**		**Interest rate**		**ENERGY COSTS**			**LCOE**		
2	What	Unit	Price per unit	Amount	I	What	I	What	%	What	Usage (kWh)	I	Year	Costs(i)	Heat (i)
3	LTGH	-	8,400,000.00	1.00	**8,400,000.00**	LTGH	185,000.00	Interest rate	0.06	Electricity	16,963,650.00	**3,053,457.00**	1.00	#########	28,808.00
4	Collective heat pump	kW	250.00	5,420.00	**1,355,000.00**	Collective heat pump	27,100.00			Heat (MWh)	28,808.00		2.00	#########	25,639.02
5	ATES	[m]	1,500.00	250.00	**375,000.00**	HT-ATES	7,500.00			Biomass	233,000.00	**9,320.00**	3.00	#########	24,187.75
6	Circulation pump	-	8,000.00	6.00	**48,000.00**	Pipe network	155,640.75						4.00	#########	22,818.63
7									I/kWh	Total	per home	1,237.49	5.00	#########	21,527.01
8	Watertank	[-]	1,800.00	0.00	**0.00**	Watertank	0.00	Electricity	0.18	Total		3,062,777.00	6.00	#########	20,308.50
9	Electrical boiler	[-]	2,500.00	0.00	**0.00**	Electrical boiler	0.00	Biomass	0.04				7.00	#########	19,158.97
10	Booster heat pump	[-]	2,500.00	0.00	**0.00**	Booster heat pump	0.00						8.00	#########	18,074.50
11	Supply set	[-]	1,650.00	2,475.00	**4,083,750.00**	Supply set	0.00			Total homes	2,475.00		9.00	#########	17,051.41
12	Biomass boiler	[kW]	1,500.00	4,220.00	**6,330,000.00**	Biomass boiler	217,860.00						10.00	#########	16,086.24
13					**0.00**					Per home	6,854.00		11.00	#########	15,175.70
14	DN-160	[m]	190.67	0.00	**0.00**								12.00	#########	14,316.69
15	DN-125	[m]	155.67	660.00	**102,740.00**	TOTAL	593,100.75						13.00	1,714,018.15	13,506.31
16	DN-110	[m]	131.08	5,730.00	**751,107.50**								14.00	#########	12,741.81
17	DN-90	[m]	94.17	5,460.00	**514,150.00**								15.00	#########	12,020.57
18	DN-75	[m]	66.58	840.00	**55,930.00**								16.00	#########	11,340.16
19	DN-63	[m]	124.75	855.00	**106,661.25**	Per home	239.64						17.00	#########	10,698.27
20	DN-50	[m]	95.08	2,625.00	**249,593.75**								18.00	#########	10,092.70
21	DN-40	[m]	79.42	510.00	**40,502.50**								19.00	1,208,315.16	9,521.42
22	DN-32	[m]	72.17	2,910.00	**210,005.00**								20.00	1,139,919.96	8,982.47
23	Connection pipe												21.00	#########	8,474.03
24	DN-32	[m]	72.17	6,825.00	**492,537.50**								22.00	1,014,524.71	7,994.37
25	DN-110	[m]	131.08	540.00	**70,785.00**								23.00	957,098.78	7,541.86
26													24.00	902,923.38	7,114.96
27	Installation pipes												25.00	851,814.51	6,712.22
28	pipes is 1/3				**2,594,012.50**								26.00	803,598.59	6,332.29
29	everything else 2/3				**5,188,025.00**								27.00	758,111.88	5,973.86
30	Total				**7,782,037.50**								28.00	715,199.89	5,635.71
31													29.00	674,716.87	5,316.71
32													30.00	636,525.35	5,015.76
33					**28,373,787.50**										**198.1658**
34					**11,464.16**										

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}} = €/Mwh$$

It is investering inclusief subside!
Mt is maintenaince kost in jaar t
Ft is fuel cost (elektriciteitkosten) is elektriciteit 0.18 euro * verbruikte kWh
r is rate of return 2.5% bron 36
t is het jaar
Ht is warmtelevering, is de sommatie van de warmtevraag
n is lifetime = 30 jaar

Figure F-1 Print screen of the sheet for the LCOE calculation of LTDH concept 1a, using heat demand strategy 1.