Towards an energy neutral heat supply in the build environment in the municipality of Groningen in 2035

Exploring the desirability of large scale solar thermal plants & storage systems

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Content

SUMMARY

The municipality of Groningen has the ambition to become energy neutral in 2035. This means that 'all the energy has to be derived from renewable sources, with the possibility to import and to export energy'. This research focusses on a part of this ambition, to have an energy neutral low temperature heat supply in the built environment in 2035, which accounted for more than 40% of the total energy consumption in the municipality of Groningen in 2016. Lands within the boundaries of the municipality of Groningen that are available for the generation of renewable energy have been identified. The desirability to install solar thermal storage systems on these lands will be explored by a comparison with solar PV systems in combination with hydrogen storage and cultivation of energy maize from which biogas is produced and stored. For the solar thermal storage system and the biogas system, a district heating network is used to deliver heat. For the solar PV system in combination with hydrogen storage, heat pumps will be used to meet the heat demand of the municipality of Groningen. These three options will be evaluated in terms of energy production, investment costs and balance implications.

This study is built upon the year 2016 and the heat demand of the built environment has been modelled on an hourly basis, as well as the generation patterns from solar PV and solar thermal collectors and a temperature dependent heat pumps COP. The heat demand shows a strong daily and seasonal pattern. Different insulation levels have been applied in order to calculate the heat demand patterns for 2035. The generation patterns of solar PV and thermal collectors show daily and seasonal pattern reversed to the heat demand. The patterns and the capacities of the system components have been implemented in EnergyPLAN, a model used to explore different scenarios.

In the first three scenarios (solar thermal, solar PV, biomass), all available lands are used for a single system and maximal insulation has been applied to the whole built environment. The energy production of the solar thermal collectors with an outlet temperature of the collector of 80°C and an inlet temperature of 40°C is the highest with 1.22 GWh/y/ha, but only around 77% of the total heat demand of the municipality of Groningen can be produced by solar thermal collectors. The energy production of solar PV is lower with 0.73 GWh/y/ha, but due to COP of the heat pumps, 171% of the total heat demand can be produced by solar PV. If energy maize is cultivated on all the available lands, only around 6% of the total heat demand can be provided, since the energy production is only 0.04 GWh/y/ha.

Due to the mismatch between supply and demand, less than 20% of the produced energy by the solar thermal and PV collectors can be utilized directly. The heat generated by the solar thermal collectors cannot be exported, but this is possible for electricity generated by solar PV collectors and accounts for more than 80 % of the produced electricity. Taking thermal storage into account, around 92% of the produced thermal heat can be utilized, fulfilling around 71% of the heat demand. In combination with hydrogen storage, around 54% of the produced electricity can be utilized, fulfilling around 93% of the heat demand.

In the two combined scenarios, the buildings connected to the district heating network are extensive insulated, while the buildings that will be heated by means of a heat pump are maximal insulated. For these scenarios, the investment costs have also been calculated. Installing a district heating network is expensive, but the avoided costs due to lower insulation levels and no need for electricity network reinforcements are estimated to be higher. Furthermore, the thermal storage system is in the range of 10 times cheaper than the hydrogen storage system if implemented on a municipality scale.

If the definition of energy neutral on a yearly basis is followed, it can be concluded that solar PV without storage should be installed on all the lands. However, this has huge balance implications for the electricity network. Taking the energy system of the Netherlands as a whole in consideration and posing that energy neutrality on an hourly basis should be reached, it is desirable to install solar thermal storage systems (a part of) these lands. Further research is needed to determine the exact neighbourhoods in which a district heating network should be installed and the solar thermal storage system, while keeping in mind that due to the system boundaries of this research, this conclusion is drawn on the scale of the municipality of Groningen and that larger scale can give other outcomes.

SAMENVATTING

De gemeente Groningen heeft de ambitie om energie neutraal te zijn in 2035. Dit betekent dat 'alle energie van hernieuwbare bronnen moet komen, met de mogelijkheid om energie te importeren en te exporteren'. Dit onderzoek focust op een deel van deze ambitie: een energie neutrale lage temperatuur warmtevoorziening in de bebouwde omgeving in 2035, goed voor meer dan 40% van de totale energieconsumptie in de gemeente Groningen in 2016. De beschikbare grond binnen de gemeentegrenzen van Groningen dat voor de opwekking van hernieuwbare energie gebruikt kan worden, is in dit onderzoek in kaart gebracht. De wenselijkheid om zon-thermische opslagsystemen te bouwen op deze grond zal onderzocht worden door een vergelijking te maken met zon-PV systemen in combinatie met waterstofopslag en het verbouwen van energiemais waar biogas van geproduceerd wordt. De warmte zal door middel van een stadsverwarming worden geleverd in het zon-thermische systeem en het biogassysteem, en bij het zon-PV systeem zal gebruikt gemaakt worden van warmtepompen aangesloten op het elektriciteitsnetwerk. Deze drie opties worden beoordeeld op grond van energieproductie, investeringskosten en balansgevolgen op het netwerk.

In dit onderzoek is het jaar 2016 als uitgangspunt genomen en de warmtevraag van de bebouwde omgeving is op uurbasis gemodelleerd, net als de opwekpatronen van zon-PV en zon-thermische collectoren en een temperatuurafhankelijke COP van de warmtepompen. De warmtevraag geeft een sterk dag-nacht- en seizoenpatroon weer. Verschillende isolatiegraden zijn toegepast om de warmtevraag in 2035 te berekenen. De opwekpatronen van zon-PV en zon-thermische collectoren geven een dag-nacht- en seizoen patroon dat tegenovergesteld is aan het patroon van de warmtevraag. De verschillende patronen en capaciteiten van de componenten van de systemen zijn in EnergyPLAN ingevoerd, een model dat gebruikt wordt om verschillende scenario's te verkennen.

In de eerste drie scenario's (zon-thermisch, zon-PV, biomassa), is aangenomen dat alle beschikbare grond gebruikt wordt voor één systeem en de bebouwde omgeving maximaal geïsoleerd is. De energieproductie van de zon-thermische collectoren met een uitlaattemperatuur van 80°C en een inlaattemperatuur van 40°C is het hoogst met 1.22 GWh/j/ha, hoewel maar 77% van de totale jaarlijkse warmtevraag van de gemeente Groningen kan geproduceerd worden met zon-thermische collectoren. De energieproductie van zon-PV is lager met 0.73 GWh/j/ha, maar door de COP van de warmtepompen kan 171% van de totale jaarlijkse elektriciteitsvraag voor warmte geproduceerd worden met zon-PV. Als energiemais wordt verbouwd op alle beschikbare grond, kan ongeveer aan 6% van de jaarlijkse warmtevraag worden voldaan, omdat de energieproductie slechts 0.04 GWh/j/ha bedraagt.

Door de discrepantie tussen de vraag en opwekking, kan minder dan 20% van de opgewekte energie door zon-thermische en zon-PV collectoren direct gebruikt worden. De warmte die is opgewekt door de zon-thermische collectoren kan niet worden geëxporteerd. Dit is wel mogelijk voor de elektriciteit die is opgewekt door de zon-PV collectoren en meer dan 80% van de opgewekte elektriciteit moet worden geëxporteerd. Als zon-thermische opslagsystem worden meegenomen, kan ongeveer 92% van de opgewekte warmte gebruikt worden en kan voor 71% van de warmtevraag worden voldaan. Als waterstofopslag wordt meegenomen, kan 54% van de opgewekte elektriciteit gebruikt worden en kan aan 93% van de warmtevraag worden voldaan.

In de gecombineerde scenario's zijn de gebouwen die aangesloten zijn op een stadsverwarming ruim geïsoleerd, terwijl de gebouwen die verwarmd worden met een warmtepomp maximaal geïsoleerd zijn. Voor deze scenario's zijn ook de investeringskosten berekend. De investeringskosten voor een stadsverwarming zijn hoog, maar de schattingen van de vermeden kosten wegens de lagere isolatiegraad en de het feit dat het elektriciteitsnetwerk niet verzwaard hoeft te worden, liggen hoger. Ook is het zon-thermische opslagsysteem rond een factor 10 goedkoper dan het waterstof opslagsysteem, als het geïmplementeerd wordt op de schaal van de gemeente Groningen.

Als de definitie van energie neutraal op jaarbasis gevolgd wordt, dan kan worden geconcludeerd dan zon-PV zonder waterstofopslag moet worden gebouwd op alle beschikbare grond. Dit heeft echter grote gevolgen voor het balanceren van het elektriciteitsnetwerk. Als het hele energiesysteem van Nederland wordt meegenomen en gesteld wordt dat energie neutraliteit op uurbasis bereikt moet worden, dan is

het wenselijk om zon-thermische opslagsystemen op (een deel van) de beschikbare grond te bouwen, hoewel er rekening mee moet worden gehouden dat door de gekozen systeemgrenzen van dit onderzoek, deze conclusie op de schaal van de gemeente Groningen wordt getrokken en dat als een grotere schaal beschouwd wordt, andere uitkomsten mogelijk zijn.

ABBREVIATIONS

AD	–	Anaerobic Digestion
ATES	–	Aquifer thermal energy storage
BTES	–	Borehole thermal energy storage
CHP	–	Combined heat and power
CH_4	–	Methane
CO_2	–	Carbon dioxide
COP`	–	Coefficient of performance
DH	–	District Heating
$eff_{e \rightarrow h}$	–	Efficiency electricity to hydrogen
$eff_{h \rightarrow s}$	–	Efficiency hydrogen to electricity
ha	–	hectare
ETC	–	Evacuated tubular collector
FM	–	Fresh matter
FPC	–	Flat plate collector
GHG	–	Greenhouse gas
oDM	–	Organic dry matter
PTES	–	Pit thermal energy storage
TTES	–	Tank thermal energy storage
T_s	–	Supply temperature
T_r	–	Return temperature
T_m	–	Mean temperature
T_a	–	Ambient temperature

1. INTRODUCTION

In 1992, countries joined the United Nations Framework Convention on Climate Change (UNFCCC), which is an international convention ratified by 197 countries and the European Union. It states that all countries will work together to combat climate change by decreasing greenhouse gas (GHG) emissions. This resulted in the signing of the Kyoto-protocol in 1997, in which participating countries legally committed to binding emission reduction targets. The first commitment period of the Kyoto protocol was between 2008 and 2012, and the second commitment period began in 2013 and will end in 2020 (UNFCCC, n.d.).

Although almost all countries ratified the Kyoto-Protocol, there was a lot of criticism that the set targets weren't enough to combat climate change. On the climate conference in 2011 in Durban, South Africa, was agreed that a new treaty was needed, in order to accelerate and intensify the actions needed to reduce GHG emissions. This resulted in the Paris Agreement in 2015. In this treaty, which is already signed by 168 countries, is agreed that the global temperature rise this century will be kept well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C (UNFCCC, 2017).

1.1 The Netherlands

The Netherlands signed the Kyoto-Protocol and the Paris Agreement, and are also bound to European targets on combating climate change. In 2020, the European Union has to cut CO_2-emissions by at least 20% compared to the 1990 levels and 20% of the total energy consumption has to come from renewable energy sources. This will be further increased in 2030, when the CO_2 emissions have to be cut by at least 40% compared to the 1990 levels and renewable energy sources have to account for 27% of the total energy consumption (EU, 2014).

Although the European Union as a whole is on track to meet these targets (EC, n.d.), this has not been a priority for the Dutch government the last decades. The CO_2 emissions of the Netherlands in 2016 were 11% lower compared to 1990 (CBS, 2017b) and only 5.9% of the total energy consumption in the Netherlands came from renewable energy sources in 2016 (CBS, 2017a). Since the Dutch government does not undertake much action in meeting these targets, decentralized governments started to take things into their own hands. Provinces, municipalities, and regional water authorities have recently presented a joined investment plan 'Naar een duurzaam Nederland' ('To a sustainable Netherlands') in order to accelerate the transition to an energy neutral and climate resistant Netherlands (VGN, 2017). Various decentralized governments have been taking action for many years. In an inventory by Urgenda (Urgenda, 2009) in 2009 it became clear that many municipalities have set targets to become energy or climate neutral, varying from very ambitious targets of becoming energy neutral in 2020, to less ambitious targets of becoming energy neutral in 2050. One of the municipalities with the ambition to become energy neutral is the municipality of Groningen.

1.1.1 Groningen

The municipality of Groningen stated in 2006 that they wanted to become energy neutral in 2025. Five years later, in the 'Masterplan Groningen Energy Neutral' (Masterplan Groningen Energie Neutraal), it was stated that the first plan was too ambitious and that the municipality of Groningen would become energy neutral in 2035 (Gemeente Groningen, 2011). This document also contains a route map with goals set for 2025 that will bring the municipality of Groningen half way on meeting the final target for 2035, involving energy saving measures and the use of renewable energy sources such as wind, heat, biomass and the sun. The municipality of Groningen realizes that billions of euros are needed and that without private investments the goals will never be reached. By working together with companies, housing corporations and inhabitants the municipality wants to facilitate and boost these private investments (Gemeente Groningen, 2015). The initiated and planned projects and the progress that has been made is being monitored online by E&E Advies (Energiemonitor Groningen, 2017).

But the current and planned developments are by far not enough to reach the goal of becoming energy neutral in 2035. Therefore, the municipality of Groningen, together with Quintel and E&E Advies, is developing a new road map. Quintel will put the data of the municipality of Groningen in the Energy Transition Model (Quintel, 2010) to research what is (theoretically) possible and these outcomes will be used to develop the new road map for Groningen to become energy neutral in 2035.

Within the municipality of Groningen, there are some different areas which can be used for the generation of renewable energy. One possibility is to use these lands for the generation of electricity. But due to the intermittency of electricity generation by solar PV panels and wind turbines, storage options will need to be implemented to balance the electricity supply and demand at every moment during the year.
It is also possible to use these lands to cultivated energy crops, which can be stored and used directly or it can be converted to biogas. However, the yields in terms of energy per unit area are far lower compared to other renewable energy generating techniques.

Another possibility is to use these lands for the generation of heat. The heating of households is responsible for around 30 % of the total energy demand and natural gas provides around 90% of this energy. In 2035, only renewable sources will be used for heating in the municipality of Groningen (Noorman & Noordenburg, 2016). Instead of generating and consuming electricity for heating, solar energy can also be used for direct heating of water by thermal solar collectors. The hot water can be stored during summer and used in winter, relieving stress on the hourly electricity and gas balance. Furthermore, hot water is easier to store than electricity and can be stored in large quantities. Multiple plants, mainly in Denmark, have been successfully installed and implemented in the network already (SDH, 2016). These plants consist of a large array of solar thermal collectors (up to almost 157,000 m^2), short-term and/or long-term storage systems (up to 203,000 m^3 of hot water, with an energy content of around 16 GWh) and different (renewable) options like combined heat and power systems (CHP) and biomass or electric boilers that fulfil the demand at times when the solar thermal collectors and the storage system cannot (Weiss et al., 2017).

1.2 Research aim

The municipality of Groningen has the goal to be energy neutral in 2035. This research will focus on a part of this challenge, to have an energy neutral low temperature heat supply in the built environment in 2035. Within the municipality of Groningen, there are large pieces of land available for the generation of renewable energy. The aim of this research is to see, by means of a comparative scenario analysis, if it is desirable for the municipality of Groningen to install large scale solar heating plants on these lands. These large scale solar heating plants will be compared with two alternatives for which these lands can also be used in order to have an energy neutral low temperature heat supply in the built environment in 2035, solar PV and biomass.

1.3 Research questions

The main question that will be answered in this study is:
'In order to have an energy neutral low temperature heat supply in the built environment in the municipality of Groningen in 2035, is it desirable to construct large scale solar thermal storage systems on available lands or is it better to construct solar PV systems in combination with hydrogen storage or a biogas system in terms of energy production, investment costs, and balance implications?'

The following sub-questions are formulated in order to help answering the main question. A distinction has been made between definitions that have the be clarified, an analysis of Groningen, and the modelling results and comparison:

Definitions

I. What are the territorial boundaries of the municipality of Groningen?

II. What is meant with ‘energy neutral’ by the municipality of Groningen? And what definition of energy neutral will be used in this research?

Analysis of the municipality of Groningen

III. What is the total and hourly low temperature heat demand of the built environment in the municipality of Groningen? And how is this heat supplied?

IV. What is the expected total and hourly low temperature heat demand of the built environment in the municipality of Groningen in 2035? How can this heat be supplied?

V. Which pieces of land within the municipality of Groningen are available for the generation of renewable energy?

Results and comparison

VI. How much energy can be generated on a yearly basis by thermal solar collectors, solar PV collectors and by the generation of biogas from energy maize on these lands?

VII. What are the impacts (yearly energy yield per hectare, investment costs and balance implications) for the municipality of Groningen in 2035 if a large solar thermal storage system, a full electric PV system, a biogas system and a combination of these systems will be installed?

1.4 Structure of the report

In the first chapter, an introduction on the topic is given and the research aim and research questions are displayed. In the second chapter, characteristics of the municipality of Groningen that are of interest for this research are discussed and some definitions are clarified. This chapter also contains an analysis of the heat demand in 2016 and factors that influence the heat demand in 2035. An overview of the different possibilities in which this demand can be met is given in chapter three, as well as a further elaboration on the systems that will be considered in this research and the costs of the different components of the systems. An explanation of the used model, a description of the explored scenarios and the system boundaries can be found in chapter four. The results are displayed in the fifth chapter and will be discussed in the sixth chapter. A conclusion will be drawn in the seventh chapter, followed by recommendations for further research in the eight chapter. As last, the reference list and the appendices, in which some subjects that are discussed in this research are elaborated further.

2. CHARACTERISTICS OF THE MUNICIPALITY OF GRONINGEN

In section 2.1, the territorial boundaries of the municipality of Groningen that will be used in this research will be determined. In section 2.2, different definitions of energy neutral will be elaborated the definition that will be used in this research will be determined. Section 2.3 will describe which lands are available for the generation of renewable energy. The heat demand in 2016 will be determined in section 2.4, as well as a description of how an hourly heat demand pattern over a year will be determined. Factors that influence the heat demand in 2035 will be described in section 2.5.

2.1 Territorial boundaries of the municipality of Groningen

Since the first of January 2017, Meerstad has been merged with the municipality of Groningen (DvhN, 2017a). The territorial boundaries of the municipality of Groningen are displayed in figure 2-1, where red lines represent the present boundaries of the municipalities of Groningen, Ten Boer and Haren. The red dotted line represents the expended boundaries of the municipality of Groningen after the merging with Meerstad.

The Province of Groningen has made plans to merge the municipalities of Groningen, Ten Boer and Haren in 2019. The municipalities of Groningen and Ten Boer have agreed with these plans and signed them (Herindeling Groningen Haren Ten Boer, 2016), but the municipality of Haren is against these plans and did not sign them. The Dutch Parliament has the last say this matter and will vote about this. This means that it is not known for certain what the territorial boundaries of the municipality of Groningen will be in 2019.

For this research, the boundaries of the municipality of Groningen that will be used are the boundaries of the municipalities of Groningen and Ten Boer. These boundaries are displayed as the inners contours of the red (dotted) line around Groningen and Ten Boer in figure 2-1. Haren, located south of the municipality of Groningen in figure 2-1, will not be considered as part of the municipality of Groningen.

