Integration of decentralized solar collectors in Dutch district heating grids

Rosanne van Miltenburg
Master Thesis Rosanne van Miltenburg

Report number: P&E-2712

Supervisor TU Delft: Dr. Ir. C.A. Infante Ferreira
Supervisor Greenvis B.V.: Ir. E. van Vliet

Process & Energy Laboratory, Energy Technology
Mechanical, Maritime and Materials Engineering Faculty
Delft University of Technology
Preface

I would like to thank my colleagues at Greennis for their help and feedback during my research. In addition to their expertise on district heating they could always help me stay motivated. More importantly, I want to thank Edwin van Vliet for his guidance.

Carlos Infante Ferreira helped me a lot whit all the aspects to come to this document. Week after week he reflected on my work and taught me the important aspects of scientific writing. Therefore special thanks to him.

I would also like to thank Peter de Keijzer. Not only for my introduction to district heating but also for reading and reflecting on this report several times.

Finally, I would like to thank everybody who listened to my complaints and struggles during this project and my previous study years. Without the support of my family, Robin and my friends I could never have achieved this.
Summary

Most of the heat in Dutch district heating networks is produced by fossil fuels. In this study the limits and most promising configurations for the feed-in of solar heat from consumers have been investigated. The results have been evaluated in terms of total annual solar gain, solar gain per collector area, solar fraction, CO$_2$ reduction and costs.

To make sure the results are applicable to more than one network, several Dutch district heating networks and building types have been used to design a network model in Matlab and Simulink. In order to reach high solar fractions, the integration of storage is analysed as well.

Three test networks have been used to show the influence of different building types. They contain 50 to 150 consumers which can all be adapted for different years of construction. These test networks have been chosen in such a way that their absolute heat losses are similar. However, the total demand varies due to the different types and amount of consumers.

The simulations show that the economically best scenario is found for 400 m$^2$ collector area placed at one apartment building and a 50 m$^3$ buffer. In this scenario 22% of the annual heat demand of 150 consumers is replaced by solar heat. Based on the current consumer heat price the pay back time of the solar system is 14 years which seems promising. More importantly it can be avoided that 500 GJ of heat is produced in fossil fuelled kettles, especially when combined with smart buffering.
# Table of Contents

1. Introduction .............................................................................................................. 6

2. State of the art .......................................................................................................... 8
   2.1 Literature overview ............................................................................................... 8
   2.2 Supply methods .................................................................................................... 10
      2.2.1 Supply methods in the Netherlands ............................................................... 10
      2.2.2 Other supply methods .................................................................................. 11
      2.2.3 Solar district heating systems ....................................................................... 12
      2.2.4 CO₂ emission ................................................................................................. 13

3. District heating grids ............................................................................................... 14
   3.1 Introduction .......................................................................................................... 14
   3.2 The network .......................................................................................................... 15
   3.3 The consumer ........................................................................................................ 15
      3.3.1 Domestic space heating demand ................................................................... 15
      3.3.2 Domestic hot water demand ......................................................................... 16
   3.4 Heat demand curve ............................................................................................... 16
   3.5 Control .................................................................................................................. 18
      3.5.1 Consumer substation ..................................................................................... 18
      3.5.2 Network control ............................................................................................ 18
      3.5.3 Pumping power ............................................................................................. 19
   3.6 Thermal solar collectors ....................................................................................... 20
      3.6.1 Solar energy in the Netherlands .................................................................... 20
      3.6.2 Collector types ............................................................................................... 21
      3.6.3 Collector yield ............................................................................................... 22
      3.6.4 Feed in ............................................................................................................ 23
      3.6.5 Substation ...................................................................................................... 24
   3.7 Storage .................................................................................................................. 25
      3.7.1 Storage in the Netherlands ......................................................................... 25
      3.7.2 Water tanks .................................................................................................. 26
      3.7.3 Aquifer Thermal Energy Storage (ATES) ..................................................... 28

4. Model components ................................................................................................... 30
   4.1 Relevant characteristics ....................................................................................... 30
   4.2 Model flow chart .................................................................................................. 31
   4.3 Pipe model ............................................................................................................ 33
      4.3.1 Heat losses ..................................................................................................... 33
      4.3.2 Pressure loss ................................................................................................ 35
4.3.3 Validation ........................................................................................................... 36
4.4 Consumer ............................................................................................................ 40
  4.4.1 Heat demand .................................................................................................. 40
  4.4.2 Influence on network ..................................................................................... 43
  4.4.3 Calibration and discussion ........................................................................... 44
4.5 Circulation pump .................................................................................................. 48
  4.5.1 Equations ..................................................................................................... 48
  4.5.2 Validation .................................................................................................... 50
4.6 Solar collector model ........................................................................................... 50
  4.6.1 Equations ..................................................................................................... 51
  4.6.2 Feed in and control ....................................................................................... 51
  4.6.3 Discussion ..................................................................................................... 52
4.7 Storage model ...................................................................................................... 53
  4.7.1 Equations ..................................................................................................... 53
  4.7.2 Validation .................................................................................................... 54
5. Method and model characteristics ........................................................................ 54
  5.1 Test networks .................................................................................................... 54
  5.2 Simulations ....................................................................................................... 57
  5.3 Network behaviour at the substation ............................................................... 57
  5.4 Data processing ................................................................................................. 58
  5.5 Effects on the pump .......................................................................................... 59
  5.6 Effects on network ............................................................................................ 60
  5.7 Storage efficiency ............................................................................................. 62
6. Results ..................................................................................................................... 63
  6.1 Collector type ..................................................................................................... 63
  6.2 Collector area ..................................................................................................... 63
  6.3 Storage capacity ............................................................................................... 65
  6.4 CO₂ emissions ................................................................................................... 67
  6.5 Economic evaluation ........................................................................................ 67
7. Conclusion .............................................................................................................. 72
8. Recommendations .................................................................................................. 74
9. Bibliography .......................................................................................................... 76
10. Nomenclature ........................................................................................................ 79
l. Simulink model ...................................................................................................... 81
  a. The initial constants ......................................................................................... 81
  b. The consumer ................................................................................................... 81
1. Introduction

Each year 1324 PJ of primary energy is used for heating purposes in the Netherlands. This accounts for 38% of the total annual energy consumption, more than for electricity. Only 2.7% of the useful heat is produced from renewable sources like biomass, solar-, geothermal heat or waste incineration (Nationaal Expertisecentrum Warmte, 2013). For the built environment, the heat is generally provided by individual boilers fuelled with natural gas, causing the emission of greenhouse gases. District heating is a more sustainable solution with its ability to spread industrial waste heat. However, most of the distributed heat is still being produced from fossil fuels as well, either directly or indirectly.

Solar collector systems are a proven alternative to save on domestic hot water heating while exploiting a renewable resource. However, most systems are designed to be combined with a natural gas boiler, which is not an option for the 5% of the Dutch households which have a district heating connection. If customers are given the possibility to deliver excess heat to their heating grid, they are given more freedom to choose their own heat source while using the advantages of district heating. At the same time the grid operator is meeting the customers’ demand and increasing the share of renewable energy without investing in a supply unit.

Solar thermal energy is already fed to district heating grids in several countries, mainly from central solar plants. Large areas of solar collectors are not always available in densely populated areas. In that case solar collectors should be installed at the roofs of buildings and their heat will be fed into the grid from multiple locations. There are many possibilities to connect these buildings to a grid, which often include possibilities to use the solar thermal heat locally for domestic hot water as well.

This study will focus on the potential of decentralized solar collectors in Dutch district heating networks (DHN). Previous studies have confirmed there is a potential, but focus on small contributions to the total heat demand (Brand et al. 2014) (Buoro et al, 2014) (Dvarioniene et al. 2013). This study will investigate the optimal contribution that can be delivered to an existing heating network from such solar collectors on buildings. Solar heat is mainly available in summer, when the heat demand is low, so in order to reach high solar fractions the integration of storage is analysed as well.

The focus in this study is on the district heating network itself, which is built to last for decades. Technologies for heat production and storage are constantly being improved, the most common types of solar collectors have been used for this study. Future improvements, which probably will lead to higher efficiencies, will improve the results of this study as well.

In order to make sure the results are applicable to more than one network, the characteristics of several Dutch DHN have been used to design a network model using Matlab and Simulink. This model is used to analyse the impact of the decentral sources and investigate the limits and most
promising configurations. The results will be evaluated in terms of total annual solar gain, solar gain per collector area, solar fraction, CO₂ emission reduction and costs.

The central question in this report is: *To what extent can consumers with solar collectors supply heat to a district heating network and how should they be integrated to avoid the most fossil fuel consumption without increasing the heat price?*

Figure 1-1 shows the different phases in the study and their location in the report. This report starts with a summary of recent studies on (solar) district heating networks, the current state of the art that has lead to the previously mentioned research question. Chapter 3 will answer the sub question: “What are the relevant characteristics of a Dutch district heating network?” It will describe the main consumer types, their demand and the network they are connected to. The next section discusses the types of solar collectors and how they could be integrated in DHN’s. The last section of chapter 3 gives an overview of storage methods and recent implementations in the Netherlands. After discussing the components, the relevant corresponding equations and assumptions needed to simulate them are described in chapter 4. The model is divided into modules for the consumer, the pipes, the pump, the solar collector and storage. Chapter 5 discusses the complete network where those components are combined. The network designed to answer the central question is introduced here. Finally, in chapter 6, the results for the simulated scenarios are discussed. In this chapter the maximum share of solar energy with and without buffering is determined and evaluated in terms of CO₂ emission reduction and costs.

![Figure 1-1: Research components and their location in the report](image-url)
2. State of the art

District heating is not a new technology, the first grids date back more than 100 years. There have been large-scale solar thermal systems connected to district heating networks for over 40 years. Nowadays, there are over 170 solar systems across Europe of which 60 with a rated thermal output of more than 1 MW. The solar thermal systems are situated either centrally at heating plants or decentrally at suitable locations. They are often combined with large seasonal heat storage (EnEff:Wärme, 2015).

Despite its long history, district heating is still being studied in several countries. In the past ten years the amount of scientific publications concerning the topic has tripled, with a record of over 4800 publications in 2015. This chapter starts with a short summary of recent studies concerning district heating. Then, in more detail, the impact and potential of solar thermal energy is discussed. Finally, the remaining questions which have lead to the research question are introduced. In the second half of the chapter the Dutch heat supply methods, their effects in terms of CO₂ emission and some of their alternatives are discussed.

2.1 Literature overview

Many of the authors focus on the role district heat could have in the future energy system. This has been done mainly for northern European countries (Lund et al. 2014) (Dalla Rosa, 2012) (Connolly et al. 2014). They predict district heating infrastructures have an important role to play in the task of increasing energy efficiency. However, in order to fulfil this role, the current heating grids must undergo some radical changes. According to the Heat Roadmap Europe (Connolly et al., 2014), an EU energy scenario with a focus on including district heating grids as part of the energy system, the future district heating systems should be able to meet the challenge of more energy efficient buildings and should be an integrated part of smart energy systems with an optimal synergy between electricity, gas and thermal grids.

Lund et al. (2014) sort and define such requirements for what they call 4th generation district heating (4GDH). Figure 2-1 shows the characteristics of the 4 generations of DHN they identify. Their paper defines the concept of smart thermal grids as a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling producing units including individual contributions from the connected buildings. Their focus is on integration and efficient use of potential future renewable energy sources as well as the operation of a grid structure allowing for distributed generation, which may involve interaction with consumers. The major challenge they predict is the utilization of low-temperature heat sources.
Figure 2-1: Development of district heating grids over time. Currently most DHN operate below 100°C and distribute heat from central sources. The 4GDH has a lower operating temperature, multiple decentral sources and interacts with the electricity grid (Lund et al. 2014).

Other authors focus on the potential or performance of a certain district, for instance in Canada (Sibbitt et al. 2012) and Asian countries (Chung et al. 1998), (Fang et al. 2015). Buoro et al. (2014) found that a distributed energy supply system performed the best for a certain industrial area. They studied the combination of a solar thermal plant with long term heat storage, a set of CHP’s and conventional components and evaluated them from an economic point of view. The amount of research and projects shows the widespread interest on the subject and, as they show the success of networks like that of the Drake Landing Solar Community in Canada (97% solar fraction, (Sibbitt et al. 2012)), is still increasing.

Brand et al. (2014), Lennermo et al. (2014) and Hassine and Eicker (2013) have studied the impact of solar thermal energy on an existing network. Brand et al. look at the changes in temperature and velocity in the pipelines of prosumers, consumers who also supply heat back to the grid. Hassine and Eicker and Lennermo et al. focus on the connection and location of the heat sources.
Brand simulates a case study with 10% of the heat demand fulfilled by local solar collectors, aggregated as 5 different solar heating systems. Furthermore, the model includes a fictitious heat plant and two heat pumps. By analysing the supply temperature, flow rate and differential pressure at different distances from the prosumers the pipe dimensions were determined. In a dynamic simulation the temperature in four nodes was studied. The simulations show that, since the supply temperature decreases due to the incorporation of solar heat, the increasing velocity is the dimensioning factor. The dynamic simulation shows temperature fronts emerging when supplying to the net, a study by E.ON showed these temperature fronts won’t influence the lifetime of the pipelines (Brand et al. 2014).