Figure 2-1. The territorial boundaries of Groningen, Ten Boer and Meerstad (red dotted line) will be considered as boundaries of the municipality of Groningen. Haren will be left outside of the boundaries of the municipality of Groningen. Adapted from (Provincie Groningen, 2016)

2.2 Energy Neutral

The city of Groningen stated her ambition to become the most sustainable city of the Netherlands in her policy program for 2006-2010. The policy program focussed on two themes: energy and the quality of the environment. The policy program for energy was further explained in 'Routekaart Groningen Energie Neutraal$^+$ 2025', which translates as 'Roadmap Groningen Energy Neutral$^+$ 2025'. Due to the growing awareness about the human influence on climate change and the need to reduce CO_2 emissions, the city of Groningen wanted to contribute to the energy transition that is needed to end the use of CO_2 emitting fossil fuels and therefore stated the ambition to become energy neutral in 2025 (Gemeente Groningen, 2008). In 2011, it became clear that this plan was too ambitious and in the document 'Masterplan Groningen Energieneutraal' the goal to become energy neutral in 2025 was adjusted to becoming half energy neutral in 2025 and energy neutral in 2035.

But, an energy neutral city, what does that mean? The 'Routekaart Groningen Energieneutraal$^+$ 2025' states that 'Energy neutral means the drastic reduction of CO_2 emissions.' This has to be achieved by prevention of energy use, energy savings and the generation of renewable energy. Also, fossil fuels have to be used as efficient as possible and the CO_2 emissions arising from the use of these fossil fuels can be compensated by planting trees (Gemeente Groningen, 2007). Another addition to this definition has been made in 'Masterplan Groningen Energieneutraal', which states that an energy neutral Groningen means that 'all the used energy over a year has to be produced CO_2 neutral' (Gemeente Groningen, 2011).

So energy neutral is defined as CO_2-neutral over a year, with the possibility to compensate CO_2 emissions by planting trees. This means that the city of Groningen has no net CO_2 emissions and is able to measure how energy neutral (or actually CO_2-neutral) they are at any point. This is happening on the website https://www.groningenenergieneutraal.nl/energiemonitor, where the most recent data about the energy use per sector (households, traffic, industry and institutions) and the use of all the different renewable energy sources in Groningen is being monitored. According to this website, energy neutral means that 'the final energy consumption is completely derived from renewable energy sources. This renewable energy can also be generated outside the borders of the municipality of Groningen.' (Energiemonitor Groningen, 2017).

As can be seen above, even within the same organisation different definitions are being used. There is no legislation for the usage of these definitions (Agentschap NL, 2010a). However, a consensus on the difference between energy neutral, climate neutral and CO_2 neutral has been tried to be reached in different studies. According to a study by BuildDesk in 2008, a municipal organisation can choose to become climate neutral, CO_2 neutral of energy neutral. A climate neutral organisation is does not influence the climate in any way, by not emitting any greenhouse gases like carbon dioxide (CO_2), methane (CH_4) and others. Being a CO_2 neutral organisation means that all CO_2-emissions are prevented, limited and compensated for if needed. In an energy neutral organisation the energy demand is completely provided by renewable resources. Storage of CO_2 in any form is therefore not an option for energy neutrality (BuildDesk, 2008). In a study commissioned by the Agentschap NL (2010b), a different distinction has been made between these definitions. In this study is argued that the term energy neutral should only be used if it is about the performance of a building. The term CO_2 neutral should be used if the performance of an organisation has to be measured and the term climate neutral should not be used, since this term can be interpreted in a much broader way.

From all these different definitions, one definition has been chosen after contact with Paul Corzaan (Corzaan P., December 5th, Gemeente Groningen, Groningen, p.c.) and Idso Wiersma (Wiersma I., December 12th, Gemeente Groningen, Groningen, p.c.) from the municipality of Groningen and states that energy neutral means that: 'all the used energy over a year has to be derived from renewable energy sources, with the possibility to import and export energy'. This definition is used by the municipality of Groningen and will be used for this research.

2.3 Available lands for the generation of renewable energy in the municipality of Groningen

As said before, the municipalities of Groningen and Ten Boer will be merged. Both municipalities have made an inventory of the lands available for the installation of solar PV parks (Gemeente Groningen, 2016; Gemeente Ten Boer, 2017).

An inventory of the lands that the municipality of Groningen possesses and which can be used for generation of electricity by solar PV been made in 'De Zonnewijzer' ('The Sundial'). This inventory does not include the lands of the municipality of Ten Boer, but even without this relatively sparsely populated municipality around 700 hectares of lands are available on which no developments will take place before 2030. Some small scale solar parks are already in development, at Vierverlaten (3 hectares), Roodehaan (19 hectares) and Woltjespoor (13 hectares), but the municipality of Groningen has plans to develop a 250 MW solar park in Meerstad Noord, which will be installed on around 250 hectares of land (Gemeente Groningen, 2016). A map of this inventory can be found in Appendix 1.

There have been some developments since this inventory has been made. The lands at 'Westpoort' are not available anymore. A former toxic depot above Zernike (Slibdepot Zernike) of around 13 hectares will be available and the municipality of Groningen is in contact with a Danish company to install solar thermal on these lands, but since this is not certain yet, these lands will be considered as available. The lands south of 'Slibdepot Driebondsweg oost' can also be used for the generation of renewable energy (Corzaan P., December 5th, Gemeente Groningen, Groningen, p.c.), which have an area of approximately 200 ha. At the lands where the former SuikerUnie factory used to be, houses will be constructed in the next years (DvhN, 2016). In table 2-1, the available lands and surface area for Groningen for 2017 are listed:

Table 2-1. Available lands in the Municipality of Groningen (Gemeente Groningen, 2016; Corzaan P., December 5th, Gemeente Groningen, Groningen, p.c.).

	Surface area (hectares)
Slibdepot Driebondsweg oost (+ south)	6.2 (+ 200)
Slibdepot Driebondsweg west	5.9
Roodehaan	47.6
Meerstad Noord	442
Slibdepot Zernike	13
Total	714.7

The municipality of Ten Boer has also made an inventory of lands that are suitable for the development of large- and small scale solar PV parks, as can be seen in Appendix 1 (Gemeente Ten Boer, 2017). The numbers 1-5 represent the location of possible large scale solar PV parks and the numbers 6-18 the location of possible small scale solar PV parks . The definition of large- and small scale depends on the energy consumption of the village where the lands are located next to. If the estimated yearly energy production of the solar PV park is larger than the prognosed energy consumption of the village in 2035, then the solar PV park is defined as a large scale solar PV park. Small scale solar PV parks have an estimated yearly energy production that is smaller than the prognosed energy consumption of the village in 2035.

The total area of the available lands has been estimated and can be found in Appendix 1. The total area of 1,745 ha is a theoretical maximum, since the policy framework states that a total of 230 hectares will be available for solar parks (Gemeente Ten Boer, 2017). However, these lands can be used for the cultivation of energy crops. Adding this to the available land area of the municipality of Groningen gives a total of around 945 hectares. Not taking into account the policy framework of Ten Boer gives a total area of around 2,460 hectares.

2.4 Heat demand in 2016

At Energieinbeeld (Energieinbeeld, 2017), the total electricity and gas consumption for each neighbourhood in the Netherlands is available. A distinction has been made between private consumers and commercial consumers. This source has been chosen after a comparison with different other sources such as the Energiemonitor (Energiemonitor, 2017), the report 'Groningen Aardgasloos in 2035' (Noorman & Noordenburg, 2016) and the Klimaatmonitor (Agentschap NL, 2017). They each make their own division between the sectors, not all the data is provided for the same years and some assumptions had to be made in order to derive a total low temperature heat demand. Further information can be found in Appendix 2.

Table 2-2 displays the gas consumption in the municipalities of Groningen and Ten Boer in 2016. Bulk consumers, such as SuikerUnie and others, are not taken into account (Energieinbeeld, 2017). The low caloric value of natural gas from the Groningen field of 31.65 MJ/m^3 (8.8 kWh/m^3) has been taken as the conversion factor (Nederlandse Gasunie, 1980).

Table 2-2. Gas consumption of the municipalities of Groningen and Ten Boer in 2016 (Energieinbeeld, 2017).

Groningen	Million m^3 natural gas	GWh	**Ten Boer**	Million m^3 natural gas	GWh
private	92	804	private	4.1	37
commercial	127	1,118	commercial	5.6	49
Total	219	1,922	**Total**	9.7	86

Gas is being used for almost the whole low temperature heat demand for households (Noorman & Noordenburg, 2016). The share of renewable heat in the total energy consumption of households was 2% in Groningen in 2016 (Energiemonitor, 2017). Since bulk consumers in the industry are not taken into account in this source, we can also assume that the total commercial gas consumption is used for low temperature heat. Notice that the gas that is being used for cooking is included, which is 40 m^3 per household on average in the Netherlands (Menkveld, 2014), but this is a neglectable amount compared to the total gas consumption and has therefore not been adjusted. The total low temperature heat demand of the municipalities of Groningen and Ten Boer combined in 2016 was 2,008 GWh, of which 841 GWh was private and 1,167 GWh was commercial and was supplied by gas.

To derive the hourly demand from the total yearly demand, data from the GasUnie will be used (Nederlandse Gasunie, 2016). The hourly demand of gas in 2016 in the Netherlands is given for consumption up to 5,000 m^3 per year (G1A) and for consumption higher than 5,000 m^3 per year (G2A) (DTe, 2006). Assumed is that the same distinction has been made between private and commercial gas consumption for the data provided by Energieinbeeld, while keeping in mind that for example flats often have one gas connection and by making this distinction, these connections are grouped under commercial.

The hourly low temperature heat demand per category has been divided by the total yearly low temperature heat demand per category in the dataset of the gas consumption of the Netherlands from Gasunie. These values will be multiplied by the total gas consumption per category in Groningen and Ten Boer in 2016 to get the hourly demand per category. Adding these values and dividing this by the total low temperature demand in Groningen and Ten Boer in 2016, will give the normalized hourly demand pattern.

2.5 Heat demand in 2035

The total yearly and hourly low temperature heat demand has been obtained for 2016 and will be used to forecast the total yearly and hourly low temperature heat demand in 2035. Factors that will influence the demand change in 2035 are population growth, better insulation in the built environment and a DH network, which are discussed below.

2.5.1 Population growth

According to a research by N. Rambharos (2016) for ‘Onderzoek en Statistiek Groningen’ the population of Groningen is expected to increase from 201,000 in 2016 to 227,000 in 2036. However, forecasts over the growth of the population of Groningen range from 214,000 to 270,000 in 2040 (DvhN, 2017c). In this research, the forecasts of Rambharos will be used, since these forecasts are close to the mean of the different forecasts.

The population of Ten Boer, 7,500 inhabitants, is expected remain unchanged (CBS, 2016). This means that the total population of Groningen and Ten Boer is expected to grow from 208,500 to 234,500, an increase of 12.5%.

2.5.2 Insulation

In the report ‘Op weg naar een klimaatneutrale gebouwde omgeving 2050’ (Towards a climate neutral built environment 2050) CE Delft has made an inventory of all the neighbourhoods in the Netherlands and divided these in 15 different neighbourhood types according to the date of construction, urbanity and function (Schepers et al., 2015).

The model that is being used in the report, CEGOIA (CE Delft, n.d.) is unfortunately not available for free, so therefore the findings of the ‘Actieplan Groningen aardgasloos 2035’ will be used (Noorman & Noordenburg, 2016). In this report all the neighbourhoods of the municipality of Groningen have been divided to one of the 15 different neighbourhood types. For the municipality of Ten Boer is assumed that it consist of type 13 and 14.

Three different insulation levels have been considered the study done by Schepers et al. (2015) and the savings and costs have been identified for the houses in each type for neighbourhood. In this research, the lowest insulation level will not be applied, since the heat savings are small for this level of insulation. Only extensive and maximal insulation will be considered in this research.

The total gas consumption per neighbourhood for 2016 is multiplied by the insulation saving factor as calculated from the data obtained from the report ‘Op weg naar een klimaatneutrale gebouwde omgeving 2050’ (Schepers et al., 2015). For neighbourhood type 10 the reduction levels due to insulation have not been given and therefore the lowest reduction factor from neighbourhood type 13 has been taken.

A decrease in annual low temperature heat demand (better insulation) has only consequences for space heating and not for hot water demand, while the total demand is only known. New total yearly demand decreases with the percentage that is being saved by insulation times the percentage of the total heat demand that is being used for spatial heating. For residential buildings, 78% of the total heat demand is used for spatial heating on average for all the different neighbourhood types. For non-residential buildings, this is 93% on average for all the different neighbourhood types (Schepers et al., 2015).

For the non-residential buildings, the payback time and yearly savings have been identified for the three different insulation levels, as can be seen in table 2-3.

Table 2-3. Insulation levels, payback time, annual heat savings and costs for non-residential buildings (Schepers et al., 2015).

Insulation level	Payback time (y)	Savings (%)	Costs
Moderate	5	17	5 x the saved yearly energy costs
Extensive	10	27	10 x the saved yearly energy costs
Maximal	20	33	20 x the saved yearly energy costs

The fact that thermostat settings change with the higher insulation of buildings, the temperature during the day does hardly differ from the temperature at night, and therefore cause a flattening effect on the demand (Melle et al., 2015), is not taken into account in this research.

3. SYSTEM DESCRIPTION

In the first part of this chapter different heat supply systems will be considered and these will be elaborated in further details in the following sub-chapters, starting with the solar thermal storage system in section 3.2. The solar PV system in combination with hydrogen storage will be described in section 3.3 and the biogas system will be explained in section 3.4. In section 3.5, an overview will be given of the considered systems and all the considered costs of the different system components can be found in section 3.6.

3.1 Heat supply in 2035

As mentioned before, almost the whole low temperature heat demand is currently being supplied by natural gas. In order to achieve an energy neutral low temperature heat supply in 2035, natural gas has to be replaced by renewable energy carriers, that can be generated on the available lands as discussed before. For this research, three different energy carriers will be considered that can be generated on these lands.

The first energy carrier that will be considered, is heat produced by solar thermal panels, placed in large arrays. The water that runs through the panels is being heated by the sun and is delivered to the built environment by the district heating network directly or can be stored to be utilized later. Another option is to use waste heat from the industry and feed this into the district heating system, but this option will not be considered since there is not much industry in Groningen and it is uncertain that waste heat will be available in the long term, due to increased efficiency standards. The heat can also be extracted from the underground, called geothermal heat. The municipality of Groningen made plans to drill a geothermal well, but since the seismic risks involving the drilling were not clear, this project has been put to hold and it is unclear if this will be allowed later (DvhN, 2017b).

The second energy carrier that will be considered is electricity. In this case, the built environment will be connected to the electricity grid only, the so called 'all electric' option. To generate the electricity, large scale solar PV parks can be installed on the available lands. Electricity can also be generated by wind turbines, but due to legislation of the Province of Groningen only small scale wind-turbines with a rotor diameter smaller than 15 meter can be considered (Provincie Groningen, 2009). A company from Groningen, EAZ wind, is producing small wind turbines with a diameter of 12 m and a capacity of 10 kW (EAZ, 2017), but this option will not be considered, due to the limited capacity. The electricity will be used by heat pumps for low temperature heating. For this option, far reaching measures to insulate the houses have to be taken (Noorman & Noordenburg, 2016) and the capacity of the electricity network will have to be upgraded in order to meet the electricity demand for very cold periods (Quintel et al., 2017).

The electricity can be imported and exported or it can be stored by means of electrolysis, a process in which hydrogen is produced by electricity and water. Hydrogen can then be converted back to electricity at times when the demand is higher than the supply. In Leeds, UK, there are plans to upgrade the existing gas network so that hydrogen can be used instead of gas (Sandler et al., 2016), but this option will not be discussed in this research. Batteries will not be considered, although they have much higher efficiencies, they are not suitable for supplying seasonal storage, as the time-dependent losses are high and the energy density is low (Broekema, 2016).

The third energy carrier that will be considered, is biogas. Biogas can be utilized in different ways for heating. Energy crops can be cultivated and the energy can be extracted in the shape of biogas by means of Anaerobic Digestion (AD), which can be used in a biogas boiler and distributed by means of a DH network. The biogas also can be upgraded to green gas and made suitable to be injected in the existing gas network, but this is an energy intensive process, 'since over a third of external energy is needed for the process itself' (Pierie et al., 2017) and this will not be considered in this research.

3.2 Solar Thermal

A large scale solar heating plant consist of an array of thermal solar collectors, a storage system and one or more systems that supply the rest of the heat.

3.2.1 Solar thermal collectors

The most common collector types are evacuated tubular collectors (ETC) and flat plate collectors (FPC). It is also possible to use concentrating collectors, but since a large part of the irradiation is diffuse in the northern part of Europe and these types do not utilise the diffuse radiation, these types will not be considered in this study.

In Europe, FPCs and ETCs make up 83.4% and 11.9% respectively of the total installed capacity (Weiss et al., 2017). An advantages of FPCs compared to ETCs is that they are made in larger units, which means a lower number of pipes connecting the collector units, lower pressure losses and a higher efficiency. The most commonly used collectors for large solar district heating plants in Denmark have an aperture area of 13-14 m^2. ETC collectors are normally more expensive compared to FPC collectors and the durability of ETCs so far has not been proved in large solar district heating systems (Trier, 2012). On the other hand, due to the overall higher efficiency, ETCs can be preferred for high temperatures (Schmidt et al., 2015).

In this research, the HTHEATstore 35/10 thermal collector will be considered (Acron-Sunmark A/S, 2016). This solar collector is manufactured by Acron-Sunmark, which developed many large scale solar thermal collector parks in Denmark (Acron-Sunmark A/S, n.d.). It has also been tested under quasi-dynamic conditions, which is essential to determine the parameters needed to calculate the efficiency and power output of the collector. The collector has a minimal lifetime of 20 years, which means that they are supposed to keep their original efficiency 20 years. Usually they are kept in operation longer, but the same performance is not guaranteed (Bava et al., 2015).

The efficiency of the solar thermal collector is not constant and can be calculated with the quasi-dynamic approach (Fisher et al., 2001). Further information about the assumptions that have been made for this research and the parameters described can be found in Appendix 4. The resulting formula (1) that will be used to calculate the power output at each hour during the year is shown below. A loss factor of 15% will be taken into account, due to shadings, non-optimal flow distributions, dust, snow, and other unforeseen losses

$$P_c = A_c \cdot (\eta_0 \cdot (G_b \cdot K_\theta + G_d \cdot K_d) - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2) \quad (1)$$

Where,

P_c: Power output of the collector	[W]
A_c: Effective collector area	[m^2]
η_0: Maximum efficiency if there is no heat loss	[–]
G_b: Beam radiation (direct) on collector plane	[W/m^2]
K_θ: Incident Angle Modifier for the incidence angle at the given time step	[–]
G_d: Diffuse radiation	[–]
K_d: Incident Angle Modifier for diffuse radiation	[–]
a_1: 1st order heat coefficient	[$W/(K \cdot m^2)$]
a_2: 2nd order heat coefficient	[$W/(K \cdot m^2)$]
T_m: Mean collector fluid temperature	[°C]
T_a: Temperature of the ambient air	[°C]

To calculate the amount of heat delivered at each hour during the year, the formula is implemented in Excel with the global horizontal irradiation and ambient temperatures as found for 2016, a year with average temperatures and irradiation, for each hour at the meteorological institute of the Netherlands in Eelde (KNMI, 2016). The global horizontal irradiation is converted to the irradiation under an angle following the method explained in Appendix 3. The global irradiation under an angle is split in direct and diffuse irradiation, following the method explained in Appendix 4. The collectors are oriented under an angle of 36 ° facing south (Spruijt, 2015). The supply and return temperature of the water of the district heating network that are being used in this research are 80°C and 40°C respectively, as is the case in many Danish DH networks (PlanEnergi, n.d.; DEA, 2015) and assumed to be constant throughout the year. The district heating network of Warmtestad that will run through a part of Groningen will have a supply and return temperature of 88-95°C and 58-65°C respectively (Venema T., January 24th 2018, Warmtestad, mail contact). These temperatures will also be used in order to make investigate the effects of higher supply and return temperatures on the energy yield. The performance parameters of the HTHEATstore 35/10 thermal solar collector are taken from (Arcon-Sunmark A/S, 2016). The direct incident angle modifier has been calculated for each hour as described in Appendix 4. For 1 m^2 effective collector area, around 3-4 m^2 land is needed *(*Sørensen, 2012*)*. This is because space is needed between the collector rows to place the pipes and to prevent shadings. In this research, we assume that 3.5 m^2 land is needed for 1 m^2 effective collector area, resulting in an efficient solar thermal area of around 28.6%.