Hassine & Eicker focuses on the structural load variations caused by solar collectors and the impact of spatial load distribution on the performance of the network. The evaluation is based on three performance indicators: primary energy factor, the relative importance of losses and the CO₂ emissions. More than 10% savings in heat loss and pumping distribution energy can be obtained, if consumers with high demand are situated closer to the power plant (Hassine & Eicker, 2013). This is a similar conclusion as by Dvarioniene et al., who show a solar collector system at two building roofs, close to the demand, is more useful than the integration of solar collectors on the roof of the biomass boiler house in the system (Dvarioniene et al. 2013).

Several questions still remain such as how much decentralized solar feed-in would be beneficial in existing district heating networks. Furthermore, pricing models still need to be conceived to be able to predict the overall expenditure for district heating systems with decentralized feed-in. Another remaining question is whether the solar thermal yields can compensate for the additional capital and operational expenditure required, such as for powering pumps.

2.2 Supply methods
There are several ways to heat water and since most DHN contain only one heat plant it is easy to determine the heat source. Common Dutch heat generation methods and some of their alternatives will be mentioned in this section. These will be followed by the yields and characteristics of the existing solar thermal plants in the Netherlands.

2.2.1 Supply methods in the Netherlands
The most common supply methods for the big Dutch DH networks are all gas fuelled. A distinction is made between combined heat and power (CHP) plants (45%) and gas fuelled electricity plants. Together they covered 77% of the heat production in 2009. In addition, there is one coal fuelled electricity plant covering 20% and a municipal solid waste plant covering the remaining 3%. Though the electricity plants are considered electricity demand driven, they are obliged to deliver enough heat. The supply of heat causes the plants electricity production to be less efficient. As a result, only a small amount of the heat provided can really be called waste heat (Schepers & Van Valkengoed, 2009).
In the past years a small part of the heat produced for the big heating networks has been produced from renewable sources like biomass plants and solar energy. These are more common for smaller DH networks which have a larger variety of supply methods like fossil based kettles or small scale CHP’s, biomass based power plants, heat pumps, geothermal or solar heat. In terms of environmental and societal benefits fossil based heat production is considered the least preferred supply method, unfortunately, due to the economic benefits this is still the most common method.

2.2.2 Other supply methods

An energy hierarchy based on environmental and societal benefits, ranking all available supply methods, has been created by Church (2016). As can be seen in Figure 2-2, the pollutants and other wasted energies are the most favourable heating method since a benefit is created out of a problem. The drawback here is that, in conventional urban planning, these streams are not located near populated areas, so the collection and distribution of the energy may become a costly exercise. These are followed by renewable resources, as they still require additional work to create or distribute the final energy product like the fabrication of thermal collectors or the transportation of biomass. The fourth category includes heat sources which can be manufactured from other renewable heat sources like a heat pump converting electricity.

![Figure 2-2: Energy hierarchy based on societal and environmental benefits (Church, 2016)](image-url)
2.2.3 Solar district heating systems

Since the 1970s large-scale solar thermal systems have been used to supply heat to a DHN (EnEff:Wärme, 2015). Most of these systems can be found in Scandinavia. When solar heat is used for district heating, supply side management is harder to achieve due to the fluctuating radiation. Additional heat sources or storage facilities are thus always needed.

Many configurations are possible when adding solar heat to a grid. In the Netherlands there is one neighbourhood designed to be heated from solar collectors in 1984. 96 row-houses in the village Beijum were equipped with solar collectors, low-temperature central heating and a large shared underground heat storage unit. With a total collector area of 2358 m\(^2\) and 23000 m\(^3\) of borehole heat storage an average of 540 MWh/year, 54% of the annual demand, was provided over the first ten years (Caddet Renewable Energy, 2000). A more recent project is the Zoneiland Almere, which can be seen in Figure 2-3. This solar plant contains 7000 m\(^2\) collectors providing 2708 MWh/year since 2010. It is connected to the primary grid which supplies over 2700 households, therefore there is more than enough heat demand so no storage is needed (Nuon, 2015).

![Figure 2-3: Zoneiland Almere, currently the biggest collector field connected to a Dutch district heating grid](tomei2014)

Though there are some more sustainable projects, there is still a lot of heat generated from fossil fuels in the Dutch heat demand driven power plants. This could be replaced by an energy source higher on the hierarchy. Though solar thermal energy is only part of the third category it is less location dependent compared to waste streams, especially when considering roof area as the target area.
2.2.4 CO₂ emission

The combustion of fuels leads to the emission of CO₂ and other greenhouse gasses. The amount of fuel needed to generate heat differs per supply method. According to the Dutch Milieubarometer, an online tool to determine the CO₂ footprint, district heat production causes 20 kg CO₂ per GJ on average (Stichting Stimular, 2015). A more detailed calculation of two gas fuelled Dutch district heating grids by De Keijzer (2016) gives higher emissions of 24.52 kg/GJ and 29.81 kg/GJ. However, due to the currently low electricity prices, an increasingly amount of heat is generated by peak supply boilers in stead of the CHP leading to higher emissions, for one of the big Dutch districts the current value is 34.81 kg/GJ (Gemeente Utrecht, 2016). In comparison, the emission of Dutch natural gas is 56 kg/GJ (van Harmelen & Koch, 2002).
3. District heating grids
This chapter gives a description of the most relevant characteristics of a Dutch district heating network, its purpose, typical operating conditions, typical consumer characteristics and other relevant characteristics.

3.1 Introduction
District heating and cooling systems are used to transfer heat from their sources to the consumer in urban areas. These sources can either be natural resources or resources that will be lost if they are not used. The heat is usually transported in pipelines containing pressurized water, which should be as short as possible to limit the expenses. Though district heating systems can clearly be separated into different components; supply units; distribution networks; substations and consumer substations, they are strongly influencing each other. In order to maintain the heat balance in the network, the suppliers must add the same amount of heat to the return flow as the consumers consume and account for the losses. In order to be useful for the consumer the heat must be at a certain minimum temperature. In addition, there are limits to the pressure and flow inside the pipelines.

There are about 80 000 district heating systems in North America, Europe, Russia, China, Korea and Japan. District cooling systems are less common, they appear in North America, Europe, the Middle East and the Far East (Frederiksen & Werner, 2013). The Netherlands currently counts 5 big district heating grids, with more than 20 000 consumers per grid, and more than 100 smaller grids (Schepers & Van Valkengoed, 2009).

![Figure 3-1 Schematic of a Dutch district heating network with three grid levels (De Keijzer, 2016)](image-url)
3.2 The network
Figure 3-1 shows a schematic of a Dutch district heating grid containing one supplier, which is the most common scenario in the Netherlands. The distribution network is hydraulically separated by heat transfer units. Depending on the size of the network, a system is generally separated into two or three grid levels, for each level the operating pressure and temperature level is different ranging from 1300 kPa and 140˚C in the network near the supplier (transportgrid) to 500 kPa and 70˚C closer to the consumer (secondary grid).

The consumer generally needs to be provided with a pressure difference of at least 30 kPa, a supply temperature of 70 to 100 degrees Celsius and a maximum flow speed of the supply water of 1.3 m/s. The network is designed in order to meet these specifications for each consumer (De Keijzer, 2016). The lower temperatures and the location near the consumer make the secondary grid the most suitable to feed-in solar heat. These operating conditions will be used in the rest of the chapters.

The water temperature in a district heating grid is adapted to the outside temperature when needed. Generally a consumer supply temperature of 70˚C is maintained, but when outside temperatures reach below 5˚C the supply can be heated up to 110˚C to make sure enough heat can be transported (De Keijzer, 2016).

3.3 The consumer
Consumers connected to heating grids are usually divided into two categories, small units like households and bigger units like utilities. The average annual heat demand for a Dutch household is 34 GJ including space heating and hot water (Milieu Centraal, 2015). Most users are connected to the grid with a maximum space heating demand of 7.5 kW and a domestic hot water demand of 30 kW. Since domestic hot water is never simultaneously used by every consumer the connecting grid dimension is adapted according to a simultaneity factor. Generally, around 250 consumers are hydraulically connected in a typical secondary grid.

3.3.1 Domestic space heating demand
The space heating demand per household depends strongly on the building type and year of construction. It varies between 6 GJ/year, for an apartment built after 2000, and 95 GJ/year for detached homes built before 1940. In 2006, about 17 percent of the Dutch homes had been built before 1940 and only 3.6 percent was built after 2000, the majority has been built between 1960 and 1980 (Folkert & van den Wijngaart, 2012). Table 3-1 shows the yearly heating demand for the most common Dutch building types for different years of construction. It can be seen that the impact of the year of construction is huge on the heat demand. Older buildings often demand
higher supply temperatures due to their heating system. In old Dutch city centres the supply temperature should thus be higher than in newly build districts.

Table 3-1: Heating demand per building type (Folkert & van den Wijngaart, 2012)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached home</td>
<td>79 GJ/year</td>
<td>48 GJ/year</td>
<td>27 GJ/year</td>
</tr>
<tr>
<td>Row house</td>
<td>40 GJ/year</td>
<td>24 GJ/year</td>
<td>12 GJ/year</td>
</tr>
<tr>
<td>Apartment</td>
<td>20 GJ/year</td>
<td>12 GJ/year</td>
<td>8.5 GJ/year</td>
</tr>
</tbody>
</table>

3.3.2 Domestic hot water demand
The average annual domestic hot water consumption is 4.3 GJ for apartments and 6.3 GJ for other building types (Folkert & van den Wijngaart, 2012). Milieu Centraal estimates it slightly higher at 7 GJ on average.

3.4 Heat demand curve
The Dutch climate is characterized by an average of 2800 degree days which indicates space heating is needed during a part of the year. The annual heat load duration curve shows a low and steady domestic hot water demand in summer and some high peaks during the winter months, as can be seen in Figure 3-2. The annual curve mainly depends on the outside temperature. In addition, solar irradiation and wind have their influence which makes it hard to accurately predict the heating demand.

![Figure 3-2: Typical Dutch annual load curve, the peaks in winter are eight times higher than the summer load.](image)

The domestic hot water usage is even more unpredictable and different for each consumer. On average, as can be seen in Figure 3-3, there is a peak around 8.30 in the morning and there is fewer demand during the nightly hours. This figure shows the heat supplied to 55 000 buildings, both
domestic and utilities. An individual only uses hot water during short time spans, for instance to do the dishes, wash hands or take a shower, so the individual demand curve looks differently compared to the total demand curve for a heating grid. The two figures show that during a cold Wednesday, with an average temperature of -8.5 °C, the peak is less steep and the average demand is much higher compared to a summer Tuesday, where the average temperature was 22.3 °C.

![Figure 3-3: Daily load curves on Tuesday 7-2-2012 (l) and Wednesday 25-7-2012 (r) for 55000 consumers of various sizes (Eneco) (De Keijzer, 2016)](image)

Though this pattern is visible on most of the days, the relative height of the peaks differs from day to day. To show this, the daily loads for a few days of another grid, containing 420 small households, is shown in Figure 3-4. Though the peaks are similar to those in Figure 3-3, it can be seen that even for subsequent days the curve does not look the same. Especially during the weekend the profile differs as the peak is less steep and shifted.

![Figure 3-4: Daily load curves on week and weekend days in winter (l) and summer (r) for a heat transfer station supplying to 420 apartments (Nuon)](image)
3.5 Control
Four independent control systems generally manage a districts’ heat supply. These are:

- Heat supply control
- Flow control
- Differential pressure control
- Supply temperature control

The first two systems are located at the consumers’ substation (Figure 3-5) while the latter are located in the heat supply units operated by the heat provider.

3.5.1 Consumer substation

![Figure 3-5: Typical consumer substations with indirect (l) or direct (r) space heating](image)

There are various types of consumer substations available. Generally, the water in the grid is used directly for space heating, domestic hot water is always separated by a heat exchanger. The pressure difference between the supply and return pipes transports the water through the buildings’ heating system. Sometimes an extra heat exchanger separates the entire consumer installation from the grid, in this case the consumer substation must contain one or more pumps to transport the water to the different systems. At the consumer side the main control points are the tap openings, for domestic hot water use, and the thermostatic valves controlling the radiators. The flow control is situated in the consumer subsystem and its set point values are the required demand for space heating, and the required hot water temperature.

3.5.2 Network control
With the flow controlled in the consumer substations, the circulation pump in the grid only manages the differential pressure. The corresponding controller adjusts the variable pump speed to a value that fixes the pressure difference between the supply and return line to a certain value set for the
furthest substation (Frederiksen & Werner, 2013), as can be seen in Figure 3-6. There are some heating grids in the Netherlands where the primary and secondary grid are hydraulically coupled. In this case a valve is used, in stead of the pump, to control the flow and pressure level in the secondary grid.

Though the pressure difference might be sufficiently high, the water in the network can cool down too far before it reaches the last consumer. To avoid this, the supply temperature control opens an extra valve which causes a massflow towards the return network.