3.2.2 Thermal energy storage

Due to the fact that most heat is generated in summer and the heating demand is highest in winter (see figure 3-1), it is hard to meet the energy demands only with solar energy. To utilise the solar energy as much as possible, seasonal storage is inevitable. In this way, the excess generated heat in summer, the yellow part in figure 3-1, can be stored and utilised in winter. In Appendix 5, more information can be found about the different thermal energy storage technologies.

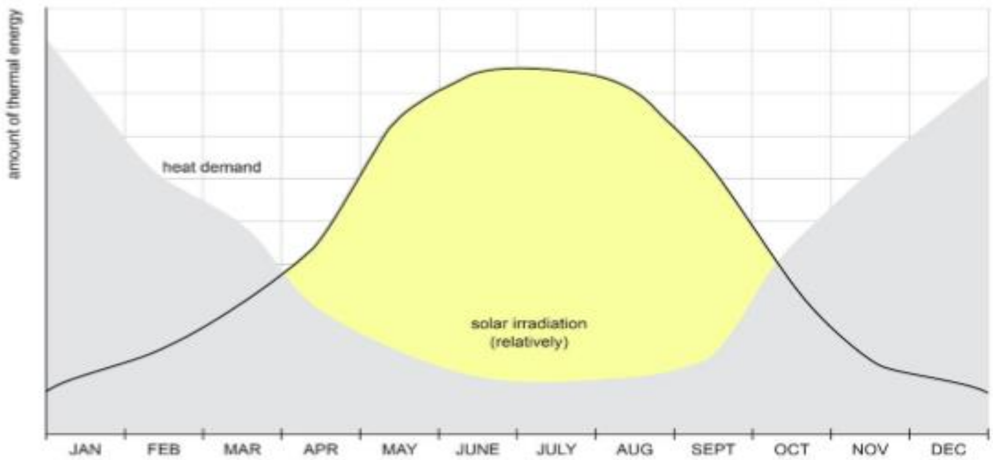

Figure 3-1. Example of the solar irradiation and heat demand during a year. (PIMES, 2012)

In this research, only tank and pit water storage will be considered. These types of storage has been chosen since they can be installed on many locations and the temperature of the water delivered to the storage is the same as the temperature of the water delivered to the district heating network. The tank thermal storage will be used as a buffer for short term storage, while the pit thermal storage can be used for seasonal storage as well.

With TTES (tank thermal energy storage) the tank is filled with water to store thermal energy. The tank structure can be made of steel, concrete or of glass fibre reinforced plastic and can be located on the ground, partially buried or completely underground. Insulation is fitted outside the tank to reduce thermal losses to the environment. Due to the relatively high investment costs, TTES is most commonly used as a short-term thermal energy storage option and can also serve as a buffer in combination with other thermal energy storage options (Guidalfajara et al., 2014; Schmidt & Miedaner, 2012). The tank is being filled with hot water that is taken from the tank directly at times when the heat demand exceeds the supply by the solar thermal collectors.

With PTES (pit thermal energy storage), the pit storage consist of an artificial pool which is closed on top. The tilted walls of the pool and the bottom are heat insulated and the roof over the artificial pool is floating on the water. The maximal stored temperature is about 80-90°C (Mangold & Deschaintre, 2015). In times when the heat supply exceeds the demand and the tank is full, the hot water from the thermal solar collectors is delivered to the pit storage directly and heats up the storage by means of a heat exchanger. This heat can be supplied at times when the demand exceeds the supply, extracted from the storage with a heat exchanger. The water in the pit storage cools down and sinks to the bottom, resulting in a stratified distribution of the water, with the hottest water in the upper part of the pit. Currently, the largest pit storage of 203,000 m^3 is located in Vojens, Denmark (Weiss et al., 2017).

Every loading period heat losses will be added to the surroundings, causing the yearly mean ground temperature to increase, the temperature gradient to decrease and therefore reducing the heat losses every loading period, until a steady-state is reached. For PTES this steady state is reached after three to five years (SUNSTORE 2, 2005). This will not be taken into account in this research, and a steady state is assumed to be reached right away. The yearly heat losses are taken from measurements at the Dronninglund pit storage, which had an efficiency of 90% in 2015 (Schmidt(a), n.d.). For simplicity, the same heat losses are assumed at for the TTES.

3.2.3 Solar thermal system

In solar thermal storage systems in Denmark, typically around 50% of the heat is supplied by solar thermal collectors and the storage. There are many different ways in which the other 50% of heat can be delivered, and this is done by a combination of boilers, CHP plants and heat pumps. The type of fuel and the capacity is location dependent. More information about the different combinations that are in use can be found in (PlanEnergi, n.d.; SDH, 2017; Schmidt et al., 2015; Schmidt (a), n.d.).

For simplicity, and in order to be able to later combine the different systems that are being researched in this thesis, a biogas boiler will be considered, with and without TTES and PTES in combination with a heat pump. The solar thermal system with storage can be seen in figure 3-2.

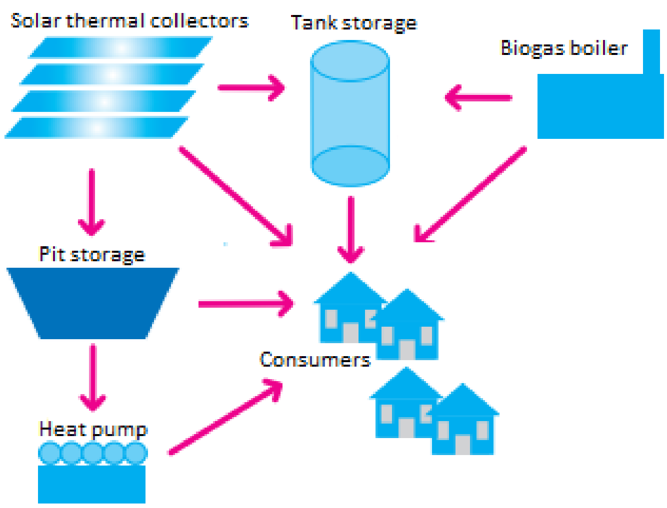

Figure 3-2. Solar thermal storage system that is considered. Adapted from (Ulberg, 2017)

At the moments when the sun is shining, heat is being generated by the thermal collectors. This can be delivered directly to the consumers by means of a DH network, and if the supply is higher than the demand, it can be stored in the tank, for short term storage. If the tank is full, the excess heat can be stored in the pit storage, for long term storage. Hot water from the tank storage will be utilized first at times when the supply from the solar thermal collectors is lower than the demand. If the tank storage is empty, either the biogas boiler, the pit storage, or the heat pump will deliver heat to the consumers, depending on the heat content of the pit storage. The biogas boiler can also fill the tank storage, that can act as a buffer and that can be used during peak demand hours in winter.

Due to the stratification of the water in the pit storage, the hottest water is located in the upper part of the storage. The more heat that is extracted from the storage, the more these stratified layers are mixed. When the pit storage does not contain any water that is warm enough to be fed in the DH network directly, the heat pump uses the storage as a heat source in order to deliver water at the desired temperature, as can be seen in figure 3-3.

According to David et al. (2017) who researched the average COP of large scale heat pumps in DH systems, the average COP for heat pumps with an output temperature of > 80°C is 3.7 which means with a capacity of 10 MW_{el}, 37 MW_{th} can be supplied.

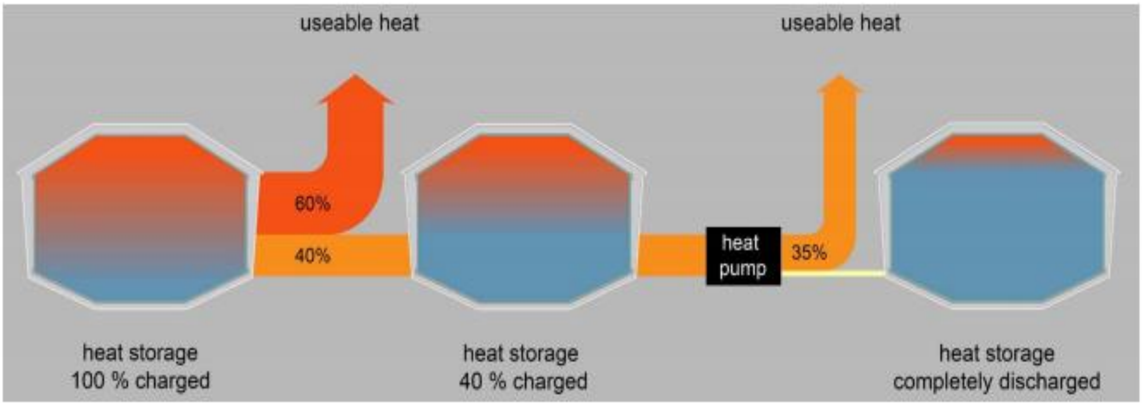

Figure 3-3. Example of energy flows in the pit storage and use of a heat pump (Mangold et al., 2016). On the left is the situation when the storage is fully charged and the hot water fed in directly in the DH network. When the water in the storage is not hot enough to be fed in directly, the heat pump uses the storage as a heat source in order to deliver the water in the DH network at the desired temperature.

The capacity to accumulate thermal energy in a sensible heat storage depends on the temperature amplitude between the minimum and maximum temperature in the storage. It also depends on the storage volume V (m^3), and the thermal capacity $\rho \cdot c_p$ (kWh/(m^3K)) of the storage material, which is 1.16 kWh/m^3K for water (Guidalfajara et al. ,2014).

$$E_{max} = V \cdot \rho \cdot c_\rho \cdot (T_{max} - T_{min}) \quad (2)$$

In the Dronninglund pit storage, the maximum temperature of the storage is 89°C and the minimum temperature 10°C (Schmidt, n.d.(a)). In this research, another maximum temperature will be considered, since the solar collectors supply heat to the storage at 80 °C. By formula 2, with a volume of 100,000 m^3 water, the storage has an energy content of 8,120 MWh.

From the monitoring results in the pit storage in Marstal, Denmark, in 2013 (Schmidt, n.d.(b)) and 2015 (Schmidt, n.d. (a)), the percentage of the stored heat that has to be extracted with a heat pump will be calculated. For 2013, this was 2,922 MWh out of a total of 7,538 MWh, which is 38.7%. For 2015, this was 1,528 MWh out of a total of 7,813 MWh, equal to 19.6%. The reason for this difference might be due to the difference in T_{min} and T_{max} of the storage in the different years. In 2013, T_{max} was 77°C and T_{min} was 12.9 °C, while in 2015 T_{max} was 84°C and T_{min} was 20 °C. Since the temperatures of the pit storage that are considered in this research, are close to the temperatures as measured in 2013, a percentage of 38.7% will be considered.

The tank storage is considered to be filled with water at 80 °C. This water is fed in directly in the DH network and delivered to the consumers, until the storage is empty. The minimum temperature that is considered here is the flow back temperature of the DH network, which is 40 °C. Using formula 2, this results in an energy content of 232 MWh for a tank with a volume of 5,000 m^3

3.3 Solar PV system with hydrogen storage

Instead of directly heating the water by the sun with solar thermal collectors, it is also possible to use solar PV panels to generate electricity from the solar irradiance and to deliver heat to the built environment by means of heat pumps, which will be discussed in the next section. The power output of the solar PV panel depends on the solar irradiation on the solar PV panel and the efficiency. The method described in Appendix 3 has been used to get the hourly values of the global irradiation under an angle. The collectors will be under an angle of 36 ° facing south (Spruijt, 2015). The efficient solar PV area is 36%, which is calculated from (Spruijt, 2015). Calibrating this to the SunPower SPR-315E-WHT-D collector (SunPower, 2009), which has a efficiency of 19.3%, gives 695.5 kWpeak per hectare. A loss factor of 15% will be taken into account, due to inverter losses, shadings, dust, snow and other unforeseen losses.

Having figure 3-1 in mind, one can see that a seasonal storage is also inevitable for the solar PV system. This can be done by the electrolysis of water to hydrogen gas at times that the supply exceeds the demand. Hydrogen can then be converted back to electricity at times when the demand exceeds the supply. The roundtrip efficiency, the electricity – hydrogen efficiency ($eff_{e\rightarrow h}$) and the hydrogen – electricity efficiency ($eff_{h\rightarrow s}$), is considered to be 45% (Andrews & Shabani, 2012; Alexander et al., 2014). Assumed is in this research is that $eff_{e\rightarrow h}$ = 60% and $eff_{h\rightarrow s}$ = 75%. The lower calorific value of hydrogen is 10.779 MJ/m^3 and the density at a temperature of 0°C and 1 bar pressure is 0.0898 kg/m^3 (Nederlandse Gasunie, 1980). This means that the 1 kg of hydrogen contains 33.34 kWh. So for 1 GWh of electricity, 0.6 GWh is converted to hydrogen by an electrolyser. This results in 18 tonnes hydrogen with a volume of 2.0 * 10^5 m^3 at normal atmospheric pressure. Under 350 bar, the volume is decreased to 5.7 * 10^2 m^3 which can deliver 0.45 GWh of electricity with a fuel cell.

3.3.1 COP of heat pumps

In order to convert electricity to heat, individual heat pumps will be used for each building. The efficiency of the electricity to heat conversion, depends on the Coefficient of Performance (COP), which depends on the source of the heat pump. The COP of an air-source heat pump depends on the outside temperature, while the COP of a ground-source heat pump depends on the temperature of ground water. In this research, only air-source heat pumps are considered. Although ground-source heat pumps have a higher efficiency, it is hard to install this in existing houses, because of the installation of heat exchangers (Melle et al., 2015)

In the study 'De systeemkosten van warmte voor woningen' (The system costs of heat for households) done by Ecofys, the COP dependence on the ambient temperature of 17 different air-source heat pumps is analysed and a linear fit has been made for the COP for space heating (35°C) and for hot tap water (50°C). These linear fits, with a COP of 1.5 at -20°C and a COP of 5 at 20°C for space heating and a COP of 1 at -20°C and 2.7 at 20°C for hot tap water, will be used in this study (Melle et al. ,2015). The linear fits are displayed in the following formulas:

$$COP(35°C) = 1.5 + 0.0875\ (20 + T)$$
$$COP(50°C) = 1 + 0.0425\ (20 + T)$$

From these two linear fits, a weighted COP will be determined, depending on the ratio of the space heating demand / total demand and the hot tap water demand / total demand respectively. These ratios have been obtained from the study 'Op weg naar een klimaatneutrale gebouwde omgeving' by CE Delft and an average for all the different neighbourhood types has been calculated, depending on the insulation level (Schepers et al., 2015). In this way, two different weighted COPs are obtained for households and utilities. The hourly heat demand after insulation of households and utilities is then divided by the weighted COPs of households and utilities respectively, which will be calculated for each hour during the year with the hourly temperatures of 2016.

3.4 Biogas system

The third option that is considered in this research for which the available lands mentioned in section 2.3 can be used, is to cultivate energy crops and extract the energy in the shape of biogas by means of AD. In this research, biogas will be considered since the upgrading of biogas to green gas is an energy intensive process and biogas can be utilized directly in a biogas boiler as well, which makes it a suitable fuel for the district heating network.

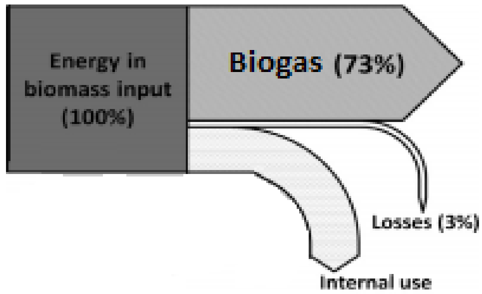

Figure 3-4. Average efficiency of the biogas utilization pathway.
(Adapted from Pierie et al., 2016)

As discussed in section 2.3, the amount of land on which energy crops can be cultivated, 2,460 hectares, is higher than the amount of land on which solar parks can be installed. According to the Dutch legislation, at least 50% of the feedstock used in an AD system must consist of manure (Pierie, 2017). In Groningen and Ten Boer combined, a total of 213,000 tonnes of mixed manure dairy is available, of which 6.4% is organic dry matter (oDM) and the biogas potential is 350 Nm^3/tonne oDM. Although most the manure is available in the winter, when the animals are held inside, assumed is in this research that the manure is available throughout the year. For the other 50%, cultivated energy maize will be considered in this research. Energy maize has a typical biomass yield of 45 tonne/ha, of which 30% oDM. The biogas potential is 606 Nm^3/ tonne oDM. This means that the oDM potential per hectare is 13.5 tonnes and the biogas potential per hectare is around 8,200 m^3. This biogas consists for around 53% of methane (Pierie et al., 2016).

The efficiency of the AD process for different utilization pathways has been determined by Pierie et al. (2016) Their findings for the green gas utilization pathway have been adapted to the biogas utilization pathway as used in this research. The external energy use in the green gas pathway is higher than it would be in the biogas pathway, since the biogas is upgraded to green gas through the use of a highly selective membrane upgrader system. The rest of the external energy use is required for the process itself (transport, electricity). The external energy will not be accounted for in this research, since we want to compare biogas with solar thermal and PV, and the energy usage of the production and installation of these collectors and facilities is outside the system boundaries. Therefore, the efficiency of the AD process is 73%, as can be seen in figure 3-4. The main properties of energy maize and mixed manure are displayed in table 3-1.

Table 3-1. Main properties of energy maize and manure mixed dairy feedstocks (Pierie et al., 2016).

	FM tonnes/ha*a	**oDM (tonnes/ha*a)**	**Biogas potential (Nm^3/ha*a)**	**Efficiency AD**
Feedstock				
Energy maize	45	13.5	8,200	73%
	Available FM (tonnes/y)	oDM (%)	Biogas potential (Nm^3/tonnes oDM)	
Manure mixed dairy	213,000	6.4	350	73%

3.5 Systems overview

In figure 3-5, the considered systems are displayed. The available lands can be utilized for solar PV panels, solar thermal panels or for the cultivation of energy maize. Electricity will be generated by solar PV panels, and can be delivered directly to the maximally insulated buildings, it can be exported or can be utilized by an electrolyser in order to make hydrogen. The hydrogen will be stored in tanks under 350 bar and at moments that the demand is higher than the supply from the solar PV panels, the hydrogen can be used by a fuel cell in order to generate electricity or electricity can be imported. If solar thermal collectors are installed on available lands, hot water will be generated and can be distributed directly to the extensively insulated buildings by means of a DH network, or stored in a tank. If the tank is full, the water can be stored in a pit storage. At moments that the demand is higher than the supply, stored water from the tank will be used to deliver heat to the extensively insulated households, and if the tank storage is empty, water from the pit storage can be used. If the water from the pit storage is not warm enough to deliver heat directly to the DH network, a heat pump will use the pit storage as a heat source and utilize electricity in order to deliver heat to the DH network. Another way in which heat can be delivered to the DH network, is by means of a biogas boiler. In this case, the available lands will be used to cultivate energy maize. The energy maize will be mixed with the same amount of mixed manure and put in the anaerobic digester, which will generate biogas. The biogas will be stored and utilized by means of a biogas boiler in order to deliver heat to the DH network directly, or stored in the tank first. Biogas can also be imported.