3.5.3 Pumping power
The pressure levels in a heating grid are maintained by several pumps. The required pumping power depends on the pressure drop and the mass flow in the network. However, since the pressure drop is proportional to the square of the mass flow, the electricity consumption at high and low flow rates shows large differences. Generally, the relative demand for electricity is around 0.5% of the heat delivery but this depends strongly on the topography of the grid (Frederiksen & Werner, 2013).
3.6 Thermal solar collectors
In order to find out to what extend consumers can supply solar heat to a network, additional components must be introduced. In this chapter available methods to capture, store and feed in solar heat within a district heating system will be described.

In order to predict the possible future collector yield into a Dutch district heating grid the most common collector types and their yields, the available roof area and the possible connections to the grid will be discussed in this chapter.

3.6.1 Solar energy in the Netherlands

![Figure 3-7: Global irradiation the Netherlands](image)

The Dutch climate varies throughout the year and is characterized by dark winters with only a quarter of the maximum solar irradiation, as can be seen in Figure 3-7. In order to achieve the highest solar gain the collectors’ surface should be directed perpendicularly to the sun. As most of the collectors are fixed on a roof, they must be located such that during the day the maximum amount of solar radiation can be converted into useful energy. At the northern hemisphere this means the collectors should face south (Sen, 2008).

The majority of the installed collector area in the Netherlands is part of small systems of up to 6 m². The average annual yield of a solar collector in the Netherlands has been 1.74 GJ/m² over the past five years (CBS, 2015), unfortunately there is no specification of the corresponding operating conditions. In order to collect enough solar energy to supply for the winter demand, the collectors would have to cover a larger area. In such cases the excess energy should be delivered to other households or a buffer during the summer.

For each Dutch building type the potential solar panel area has been estimated. Table 3-2 shows the average available area for the most common building types. The average varies between 13.9 and
The most common building type has an average available area of 32.5 m² (Lemmens et al. 2014). It is assumed that the area available for solar collectors will be equal to that for solar panels.

Table 3-2: Roof area suitable for solar panels per building type (Lemmens et al. 2014)

<table>
<thead>
<tr>
<th>Building type</th>
<th>Average available roof area per household [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached</td>
<td>61.7</td>
</tr>
<tr>
<td>Row</td>
<td>32.5</td>
</tr>
<tr>
<td>High flat</td>
<td>13.9</td>
</tr>
<tr>
<td>Apartment</td>
<td>24.8</td>
</tr>
</tbody>
</table>

3.6.2 Collector types

There are several methods to gain solar energy, solar collectors are used to absorb the sunlight by heating up a liquid flow. A solar collector is usually a heat conducting material covering a fluid which is circulated in order to transport the heat. The yield and operating temperatures depend on the type of collector. These can be concentrating or non-concentrating referring to the usage of mirrors or lenses to focus a large area of solar irradiation onto a smaller area. Non-concentrating is the common type for domestic use so only this technique will be explained. The non-concentrating collectors can be divided between the flat plate and evacuated tube type.

Figure 3-8: Flat plate solar collector (Solartribune, 2015)

Flat plate collectors are the most commonly applied type of solar collectors for domestic solar water and space heating applications. They are based on two principles as can be seen in Figure 3-8: a black base that absorbs the solar radiation and a glass lid to keep the heat in. The sun’s rays go through the air and glass cover to warm up the black metal plate which will heat the water. With the
heat in the water it can now be transported, the simplest method for this is used in a thermo-siphon system. Its operation is based on the rise of hot water which causes circulation in the system: the water in the collector rises to the top as the collector heats up and is pushed into a buffer tank. This hot water replaces some of the cold water in the tank by pushing it out of the bottom, into the collector. More advanced systems include a circulation pump and may have an additional second glazing layer to reduce the heat losses (Sen, 2008). Operating temperatures for flat plate collectors vary between 40°C and 80°C.

Evacuated tube collectors are constructed of a number of glass tubes, similar to fluorescent lamps, in which a vacuum is created during manufacturing. The absorber plate is a metal strip down the centre of this tube. The vacuum suppresses convective heat losses so higher temperatures can be achieved at the absorber plate compared to flat plate collectors.

### 3.6.3 Collector yield

The amount of radiation converted to thermal energy depends not only on the incident angle but also on other energy losses. Figure 3-9 shows the different losses, these are due to reflection and heat losses through radiation, convection and conduction.

![Type of losses (Sen, 2008)](image)
The collector efficiency is different for each collector type, so in order to compare different models standard test methods have been created.

3.6.4 Feed in

The efficiency of a solar collector depends on the collector temperature which, within a district heating network, depends on the feed in method. There are basically four possible feed in strategies: from return to supply (RS), from return to return (RR), from supply to supply (SS) or from supply to return (SR). Energetically we can easily eliminate the SR feed in, the other three, which are shown in Figure 3-10, have been compared by Hassine and Ecker (2013). Within these strategies there are several possibilities as well, solar collectors can be directly delivering to the grid or can be used to (pre)heat domestic hot water first.

![Figure 3-10: Different feed-in configurations (Lennermo et al. 2014)](image)

The RR-assisted integration of the existing solar collectors is energetically the most effective strategy according to Hassine and Ecker (2013). However, Lennermo et al. (2014) choose to use the RS connected solar installation, according to them it is the most common and promising alternative in Sweden. The difference between the two configurations is that RS can produce its own flow in the DH piping system while the RR is limited by the amount of heat the flow can take. When many substations are connected and feed in on the return line, performances of the decentralized solar system are linked and decrease with increasing return temperature.

An important limiting factor for the RS feed in is the temperature demand set for the supply, the lower the temperature the higher the obtained heat rate for the solar collector. However, the requirements of the DH network demand a certain temperature (Lennermo et al. 2014). To avoid these limits, Paulus and Papillon (2014) add a third pipe to the network to disconnect the flow rates of the solar and the district heating loop. This extra pipe connects the solar collectors to a thermal storage as can be seen in Figure 3-11. This provides the solar collectors with enough flow and an equally low temperature so their performance can be optimized.
Since this study focuses on existing networks, adding a third pipe is not considered as an option. As the goal of this study is to determine the maximum possible solar contribution, the RS feed in has been chosen in the model.

### 3.6.5 Substation

In order to be able to feed in on the network a substation with a reversed flow direction is needed. The Dresden University of Technology has designed a pilot combined house connection and grid feed-in station (HANEST). In this subsystem, which is shown in Figure 3-12, an extra pump allows the flow direction in the heat exchanger to be reversed to pump water from the return to the supply grid. The figure on the left shows the situation when there is more solar heat available than the consumer demands. If there is no, or too little, solar heat available the flows will be as in the figure on the right, similar to a normal substation.
Figure 3-13 shows the current test installation at the TU Dresden. Though the substation is still in a pilot state, it is assumed this or similar substations will become available in the future.

Figure 3-13: CAD-Modell and experimental set-up of the HANEST substation (EnEff:Wärme, 2015)

In the substation a pump is needed to transport water from the return to the supply network, consuming extra energy. However, since the pressure differences in a secondary grid are relatively small, the energy consumption by such a pump is around 100 W which is far less than the heat gained (Grundfos, 2015).

3.7 Storage
Most of the energy production by solar collectors occurs in summer at midday, when the sky is clear, while the highest heat demand is in winter mornings and nights. Some sort of buffering is thus needed in order to match the supply and demand of heat. The surrounding consumers in the grid will be sufficient to act as a buffer itself for small solar fractions, but when more collectors are integrated in the network diurnal or seasonal storage is needed.

There are several storage methods, characterized by their storage medium and storage temperature. Though latent or chemical storage require smaller volumes, sensible storage is a simpler and cheaper alternative and therefore the only widely used concept. Due to its high heat capacity, low cost and low environmental risk, water is the most common storage medium. Since it combines well with district heating systems this chapter will discuss only thermal heat storage in water.

It has been shown that it is possible to store hot water (up to 95 °C) for several months with very small losses incurred (as low as 1 °C per month) (Thomsen & Overbye, 2016).

3.7.1 Storage in the Netherlands
The Dutch soil has proven suitable to store heat surpluses during summer and is the mostly used medium for seasonal storage. Heat is exchanged with it directly in an open system or indirectly using a buried heat exchanger, a closed system. Most Dutch systems are open and use ground water from aquifers as their medium; these are cheaper than closed systems when using sources of depths up to 200 m.
Based on the amount of permits, over a thousand open thermal storage systems have been realized in the Netherlands. Over 99% of these systems operate at 25°C or less, most of these systems are combined with a heat pump to use the heat. In the past 30 years only nine high or medium temperature open heat storage systems have been built in the Netherlands, of which three have already stopped operating. Their operating temperatures vary from 30°C up to 90°C and their capacities from 1.45 MW up to 6 MW. To avoid ground water pollution and other environmental effects, such high temperatures have only been allowed for pilot projects.

In Utrecht and Zwammerdam aquifer thermal energy storages at 90°C have been realized but neither of these systems is in use nowadays. The system in Utrecht could store up to 21600 GJ/year in an aquifer at 220 meter depth. The heat source was damaged after 8 years of operation which forced the project to stop. Except for the damage, which cause is still unknown, the installation functioned successfully both technically and economically. Though the storages efficiency was only 27% on average, which was mainly due to heat surpluses at the end of the heating season, in a year with less heat storage 80% thermal efficiency was reached. This confirmed the importance of choosing the right operating conditions when designing the system, both economically and energetically an optimum has to be identified (Drijver, 2012).

In Zwammerdam the experiences from Utrecht helped improve the system, an 8100 GJ/year aquifer storage at a depth of 180 m. Even with higher heat losses due to the smaller capacity of the system, an average thermal efficiency of 65% was reached during the 5 years of operation. The exploitation of the system was stopped because the financial benefits turned out to be too low (Drijver, 2012).

### 3.7.2 Water tanks

The simplest form of this storage is in water tanks, those can be either artificial or a geological cavity. Heat is transported to or from water tanks by a flow of water or through a heat exchanger inside the tank. A system with an external heat exchanger is most common. A typical domestic solar collector system includes a buffer with a capacity of up to two times the daily water consumption which varies between 500 and 3000 litres. Within a heating district a larger tank can be used for buffering. Verda and Colella (2011) analyse the operation of a 1000 m³ storage tank. They show how short term storage can be used to reduce the primary energy consumption and the total operational costs of a CHP system.
Mixing causes a lot of useful exergy to be lost, a perfectly stratified water tank can make a solar system produce 38% more heat than a fully mixed tank (Hollands & Lightstone, 1989). In order to avoid mixing, storage systems that allow heat to be injected at several locations, where the temperature is similar to the injected heat, have been developed. Figure 3-14 shows the sharp thermocline in such a water tank. Some characteristics of this commercially available stratified storage tank are listed in Table 3-3. As can be seen the heat losses are limited to a very small fraction of the stored heat.

<table>
<thead>
<tr>
<th>Volume [m$^3$]</th>
<th>Standby heat loss at 95°C[W]</th>
<th>price</th>
<th>Price /m3</th>
</tr>
</thead>
<tbody>
<tr>
<td>500*</td>
<td>2700*</td>
<td>250000*</td>
<td>500*</td>
</tr>
<tr>
<td>50*</td>
<td>900*</td>
<td>35000*</td>
<td>700*</td>
</tr>
<tr>
<td>20</td>
<td>600*</td>
<td>16800</td>
<td>840</td>
</tr>
<tr>
<td>5</td>
<td>297</td>
<td>4500</td>
<td>900</td>
</tr>
<tr>
<td>0.5</td>
<td>100</td>
<td>805</td>
<td>1610</td>
</tr>
</tbody>
</table>

*expected by linearizing available data

Water tanks can compensate for the diurnal offset but in order to compensate for the seasonal mismatch much larger storage volumes are needed. Nevertheless, seasonal storage has potential as
investment costs of seasonal storage compared to short term storage, for large scale solar plants, are only twice as high per square meter of collector area while significant reductions in solar collector area required are achieved (Pinel et al. 2011).

### 3.7.3 Aquifer Thermal Energy Storage (ATES)

When aquifers are used for long term storage a hot and a cold source are coupled to distract or store ground water at the available temperature. The sources are hydraulically separated from the water in the building by a heat exchanger. When there is a heat surplus, water from the cold source is pumped to the hot source through this heat exchanger so heat from solar collectors can be added to the ground water. When there is heat demand the direction of the medium changes and the heat is distracted from the water moving from the hot to the cold source. Figure 3-15 shows a schematic of the system.

Aquifer Thermal Energy Storage can vary in temperature and size. A distinction is generally made between low temperature storage up to 30°C, medium temperatures from 30°C to 60°C and higher temperatures. High temperature systems require more expensive materials, water treatment and have higher heat losses, they are mainly applied to bigger projects. Mainly due to Dutch regulations only pilot projects have been realized at high temperatures (Drijver, 2012).

![Figure 3-15: Schematic of Aquifer Thermal Heat Storage (Drijver, 2012)](image-url)
4. Model components
In this chapter the district heating grid and additional components will be analysed with the aim to model their behaviour in Simulink modules. The solar collectors will be assumed to deliver to the supply grid at the local temperature and pressure. This will be possible with a consumer substation like the HANEST designed by the TU Dresden.

First the purpose, boundaries, relevant phenomena and assumptions of the whole system will be discussed followed by a division into several subsystems. For each subsystem the former steps will be repeated and summarized into a description. The corresponding equations can than be determined. These equations will serve as a base for the Simulink modules. All sub modules will be combined so that simulations of the entire system can be run.