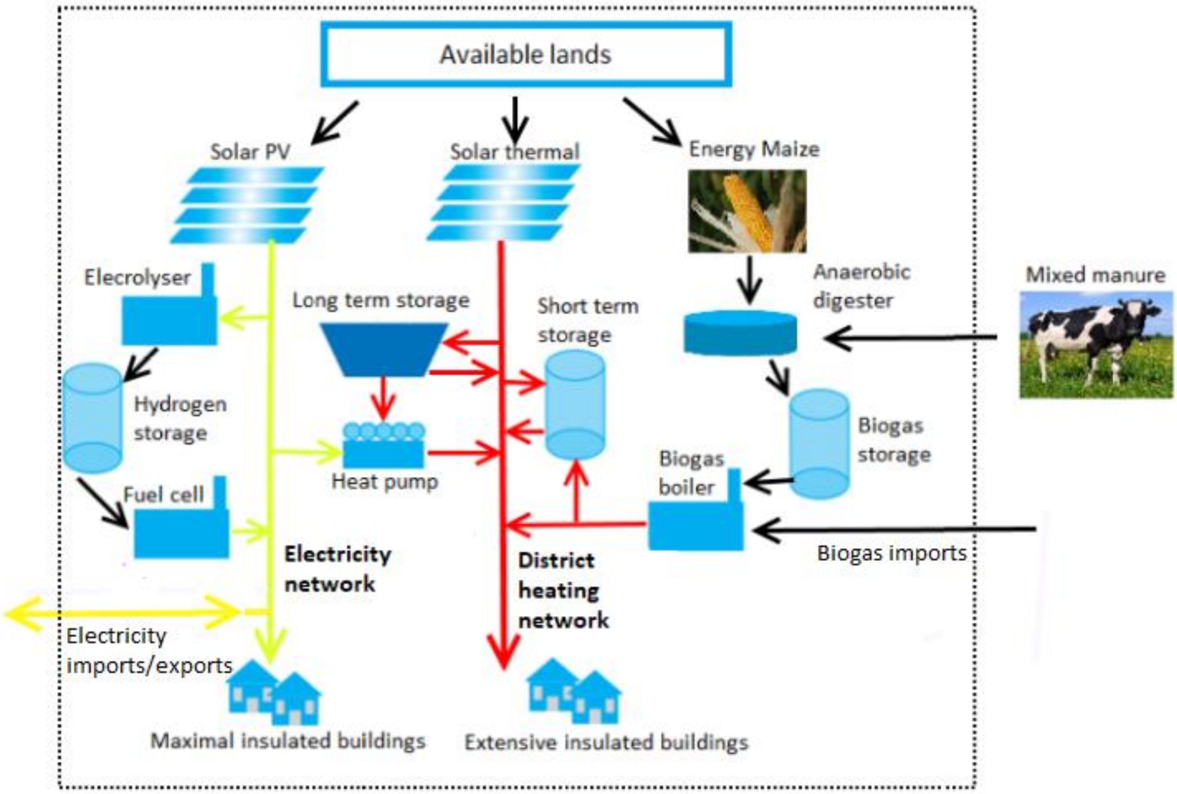

Figure 3-5. Overview of the considered systems and the relations between the system components.

3.6 Costs of the system components

In this section, the costs of the components of the explored systems will be given. These values will be used in the scenarios in the next chapter and all the costs will be normalized to a lifetime expectancy of 25 years. A summary can be found in Appendix 7 table 0-13.
The costs of solar thermal collectors, including collector installation, pumps, control and others, are estimated to be in the range of 180 €/m^2 (Solarheatdata, 2016) to 250 €/m^2 (Nielsen, 2017). At Solarheatdata, the total costs for the thermal collectors and the effective collector area of the solar thermal collector system is given and dividing these two gives 180 €/m^2. Since we assume that 1 m^2 effective collector area is placed on 3.5 m^2 land, the costs per hectare range from €510,000 or €710,000, with a lifetime of 25 years. For solar PV collectors, the costs including installation are €650,000 per hectare according to (Spruijt,2015). Assumed is that the more efficient solar panels used in this research have the same price and that the lifetime of the solar panels is 25 years. For the cultivation of energy maize is assumed that there are no costs.

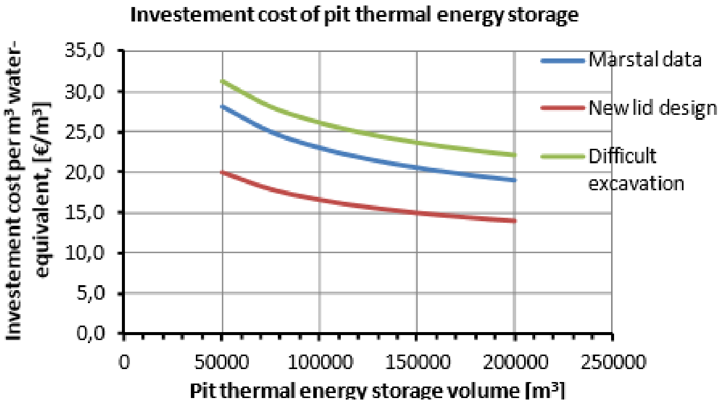

Figure 3-6. Estimated cost curves of PTES (Maripuu & Dalenbäck, 2011)

Four different storage systems are considered in this research. PTES, TTES, hydrogen storage and biogas storage. For PTES, the investment costs PTES depends mainly on the size and the geological conditions. Figure 3-6 shows the investment costs in three different cases. The central line is based on the result of the 75,000 m^3 storage in Marstal. The top line is the upper limit and the lower line represent possible savings by further developments in the design of the PTES (Maripuu & Dalenbäck, 2011). In table 3-2, the parameters and formula described in section 3.2.1 taken and have been calculated for a PTES with a volume of 200,000 m^3 water. This is almost the same size as the PTES in Vojens, which has a volume of 203,000 m^3 (Weiss et al., 2017). For TTES, 5,000 m^3 steel water tanks can be constructed for a price ranging from around 85 €/m^3 (Ellehauge & Pedersen, 2007) to 160 €/m^3 (Guidalfajara et al., 2014) and even higher for smaller volumes. For both TTES and PTES, an expected lifetime of 25 years is considered in this research.

Table 3-2. Energy content and costs for PTES and TTES.

	Energy content (MWh)	Costs (million €)	€/MWh storage
Volume: 200,000 m^3			
PTES difficult	16,240	4,400	271
PTES new lid design	16,240	2,800	172
Volume: 5,000 m^3			
TTES high	232	0.8	3,450
TTES low	232	0.425	1,830

As explained in section 3.2.3, a heat pump is used to completely empty the storage. The typical investment costs for industrial size heat pumps are around €300,000/MW (Maripuu & Dalenbäck 2011). The lifetime is assumed to be the same as for the air-source heat pumps, which is considered to be a valid assumption since the heatpump will be used only in combination with the discharging of the seasonal storage and will therefore only be used a part of the year.
The costs of hydrogen storage tanks at 350 bar are 440 €/kg in 2010 and are expected to decrease to 240 €/kg in 2030. The lifetime is expected to stay at 25 years. Elektrolysers are expected to decrease linearly in price from 1,200 €/kW in 2010 to 100 €/kW in 2030, and for fuels cells this is expected to be

from 1,600 €/kW in 2010 to 100 €/kW in 2030 (Andrews & Shabani, 2012). Prices are given in dollars and assumed in this research is that 1 $ = 0.8 €. The lifetime is expected to increase from 10 years in 2010 to 20 years in 2030. Two different prices and lifetimes will be considered, a lower boundary (2030) and an upper boundary (2016).

The storage costs for biogas are in the range of 25-35 €/m^3 (TUV, 2012), and for this research a price of 30 €/m^3 is used. A lifetime of 25 years is assumed, similar as that of the hydrogen storage tanks. For the biogas AD system and the feedstock pretreatment, the total investment costs are €53.64 and €3 per tonne per year respectively, with a lifetime of 25 years (Pierie et al., 2016). For the biogas boiler, the investment costs amount to €60,000 per MW and the lifetime is 25 years (DEA, 2016).

The costs of air source heat pumps for buildings, including installation, are €8,000 each (Rooijers et al., 2018). The theoretical lifetime is between 15-20 years, but in practice many heat pumps have a lifetime which is longer than 30 years (Daikin, n.d.). In this research, a lifetime of 25 years is assumed. For simplicity is assumed that each building needs the same heat pump, although in practice the needed capacity of the heat pumps varies per building and household. With the installation of heat pumps, the demand for electricity increases significantly and reinforcements to the electricity grid are needed. According to Rooijers et al. (2018) the costs per kW reinforcement are €961 and per maximally insulated building with an air source heat pump 4.1 kW of reinforcement is needed, with a lifetime of 40 years. The costs for the extensive and maximal insulation, with a lifetime of 40 years, have been obtained from (Schepers et al., 2015) and are displayed in table 3-3.

Table 3-3. Insulation costs per house for the different neighbourhood types and insulation level in thousands of euros (Schepers et al., 2015)

Neighbourhood type	Extensive insulation (k€)	Maximal insulation (k€)
2	5.5	15
3	7.5	13.5
6	5	14.5
7	4.5	13
8	5	22.5
9	5	26
10	8	22.5
11	1	17
12	1	30
13	8	22.5
14	8.5	34
15	3	27

For connections to the district heating network, different prices have been found. According to Rooijers et al. (2018), the costs to connect a house is €12,000 and an apartment €8,000, but for an average house this can also be in the range of €20,000 to €25,000. For this research, a lower boundary and an upper boundary will be considered, with the amount of €10,000 and €25,000 respectively.
Since the lands where the solar thermal collectors are placed, are not always directly next to the DH network, this water needs to be transported to the DH network. According to an assessment done by the Department of Energy & Climate Change in the UK (DECC, 2015), the costs range from 980 €/m to 1,650 €/m, assuming that £1 = €1.12. The lifetime of these pipe connections is expected to be 50 years and the same lifetime will be assumed for connections to the district heating network.

4. METHODS

In this research, a comparative scenario analysis is carried out. The model that is being used to explore the different scenarios is EnergyPLAN, which will be discussed first in section 4.1. Afterwards, the different scenarios that will be explored in this research, will be elaborated in section 4.2 and in section 4.3 the system boundaries will be described.

4.1 EnergyPLAN

EnergyPLAN has been developed by the Aalborg University and expanded on a continuous basis since 1999. The analysis is carried out in hourly steps for one year and the consequences are analysed on the basis of different technical simulation strategies as well as market-economic simulation strategies. The identification and interpretation of the results are left for the user of the model. An overview of the components of the energy system of EnergyPLAN can be seen in figure 4-1.

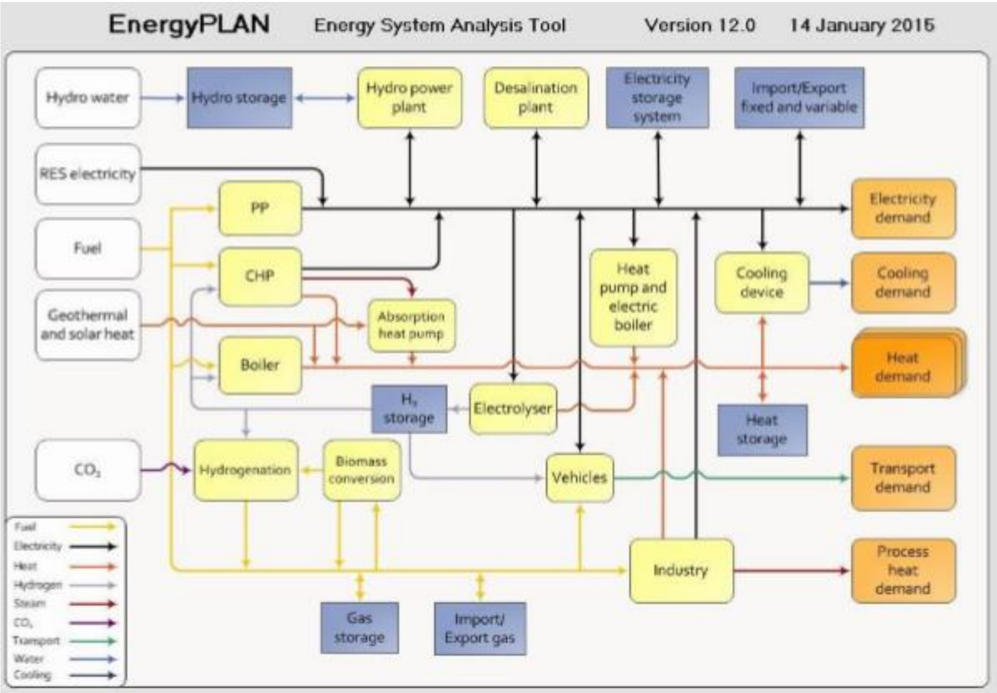

Figure 4-1. Overview of components of EnergyPLAN (Lund, 2015)

The model is an input/output model. General inputs are demands, renewable energy sources, energy plant capacities, costs and a number of optional different simulation strategies emphasising import/export and excess electricity production. The demand and supply patterns that are described in the chapters above, are calculated following the methods described and will be used as inputs for the model. Outputs are energy balances and resulting annual productions, fuel consumption and import/exports (Lund, 2015). These outputs are rounded off to units of 10 GWh. The model includes a lot of different options that will not be used in this research. The main focus of this research is on spatial heating. All other options, like industry, transport and others, will be set to zero in order only to consider spatial heating (Hansen K., November 27th 2017, EnergyPLAN team, Aalborg University, mail contact). The same holds for the different energy generating technologies that will not be included in this research.

Unfortunately, it was not possible to model the large scale heat pump in combination with the PTES and the hydrogen storage in EnergyPLAN. Therefore, these options will be considered outside EnergyPLAN.

4.2 Scenarios

In the above, all parameters and methods are described, which are the base to explore different scenarios towards an energy neutral low temperature heat supply for the municipality of Groningen. Scenario 0 resembles the base scenario, in which only the population growth is taken into account and no further insulation or change in heat supply is assumed. Then, a comparison will be made between the three energy carriers described in the above. All the available lands will be utilized for the generation of that energy carrier and transport losses from the generation site to the network are not taken into account. Assumed in these 3 scenarios is that maximum insulation has been applied. In the scenarios after, a combination of the three energy carriers is considered, with and without storage, and different insulation levels. For the combined scenarios, also the costs will be calculated. An overview can be found in table 4-1 on the next page.

0. Reference Scenario: In this scenario only the population growth is taken into account.
1. 'Full thermal solar': Solar thermal collectors will be placed on all the available lands, with and without seasonal storage, and heat is delivered to the built environment with a district heating network. The supply and return temperatures of the district heating network that will be considered are 80 – 40°C and 91.5 – 61.5 °C.
2. All-electric PV: Solar PV collectors placed on all the available lands, air-source heat pumps are being used as heating technique, without storage (2 no st.) and with hydrogen storage (2 high)
3. All biogas: Energy maize is cultivated on all available lands, it will be mixed with the same amount of mixed dairy manure in an AD and used in a biogas boiler to deliver heat to the built environment with a DH network
4. Warmtestad Scenario: A DH network is being installed in the north of Groningen, in the neighbourhoods of Selwerd, Paddepoel and surroundings (DvhN, 2017d). This location has been chosen, because it was close to the planned geothermal well. But as said before, it is uncertain if that well will ever be installed. Assumed is that a DH network will be installed in the neighbourhoods of: Kostverloren, Vinkhuizen-noord, Vinkhuizen-Zuid, Hoendiep, Concordiabuurt, Selwerd, Paddepoel-Zuid, Paddepoel-Noord, Universiteitscomplex. These houses will be extensively insulated **.** The rest of the neighbourhoods will be maximal insulated and heat pumps will be used for heating. Solar thermal collectors will be installed at the baggerdepot Zernike and the Driebondsweg, 225 hectares in total. On the other 720 hectares available, solar PV will be installed. The remaining 1,515 hectares of lands will be used for the cultivation of energy maize. Different hydrogen storage, TTES & PTES sizes will be considered in this scenario.
5. Optimized Scenario: The neighbourhoods close to available lands have been identified in order to lose as less heat as possible between the generation and the supply site. This results in a DH network in: Korrewegwijk, Oosterparkwijk, Oosterpoortwijk, Herewegwijk & Helpman, Noorddijk. These buildings will be insulated extensively. On the lands of Roodehaan, Slibdepot Driebondsweg and the locations 3, 16, 17 in Ten Boer as can be found in Appendix 1, solar thermal collectors will be installed with a total area approximately 426.5 ha. The rest of the neighbourhoods will be maximal insulated and heat pumps will be used for heating. An area of 518.5 ha will be available for the installation of solar PV parks and 1,515 ha available for cultivation of energy maize. Different hydrogen storage, TTES & PTES sizes will be considered in this scenario.

Table 4-1. Scenarios overview

Scenario	Technique	Area (ha)	Network	Network Temp(°C)	Insulation level	Storage
0.	Natural gas	-	Natural Gas	-	-	-
1. 80-40 no st.	Solar thermal	945	DH	80-40	Maximal	-
1. 80-40 high	Solar thermal	945	DH	80-40	Maximal	TTES/PTES
1. 91.5-61.5 no st.	Solar thermal	945	DH	91.5–61.5	Maximal	-
1. 91.5-61.5 high	Solar thermal	945	DH	91.5–61.5	Maximal	TTES/PTES
2. no st.	Solar PV	945	Electricity	-	Maximal	-
2. high	Solar PV	945	Electricity	-	Maximal	Hydrogen
3.	Biogas	2,460	DH	80-40	Maximal	Biogas
4.	Solar PV	720	Electricity	-	Maximal	- & Hydrogen
	Solar thermal	225	DH	80-40	Extensive	- & TTES/PTES
	Biogas	1,515	DH	80-40	Extensive	Biogas
5.	Solar PV	518.5	Electricity	-	Maximal	- & Hydrogen
	Solar thermal	426.5	DH	80-40	Extensive	- & TTES/PTES
	Biogas	1,515	DH	80-40	Extensive	Biogas

4.3 System boundaries

The municipality of Groningen, including the municipality of Ten Boer, has the challenge to be energy neutral in 2035 and has large pieces of land available within its territorial boundaries for the generation of renewable energy. This research will focus on a part of this challenge, to make the low temperature heat supply in the built environment in the municipality of Groningen energy neutral in 2035. Therefore, only the heat demand in the built environment in the municipality of Groningen is considered. Different possibilities to generate the demanded heat on these available lands will be considered in this research and will be evaluated and compared in terms of energy produced per hectare, costs, implications for the balance between demand and supply.