4.1 Relevant characteristics
The purpose of the model is to analyse the feasibility of a district heating grid with decentralized heat supply from solar collectors. This is done by simulating heat and mass flows within the grid and to the surroundings for different configurations. The model should be able to simulate different secondary networks of which the boundaries are chosen outside the heat exchanger to the primary grid.

There are several phenomena occurring in a district heating grid. The most important is the heat transfer through the network. This is the heat transfer to customers and the heat losses to the environment. The amount of thermal energy transported depends on the mass flow and temperature. To calculate the energy needed to cause this mass flow, the pressure distribution and pump energy are also relevant.

In order to limit computation time and simplify the model, several assumptions have been made. For the complete grid the flow is assumed to be an one-dimensional turbulent, uniform and incompressible flow of water. The pipes are assumed to be straight, of constant height and free of leakages everywhere. Losses in the branches to consumers are neglected since they have no influence on the supply temperature in the main pipe and little influence on the return temperature.
4.2 Model flow chart

As described in section 3.5.2, the control of a secondary district heating network depends on measurements at the consumer furthest away from the supply unit. This is the n\textsuperscript{th} consumer in Figure 4-1. The minimum pressure difference and temperature for this consumer are used as the initial conditions in the Simulink model.

As can be seen in the model flow chart, Figure 4-2, the calculations proceed from the n\textsuperscript{th} consumer towards the substation. A temperature difference and a pressure difference are calculated for the return and supply flow for each pipe segment. The calculation of the losses is described in section 4.3. These losses are added to the supply flow conditions and subtracted from the return flow conditions. In this way the input conditions for the subsequent consumer are calculated.

The mass flow is, though opposite in direction, equal in the supply and return network. The mass flow increases from the n\textsuperscript{th} to the first consumer dependent on the heating power required as explained in section 4.4.2. In the situation of feed-in from solar collectors, that mass flow is subtracted from the total to simulate the flow from return to supply grid, this is explained in section 4.6.2.

If there is more heat fed-in than needed by the consumers between the feed-in point and the n\textsuperscript{th} consumer, the rest of the heat will flow in the direction of the substation. This is represented by a negative mass flow in the model. In this case the pressure and temperature difference between the supply and return flow will decrease towards the substation.

If the temperature difference over the grid is too high, extra flow is needed to guarantee a sufficient temperature near the furthest consumer. A higher initial mass flow $m_0$ is used if the temperature
difference between the \( n^{th} \) consumer and the substation is too high. This is done in order to mimic the function of the temperature controlling valve near this consumer, shown in Figure 4-1. Due to this initial mass flow the temperature in the return pipe at the last consumer is equal to the supply temperature.

In the substation, where the calculation of the model ends, the temperature difference and pressure difference determine the thermal energy demand from the primary grid and the electricity consumption of the pump. The basic calculation flow scheme can be found in Figure 4-2.

Figure 4-2: Model flowchart
4.3 Pipe model

The network mainly consists of pipes so the majority of the losses take place there. Friction causes pressure losses and heat is lost to the surroundings. In order to know the amount of heat to be fed into the network and the pressure difference over the pump, these losses must be calculated.

The losses depend on several characteristics of the pipe, schematically shown in Figure 4-3. The heat losses depend on the insulation and the temperature difference between the medium and the pipe surroundings while the pressure losses depend on the roughness of the inner pipe surface. Both losses also depend on the diameter of the pipe and the mass flow of the medium.

![Figure 4-3: schematic of a pipe segment](image)

The pipe is considered as a resistive component, without mass accumulation, with a fully turbulent one dimensional flow inside. Only the heat transfer through the walls is calculated. Since the length of the pipe segments is small, it is assumed the temperature difference over L, the length of a segment, can be neglected. The medium temperature per segment is assumed to stay constant at the local inlet temperature.

4.3.1 Heat losses

In more detail, the pipe generally consists of three layers as can be seen in Figure 4-4. A steel inner pipe is surrounded by an insulation layer and a shell pipe to protect the insulation. There are several possible insulation materials. The thickness of the layer depends on the pipes diameter and the insulation class. All these characteristics influence the amount of heat loss. The most commonly used pipe is Steel-PUR-PE where polyurethane and polyethylene cover the steel medium pipe. The overall heat transfer for Steel-PUR-PE pipes of different diameters is calculated according to:

\[
UA = L \times \left( \frac{1}{a_{\text{water}}} + \frac{1}{2\pi} \left( \frac{1}{\lambda_{\text{steel}}} \ln \frac{d_{i,\text{steel}}}{d_{o,\text{steel}}} + \frac{1}{\lambda_{\text{PUR}}} \ln \frac{d_{i,\text{PUR}}}{d_{o,\text{PUR}}} + \frac{1}{\lambda_{\text{PE}}} \ln \frac{d_{i,\text{PE}}}{d_{o,\text{PE}}} + \frac{1}{\lambda_{\text{soil}}} \ln \frac{4 \times \text{depth}}{d_{o,\text{PE}}} \right) \right)
\]  

(1)
Since $\alpha_{\text{water}}$, $\lambda_{\text{steel}}$ and $\lambda_{\text{PE}}$ are relatively high, the quotients they are part of can be neglected. The insulation layer has the biggest influence on the total heat transfer coefficient, the most common value for $\lambda_{\text{PUR}}$ is $0.03 \text{ Wm}^{-1}\text{K}^{-1}$. $\lambda_{\text{soil}}$ is strongly dependent on the moisture and structure of the soil and varies between 0.9 and 3 Wm$^{-1}$K$^{-1}$.

Table 4-1 lists the overall heat transfer coefficients times the circumference $C$ of new, buried Steel-PUR-PE pipes. The table shows that, due to a difference in thickness of the layers, the overall heat transfer coefficient changes (ISSO, 2012). The values are based on an average $c_{p_w}$ of 4.187 Jkg$^{-1}$K$^{-1}$, a depth of 0.8 m, and a soil conductivity $\lambda_{\text{soil}}$ of 1.2 Wm$^{-1}$K$^{-1}$ (Isoplus, 2012).

The effectiveness of PUR slightly decreases over time as can be seen in Figure 4-5, the actual heat losses might thus increase as the grid ages.

**Figure 4-4: Schematic cross section of a Steel-PUR-PE pipe with the diameters of the layers**

Since $\alpha_{\text{water}}$, $\lambda_{\text{steel}}$ and $\lambda_{\text{PE}}$ are relatively high, the quotients they are part of can be neglected. The insulation layer has the biggest influence on the total heat transfer coefficient, the most common value for $\lambda_{\text{PUR}}$ is $0.03 \text{ Wm}^{-1}\text{K}^{-1}$. $\lambda_{\text{soil}}$ is strongly dependent on the moisture and structure of the soil and varies between 0.9 and 3 Wm$^{-1}$K$^{-1}$.

Table 4-1 lists the overall heat transfer coefficients times the circumference $C$ of new, buried Steel-PUR-PE pipes. The table shows that, due to a difference in thickness of the layers, the overall heat transfer coefficient changes (ISSO, 2012). The values are based on an average $c_{p_w}$ of 4.187 Jkg$^{-1}$K$^{-1}$, a depth of 0.8 m, and a soil conductivity $\lambda_{\text{soil}}$ of 1.2 Wm$^{-1}$K$^{-1}$ (Isoplus, 2012).

The effectiveness of PUR slightly decreases over time as can be seen in Figure 4-5, the actual heat losses might thus increase as the grid ages.
Table 4-1: pipe diameters and corresponding heat transfer coefficients (ISSO, 2012)

<table>
<thead>
<tr>
<th>DN</th>
<th>d_i [m]</th>
<th>d_o [m]</th>
<th>U*C [Wm^-1K^-1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.0217</td>
<td>0.090</td>
<td>0.136</td>
</tr>
<tr>
<td>25</td>
<td>0.0285</td>
<td>0.090</td>
<td>0.165</td>
</tr>
<tr>
<td>32</td>
<td>0.0372</td>
<td>0.110</td>
<td>0.160</td>
</tr>
<tr>
<td>40</td>
<td>0.0431</td>
<td>0.110</td>
<td>0.194</td>
</tr>
<tr>
<td>50</td>
<td>0.0545</td>
<td>0.125</td>
<td>0.215</td>
</tr>
<tr>
<td>65</td>
<td>0.0703</td>
<td>0.140</td>
<td>0.253</td>
</tr>
<tr>
<td>80</td>
<td>0.0825</td>
<td>0.160</td>
<td>0.261</td>
</tr>
<tr>
<td>100</td>
<td>0.1071</td>
<td>0.200</td>
<td>0.276</td>
</tr>
<tr>
<td>125</td>
<td>0.1325</td>
<td>0.200</td>
<td>0.318</td>
</tr>
<tr>
<td>150</td>
<td>0.1603</td>
<td>0.250</td>
<td>0.375</td>
</tr>
<tr>
<td>200</td>
<td>0.2101</td>
<td>0.315</td>
<td>0.401</td>
</tr>
<tr>
<td>250</td>
<td>0.2630</td>
<td>0.400</td>
<td>0.357</td>
</tr>
<tr>
<td>300</td>
<td>0.3127</td>
<td>0.450</td>
<td>0.456</td>
</tr>
</tbody>
</table>

4.3.2 Pressure loss

The pressure loss due to the friction force in a circular pipe can be calculated using the Darcy-Weisbach formula (White, 2001);

\[
P_L = P_E - \frac{8 f_f L \dot{m}^2}{d_i^5 \pi^2 \rho_w}
\]  

(2)

The friction factor is calculated using the Colebrook formula (White, 2001);
\[
    f_f = -2 \log\left(\frac{2.51}{Re} + \frac{\varepsilon/d_i}{3.7}\right)
    
    \text{Which is solved using the Matlab function fsolve. The Haalands equation (White, 2001) is used as initial guess for the friction factor;}
    
    f_f = \{-1.8\log\left[\frac{6.9}{Re} + \left(\frac{\varepsilon}{d_i}\right)^{1.11}\right]^{-2}
    
    \text{The temperature drop is assumed constant through the pipe segment and follows from the energy balance}
    
    \dot{m} c_{p,w}(T_E - T_L) = UA(T_E - T_{soil})
    
    \text{Which can be rewritten with the values from Table 4-1 as}
    
    T_L = T_E - \frac{U CL (T_E - T_{soil})}{\dot{m} c_{p,w}}
    
    \text{Since only resistive effects are considered the mass conservation equation can be simplified to:}
    
    \dot{m}_E = \dot{m}_L = \dot{m}
    
    \text{4.3.3 Validation}
    
    \text{To validate the heat and pressure losses in the model, an example static calculation has been compared to a static calculation in Networks DHC, a software program designed to calculate district heat and cold grids (Greenvis B.V., 2015). The test network presented in Figure 4-6 has been used for both calculations.}
    
    \text{Networks has been validated using practical data and can thus be seen as a reliable comparison. The pressure drop calculation in Networks is mainly based on the same equations: the Colebrook and the Darcy-Weisbach equations. Different parameters have been used so some differences are expected. The temperature losses in Networks are based on a more accurate calculation of the overall heat transfer coefficient, which may also cause a slight deviation.}
Figure 4-6: Schematic of the network used for the static calculations in Networks DHC and Simulink with the corresponding dimensions, the blocks represent consumers 1 to n=60 with a static heating power demand of 10 kW each. The substation is represented by a triangle.

The output of Networks is rounded off to 0.01 K and 1 kPa by the programme. The deviations mentioned have been calculated according to

\[
\text{relative deviation} = \frac{\text{value model} - \text{value networks}}{\text{value networks}} \times 100
\]  

(8)

The test network is optimized such that the medium velocity in the pipes never exceeds 1.5 m/s. As can be seen in

Figure 4-7: Medium velocity in the test network. Before the maximum velocity of 1.5 m/s is reached the pipe diameter is increased causing the drop in velocity.
Figure 4-8 shows the results of the pressure calculation for both methods. The pressure losses in the model differ slightly from the reference values, with a maximum relative deviation of 3.3%.

![Pressure distribution](image)

**Figure 4-8:** Pressure distribution from the substation to the n\(^{th}\) consumer according to a static calculation in Networks DHC and the Simulink model.

Figure 4-9 shows the supply temperature distribution throughout the grid, the temperature drop in the Simulink model is slightly lower than expected. The difference is probably an effect of the different calculation of UA. Since the maximum deviation is only 0.2% the simplification used in the model is assumed to be valid.

![Temperature distribution](image)

**Figure 4-9:** Supply temperature distribution from the substation to the n\(^{th}\) consumer, according to a static calculation in Networks DHC and the Simulink model.
The return temperature calculation, shown in Figure 4-10, has a higher deviation of 2%. In the Networks calculation, the return temperature from each consumer is assumed to be 30 degrees lower than the supply temperature at the same point in the grid. This makes these return temperatures at a small distance from the substation higher than at a further distance. The Simulink model assumes a constant return temperature for all consumers, here at 39.2 °C, which explains the flatter curvature.