5. RESULTS

In this chapter, the results of the scenarios as described in the last paragraph are given. First, the heat demand of the reference scenario will be discussed. Then will be discussed what the heat demand of the municipality of Groningen is after applying maximum insolation, and the heat demand patterns in 2035 if a DH network is considered and if the built environment will be heated with heat pumps. The electricity and heat generation curves will be given in section 5.2 and in section 5.3 single scenarios will be explored, in which only solar thermal, solar PV and biogas production will be considered. An overview of these scenarios will be given in table 5-6 in section 5.4. Afterwards, combined scenarios will be explored in section 5.5, consisting of a combination of the three systems and for these scenarios also the costs are calculated. An overview will be given in section 5.6.

5.1 Heat demand

In the reference scenario for 2035, the heat demand patterns of 2016 are taken from the Gasunie, the yearly heat demand per neighbourhood from Enexis as explained in section 3.1 and 3.2 and multiplied by the population growth factor. The total heat demand in 2035 is 2,259 GWh and the hourly heat demand is shown for a week in January and July in the figure 5-1 and 5-2.

Applying extensive and maximum insulation to households (private) and utilities (commercial) for all the different neighbourhood types and multiplying this with the population growth of 12.5% gives the following total yearly heat demands for 2035 for the municipality of Groningen and Ten Boer. The total yearly heat demand can be found in table 5-1 and the hourly heat demand after applying maximum insulation are displayed for a week in January and July in the figure 5-1 and 5-2. The costs for applying extensive and maximum insulation to houses are given in the last row of table 5-1.

Table 5-1.Yearly energy demand of the municipality of Groningen in 2016 and with extensive and maximal insulation in 2035

Heat demand	2016 (GWh)	2035 extensive insulation (GWh)	2035 maximal insulation (GWh)
private	841	472	446
commercial	1,168	984	911
Total	2,008	1,456	1,356
Costs		€ 404 million	€ 1,368 million

For the district heating demand at maximum insulation, 10% distribution losses are taken into account. This results in a yearly heat demand of 1,492 GWh, with a maximum demand of 646 MW, for a week in January and July as can be seen in the figure 5-1 and 5-2.

As described in section 3.2.2, the COP of the heat pumps has been calculated for each hour and divided by the heat demand at the base scenario. The results can be seen in for a week in January and July in the figure 5-1 and 5-2. The total yearly electricity demand is 400 GWh, with a peak demand of 229 MW.

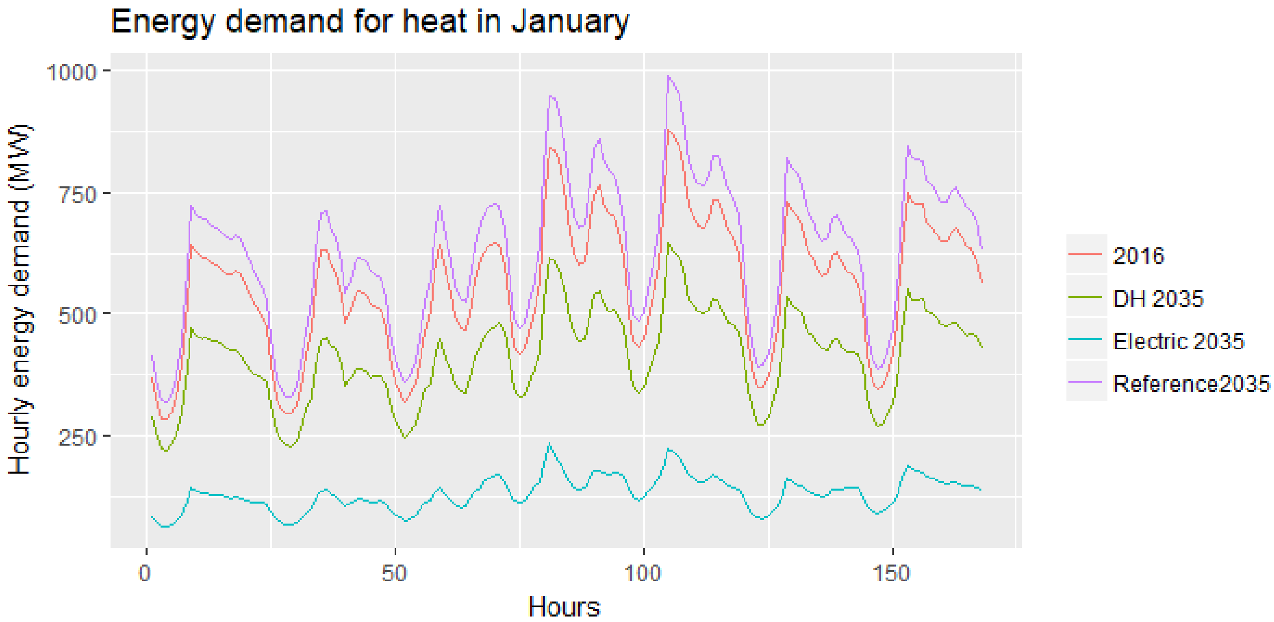

Figure 5-1. Hourly energy demand during a week in January. The purple line on top is the heat demand of the reference scenario. The red line is the heat demand in 2016, while the green line is the heat demand in case of a district heating network in 2035 after applying maximum insulation. The blue line is the electricity demand for heating in 2035 with maximum insulation and if the heat is delivered by means of a heat pump in each building.

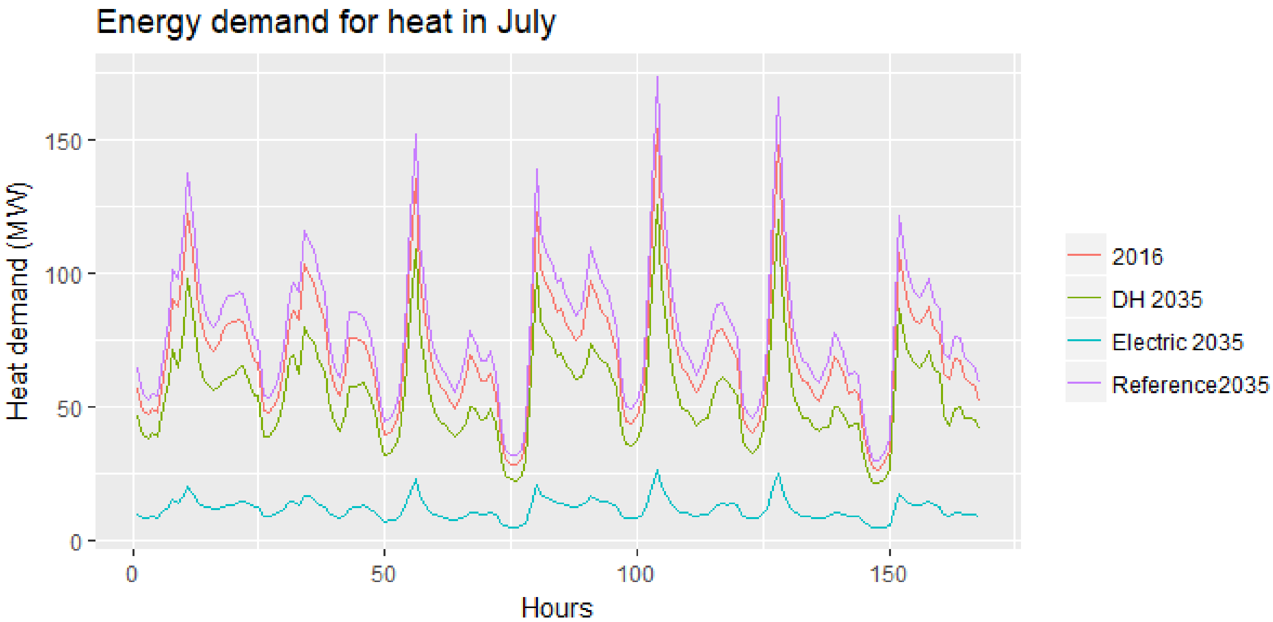

Figure 5-2. Hourly energy demand during a week in July. The purple line on top is the heat demand of the reference scenario. The red line is the heat demand in 2016, while the green line is the heat demand in case of a district heating network in 2035 after applying maximum insulation. The blue line is the electricity demand for heating in 2035 with maximum insulation and if the heat is delivered by means of a heat pump in each building.

5.2 Solar generation

In figure 5-3 and 5-4 on the next page, the generation patterns of solar thermal collectors and solar PV, as described in section 3.1 and 3.2, are displayed during a week in January and a week in July. As can be seen, the yields of solar thermal are higher and with a lower supply and return temperature of the water flowing through the collector. The energy yield per hectare for solar thermal collectors with a supply and return temperature of 80-40°C is 1.22 GWh. Increasing these temperatures to 91.5–61.5°C results in an energy yield of 0.99 GWh per hectare. For solar PV, this is 0.73 GWh per hectare, but as can be seen in figure 5-3 of the generation in January some electricity can be generated at times when the thermal solar collectors do not generate any heat, which is at low levels of irradiation.

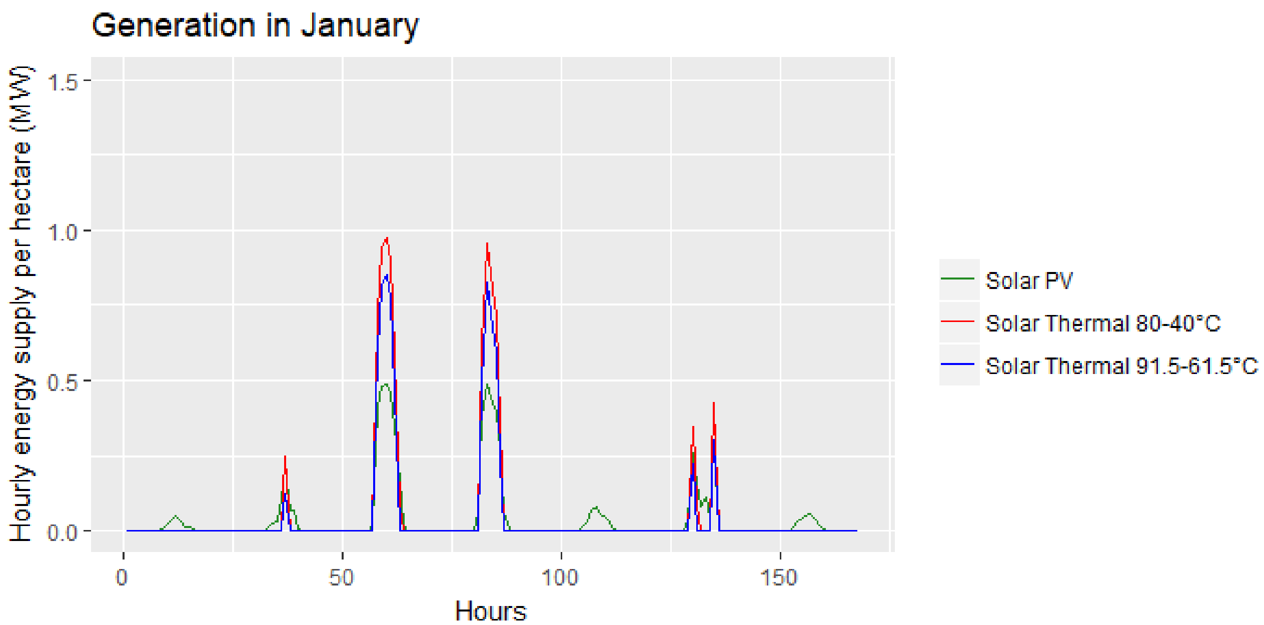

Figure 5-3. Hourly generation patterns of solar PV and solar thermal collectors at two different supply and return temperatures during a week in January.

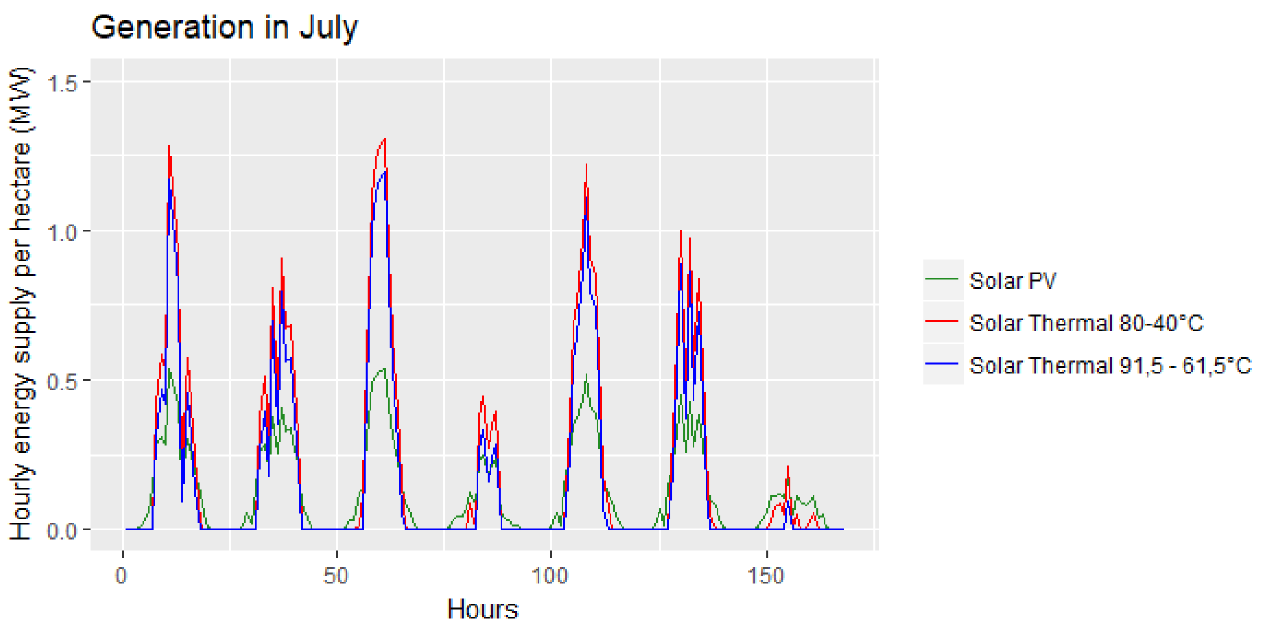

Figure 5-4. Hourly generation patterns of solar PV and solar thermal collectors at two different supply and return temperatures during a week in July.

5.3 Single system scenarios

In this section, single solution scenarios will be explored. For each scenario, the three different energy carriers that are considered in this research will be installed on all the available lands and maximum insulation will be applied to the building environment.

5.3.1 Solar thermal scenario (1)

The first scenario that will be considered is the solar thermal no storage (no st.) scenario. The assumptions and results of this scenario are displayed in table 5-2. The different column titles containing corresponding assumptions or results will be marked in bold and cursive. In ***Scenario*** 80-40 no st., the whole municipality of Groningen will be connected to a DH ***Network*** with an 80°C outflow temperature and a return temperature of 40°C. All buildings will be insulated maximally and the total yearly heat demand is 1,356 GWh. Assuming 10% distribution losses and not taking into account the heat losses from the distance between the generation sites and the DH network, gives a total yearly ***Demand*** of 1,492 GWh, with a ***Peak*** demand of 646 MW. The heat will be ***Supplied with*** solar thermal collectors, installed on all available lands with a total ***Area*** of 945 hectares. Yearly, 1,155 GWh will be ***Produced*** by the solar thermal collectors. A total effective collector area of 270 hectares can been installed on 945 hectares of land, resulting in a yearly energy yield of 1.22 GWh/ha, or 428 kWh/m^2 effective collector area. Without storage, 230 GWh per year can be ***Utilized***. As a results, 1,262 GWh of yearly ***Imports*** is needed, with a ***Peak import*** of 646 MW. The hot water that is not being utilized, cannot be exported. Therefore there is no ***Export*** during the year and there is no ***Peak export***.

Table 5-2.Results of the solar thermal scenario 80-40 no st. and scenario 91.5-61.5 no st.

Scenario	Net-work	Demand (GWh/y)	Peak (MW)	Supply with	Area (ha)	Produced (GWh/y)	Utilized (GWh/y)	Import (GWh/y)	Peak import (MW)	Export (GWh/y)	Peak export (MW)
80-40 no st.	DH	1,492	646	Thermal	945	1,155	230	1,262	646	-	-
91.5-61.5 no st.	DH	1,492	646	Thermal	945	933	190	1,302	646	-	-

In scenario 91.5-61.5 no st., displayed in the second row of table 5-2, the same assumptions hold as in scenario 80-40 no st., but an outflow temperature of 91.5°C and an return temperature of 61.5°C is considered. The annual output per hectare decreases from 1.22 to 0.99 GWh per hectare, or from 428 to 346 kWh/m^2 effective collector area, resulting in a yearly 933 GWh total generation. The amount of heat that can be utilized without storage decreases from 230 GWh per year to 190 GWh per year.

For both scenarios 80-40 high and 91.5-61.5 high, the amount of heat that can be supplied by the solar thermal system has been calculated with different storage capacities, as can be seen in figure 5-5. More detailed information about the utilized solar thermal energy for different storage capacities can be found in Appendix 6 (table 0-6 and table 0-7).

In scenario 80-40 high, there is a yearly heat production of 1,155 GWh, of which 230 GWh can be utilized without storage and 10% losses yearly, the maximum utilized heat from solar thermal storage is 1060 GWh at 600 GWh storage capacity. This results in a shortage of around 430 GWh per year.

In scenario 91.5-61.5 high, the yearly heat production is 933 GWh, of which 190 GWh can be utilized without a storage and 10% losses yearly, the maximum utilized heat from solar thermal storage is around 860 GWh at 450 GWh storage, resulting in a total amount of heat used from the solar thermal storage system of 860 GWh and a shortage of around 630 GWh.

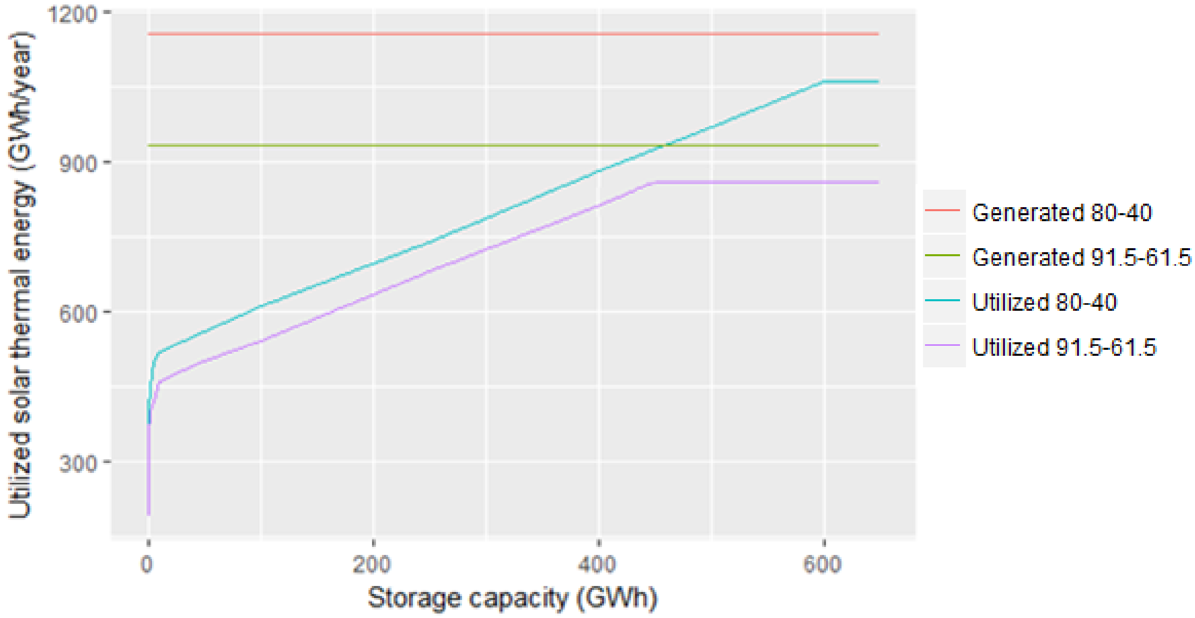

Figure 5-5. The blue line represents the amount of yearly utilized heat at a certain storage capacity at a T_{supply} and T_{return} of 80°C and 40°C respectively. The red line represents the amount of yearly generated heat at those temperatures. The purple line represents the amount of yearly utilized heat at a certain storage capacity at a T_{supply} and T_{return} of 91.5°C and 61.5°C respectively. The green line represents the amount of yearly heat generated at those temperatures.