To give a better comparison, the Simulink model has been adapted and a calculation has been done using a variable return temperature like in Networks. The results are shown in Figure 4-11, the maximum deviation is now 0.1%. Since it is assumed a fixed return temperature for each substation is more realistic than a fixed temperature drop, the fixed return temperature is used in the rest of the calculations.
The maximum absolute deviations are 4 kPa and 0.11 K, which are acceptable given the accuracy of the networks results. The most important results are pressure difference and temperature difference between the supply and return network at the heat source, so at 0 m distance. These results determine the pump work and the total heat demand at the substation. The calculated maximum pressure difference deviation is 1.6%, the calculated maximum temperature difference deviation is -0.4%. The temperature difference deviation using the fixed return temperature is 2.3%. All the calculated deviations are assumed to be acceptable for the purpose of the model.

4.4 Consumer

The dynamic heat demand per consumer determines the requirements on the grid. It consists of a domestic hot water demand and a space heating demand. Since the perception of comfort and the daily routine is different for each person a general approximation needs to be developed. Unfortunately, none of the big Dutch grid operators collect hourly heat consumption data on a building level. A model has been made to predict this.

Studying Figure 3-5 it becomes clear that the most relevant phenomenon in the substation, affecting the grid, is the mass flow through the heat exchanger between the supply and the return pipe. A prediction of the heat demand is needed to determine the required mass flow and its effects on the temperature and pressure in the connected pipe.

4.4.1 Heat demand

As explained in section 3.4, most domestic consumers only have a space heating demand during the colder months of the year. To simulate this, the space heating demand is assumed to be depending on the outside temperature $T_a$. The difference between the room temperature, which is assumed to be 20°C, and $T_a$ causes a heat loss to the environment through the buildings’ outer shell, its walls and floor. This heat loss must be compensated for by the buildings’ heating system. The heat loss depends on the area of the building $A_i$ and the overall heat transfer coefficient $U_i$ corresponding to the wall material. The corresponding $UA = \sum A_i \times U_i$ for the average Dutch building stock up to 2005, shown in Table 4-2, can thus be used to calculate the space heating demand for each building type. It is assumed that there is no heating demand for outside temperatures above 16°C so the demand at a certain time can be calculated from 7.

$$\dot{Q}_h = \begin{cases} 
UA \times (20 - T_a), & T_a < 16 \\
0, & T_a \geq 16 
\end{cases}$$

(9)

Since most heating systems are only active during the heating season, the space heating demand is assumed to be zero in the summer months June, July and August.
However, a building is not only heated actively. Equipment, people and the sun heat a building passively which causes the space heating demand to be lower. The influence of people and equipment is assumed to be negligible, but solar radiation is not. To account for the sun’s heat, the window area of each building type, see Table 4-2, is multiplied by the solar irradiation. taking into account the filtering of the glass, the new equation becomes:

\[
\dot{Q}_h = \begin{cases} 
UA \times (20 - T_a) - A_w \times f_g (G_d + \frac{1}{4} G_b), & T_a < 16 \\
0, & T_a \geq 16 
\end{cases}
\]  \hspace{1cm} (10)

Where \( f_g \) is the g-value, used to express the transmittance factor of glass and the factor \( \frac{1}{4} \) compensates for the sun’s orientation. Of course, negative values are impossible so if the solar gain causes a negative value in (10), \( \dot{Q}_h \) is set to 0. Figure 4-12 gives a visual impression of the building model.
As shown by the average heating demand peaks in Figure 3-3, most people only use their heating system during the day and only if they are at home. Though this is hard to predict for an individual consumer, the total heat demand is more important to determine whether solar heat can be fed into the grid. To make sure the total heat demand shows the characteristic peaks, (10) is multiplied by a value between 0.7 and 1.3 depending on the time of the day, the time dependency correction factor $f_t$. As can be seen in Figure 4-13 this factor follows the same curve as Figure 3-3.

![Schematic of the building model](image)

**Figure 4-12: Schematic of the building model**

![time-dependency correction factor](image)

**Figure 4-13: time-dependency correction factor**
To make the heating demand vary for each building type, a random number generator produces either a positive or a negative value $R_h$, equally distributed. Only for the positive values the heating system is assumed to be active. So (10) finally becomes:

$$Q_h = \begin{cases} f_t \times (U A \times (20 - T_a) - A_w \times f_g \left(G_d + \frac{1}{4} G_b\right)), & T_a < 16 \text{ and } R_h > 0 \\ 0, & T_a \geq 16 \text{ or } R_h \leq 0 \end{cases}$$  

(11)

Such a random number generator is also used to simulate the domestic hot water (DHW) demand $\dot{Q}_w$. Since there is only hot water demand during several minutes a day, the DHW demand value is assumed to vary between 0.5 kW and 5 kW. This means there should be no demand on some hours as well, to end up at the yearly average. This is simulated by a normally distributed random signal $R_w$, where the mean is chosen at -1, the variance at 2.5 and only values above 0.5 are used.

Again, the time-dependency correction factor is used to make sure there is more heat demand during the peak hours. This factor is the same as for the space heating most of the time but is set to zero between 12 p.m. and 4 a.m. since it is assumed that the hot water use during the night can be neglected. The resulting hot water demand thus follows from:

$$\dot{Q}_w = \begin{cases} f_t \times R_w, & hr > 4 \text{ and } R_w > 0.5 \\ 0, & hr \leq 4 \text{ or } R_w \leq 0.5 \end{cases}$$  

(12)

The total heat demand is the sum of the hot water and the space heating demand:

$$\dot{Q} = \dot{Q}_h + \dot{Q}_w$$  

(13)

The total mass flow towards the consumer now follows from:

$$m_c = \frac{\dot{Q}}{c_p, w (T_{E,S} - T_R)}$$  

(14)

4.4.2 Influence on network

![Figure 4-14: mass balance consumer substation](image)
There is no accumulation of mass in the consumer substation, the following mass conservation equation is valid:

\[ m_{L,R} + m_{L,S} = m_{E,R} + m_{E,S} \] (15)

As can be seen in Figure 4-14 the outgoing mass flows become:

\[ m_{L,S} = m_{E,S} - m_c \] (16)
\[ m_{L,R} = m_{E,R} + m_c \] (17)

Return flow from the consumers is assumed to be cooled to \( T_R \) so the new return temperature is

\[ T_{L,R} = \frac{m_{E,R} T_{E,R} + m_r T_R}{m_{L,R}} \] (18)

Since there is no water added to the supply flow, it is assumed there is no temperature change there:

\[ T_{L,S} = T_{E,S} \] (19)

The pressure balance on the supply and return side results from Bernoulli’s principle:

\[ P_L = P_E + \frac{1}{2} \rho (v_E^2 - v_L^2) = P_E + \frac{1}{2} \rho \left( \frac{m_E}{\rho \pi \frac{1}{4} d_l^2} \right)^2 - \left( \frac{m_L}{\rho \pi \frac{1}{4} d_l^2} \right)^2 \] (21)

### 4.4.3 Calibration and discussion

The model has been run 10 times for each combination of building type and year of construction as listed in Table 4-2. The average result and corresponding deviations are listed in Table 4-3. As can be seen the average \( U_A \) and \( A_w \) values do not correspond to the expected demand \( Q_{\text{reference}} \), especially for the flat.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>building type</td>
<td>( Q_{\text{ref}} ) [GJ]</td>
<td>( Q_{\text{model}} ) [GJ]</td>
<td>deviation</td>
</tr>
<tr>
<td>Detached home</td>
<td>79</td>
<td>82.09</td>
<td>+3.91%</td>
</tr>
<tr>
<td>Rowhouse</td>
<td>40</td>
<td>40.39</td>
<td>+0.99%</td>
</tr>
<tr>
<td>Flat</td>
<td>20</td>
<td>14.83</td>
<td>-25.84%</td>
</tr>
</tbody>
</table>
To correct for these deviations, all UA values have been modified according to

\[ UA_{modified} = UA \times (1 - deviation) \]  

(22)

The new values, their results and deviations are shown in Table 4-4. Since the values are all based on averages the deviations are considered acceptable.

**Table 4-4: corrected UA values**

<table>
<thead>
<tr>
<th>Building type</th>
<th>Year of construction</th>
<th>( UA ) - modified [W/K]</th>
<th>( Q_{model} ) [GJ]</th>
<th>deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached home</td>
<td>1965-1974</td>
<td>670</td>
<td>80</td>
<td>1.08%</td>
</tr>
<tr>
<td></td>
<td>1974-1991</td>
<td>431</td>
<td>49</td>
<td>1.76%</td>
</tr>
<tr>
<td></td>
<td>1991&lt;</td>
<td>265</td>
<td>27</td>
<td>-0.19%</td>
</tr>
<tr>
<td>Rowhouse</td>
<td>1965-1974</td>
<td>352</td>
<td>40</td>
<td>-0.56%</td>
</tr>
<tr>
<td></td>
<td>1974-1991</td>
<td>218</td>
<td>24</td>
<td>-1.03%</td>
</tr>
<tr>
<td></td>
<td>1991&lt;</td>
<td>121</td>
<td>12</td>
<td>-1.17%</td>
</tr>
<tr>
<td><strong>flat</strong></td>
<td>1965-1975</td>
<td>177</td>
<td>19</td>
<td>-3.50%</td>
</tr>
<tr>
<td></td>
<td>1974-1991</td>
<td>114</td>
<td>12</td>
<td>0.58%</td>
</tr>
<tr>
<td></td>
<td>1991&lt;</td>
<td>81</td>
<td>8</td>
<td>-8.47%</td>
</tr>
</tbody>
</table>

Figure 4-15 shows the annual heat demand for the sum of 60 row houses, built between 1974 and 1991. The heat demand in winter is a factor 10 higher than the heat demand in summer, which corresponds to the heating demand curves discussed in section 3.4.

![Figure 4-15: Model output for the annual heating power demand for 60 row houses](image)
Figure 4-16 shows the model output during a cold winter Tuesday, the characteristic morning and afternoon peaks are clearly visible. Figure 4-17 shows the heat demand curve for one of the buildings on the same day, the maximum heat demand of 8 kW is a realistic value, the fluctuation of the graph is caused by the random factor $R_h$.

Figure 4-16: Total heating power demand for 60 row houses, on 01-01-2003 as predicted by the model

Figure 4-17: Individual heating power demand for a row house on 01-01-2003 as predicted by the model
The fluctuation of the power demand is shown in Figure 4-18 and varies between 1 kW and 5.7 kW. Due to the time step of an hour, the maximum power demand is lower than it would be in reality. Figure 4-19 shows the total domestic hot water power demand during a day, the simultaneous heat demand corresponds to the heat demand curves discussed in section 3.4. The predicted average annual hot water requirement per household is 6.14 GJ, a slight deviation from the Dutch average. The curve for one of the 60 buildings, Figure 4-20, shows only a few peaks and looks different for each building. As expected the DHW power demand is more fluctuating than the space heating power demand.
4.5 Circulation pump

The water in the heating grid is pressurized making use of a central pump. The Grundfos CME25-2 AS-A-V-AQV-96806979 horizontal multistage centrifugal pump has been used as a reference, this it is a typical pump type for heating districts. To simulate this pump, a Simulink module has been made following the equations used by van Putten and Colonna (2007).

The modelled pump is a centrifugal, forward bladed pump with a parabolic pump characteristic. The fluid in the pump is accelerated under constant pressure by the rotating pump blades, pressure is created by slowing down the fluid. It is assumed there are no heat losses; the liquid is isothermal with the metal walls and the walls are isolated from the environment. The heat accumulation in the metal parts is dealt with using the heat capacity of the metal, therefore the pump can be seen as just a resistive component and mass accumulation can be neglected.

4.5.1 Equations

Since only resistive effects are considered the mass conservation equation can be simplified to:

\[ \dot{m}_E = \dot{m}_L \]  \hspace{1cm} (23)

the energy conservation equation can be written as a function of \( h_L \):

\[ \frac{dh_L}{dt} = \frac{1}{\rho V} \left[ \dot{m}_E (h_E - \bar{h}) - \dot{m}_L (h_L - \bar{h}) + \dot{Q} + \dot{W} \right] \] \hspace{1cm} (24)

and conservation of momentum can be neglected.

Because all heat flux is going to the metal casing the heat flux can be rewritten:
\[-\dot{Q} = \dot{Q}_M = \frac{m_M c_{p,M}}{c_{p,F}} \frac{dh_L}{dt}\]  

(25)

So by substituting (23) and (25), (24) can be rewritten as:

\[ \frac{dh_L}{dt} = \frac{[\dot{m}_L (h_E - h_L) + \dot{W}]}{\rho \dot{V} + \frac{m_M c_{p,M}}{c_{p,F}}} \]  

(26)

From the pump design parameters \( V_0, H_0, n_d, D_0 \) and the on-design values \( V_d, H_d \) the rotational speed can be obtained using a parabolic pump characteristic (van Putten & Colonna, 2007):

\[ n = \frac{-b \dot{V} - \frac{b^2 \dot{V}^2}{g^2 D_0^2} + 4c \left( \frac{H D_0}{g} - \frac{a \dot{V}^2}{g^2 D_0^2} \right)}{2c D_0^2} \]  

(27)

The parameters a, b and c are obtained by substituting the head and volume flow in the pump characteristic equation:

\[ H_{nd} = a \dot{V}_{nd}^2 + b \dot{V}_{nd} + c \]  

(28)

\[ H_{nd} = \frac{gH}{n^2 D^2}, \quad \dot{V}_{nd} = \frac{\dot{V}}{n D^3} \]  

(29)

Now the following system of equations can be solved:

\[
\begin{align*}
\frac{g H_d}{n_d^2 D^2} &= a \left( \frac{\dot{V}_d}{n_d D_d} \right)^2 + b \frac{\dot{V}_d}{n_d D_d^3} + c \\
0 &= a \left( \frac{\dot{V}_0}{n_d D_d} \right)^2 + b \frac{\dot{V}_0}{n_d D_d^3} + c \\
\frac{g H_0}{n_d^2 D^2} &= c
\end{align*}
\]  

(30)

Finally the last unknowns can be found using:

\[ \dot{W} = \frac{\Delta P \dot{m}_L}{\eta_{is} \rho} \]  

(31)

Where, :

\[ \eta_{is} = \eta_d \left[ 1 - \left( 1 - \frac{\dot{V}}{\dot{V}_d} \cdot \frac{n_d}{n} \right)^2 \right] \]  

(32)
4.5.2 Validation
Though a comparison with the actual pump would be preferred this data is not available. Instead, the model outputs will be compared to data from the manufacturer.

Equation (28) combined with the characteristic pump parameters can be plotted, leading to the pump characteristic in Figure 4-21. The parabolic curves are as expected for a centrifugal pump and match the curves from the manufacturer sufficiently.

![Pump characteristic graph](image)

**Figure 4-21:** Pump characteristics from the manufacturer combined with the characteristics from the model (adapted from Grundfos, 2015)

4.6 Solar collector model
The energy from solar radiation is used for heating the collector fluid, this hot water can be used directly by the consumer or can be fed to the grid. The Swiss Institut für Solartechnik share test results obtained during a standardized test according to EN12975. These describe the efficiency of the collector under certain conditions of irradiation and temperatures. The test results for a selection of collectors available on the Dutch market are shown in Table 4-5 (SPF Institut für Solartechnik, 2015).
Table 4-5: Efficiency coefficients, price and test results of three commercially available collector types (SPF Institut für Solartechnik, 2015)

<table>
<thead>
<tr>
<th>Type</th>
<th>$\eta_0$</th>
<th>$a_1$ [W/m²K]</th>
<th>$a_2$ [W/m²K²]</th>
<th>Annual yield [GJ/m²]</th>
<th>Cost* [€/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearline V30, flat plate</td>
<td>0.722</td>
<td>3.45</td>
<td>0.0079</td>
<td>1.83</td>
<td>299.66</td>
</tr>
<tr>
<td>Tigi HC-1, flat plate</td>
<td>0.683</td>
<td>2.15</td>
<td>0.0049</td>
<td>1.93</td>
<td>568.35</td>
</tr>
<tr>
<td>Burg High power pro 3000, evacuated tube</td>
<td>0.375</td>
<td>0.94</td>
<td>0.0063</td>
<td>1.89</td>
<td>519</td>
</tr>
</tbody>
</table>

* (Groene - Energie Winkel, 2015)

4.6.1 Equations

Incoming radiation, surrounding temperature and the mean collector temperature are assumed to be the only variables influencing the efficiency of the collector according to (34), the efficiency formula from the Swiss Institut für Solartechnik (SPF). By varying the efficiency coefficients different collector models can be compared. The collector output follows from the following:

$$\dot{Q}_{solar} = \eta \times G \times A_{\text{collector}}$$

(33)

Where the efficiency is calculated using efficiency coefficients provided by SPF, these are listed in Table 4-5. The efficiency at an irradiation $G$, a mean collector temperature $T_m$ and the ambient temperature $T_a$ can be computed from:

$$\eta = \eta_0 - a_1 \times T^*_m - a_2 \times G \times T^*_m^2$$

(34)

Where $G$ is the total irradiance on a horizontal surface, the sum of the direct (beam) and diffuse irradiance:

$$G = G_b + G_d$$

(35)

And

$$T^*_m = \frac{T_m - T_a}{G}$$

(36)

4.6.2 Feed in and control

The mean collector temperature influences the efficiency. The feed in conditions thus influence the collector output. Local domestic hot water is heated from 10 to 65°C leading to a lower mean collector temperature than when delivering to the grid. Especially since the return temperature in the grid is higher in summer due to the temperature controlling valve at the end.
The mean collector temperature depends on the hot water demand and the local grid temperature according to:

\[
T_m = \begin{cases} 
\frac{T_S + 5 - T_R}{2}, & \dot{Q}_w = 0 \\
\frac{T_S + 5 - 15}{2}, & \dot{Q}_w > 0 
\end{cases}
\]  

(37)

It is assumed the heat is used locally first, leading to the following combination of equations (13) and (33):

\[
\dot{Q}_c = \dot{Q}_h + \dot{Q}_w - \dot{Q}_{solar}
\]

(38)

When the solar gain is higher than the local demand, (38) results in a negative value. When used in (14) this represents a mass flow in the opposite direction.

In case of solar feed-in, there is a risk that the consumer wants to supply more heat than the network is designed for. To avoid too high velocities in the pipes the maximum feed in can be determined according to:

\[
\dot{m}_L = \begin{cases} 
\dot{m}_{max}, & \dot{m}_L < -v_{max} \rho_w \pi \frac{d_i^2}{4} \\
\dot{m}_L, & \dot{m}_L \geq -v_{max} \rho_w \pi \frac{d_i^2}{4} 
\end{cases}
\]

(39)

4.6.3 Discussion

The test reports by SPF indicate an expected annual yield. These have been used to check the order of magnitude of the collector output from the model. The calculated annual yield for a constant mean temperature and a varying mean temperature, which results from the network model, are listed in Table 4-6.

<table>
<thead>
<tr>
<th>Collector model</th>
<th>Expected yield [GJ/m²]</th>
<th>Yield at T_m=57.5 [GJ/m²]</th>
<th>Yield at simulated T_m [GJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearline V30, flat plate</td>
<td>1.83</td>
<td>2.07</td>
<td>1.29</td>
</tr>
<tr>
<td>Tigi HC-1, flat plate</td>
<td>1.93</td>
<td>2.95</td>
<td>1.53</td>
</tr>
<tr>
<td>Burg High power pro 3000, evacuated</td>
<td>1.89</td>
<td>1.71</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The difference in yield indicates that the high temperatures in the DHN have a negative effect on the collectors’ efficiency. The annual yield is lower than predicted by the SPF and lower than the Dutch average of 1.74 GJ/m². This effect is as expected since the temperature requirements of the
grid are higher than for direct domestic use. The annual yield of the evacuated tube collector differs more from the expected yield than the flat plate collectors.

4.7 Storage model

The heat surpluses at the substation have been used to calculate the effect of buffering. Though mixing and the temperature of the buffer will influence the heat losses, those have not been calculated in detail. The buffer has been simplified as an energy storage with a constant loss percentage of 0.05% per hour. The storage model has not been made in Simulink. In stead, buffering is simulated only numerically.

4.7.1 Equations

This has been done by adding the energy stored in the mass flow that reaches the substation in case of a solar heat surplus. The change of energy is:

\[ dQ = |\dot{m}| * c_p * (T_s - T_r) \]  \hspace{1cm} (40)

And the change in volume:

\[ dV = \frac{|\dot{m}|}{\rho} * t \]  \hspace{1cm} (41)

For each hour the changes in volume and energy are either added or subtracted, depending on the sign of the mass flow. This corresponds to emptying or filling the buffer:

\[ Q_{total}(i) = \begin{cases} Q_{total}(i - 1) * \eta_{buffer} + dQ, & m < 0, V_{total} < V_{max} \\ Q_{total}(i - 1) * \eta_{buffer} - dQ, & m > 0, Q_{total} > 0 \end{cases} \]  \hspace{1cm} (42)

Where

\[ \eta_{buffer} = 1 - 0.0005 \]  \hspace{1cm} (43)

And

\[ V_{total}(i) = \begin{cases} V_{total}(i - 1) + dV, & m < 0, V_{total} < V_{max} \\ V_{total}(i - 1) - dV, & m > 0, Q_{total} > 0 \end{cases} \]  \hspace{1cm} (44)

Emptying of the buffer can only occur if there is enough energy stored, if eq. (42) results in a negative value the resulting mass flow is calculated according to:

\[ \dot{m} = \begin{cases} \frac{Q_{total}(i)}{c_p * (T_s - T_r)}, & Q_{total}(i) < 0 \\ 0, & else \end{cases} \]  \hspace{1cm} (45)
The needed buffer volume to store as much heat as possible is the maximum value of $V_{\text{total}}$. To simulate the effect of different buffer sizes a maximum volume $V_{\text{max}}$ can be chosen.

### 4.7.2 Validation

The remaining heat demand at the substation, in case of an infinitely large buffer tank, can be found in Figure 4-22. The heat is supplied by the collectors and the buffer during a large part of the year, in winter the substation subtracts heat from the primary grid. The buffer is at its maximum capacity at the end of the summer as expected.

![Graph showing heat demand and buffer capacity](image)

**Figure 4-22:** The remaining heating power demand at the substation, the solar power and the energy stored in the buffer for 800 m$^2$ collector combined with infinite buffer capacity.

### 5. Method and model characteristics

The modules from the previous chapter are combined to form the network model. This model is used to test different feed-in scenarios. These scenarios include three different combinations of buildings and several collector areas and buffer volumes. The influence of a more efficient network and of more recently built buildings is shown additionally.

#### 5.1 Test networks

The network introduced in Figure 4-6 has been adapted to form two extra scenarios. For scenario b, a block of 10 row houses has been replaced by two apartment buildings, with 50 apartments each. For scenario c two blocks of row houses have been replaced by 10 detached houses. Figure 5-1 shows the buildings and pipe lengths for the scenarios a, b and c. The distance between the
consumers has been adjusted to the building type. There is 5 m of pipes between two row houses, 10 m between two detached houses and 100 m between an apartment building and the next consumer. Such distances are common in Dutch neighbourhoods. The distance between two buildings in Figure 5-1 is the length of the pipe segment used to calculate the losses according to section 4.3.

The initial conditions, the temperature and pressure requirements for the last consumer and the initial mass flow $m_0$, are listed in Table 5-1. Both the heating demand and the collector yield depend on the weather. A reference file with the hourly data for a typical Dutch year has been used for the following simulations. This “year” is a gathering of representative months between 1986 and 2004 which makes it suitable to predict an average heat demand.

Table 5-1: Initial modelling conditions

<table>
<thead>
<tr>
<th></th>
<th>$T_s,0 , [^\circ C]$</th>
<th>$dT_0 , [^\circ C]$</th>
<th>$dP_0 , [kPa]$</th>
<th>$m_0 , [kg/s]$</th>
<th>$m_0 , [kg/s]$</th>
<th>$dT_{max} , [^\circ C]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>65</td>
<td>30</td>
<td>50</td>
<td>0.01</td>
<td>0.1</td>
<td>3</td>
</tr>
</tbody>
</table>
The pipe diameters as introduced in 4.3.3 have been slightly adapted to two alternatives. The regular diameters are based on an existing Dutch grid with houses built around 1965, the narrow diameters are based on newer designs. The DN diameters of the two alternatives are shown in Figure 5-2. The heat losses decrease slightly for the narrow alternative.

![Figure 5-2: The two alternatives of pipe diameters used in the simulations.](image)

The test networks have been chosen in such a way that their absolute heat losses are similar, as can be seen in Figure 5-3. However, their total demand varies due to the different types and amount of consumers, this is shown in Figure 5-4. Relatively, the losses are thus a lot higher for the networks without apartments and with newer buildings. This variation in heat demand is mainly due to differences in space heating demand. Since most solar heat is created in summer, the networks with a relatively low space heating demand, thus with the newer buildings and apartments, are likely to reach higher solar fractions.

![Figure 5-3: Absolute annual heat losses for test scenarios a, b and c depending on pipe diameters and network temperature.](image)
Figure 5-4: Total consumer heat demand for a secondary network containing buildings built between 1974 and 1991 and built after 1991 per network type

5.2 Simulations

The influence of different areas of solar collectors is tested for the combinations listed in Table 5-2. The areas have been chosen according to the available roof area for each building type. Therefore, the area at network a is always a multiple of 30 m², and for detached houses of 60 m². The maximum available area per apartment building has been estimated at 800 m². The collectors are always placed at the buildings closest to the substation since the diameter of the pipe is biggest here.

All tests have been done for the narrow network containing buildings built after 1991. The tests at network c have been repeated for the regular network with buildings built between 1974 and 1991.

Table 5-2: Tests run per network type and collector area for the narrow network with buildings built after 1991 and built between 1974 and 1991 (*).

<table>
<thead>
<tr>
<th>Network</th>
<th>0</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>450</th>
<th>600</th>
<th>750</th>
<th>800</th>
<th>900</th>
<th>1200</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c*</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3 Network behaviour at the substation

The supply and return temperature at the substation vary as a function of the relative heat losses. If the mass flow is low, a higher supply temperature is needed at the substation to make sure the furthest consumer receives water at the right temperature. This is clear in Figure 5-5. This influences the losses, which explains the higher absolute losses for network c. The fixed return temperature from each consumer, as explained in section 4.3.3, is an assumption that influences the efficiency of
the grid in a positive way. For a simulation with a return temperature of 45°C instead of 35°C, the heat losses increased with 4%.