5.3.2 Solar PV scenario (2)

In the solar PV scenario, all available lands are being used for the generation of solar PV. Since the efficient area of the solar panels is 36% of the total area, we have 341 hectare effective solar collector area (Spruijt, 2015). This gives a total capacity of 658 MWp. Including 15% losses due to dust, shadings, inverter losses and other unforeseen losses, the expected total electricity production is 684 GWh per year.
All the houses will be maximally insulated and heated with heat pumps, resulting in a total electrical yearly demand is 400 GWh. Although there is a yearly electricity production of 684 GWh per year, only 120 GWh of that is being used directly. Another 280 GWh needs to be imported, mainly during winter and at night. The results can be seen in table 5-3 .

Table 5-3. Results of solar PV scenario no st.

Net-work	Demand (GWh/y)	Peak (MW)	Supply with	Area (ha)	Production (GWh/y)	Utilized (GWh/y)	Import (GWh/y)	Import max (MW)	Export (GWh/y)	Export max (MW)
Electric	400	233	PV	945	684	120	280	230	560	641

In scenario no st., assumed is that all the excess electricity can be exported and it can be imported at times of an electricity deficit, but in scenario high, hydrogen storage is considered. In order to determine the capacity of the electrolyser, hydrogen storage and the fuel cell, the electricity load duration curve without storage has been displayed in black in figure 5-6. More detailed information about the electricity utilization at different electrolyser capacities can be found in Appendix 6 (table 0-8).

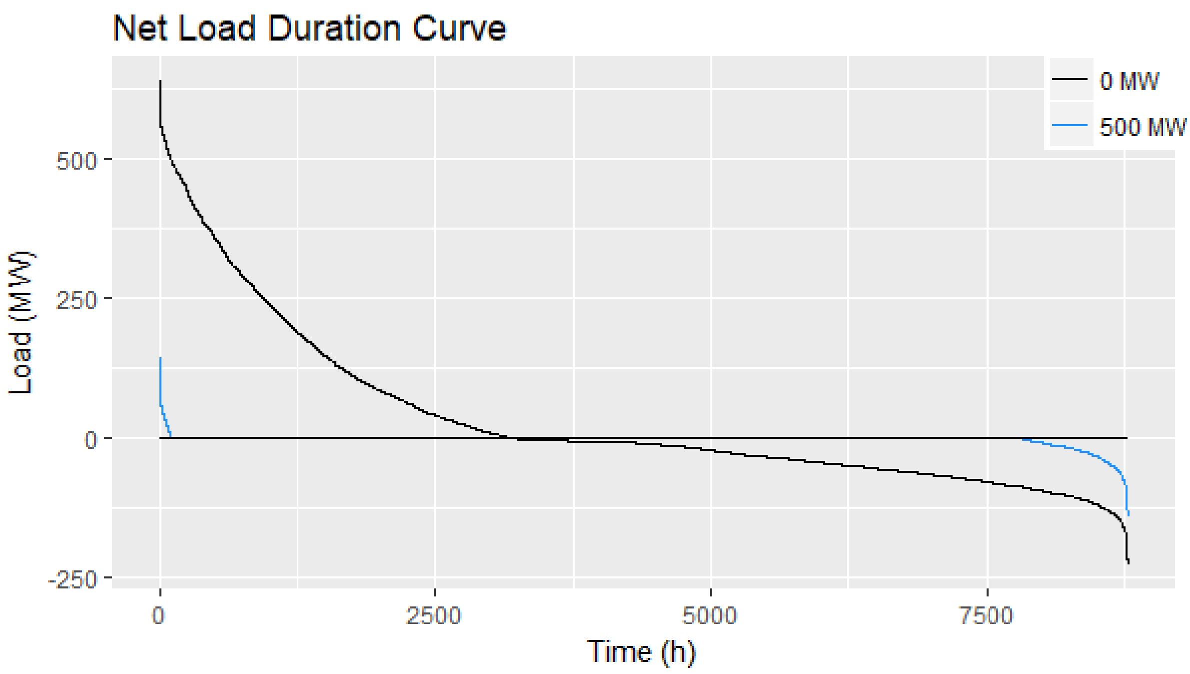

Figure 5-6. Net load duration curve of the solar PV scenario without storage (black line) and with storage (blue line). Without storage, the total surplus is 560 GWh and the total shortage is 280 GWh. With storage, the total surplus is 3 GWh and the total shortage is 28 GWh.

Assuming the roundtrip efficiency of 45%, 252 GWh of the 280 GWh electricity deficit can be supplied through the conversion of electricity to hydrogen and back. However, an electrolyser with a capacity of 500 MW is needed for this. Using the numbers described in section 3.3.2, 560 GWh of electricity that is converted to hydrogen, results in a total mass of 6,048 tonnes of hydrogen. Under 350 bar, this results in a storage capacity of 3,4 * 10^6 m^3. A fuel cell with a capacity of 233 MW is needed to provide the peak electricity demand and to provide 252 GWh of electricity, resulting in an electricity shortage of 28 GWh per year, as shown in the blue line in figure 5-6.

5.3.3 Biogas scenario (3)

As said before, cultivating energy maize results in a fresh matter yield of 45 tonnes/ha per year. For the cultivation of biomass, 2,460 hectares of land is available, resulting in a total yield of 110,700 tonnes/year. According to the Dutch legislation, this has to be mixed with 110,700 tonnes of mixed dairy manure. The results are displayed in the table 5-4, using the parameters described in section 3.3.

Table 5-4. Biogas production

Feedstock	Production FM (tonnes)	oDM (tonnes)	Biogas potential (mln m^3)	Biogas production (mln m^3)
Energy maize	110,700	33,210	20	14.7
Manure mixed dairy	110,700	7,085	2.5	1.8

Since most the biogas production comes from the energy maize, we can assume that the total amount of biogas that can be produced yearly is 16.5 million m^3. Assuming that the methane content is responsible for the energy content and leaving out traces of ethane, propane and others gives a low caloric value of 53/81.3 * 31.65 MJ/m^3 = 20.6 MJ/m^3. With a total biogas production of 16.5 million m^3, this gives a yearly total production of 94 GWh (340 TJ). Per hectare, this is 0.04 GWh. Using a biogas boiler with an efficiency of 104%, a 11.2 MWth boiler can run throughout the whole year, providing 98 GWh of the 1,492 GWh needed, resulting in a total import of 1,394 GWh. The results are displayed in table 5-5.

Table 5-5. Results of the biogas scenario

Network	Demand (GWh/y)	Peak (MW)	Supply with	Area (ha)	Production (GWh/y)	Utilized (GWh/y)	Import (GWh/y)	Import max (MW)	Export (GWh/y)	Export max (MW)
Electric	1492	646	biogas	2,460	94	98	1394	646	-	-

5.4 Summary of the single system scenarios

In table 5-6 and figure 5-7, a summary has been made of the three first scenarios. For all these scenarios, maximal insulation has been assumed. As can be seen, the energy yield per hectare is the highest for solar thermal collectors, and the highest for with an 80-40°C outlet and return temperature of the DH network. But at the same time, the energy demand is higher with a DH network than with an electric network, due to the fact that heat pumps are being used for the latter.

Following the definition of energy neutral that ‘all the used energy over a year has to be derived from renewable energy sources, with the possibility to import and export energy’, one can see that for the Solar PV scenario (2) the yearly production of electricity of 684 GWh and the 564 GWh of electricity that can be exported, is higher than the 280 GWh of electricity that needs to be imported. For scenario 1 and 3, there always is a shortage, so one can say that this would be the best solution. The capacity to export this amount of electricity is available, since there are multiple stations of 110 kV and 220 kV, with a capacity of 100-150 MVA and 1000 MVA respectively (Eilers P., March 16th 2018, TenneT, mail contact). However, this will cause problems for the balancing of the electricity system outside the boundaries of the municipality of Groningen, since the exports will mainly take place in summer during the day and at this moment, all solar PV panels in the Netherlands will be producing electricity, causing a surplus in electricity for which there is little demand. This emphasizes the need for storage once more, and introducing storage in both scenario 1 and 2 increases the amount of utilized energy significantly, with just 28 GWh per year of imports in the solar PV scenario 2 high. In the following scenarios, a combination of the three systems will be explored, with different levels of insulation and the investment costs of these systems will also be taken into account.

Table 5-6. Summary of the first three scenarios

Scenario	Heat demand (GWh/y)	Network	Supply with	Energy yield (GWh/ha/y)	Production (GWh/y)	Utilized (GWh/y)	Import (GWh/y)
0.	2,259	Natural gas	Natural gas	-	-		
1. 80-40 no st.	1,492	DH	Solar thermal	1.22	1,155	230	1,260
1. 80-40 high	1,492	DH	+ storage	1.22	1,155	1,060	430
1. 91.5-61.5 no st.	1,492	DH	Solar thermal	0.99	933	190	1,300
1. 91.5-61.5 high	1,492	DH	+ storage	0.99	933	860	630
2. no st.	400	Electric	Solar PV	0.73	684	120	280
2. high	400	Electric	+ hydrogen storage	0.73	684	372	28
3.	1,492	DH	Biogas	0.04	94	98	1,394

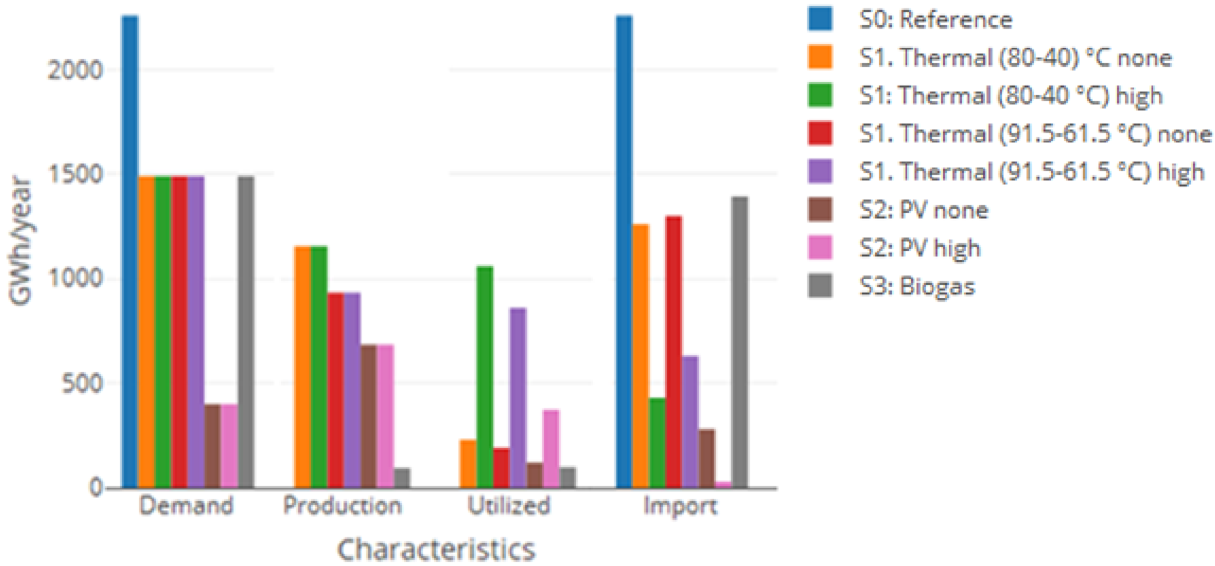

Figure 5-7. Summary of the first three scenarios. On the left is the total demand per year displayed for each scenario. Then the total yearly production, the amount of produced energy per year for each of the scenarios and on the right is the total amount of energy imports needed for each scenario.

5.5 Combined scenarios

In the previous scenarios, only one energy carrier has been considered to deliver heat to the built environment. In the following scenarios, a combination of the three energy carriers will considered. In the Warmtestad scenario is assumed that the DH network that is being installed in the municipality of Groningen will be installed in these neighbourhoods. In the Optimized scenario, the neighbourhoods that are close to the available lands are identified and assumed to be connected to a DH network.

5.5.1 Warmtestad scenario (4)

In the Warmtestad scenario, assumed is that the neighbourhoods of Kostverloren, Vinkhuizen-noord, Vinkhuizen-Zuid, Hoendiep, Concordiabuurt, Selwerd, Paddepoel-Zuid, Paddepoel-Noord and Universiteitscomplex are connected to a district heating network, which accounted for around 13% of the total heat demand in the municipality of Groningen in 2016. These neighbourhoods are displayed as the inner contours of the red line in figure 5-8. These buildings will be insulated extensively, since there is no need for maximum insulation of houses that are connected to a district heating network. All the buildings in the other neighbourhoods will be maximal insulated, since heat pumps will be used to deliver heat.

The total demand in the neighbourhoods after extensive insulation with a DH network is expected to be 296 GWh. Due to the 10% DH distribution losses, the total demand is 329 GWh. The heat demand in the houses which are maximal insulated and in which heat pumps will be installed in order to deliver the heat, is expected to be 1,118 GWh. This results in an electric demand of 336 GWh, after dividing this to the weighted COP of the heat pumps as explained in section 3.3.1.

The total area used for solar thermal collectors, is the area that is closest to the district heating network. These are the lands at the Driebondsweg and the Slibdepot Zernike, with a total area of 225 hectares, as can be seen in figure 5-8. Another 720 hectares will be used to install solar PV parks and on the remaining 1,515 hectares energy maize will be cultivated. An area of 225 hectares results in a total solar thermal production of 275 GWh per year. But due to the distance between the generation site and the delivery site, assumed that the distance from the Driebondsweg to Selwerd is 5 km and with a pipe heat loss per km ratio of 2% (Nielsen & Battisti, 2012), the total amount of delivered heat to the district heating network will be 248.5 GWh per year. On 720 hectares a total capacity of 501 MWp of solar PV can be installed, with an expected total yearly energy yield of 519 GWh.

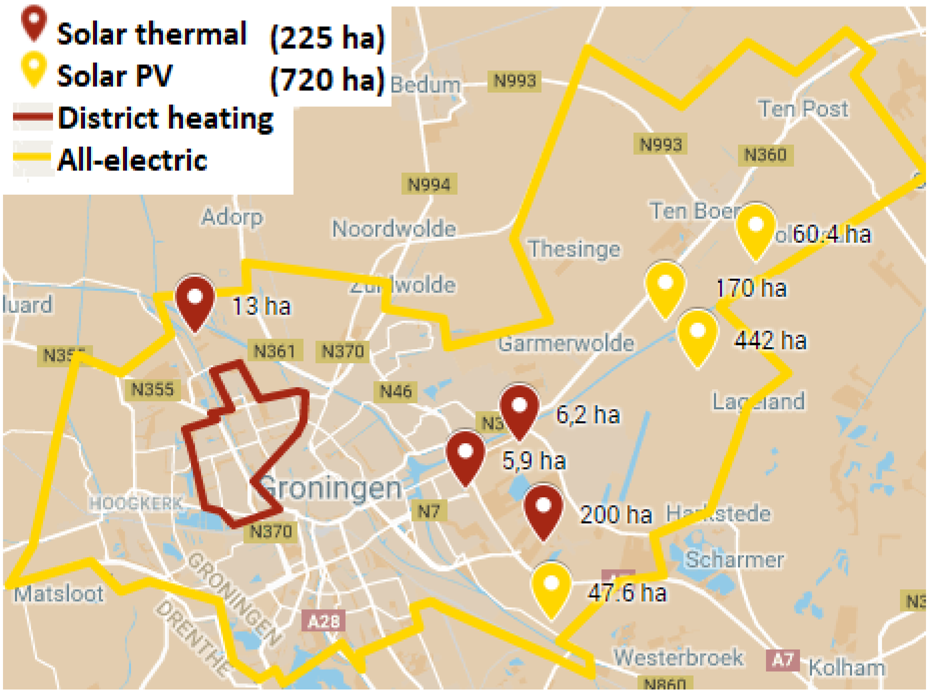

Figure 5-8. The neighbourhoods in which a DH network will be installed are within the contours of the red line and the neighbourhoods which will heat their buildings by means of a heat pump are within the contours of the yellow line. The red and yellow marks indicate the locations where solar thermal collectors and solar PV collectors will be installed. The remaining 1,515 hectares on which energy maize will be cultivated from which biogas will be produced and which will be used to deliver heat to the DH network, are not displayed in this figure.

The expected yearly yields of energy maize on 1,515 hectares is 68,175 tonnes of FM. This will be mixed with the same amount of mixed dairy manure and the total yearly biogas production by the AD process is expected to be 10.1 million m^3, with an energy content of around 58 GWh. Using a biomass boiler with an efficiency of 104%, gives a total energy supply by biogas of 60 GWh per year. The capacity of the biomass boiler is chosen to be 135 MW in all scenarios, which is high enough to meet the peak demand at all times and can act as backup when storage is considered. The results are displayed in the table 5-7.

Table 5-7. Results of the Warmtestad scenario no st.

Network	Demand (GWh/y)	Peak (MW)	Supply with	Area (ha)	Production (GWh/y)	Utilized (GWh/y)	Import (GWh/y)	Import max (MW)	Export (GWh/y)	Export max (MW)
Electric	336	197	PV	720	519	100	236	197	420	487
District Heating	329	140	Thermal	225	248.5	50	-	-	-	-
			Biogas	1515	58	60	219	140	-	-

As can be seen, there is a large mismatch between supply and demand. Only around 20% of the heat and electricity generated by the sun can be used directly. The rest of the electricity can be exported or stored as hydrogen after electrolysis and converted by to electricity as described in section 3.3. .

Four different storage capacities will be considered. In scenario no st. is assumed that all the excess electricity can be exported and that electricity can be imported at times of an electricity deficit, but in scenario low, medium and high, different hydrogen storage volumes will be considered. In order to determine the capacity of the electrolysers, hydrogen storage and the fuel cells, the electricity load duration curve has been determined, as displayed in figure 5-9. More detailed information about the electricity utilization for different electrolyser capacities can be found in Appendix 6 (table 0-9).