![Figure 5-5: Temperatures of the supply (b) and return (r) flow at the substation for network c with buildings from 1974-1991](image1)

![Figure 5-6: Mass flows at the substation for the three networks during a winter (solid) and summer (dashed) day](image2)

The mass flow at the substation is mainly a result of the total heat demand, so for the test network with the apartments the mass flow will be higher. This is shown in Figure 5-6. The higher mass flow in summer for network b indicates the potential for solar feed in.

### 5.4 Data processing

By varying the network characteristics an optimal combination of solar collectors and storage can be found. This optimal combination will be indicated by several output variables. The model collects
the hourly values of the individual solar gain and demand per consumer and the mass flow, pressure and temperature at the substation. These values can be used to evaluate the simulated network.

Due to the random factors used for the consumers’ behaviour their demand differs slightly each time the model is run, the total annual demand is the first output variable. The absolute heat losses are relatively the same for a certain network so the higher the demand, the lower the relative annual heat losses. To calculate these losses, the total demand, the sum of all individual annual demands, is subtracted from the annual heat demand at the substation $Q_{\text{substation}}$ according to:

$$
\eta_{\text{network}} = 1 - \frac{Q_{\text{substation}} - \sum Q_1 + \cdots + Q_n}{\sum Q_1 + \cdots + Q_n}
$$

(46)

If there is heat produced by the solar collectors, this should also be added in (46) leading to:

$$
\eta_{\text{network}} = 1 - \frac{Q_{\text{substation}} + \sum Q_{s,1} + \cdots + Q_{s,n} - \sum Q_1 + \cdots + Q_n}{\sum Q_1 + \cdots + Q_n}
$$

(47)

The solar fraction is the fraction of the total demand produced by the solar collectors. However, not all solar heat can be used. The reduction in demand at the substation, compared to a reference calculation without solar collectors, is used to indicate the amount of solar heat used in the network, the solar gain.

$$
Q_{\text{solargain}} = Q_{\text{substation(reference)}} - Q_{\text{substation}} - (\sum Q_{\text{reference}} - \sum Q_1 + \cdots + Q_n)
$$

(48)

$$
f_{\text{solar}} = \frac{Q_{\text{solargain}}}{\sum Q_1 + \cdots + Q_n}
$$

(49)

The individual solar gain is another output value of the Simulink model which can be used to calculate the solar surplus by:

$$
f_{s,\text{surplus}} = \frac{\sum Q_{s,1} + \cdots + Q_{s,n} - Q_{\text{solargain}}}{\sum Q_{s,1} + \cdots + Q_{s,n}}
$$

(50)

5.5 Effects on the pump

The flow in the test networks is lower than expected when choosing the pump. The pump that has been modeled is not the optimal one for this network resulting in very low pump efficiencies. Since, even with those efficiencies, the electrical energy demand of the pump is low compared to the total heating energy demand the pump model has not been adapted. The influence of the changes in the heat grid on the pump will not change for a more optimal pump.

The pump in the substation has a slightly lower energy demand than without solar feed-in, but this is compensated by the energy consumed by the extra pump at the consumer substation. Figure 5-7

59
shows the power needed by both pumps throughout the year. In total, the consumers’ pump, in case of 600 m² collector, will need 890.67 kWh in total while the pump at the substation consumes 4389.0 kWh. Though the energy consumption by the pumps changes relatively, the total consumed energy stays around 5 MWh for all scenarios. This is less than 1% of the required heating power. The relatively low energy consumption in the test scenario corresponds to the small secondary grid.

5.6 Effects on network
By adding solar collectors, the mass flow, pressure and temperature distribution throughout the network change. Especially for large areas of collectors which reverse the flow direction. Figures 5-8 to 5-10 show the influence of up to 600 m² collector fed-in from 10 detached homes.
Figure 5-8 shows the produced heat causes a higher, reversed, mass flow than the reference mass flow. However, for the simulated networks, the fluid velocity never passed the limit of 1.5 m/s. As can be seen in Figure 5-9 the flow speeds are much lower. For larger collector area’s or for collectors placed at positions further down the grid, where the pipe diameters are generally smaller, the risk of too high flow speeds must be taken into account. Another risk occurs when only a small amount of solar heat is fed-in. As can be seen in Figure 5-10, for the 150 m² the reduction of the mass flow causes a bigger temperature drop.
5.7 Storage efficiency

For the previous figures it is assumed the efficiency of the used buffer is 0.9995 per hour, based on the heat losses of the stratified buffer in Table 3-3. The influence of the buffer efficiency on the amount of solar heat that can be reused can be seen in Figure 5-11. Only for large buffer volumes the efficiency significantly influences the solar fraction.

**Figure 5-11: Influence of buffer efficiency on solar fraction for 600 m² of collectors**
6. Results
Using the model discussed in the previous chapter, the influence of several variables on the heat losses and solar fraction will be discussed. By using the test networks as introduced in the previous chapter a limited amount of simulations is used to answer the research question in this report. The created Simulink model can easily be adapted to additional scenarios.

6.1 Collector type
As introduced in 4.6 three different collector types have been compared in the model. The highest solar gain is achieved with the Tigi HC-1 flat plate collector which corresponds to the expectations. The vacuum tube collector has the lowest annual yield, even though it has a relatively higher efficiency during the winter months this is still lower than the Tigi HC-1. As can be seen in Figure 6-1 the buffer volume varies strongly for the different types, this is partly due to the annual profile. Since the other two collector types are almost twice as expensive, the Clearline flat plate collector has been used in all simulations. The increase in solar gain or decrease in buffer volume can not compensate for the extra expenses.

![Figure 6-1: Comparison of different collector types, solar gain and buffer volume for 400 m² of collector area](image)

6.2 Collector area
As can be seen in Figure 6-2 solar fractions of almost 14% of the total heat demand can be reached without any extra buffering. The figure shows that increasing the collector area any further has only little effect on the solar fraction. It is remarkable that the three curves are similar while the heat demand of network b is a lot higher than for a and c.
Figure 6-2: The solar fraction for test networks a, b and c for different collector areas, for larger collector areas the increase in solar fraction stagnates around 14%.

This is partly due to the amount of heat that can not be directly used in the grid, the solar surplus. At a collector area of 400 m² you can only use half of the generated heat even for the best scenario with apartments. Figure 6-3 shows the fraction of the collector gain that cannot be used. Considering the cost of the collectors it is unlikely that large area’s with such high surpluses will be installed.

Figure 6-3: Solar heat surplus for the different test networks, for 100 m² of collectors the heat can always be directly used in network b.
6.3 Storage capacity

If the heat surpluses from Figure 6-3 are gathered in a water tank near the heat source of the network, the maximal achievable solar gains increase. As can be seen in Figure 6-4 over half of the annual demand can be generated by the sun.

![Graph showing solar fraction vs collector area]

**Figure 6-4:** Solar fraction when combined with infinite buffering, much higher solar fractions can be reached than without buffering.

However, as can be seen in Figure 6-5, in order to buffer all the generated heat the needed buffer volume increases rapidly. This is as expected because the heat needs to be stored during a longer period. The longer the heat stays within the buffer, the bigger the influence of the storage efficiency.

![Graph showing buffer volume vs collector area]

**Figure 6-5:** Maximal buffer volume at different collector areas

Figure 6-6 shows the effect of buffer volume on the total solar gain for 600 m² solar collector. Despite the big maximal volumes, a 20 m² buffer already doubles the solar gain while an almost 100
times bigger buffer volume is needed to reach a similar increase in solar gain. Buffering of solar heat will thus allow the solar gain to be more than doubled but the effect per added volume decreases.

Figure 6-6 shows another interesting effect, for the same collector area the solar gain in network b is much higher. This is due to the assumption that the water flowing towards the solar collector will be cooled down to a temperature lower than the return temperature of the heating district, since there is always some hot water usage in one of the apartments. The lower mean collector temperature increases the collector’s efficiency causing the higher solar gain.

The assumption causing this difference should be validated by a more detailed model. However, it gives an indication of the effect of the heating grid on a solar collector system. High return temperatures, which increase in summer due to the circulation of water past the last consumer, causes the collector efficiency to drop. As a result, the average annual collector output varies between 1 to 1.5 GJ/m$^2$ which is far lower than the Dutch average of 1.74 GJ/m$^2$ discussed in section 3.6.1.

![Figure 6-6: Solar gain from 600 m$^3$ of collector for the three networks at different buffer volumes](image)
The combined effect of the buffer volume and collector area on the solar fraction of network b can be seen in Figure 6-7. For small buffer volumes the solar fraction stagnates and more heat will be a surplus.

![Figure 6-7: Combined influence of collector area and buffer volume on the solar fraction in network b](image)

### 6.4 CO₂ emissions

The avoided CO₂ emissions depend on the heat source of the DHN. If the average Dutch value of 20 kg/GJ is assumed, the test networks emit between 29 and 75 tons CO₂. A solar fraction of 25% will thus avoid the annual emission of up to 18.75 tons. If, for instance by smart buffering, the heat from peak supply kettles can be replaced, more than twice as much emission of CO₂ can be avoided.

### 6.5 Economic evaluation

In addition to the technical feasibility, the price of the system needs to be compatible to other heat sources. An estimation of the costs of the most promising alternatives found in this chapter will be made. Actual market prices have been found for a collector and a buffer but a price for the consumer substation is not available yet. Especially for individual households the price of the consumer substation will have a big influence.
A rough estimation of €20 000 per substation has been made based on the price for large consumer substations suitable for apartment buildings. Furthermore, the actual maximum heat price for Dutch consumers of €24 per GJ has been used to calculate the annual savings. As can be seen in Figure 6-8 this is slightly higher than the European average for useful heat from natural gas, which is €21.4 per GJ. Inflation, service and installation costs have not been included in the calculations.

The total cost of the system has been calculated according to:

$$C_0 = -(\text{collector area} \times €299 + \text{price buffer} + €20 \ 000)$$

The savings according to:

$$C_t = t \times €24 \times Q_{\text{sol argain}}$$

To compare the different networks, the time needed for the total savings to equal the investment is calculated in Figure 6-9. It becomes clear from this figure there is an optimum in the buffer volume that differs per network and collector area.
Figure 6-9: The pay back time versus the buffer volume for several network and collector combinations, network b has the shortest pay back times and network a and c have similar results. For network c, the only pay back time under 20 years can be found for 200 m² of collectors.

The internal rate of return (IRR) is used to indicate the profitability of potential investments. It shows the annual discount rate that makes the net present value (NPV) of the costs and benefits equal to zero for a certain timespan. The higher the IRR, the more profitable the investment. The IRR for a time span of 15 and 25 years has been calculated for a few of the optimum combinations in Figure 6-9. These have been calculated according to (52), the results are listed in Table 6-1.

\[
NPV_T = \sum_{t=0}^{T} \frac{C_t}{(1 + IRR_T)^t} = 0
\]  

Table 6-1: Solar fraction and IRR for several test networks. It becomes clear that the investments for low solar fractions have a higher profitability and that network b has the highest IRR.

<table>
<thead>
<tr>
<th>Network</th>
<th>Collector area [m²]</th>
<th>Buffer volume [m³]</th>
<th>Solar fraction [%]</th>
<th>IRR₁₅ [%]</th>
<th>IRR₂₅ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>300</td>
<td>20</td>
<td>24</td>
<td>-3.0</td>
<td>2.1</td>
</tr>
<tr>
<td>a</td>
<td>600</td>
<td>50</td>
<td>35</td>
<td>-5.6</td>
<td>0.1</td>
</tr>
<tr>
<td>b</td>
<td>400</td>
<td>20</td>
<td>21</td>
<td>1.6</td>
<td>5.6</td>
</tr>
<tr>
<td>b</td>
<td>600</td>
<td>50</td>
<td>34</td>
<td>0.2</td>
<td>4.0</td>
</tr>
<tr>
<td>c</td>
<td>200</td>
<td>10</td>
<td>18</td>
<td>0.3</td>
<td>4.6</td>
</tr>
<tr>
<td>c</td>
<td>600</td>
<td>50</td>
<td>36</td>
<td>-5.9</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

The table shows that only three of the scenarios have a positives IRR₁₅. When the savings during 25 years are included in the calculation, only the last scenario results in a negative IRR₂₅. This means...
that, at a consumer heat price of €24 per GJ, only small profits can be made on solar heat. Though the savings are small, they are more promising than for individual solar boilers without a district heating connection. Those currently have pay back times of more than 25 years thus a negative IRR$_{25}$ (Gemeente Utrecht, 2016).

To show the influence of both the collector area and the buffer volume the return on investment (ROI) after 25 years has been calculated according to:

$$ROI_T = \frac{C_t + C_0}{|C_0|}$$  \hspace{1cm} (54)

Figure 6-10 gives an overview of the ROI$_{25}$, the percentage of the initial costs that has been saved after 25 years, for network b. Like in Figure 6-7: Combined influence of collector area and buffer volume on the solar fraction in network b the influence of the buffer volume and collector area is combined to show the optimum. The highest ROI$_{25}$ of 88% occurs when 400 m$^2$ collector is combined with a 20 m$^3$ buffer and when 200 m$^2$ is combined with 10 m$^3$. For larger collector areas the ROI$_{25}$ is highest when combined with a 50 m$^3$ buffer. For higher buffer volumes or collector areas the ROI$_{25}$ only decreases further. Despite the higher solar fractions resulting from the bigger areas or volumes, the expenses of the storage can not be compensated by extra savings with the current energy prices. Without a buffer, the investment currently needed for 800 or 600 m$^2$ of collectors can not be earned back within 25 years.

Figure 6-10: ROI after 25 years at different buffer and collector sizes for network b, the highest ROI is obtained when relatively small buffer volumes and collector areas are combined.
7. Conclusion

To contribute to the integration of renewables in district heating grids, the impact, limits and optimal usage of thermal solar collectors in Dutch district heating grids have been evaluated. Previous studies have confirmed the potential of decentralized solar collectors in district heating but focus only on small contributions to the total heat demand. In this study those results have been combined with the characteristics of Dutch heating grids. A model has been developed to simulate the influence of solar heat in those grids. In this way the maximal annual solar gain and solar fraction have been determined. Furthermore, the influence of the network topography, type of consumers and type of collectors on those indicators and the economic benefits have been shown.

The consumer substation that is generally used in the Netherlands does not allow the feed-in of heat to the supply side of the grid. To be able to do this, the flow in the domestic hot water heat exchanger needs to be reversed. An extra pump is needed to overcome the pressure difference between the supply and the return side. The HANEST substation, which is being developed in Germany, has those extra features. This will make decentralized feed-in of solar heat into district heating grids possible soon.

Since the technique does not differ much from a conventional substation no further adaptations have to be made to the grid. The results confirm the results by Brand et al., the mass-flow generated by large areas of solar collectors might be higher than the mass flow due to that consumers’ heat demand. What needs to be considered when allowing heat feed-in, is the location in the grid. The diameter of the pipes generally narrows down further away from the substation. To avoid too high flow speeds, the buildings close to the substation have more potential to act as heat supplier.

The simulations have shown that there is a limit to the amount of heat needed in a secondary grid. If all excess heat would be wasted, like in the first set of results, a maximum solar fraction of 14% can be achieved in the test networks. However, this means that over 80% of the generated heat can not be used. Therefore, dependent on the type of consumers on the grid, a total collector area with a heat production of around 5% to 10% of the total demand would be a better investment. Larger collector areas will mainly lead to bigger heat surpluses.

The addition of a buffer tank will allow around three times as much solar heat to be fed-in, with solar fractions of over 50%. However, not all of the buffer volume is needed throughout the year. This makes small buffer volumes the most profitable. A solar fraction of 25% will avoid the annual emission of 18.75 tons of CO₂ for the test network. If, for instance by smart buffering, the heat from peak supply kettles can be replaced, more than twice as much emission of CO₂ can be avoided.

The smaller, densely built and newer buildings, which have a relatively higher hot water demand compared to space heating, have the most potential to reach such high solar fractions. If more households share a consumer substation, like in an apartment building, the temperature of the flow
towards the solar collectors can be lower than the return temperature of the grid. This has a positive effect on the collector efficiency.

This efficiency differs for different types of solar collectors. Evacuated tube collectors produce more heat during the heating season compared to flat plate collectors. However, the overall solar gain is lower for the model that has been used in the simulations. The two flat plate collector types that have been compared also differ in total solar gain. It must be taken into account that the results of the tests will differ for various collectors. Since there is a big price difference between the collectors compared in this report, this has been the decisive characteristic.

From an economic perspective there is an optimum in profit dependent on the buffer size. The absolute solar gain per square meter collector is the highest for networks with relatively small collector areas. However, due to the estimated price of the consumer subsystem, the savings can be higher if more collectors are combined. This makes a shared consumer subsystem, like in apartment buildings, the most promising to be replaced.

The maximal achievable solar fraction in the simulated networks is 14% without and 55% with buffer. Economically lower solar fractions of 5% and 25% are more attractive. At the current consumer heat price, it is possible to pay back such solar fractions, corresponding to a collector area of 400 m$^2$ and a 50 m$^3$ buffer, within 14 years.
8. Recommendations

The effects on the primary grid should be described in more detail. It must be avoided that big temperature changes occur in the primary grid since this may damage the pipes. Higher relative heat losses in the grid due to the decrease in demand should be quantified as well as the influence on the main heat source of an actual grid. If heat can be transferred to the primary grid storage might not be needed. Heat losses and extra expenses can be avoided this way. This option should thus be evaluated. Perhaps a large substation similar to the HANEST substation could be used for this. The increase in heat losses through the heat exchanger should be compared to the storage heat losses.

The assumption that the collector efficiency increases if there is more hot water demand, due to the lower mean temperature, should be validated. If the effect is as high as expected, lowering the return temperature in the network could increase the efficiency of the collectors and other heat suppliers. The buffer return temperature is assumed to be depending on the grid. Lowering the buffer return temperature might increase the efficiency of the grid. More tests, at different network temperatures could be run to indicate the effects.

The collector model has been simplified to an efficiency equation. However, the annual yield turned out lower than expected, especially for the evacuated tube collector. A more detailed model of the entire system should be used to validate the results. The buffer model has also been simplified. A buffer model simulating the temperature of the fluid inside would be preferred over the used model. This will avoid the risk at unrealistic results if the temperature in the buffer is lower than the temperature demanded by the grid. Different types of collectors and storage should be compared to indicate the optimal combination, preferably with the addition of heat pumps.

Since there is no detailed consumer data available it had to be predicted. The variation in heat demand during the day influences how much solar heat can be used directly. A validation of the heat demand prediction with real data is thus recommended. Other consumer types and utilities, especially with high heat demand in summer, could also be considered to give a complete indication of the potential in a certain area.

The economic evaluation is based on the current maximal heat price and an estimated substation price. The effects of price differences should be considered. Furthermore, it is assumed heat consumption and feed-in can be balanced, leading to the calculated savings. This is currently possible for electricity but this is not possible for heat in the Netherlands. The positive influence subsidies might have on the profit from a solar thermal system might also influence the economic situation.

The storage is only used for solar heat surpluses in this report. The benefit of the buffer by peak shaving could lead to higher CO₂ savings and a lower overall heat price.
9. Bibliography


Greenvis B.V. (2015). Networks DHC.


ISSO. (2012). ISSO-publicatie 7 grondleidingen voor warmte- en koudetransport. ISSO.


Nationaal Expertisecentrum Warmte. (2013). Warmte en koude in Nederland. den Haag: Agentschap NL.


10. Nomenclature

<table>
<thead>
<tr>
<th>Latin</th>
<th>Greek</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area, [m²]</td>
</tr>
<tr>
<td>a</td>
<td>Collector loss coefficient, [-]</td>
</tr>
<tr>
<td>a</td>
<td>Pump characteristic parameter, [-] (Section 4.5)</td>
</tr>
<tr>
<td>b</td>
<td>Pump characteristic parameter, [-]</td>
</tr>
<tr>
<td>C</td>
<td>Capital, [€] (Section 8.6)</td>
</tr>
<tr>
<td>C</td>
<td>Circumference, [m]</td>
</tr>
<tr>
<td>c</td>
<td>Pump characteristic parameter, [-]</td>
</tr>
<tr>
<td>( c_p )</td>
<td>Specific heat capacity, [J/(kg K)]</td>
</tr>
<tr>
<td>D</td>
<td>Impeller diameter, [m]</td>
</tr>
<tr>
<td>d</td>
<td>Diameter, [m]</td>
</tr>
<tr>
<td>f</td>
<td>Factor, [-]</td>
</tr>
<tr>
<td>G</td>
<td>Solar radiation, [W/m²]</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration, [m/s²]</td>
</tr>
<tr>
<td>H</td>
<td>Head [m]</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy, [J/kg]</td>
</tr>
<tr>
<td>( \bar{h} )</td>
<td>Average enthalpy, [J/kg]</td>
</tr>
<tr>
<td>L</td>
<td>Length, [m]</td>
</tr>
<tr>
<td>m</td>
<td>Mass, [kg]</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>Mass flow, [kg/s]</td>
</tr>
<tr>
<td>n</td>
<td>Rotational speed, [rpm]</td>
</tr>
<tr>
<td>P</td>
<td>Pressure, [kPa]</td>
</tr>
<tr>
<td>Q</td>
<td>Heat, [kWh]</td>
</tr>
<tr>
<td>( \dot{Q} )</td>
<td>Heat flux [W]</td>
</tr>
<tr>
<td>R</td>
<td>Random value, [-]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$U$</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Volume flow</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$W$</td>
<td>Work</td>
</tr>
<tr>
<td>$nd$</td>
<td>Non-dimensional</td>
</tr>
<tr>
<td>$o$</td>
<td>Outside</td>
</tr>
<tr>
<td>$R$</td>
<td>Return</td>
</tr>
<tr>
<td>$S$</td>
<td>Supply</td>
</tr>
<tr>
<td>$s$</td>
<td>Solar</td>
</tr>
<tr>
<td>$T$</td>
<td>Total timespan</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$w$</td>
<td>Water</td>
</tr>
<tr>
<td>$w$</td>
<td>Window</td>
</tr>
</tbody>
</table>
I. **Simulink model**

One of the sub-goals of this project is to create an easily adaptable model, suitable to calculate different districts. A modular approach has been used to create the test network. Many of the modules can be repeated for each consumer connected to the grid. In order to adapt all these blocks at the same time, a Simulink library is used. Figure I-2 shows the complete Simulink model for test network c. The subsystems are linked according to the model hierarchy in Figure I-1. Figures 3 to 9 show some of the Simulink subsystems in the order of the hierarchy.

**a. The initial constants.**
The calculation starts with the initial constants. A switch functions as the dT control where the control variable is the difference between the initial supply temperature and Twos, the supply temperature at the substation from the previous hour.

**b. The consumer**
Each subsystem called 5x Domestic in Figure I-2 contains 5 consumer blocks and 5 pipe segment blocks. They have been clustered in order to be able to adapt their characteristics simultaneously. This can be done using the parameter mask shown in Figure I-3. By changing the mask parameters for the building type, pipe length and diameter and collector area, the effects of these variables can be compared and different networks can be created easily.

Each consumer substation is represented by an apartment subsystem like Figure I-5. The consumer heat demand is determined first in the substation of Figure I-6. The next step is determining the solar collector output. The consumer heat demand determines the collector’s inlet temperature through the switch shown in Figure I-7. The collector output is also influenced by the weather, network temperatures and collector type. The efficiency coefficients can be easily adapted in the corresponding mask.

The Q and temperature on the cold side of the heat exchanger are used to determine the consumer mass flow according to eq. (14). An extra control step is added to avoid too much solar feed-in, this happens in the “determine solar feed-in” subsystem shown in Figure I-8. Now the influence on the temperature and pressure in the supply and return pipe can be calculated in the resulting two subsystems. Saturation blocks and the addition of the smallest number “realmin” avoid negative temperatures and division by zero.

**c. The pipe**
Each pipe subsystem contains two similar subsystems for the return and supply flow like the one shown in Figure I-9. For both subsystems, the density and specific heat capacity of the medium are obtained from a thermodynamic property library (Hummeling Engineering, 2015). Then the heat and pressure loss in the pipe segment are calculated in the Matlab function block.

**d. The substation**
The substation collects the data and sends it to the Matlab workspace. The supply temperature is used to determine the initial mass flow for the next timestep.

e. The pump

The pump model can be connected to the supply and return flow at the substation or can be run separately when needed.

Figure I-1: Hierarchy of Simulink subsystems and Matlab files
Figure I-2: Complete model interface

Figure I-3: Mask parameter interface for a 5x Domestic block. The building and location specific characteristics can be adapted easily. The example shows how a row house, without solar collectors and built after 1991 is chosen.
Figure I-4: Screen shot of the 5x Domestic building block containing 5 buildings, 5 supply pipes and 5 return pipes. The signals for mass flow, pressure and temperature are continuously adapted by every block. Every building creates its own demand and solar output signal (Qd and Qi).

Figure I-5: Complete consumer model with subsystems where the demand and collector output is determined and where the influence of this demand on the temperature, pressure and mass flow of the medium on the supply and return side is calculated.
Figure I-6: Demand subsystem where the heat demand for a consumer is created from two random variables, the time and weather conditions.

Figure I-7: In and outputs of the collector subsystem, the consumer heat demand determines the ingoing temperature for the collector, the total heat consumption or production $Q$ is send to a switch to determine the return temperature on the cold side of the heat exchanger to the grid. This temperature is either 30 degrees below the initial supply temperature or the local return temperature of the heat grid.
Switches 1 and 2 evaluate the outgoing massflow, if the velocity is higher than the threshold determined by: \(-1.5 \times \text{rho \_waters} \times \pi \times 0.25 \times (d \_L/2)^2 \) [1.5 m/s] the mass flow is limited to constant 1 by Switch 2 and the surplus is registered by Switch 1.

Figure I-8: Control mechanism to avoid too high feed-in flows

Figure I-9: Pipeloss subsystem, the interface for pipelossS and pipelossR are similar. All calculations are done using Matlab functions.