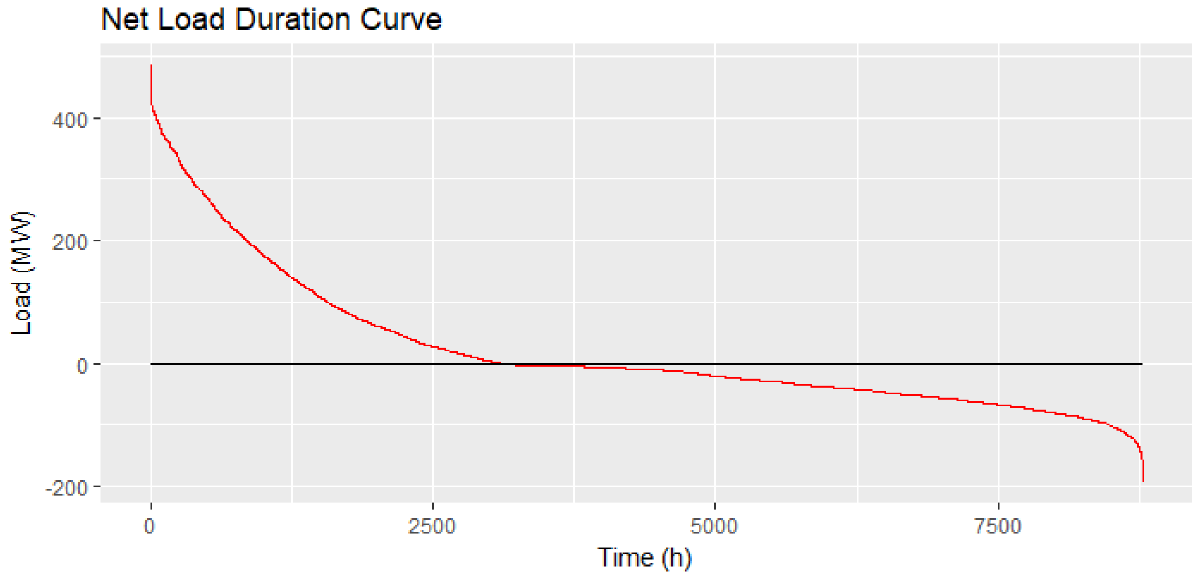

Figure 5-9. Net load duration curve of the electricity in the Warmtestad scenario no st., with a surplus of 420 GWh and a shortage of 236 GWh.

Three different capacities for the electrolyser will be considered. Scenario low has an electrolyser with a capacity of 50 MW, converting 130 GWh electricity to hydrogen. The electrolyser in the scenario medium has a capacity of 250 MW, still utilizing 380 GWh out of the produced 420 GWh per year. Scenario high has an electrolyser with a capacity of 400 MW, almost completely utilizing all the of the 420 GWh of excess electricity. .

Assuming the roundtrip efficiency of 45%, 189 GWh of the 236 GWh electricity deficit can be supplied through the conversion of electricity to hydrogen and back. However, an electrolyser with a capacity of 400 MW is needed for this. Using the numbers described in section 3.3, 420 GWh of electricity that is converted to hydrogen, results in a total mass of 4,536 tonnes of hydrogen. Under 350 bar, this results in a storage capacity of 1.4 * 10^5 m^3. A fuel cell with a capacity of 194 MW is needed to provide the peak electricity demand and to provide 189 GWh of electricity, resulting in an electricity deficit of 47 GWh per year. The same has been done for the electrolyser with a capacity of 250 MW and of 50 MW, but assumed here is a fuel cell of 121 MW and 24 MW respectively, a reduction which is proportional to the reduction of the electrolyser capacity, while realizing that the peak demand cannot be met during winter with the fuel cells alone. The results are displayed in table 5-8.

Table 5-8. The hydrogen storage parameters in the scenarios low, medium and high

Scenario	Electrolyser capacity (MW)	Electricity utilized (GWh/y)	Hydrogen produced (tonnes)	Storage capacity 350 bar (* 10^5 m^3)	Fuel cell capacity (MW)	Electricity produced (GWh/y)	Import (GWh/y)
Low	50	130	1,400	0.44	24	97.5	136.5
Medium	250	380	4,104	1.3	121	171	63
High	400	420	4,536	1.4	194	189	47

Besides the storage of electricity, different storage capacities for the generated hot water by the solar thermal collectors will be taken into account in the scenarios low, medium and high. Since the hot water cannot be exported, different thermal storage capacities have been considered and are displayed in figure 5-10. As can be seen, installing a 0.5 GWh storage already doubles the amount of utilized hot water. This is due to the fact that the production can be stored for the short term and utilized at night. For higher capacities from around 5 GWh, which can be seen as seasonal storage, the utilized heat increases around the same as the increase in capacity, what can be expected. More detailed can be found in Appendix 6 (table 0-10).

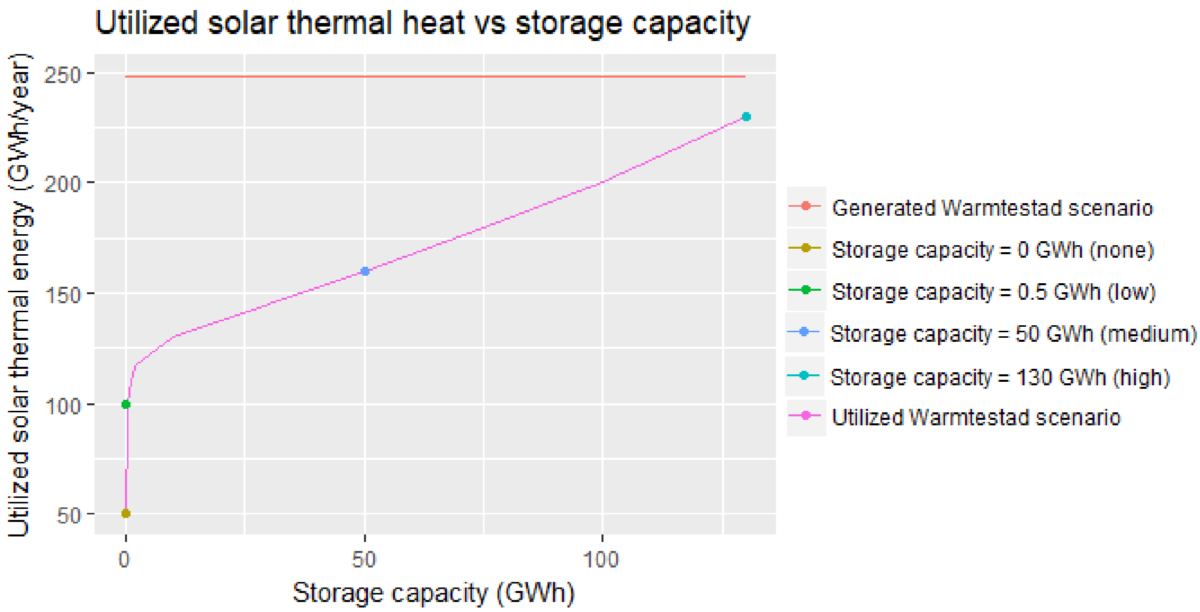

Figure 5-10. The amount of generated solar thermal heat that can be utilized vs the storage capacity. The four different storage capacities that are considered in the different scenarios are displayed as dots, while the purple line represents the amount of solar heat

In scenario no st. is assumed that there is no storage, but in scenario low, medium and high storage capacities of 0.5 GWh, 50 GWh and 130 GWh will be considered. For scenario medium and high, in combination with the PTES, a heat pump is utilized to completely empty the storage, with a capacity of 10 MW_{el} (37 MW_{th}) and 26 MW_{el} (96.2 MW_{th}) respectively. As described in section 3.2.3., 38.7% of the pit storage heat content has to be extracted by the heat pump with a COP of 3.7. This means that for scenario medium and the high, an additional 5 GWh and 14 GWh electricity are needed, which are added to the electricity imports in table 5-10.

The costs in total and per group for the low and high boundary, as indicated in section 3.4, have been normalized to a lifetime of 25 years, calculated and are shown in table 5-9. A distinction has been made between the costs that have been made for the neighbourhoods that will be heated with an air-source heat pump (electric) and the neighbourhoods that will be connected to a DH network (DH). The demand and the imports needed for electricity and heat are shown in the last columns.

Table 5-9. The percentage of the demand in 2016, the costs per group and the total costs, the yearly demand and imports for the electric system and the DH system for scenario no st.

Scenario no st.	Demand 2016 (%)	Network (M€)	Generation (M€)	Buildings (M€)	Storage (M€)	Total (M€)	Demand (GWh/y)	Imports (GWh/y)
Electric low – high	87	198	468	1,380	0	2,046	336	236
DH low – high	13	72 - 179	135 - 176	44	303	554 - 702	329	219

For the scenarios low, medium and high, the additional costs of the storage systems for the two groups have been calculated and are displayed in table 5-10. An overview of the components and their costs can be found in Appendix 7 in table 0-14.

Table 5-10. The storage costs, in total, the yearly demand, the extra electricity consumed by the heat pump in combination with the PTES and imports for the electric system and the DH system for scenario low, medium and high.

	Storage (M€)	Total (M€)	Extra Utilized (GWh/y)	Extra consumed (GWh/y)	Imports (GWh/y)
Scenario low					
Electric low – high	343 – 603	2,389 – 2,649	97.5	0	136.5
DH low – high	1 – 2	555 - 704	50	0	170
Scenario medium					
Electric low – high	1,021 - 1,916	3,067 - 3,962	171	5	68
DH low – high	12 – 18	566 - 720	110	0	110
Scenario high					
Electric low – high	1,144 – 2,293	3,190 – 4,339	189	14	61
DH low – high	31 – 45	585 - 747	180	0	40

5.5.2 Optimized scenario (5)

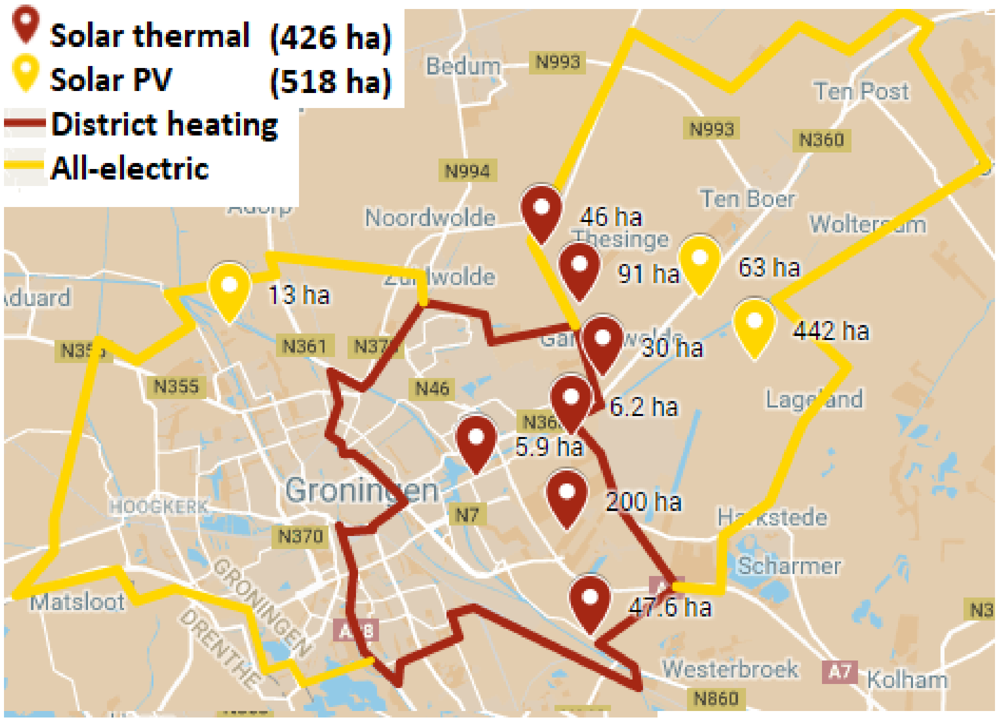

Figure 5-11. The neighbourhoods in which a DH network will be installed are within the contours of the red line and the neighbourhoods which will heat their buildings by means of a heat pump are within the contours of the yellow line. The red and yellow marks indicate the locations where solar thermal collectors and solar PV collectors will be installed. The remaining 1,515 hectares on which energy maize will be cultivated from which biogas will be produced and which will be used to deliver heat to the DH network, are not displayed in this figure.

In this scenario, assumed is that the districts Korrewegwijk, Oosterparkwijk, Oosterpoortwijk, Herewegwijk & Helpman and Noorddijk are connected to a DH network, which accounts for around 46% of the total heat demand in 2016. These districts are within the red lines as can be seen in figure 5-11 and are located on the east side of the city, closer to the available lands. As in the previous scenario, the buildings in these neighbourhoods will be insulated extensively. The buildings remaining neighbourhoods will be maximal insulated and heat pumps will be used to deliver heat. The yearly demands are displayed in table 5-11. As in the previous scenario, 4 different storage capacities will be considered.

The lands that will be used for the generation of hot water, are the lands at Roodehaan, Slibdepot Driebondsweg and the locations 3, 16, 17 in Ten Boer as can be found in Appendix 1, with a total area of 426.5 ha. These lands are also displayed by the red marks in figure 5-11. This will give a total solar thermal production of 521 GWh per year. Due to the distance between the generation site and the delivery site, assumed that the average distance is 3 km and the pipe heat loss ratio per km of 2% (Nielsen & Battisti, 2012). Therefore, the total solar thermal yearly production of 490 GWh. It is assumed that three pipes with that length run from the Roodehaan, Driebondsweg and the locations in Ten Boer. A total of 518 hectares will be left for solar PV fields, indicated by the yellow marks, on which 361 MWp can be installed with an expected yearly production of 375 GWh. Cultivation of energy maize on the remaining land is the same as in the previous scenario, but a biomass boiler of 362 MW will be used in this scenario to be able to meet the peak demand and to act as a backup. The results without hydrogen or thermal storage, scenario no st., are displayed in table 5-11.

Table 5-11. Results Optimized scenario no st.

Network	Demand (GWh/y)	Peak (MW)	Supply with	Area (ha)	Produced (GWh/y)	Utilized (GWh/y)	Import (GWh/y)	Import max (MW)	Export (GWh/y)	Export max (MW)
Electric	224	130	PV	518.5	375	64	160	129	309	351
District Heating	828	362	Thermal	426.5	490	120	-	-	-	-
			Biogas	1,515	58	60	648	362	-	-

As can be seen again from the results of this scenario, is that there is a mismatch between supply and demand and a lot of the generated energy is not being utilized. As in the Warmtestad scenario, in scenario no st. is assumed that all the excess electricity can be exported and that electricity can be imported at times of an electricity deficit, but in scenario low, medium and high, different hydrogen storage volumes are considered. In order to determine the capacity of the electrolysers, hydrogen storage and the fuel cells, the electricity net load duration curve has been determined, as displayed with the black line in figure 5-12. More detailed information about the electricity utilization for different electrolyser capacities can be found in Appendix 6 (table 0-11).

Table 5-12. The hydrogen storage parameters in the different scenarios

Scenario	Electrolyser capacity (MW)	Electricity utilized (GWh/y)	Hydrogen produced (tonnes)	Storage capacity 350 bar (* 10^5 m^3)	Fuel cell capacity (MW)	Electricity produced (GWh/y)	Imports (GWh/y)
Low	25	70	756	0.24	13	31.5	128.5
Medium	150	250	2,700	0.83	77	112.5	47.5
High	250	300	3,240	1.0	129	139.5	20.5

The three electrolyser capacities that will be considered for the scenarios low, medium and high are 25 MW, 150 MW and 300 MW respectively. The amount of hydrogen that can be produced and the storage capacity is calculated according to section 3.3 and is displayed in the table 5-12. The fuel cell capacity corresponding to the electrolyser capacity of 300 MW is chosen to be 129 MW in order to meet the peak import. The same ratio between the electrolyser capacity and the fuel cell capacity for the remaining two scenarios. The effects on the net load duration curve with different electrolyser capacities is shown in figure 5-12.

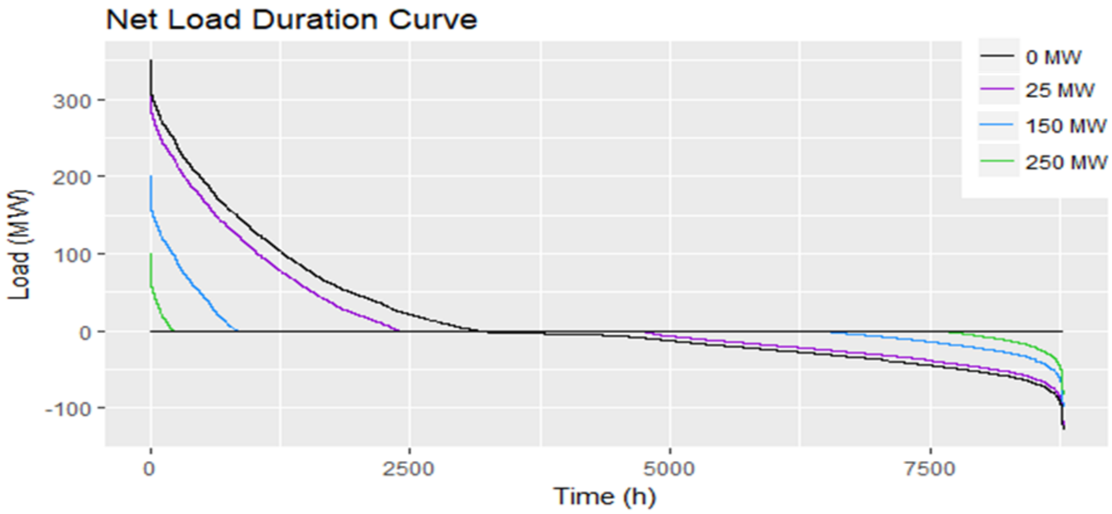

Figure 5-12. Net load duration curve of the electricity in the Optimized scenario for the different electrolyser capacities.

In figure 5-13 the utilized solar thermal heat is plotted against the storage capacity, including yearly losses of 10%. Just as in the previous scenario, it can be seen that the amount of solar heat that can be utilized increases with 80 GWh if a 0.5 GWh storage is installed. With storage capacity larger than 5 GWh, the hot water is being stored to be utilized during the winter and the increase in capacity is around the same as the increase in utilized solar heat again. But even with a 225 GWh storage capacity, 220 GWh of biogas need to be imported per year. More detailed information can be found in Appendix 6 (table 0-12).

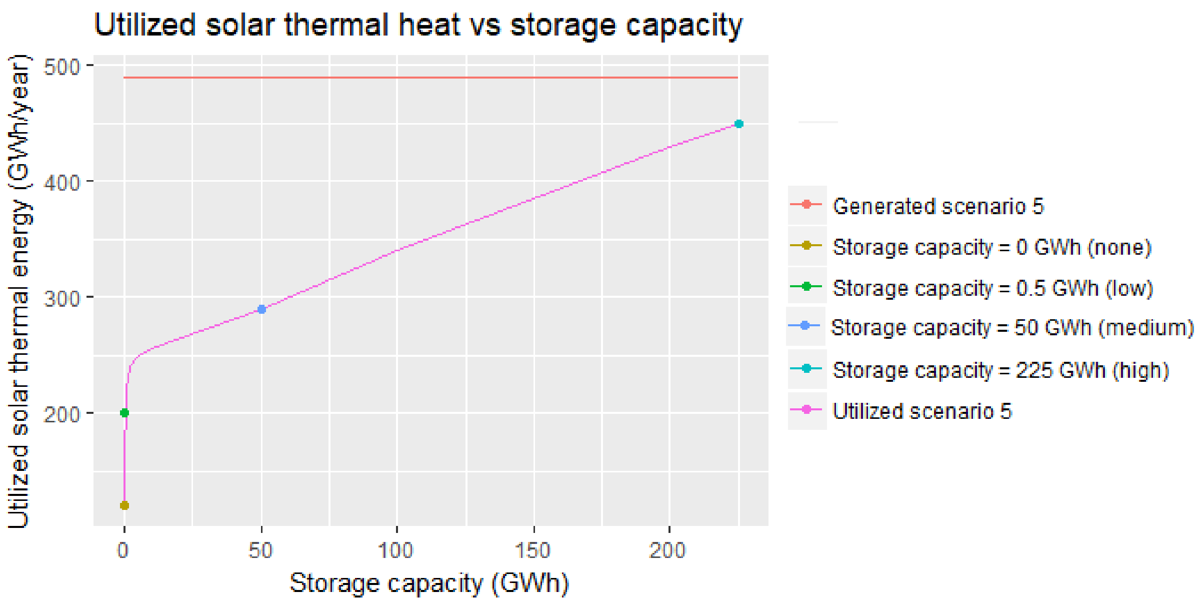

Figure 5-13. The amount of generated solar thermal heat that can be utilized vs the storage capacity. The four different storage capacities that are considered in the different scenarios are displayed as dots, while the purple line represents the amount of solar heat that can be utilized at a certain storage capacity. The red line above displays the total amount of solar heat that is yearly generated.

In scenario no st. is assumed that there is no storage, but in scenario low, medium and high, storage capacities of 0.5 GWh, 50 GWh and 225 GWh will be considered. For scenario medium and high, in combination with the PTES, a heat pump is used to completely empty the storage, with a capacity of 10 MW_{el} (37 MW_{th}) and 45 MW_{el} (166.5 MW_{th}) respectively. The yearly electricity consumption of the heat pump in scenario medium and high is 5 GWh and 23 GWh respectively, displayed in table 5-14.

The costs per group and in total, as well as the demand and the imports, have been calculated for scenario no st. as in the previous subsection and the results are displayed in table 5-13.

Table 5-13. The percentage of the demand in 2016, the costs per group and the total costs, the yearly demand and imports for the electric system and the DH system for scenario no st.

Scenario no st.	Demand 2016 (%)	Network (M€)	Generation (M€)	Buildings (M€)	Storage (M€)	Total (M€)	Demand (GWh/y)	Imports (GWh/y)
Electric low – high	54	118	337	888	0	1,343	224	160
DH low - high	46	201 -501	250 - 338	98	303	852 – 1,240	828	628

For the scenarios low, medium and high, the additional costs of the storage systems for the two groups have been calculated and are displayed in table 5-14. An overview of the costs of all the system components for the different scenarios can be found in Appendix 7 in table 0-15.

Table 5-14. The storage costs, the total costs, the yearly demand, the extra electricity consumed by the heat pump in combination with the PTES and imports for the electric system and the DH system for scenario low, medium and high.

	Storage (M€)	Total (M€)	Extra Utilized (GWh/y)	Extra consumed (GWh/y)	Imports (GWh/y)
Scenario low					
Electric low – high	185 - 323	1,528 – 1,666	31.5	0	128.5
DH low – high	1 – 2	853 – 1,242	80	0	510
Scenario medium					
Electric low – high	707 – 1,254	2,050 – 2,591	112.5	5	52.5
DH low – high	13 – 18	865 – 1,268	170	0	420
Scenario high					
Electric low - high	831 – 1,731	2,174 – 3,076	139.5	23	43.5
DH low – high	44 – 78	896 – 1,318	330	0	220

5.6 Summary of the combined scenarios

In the previous two scenarios a combination of a solar thermal storage system, a solar PV system in combination with hydrogen storage and a biogas system have been explored. In both scenarios the municipality of Groningen has been divided in a part that will be heated by a DH network and a part that will be heated by heat pumps which are connected to the electricity network. The DH network is fed by solar thermal collectors and by biogas, while the electricity network is fed by electricity produced by solar PV panels.

In both scenarios, 1,515 hectares are used for the cultivation of energy maize, from which 60 GWh of heat can be delivered to the DH network by burning biogas in the biogas boiler. The investment costs for the AD system are estimated to be 7.7 million euros, while the investment costs for the biogas storage are 303 million euros.

Looking at Warmtestad scenario and Optimized scenario no st., one can see that the yearly amount of electricity produced by the solar PV panels, 519 GWh and 375 GWh, is respectively 54% and 67% higher than the yearly electricity demand, but that only around 29% of electricity demand can be provided directly. As said before, this will cause problems for the balancing of the electricity system outside the boundaries of the municipality of Groningen.

Introducing hydrogen storage increases the amount of electricity that can be used directly with 139.5 GWh and 189 GWh respectively, to around 81% in both scenarios high. However, the investment costs will increase significantly, from € 2,046 million to € 3,190 – 4,339 million in the Warmtestad scenario high and from € 1,343 million to € 2,174 – 3,076 million in the Optimized scenario high. This is mainly due to the hydrogen storage costs, estimated to be € 1,085 – 1,718 million in the Warmtestad scenario high and € 778 – 1,231 million in the Optimized scenario high. Also, due to the hydrogen cycle efficiency of 45%, there will be a shortage in electricity of 19% of the yearly demand.

The yearly amount of heat produced by the solar thermal panels, 248.5 GWh and 490 GWh respectively, is 24% and 41% lower than the yearly heat demand for both scenarios and only around 20% of the produced heat can be used directly. Introducing TTES in both scenarios low, with an estimated investment cost of €1 – 2 million, doubles the amount of produced heat that can be used. Adding PTES in both scenarios high, with investment costs of around €31 – 45 million and € 44 – 78 million, increases the amount of produced heat that can be used with 180 GWh and 330 GWh respectively, utilizing around 92% of the produced heat. However, due to the heat pump that is used to empty the storage, there is an increase in yearly electricity consumption of 14 GWh and 23 GWh respectively. Also, in both scenarios high there will still be need to import 40 GWh and 220 GWh of biogas (or green gas) per year.

The difference in investment costs for buildings can be seen clearly table 5-13 in Optimized scenario no st. Even though the division between buildings that are connected to a DH network and to the electricity network are almost the same, the investment costs for buildings that are connected to the electricity network, € 888 million, are almost 9 times higher than for buildings that are connected to the DH network, which are estimated to be € 98 million. This is partly due to the fact that the buildings that are connected to an electricity network need to install heat pumps, with an investment of around €382 million, but the investment costs for the insulation of the maximally insulated buildings are still 5 times higher than for the extensively insulated buildings. This is the other way around for the investment costs for the networks, which are between €201 – 501 million for the DH network and €118 million for the electricity grid reinforcements.

The results will be discussed further in the next chapter, together with the assumptions that have been made for this research and the influence this might have on the results.

6. DISCUSSION

This research focused on the task to make the built environment of the municipality of Groningen energy neutral in 2035 by using available lands within the municipality of Groningen. The desirability to install solar thermal storage plants on these lands has been explored by comparing this option with solar PV parks in combination with hydrogen storage and with the cultivation of energy maize from which biogas is produced. In this chapter, the most important assumptions and some points that are not taken into account in this research, but that might have an influence on the results, are discussed.

The yearly heat demand and the number of gas connections have been obtained by data from Enexis on a neighbourhood level. For the latter, the total number of gas connections in the municipality of Groningen in 2016 was around 71,000, while the number of households in Groningen was around 120,000 in 2015 (CBS, 2015). This is due to the fact that many flats and stacked houses share a gas connection, and because of the large amount of students. This will not have influenced the total heat demand, but it will have caused lower calculated investment costs for insulation, the DH network and the electricity grid reinforcements. It might also have had an influence on the hourly heat demand, since the distinction that has been made by Gas Act (DTe, 2006) between G1A (up to 5,000 m^3 per year) and G2A (from 5,000 m^3 per year) consumers, is not the same as the distinction that has been made by Enexis between commercial and private. Another factor that was not taken into account is the effect of a more flattened heat demand pattern after high insulation. The installation of solar thermal or PV panels on the roofs of buildings has not been taken into account either. Taking the installation of solar thermal or PV panels will cause a lower demand, but increases the need for heat storage and the amount of heat that can be stored, since less heat has to be delivered to the buildings directly at moments when the sun is shining. For solar PV, the excess electricity will be supplied to the grid, or these can be stored in batteries, but that has not been considered in this research.

For the generation of heat by the solar thermal collectors, the quasi dynamic method has been used. The measured amount of global irradiation on a horizontal surface has been used in the Hay, Davies, Klucher, Reindl model to calculate total radiation on the tilted surface, and all the assumptions made by implementing this model can be found in Appendix 3. The calculated yearly output of 428 kWh per m^2 collector area at a supply- and return temperature of 80°C and 40°C respectively, is in line with the yearly output as measured in Denmark. Noussan et al. evaluated the performance of 8 solar heating systems that have been chosen to be representative of all systems between 2007 and 2016. They concluded that 'all the systems show annual specific productions between 400 and 500 kWh/m^2, with some differences from year to year. These variations are mostly related to weather conditions, but in some cases also the installation of new collectors can lead to a variation of the average efficiency.'(Noussan et al., 2017). The amount of global irradiation in Denmark is quite similar to the Netherlands. In Groningen, the mean annual horizontal irradiation between 1981-2010 was 975 kWh/m^2 (KNMI, n.d.(a)), while in Denmark, the mean annual irradiation between 2001-2010 varied between 1000-1100 kWh/m^2 (Skalík et al., 2012). However, this study is based on the situation in 2016, which was an average year. Taking a different year, with different solar irradiation patterns and amounts, as well as a different amount of cold days, gives different results in the solar generation patterns. The same holds for the heat demand patterns and especially for the buildings heated by a heat pump, since the COP of heat pumps will decrease with lower ambient temperatures.

Two different insulation levels have been considered in this research. As can be seen in table 5-1, the reduction in heat demand from extensive to maximal insulation is just 7%, while the costs increase with a factor 3.4. Maximum insulation is needed for houses that are heated with a heat pump, in order to have a good performing heat pump. Only air source heat pump have been considered in this research, while for some houses a ground source heat pump can be implemented as well, which has a better COP which does not fluctuate with the ambient temperature. The impacts that insulation of buildings has on the habitants has not been taken into account, but in many cases habitants have to leave their houses for weeks. Also, the estimated costs that have been used in this research, might actually be higher. In a session organized by the municipality of Groningen became clear that the costs can go up to €90.000 per house (Atelier Woningen Energie Neutraal, January 18th 2018, Groningen, meeting). The investment costs for utilities have been displayed as costs that can be paid back over a period of 10 and 20 years and have not been calculated, but these costs will be significant as well and it is not certain if every utility has the means to make such an investment. The centre of Groningen has been assumed to be heated with heat pumps, but it is not feasible to insulate the old and monumental houses maximally. The same holds for installing a DH network in the centre. Hybrid heat pumps might be an option for this part of the city, as well as heating these buildings with biogas or green gas, but further research is needed about the feasibility of these options.

The considered biogas system is expensive, due to the storage costs. In this research has been chosen for biogas instead of green gas, because of the extra electricity consumption for the upgrading process, but in retrospect green gas might have been a better option, since the gas grid can be used as a storage. Also, the fact that energy maize will be cultivated on lands on which something else was cultivated before, is not taken into account. The same holds for fact that there is less manure available during summer, because the dairy is not inside then and a reduction in the available manure when some lands on which dairy was grazing before, might be used for the cultivation of energy maize.

Two different options have been considered for the excess and shortage of electricity. The first option was import and export, for which the capacity is available. But since this will cause problems for the balancing of the electricity system outside the municipality of Groningen, hydrogen storage has also been considered. However, it has to be noted that electricity from off shore wind turbines will have a mitigating effect on the need for storage, but the need for storage will not vanish if this is taken into account. Due to the low efficiency of the hydrogen cycle, in case of scenarios with high hydrogen storage, electricity still needs to be imported. Also, the costs of the hydrogen storage system, although with a wide range, are significant. Especially the costs for the storage of hydrogen under high pressure. This is partly due to the low calorific value of hydrogen, so that high storage volumes are needed, and as well as the fact that large steel tanks under high pressure are considered in this research. Furthermore, the heat that is released in by the fuel cells has not been considered, but this can be a useful heat source for the DH network, since the fuel cells will be mainly used in winter.

In this research, PTES and TTES have been considered. However, borehole thermal storage and aquifer thermal storage options are not taken into account in this research and might be feasible as well. With PTES for every loading period heat losses will be added to the surroundings, causing the yearly mean ground temperature to increase, the temperature gradient to decrease and therefore reducing the heat losses every loading period, until a steady-state is reached after 3-5 years. Assuming a 40% heat loss factor for the first year and using this efficiency for the PTES in Optimized scenario high, will reduce the amount of heat that can be extracted from the storage from 330 GWh to around 220 GWh. This means that instead of 220 GWh of green gas imports, 270 GWh of green gas imports are needed. Predicted is that in 2030 0.75 billion m^3 green gas is available for the built environment and this rises to 1.5 billion m^3 in 2050 (Melle et al., 2015). We can therefore assume that 0.94 billion m^3 green gas is available for the built environment in 2035. The population of the Netherlands is predicted to rise to 18 million (CBS, 2017c), of which 234,500 live in the municipality of Groningen. This means that 1.3% of the population will live in the municipality of Groningen in 2035 and that 12.2 million m^3 green gas is available. This amount of green gas can deliver around 112 GWh of heat to a DH network by use of the biogas boiler, which is not sufficient for the Optimized scenario high. However, many possibilities to provide heat have not been taken into account in this research. Biomass boilers or bio based oil boilers can be used, as well as electric boilers or the heat pump that can heat up the storage at times when there is an electricity surplus. There might also be more lands available in Haren or other surrounding municipalities on which more solar thermal collectors can be placed.

7. CONCLUSION

This research has provided an overview some of the possibilities and the bottlenecks to reach an energy neutral low temperature heat supply in the built environment in the municipality of Groningen in 2035. The research question that was posed in the introduction was the following:

'In order to have an energy neutral low temperature heat supply in the built environment in the municipality of Groningen in 2035, is it desirable to construct large scale solar thermal storage systems on available lands or is it better to construct solar PV systems in combination with hydrogen storage or a biogas system in terms of energy production, investment costs, and balance implications?'

The answer consists of several parts, just as posed in the question. In terms of energy production, the yearly energy yield per hectare was the highest for the solar thermal collectors with a T_s of 80°C and a T_r of 40 °C, which reached 1.22 GWh. For a T_s of 91.5°C and a T_r of 61.5°C the energy yield per hectare decreased to 0.99 GWh, but this was still higher than the energy yield of the solar PV panels, which was 0.73 GWh per hectare. The biogas system reached a far lower yield per hectare of 0.04 GWh, but this system can be complementary to the other systems, due to the maximum amount of land that is available on which solar PV or thermal collectors can be placed.

In terms of investment costs, the costs for solar PV and solar thermal collectors are in the same range, but the costs to make the buildings suitable to be heated by heat pumps are 3.4 times higher on average than the insulation costs will be for buildings that are connected to the DH network. Furthermore, the costs per heat pump and the electricity grid reinforcement that are needed amount around €8,000 and €4,000 respectively, bringing it in the same range as the costs per building that has to be connected to a DH network, which amount between €10,000 and €25,000.

Not taking storage into account and following the definition of energy neutral that 'all the used energy over a year has to be derived from renewable energy sources, with the possibility to import and export energy', solar PV systems would be desirable, due to the fact that the yearly generation of electricity is higher than the demand in the explored scenarios. But as can be seen in the NLDCs in figures 5-6, 5-9 and 5-12, imports would be needed for around 70% of the time. This has big implications for the balancing of the electricity system outside the boundaries of the municipality of Groningen, especially when more of these solar PV fields in other municipalities arise, for which the same holds. For these reasons, the implementation of solar thermal systems seem desirable, although without storage only 20% of the generated heat can be utilized and therefore storage is inevitable.

Implementing storage for solar PV and solar thermal systems increases the amount of utilized heat for the latter up to 92%. However, imports are still needed in this case, and due to the low efficiency of the hydrogen cycle, the same holds for the solar PV system. Both storage systems release stress on balancing of the network, although around 20% of the yearly electricity and heat demand has to be imported in both combined scenarios.

Looking at the costs for the storage systems, one can see that the storage of thermal heat is significantly cheaper than the hydrogen storage, with the hydrogen storage being in the range of a billion euros, while the estimations for the thermal storage did not exceed a hundred million euros. This makes solar thermal storage systems more desirable over solar PV systems in combination with hydrogen storage, while keeping in mind that this might be due to the system boundaries of this research and that looking at hydrogen storage on a national scale instead of a municipality scale can change these outcomes. The same holds regarding the efficiency of the two systems, with only 10% heat losses for thermal storage against 55% efficiency losses of the hydrogen storage cycle.

The biogas system that has been considered in this study is also desirable in terms of balance implications, but the investment costs for the storage that has been considered are significant compared to thermal storage and as said in the discussion, green gas might be a more desirable option.

Not following the exact definition of energy neutral of the municipality of Groningen, but taking the energy system of the Netherlands as a whole in consideration and posing that energy neutral on an hourly basis should be reached, it can be concluded that it is desirable to construct large scale solar thermal storage systems on the available lands in order to reach an energy neutral low temperature heat supply in the municipality of Groningen in 2035. However, imports will still be needed in order to fulfil the heat demand during the whole year. The considered biogas system can be supplementary to the solar thermal system, but the considered biogas storage is expensive and therefore further research into alternatives is needed. Some lands that are too far away from the DH network can be used for the construction of solar PV parks, since it is not feasible to connect the whole municipality of Groningen to a DH network and the generated electricity can be used to supply a part of the heat demand to new buildings which are already insulated well. But the implementation of hydrogen storage systems is not feasible on a municipality level due to the high costs and therefore imports and exports of electricity will still be needed.

8. RECOMMENDATIONS

This study is meant as a starting point to explore the desirability of solar thermal storage systems in the municipality of Groningen, which seem promising, but the exact neighbourhoods that will be connected to the DH network should be investigated further, as well the number of neighbourhoods.

In this study, the heating of buildings by green gas has not been explored, as well as heating by hybrid heat pumps. As said in the discussion, this seems a good option for the centre of Groningen, but has to be investigated further. A comparison between solar thermal storage systems and hybrid heat pumps should be made as well, in order to confirm the desirability of large scale solar heating plants.

A solar thermal storage system seems promising, but the exact design of the solar thermal system has to be further researched. This contains further research about the placing of the collectors, the collector field hydraulics, the piping, pressure maintenance, the design of the heat pump, the different seasonal storage options, as well as the location of the storages, to see if it is desirable to place the storages close to the consumers or centralized next to the solar thermal collectors. Also, only biogas and green gas have been considered to supply heat to the DH network if the solar thermal storage system, but as said before, there are many other options of combinations already in use (PlanEnergi, n.d.; SDH, 2017; Schmidt et al., 2015; Schmidt(a), n.d.) and these options should be investigated further.

Assumptions have been made for the angle under which the thermal panels are placed, as well as the amount of collectors that can be placed per hectare and the heat losses. The same holds for the solar PV panels and further research is needed to optimize these collector arrays further. The collectors have been assumed to be placed under an angle with a southern direction, but an east-west placing under a small angle could be viable for PV collectors as well, since will increase the amount of Wp that can be placed per hectare and will cause more flattened generation pattern, having a flattening effect on the LDCs.

PTES and TTES have been assumed to be the storage options in this research, but borehole thermal energy storage might be a good option as well, since the subsurface of Groningen is very suitable for this kind of storage up to 50°C (IF Technology, 2012; Gemeente Groningen, n.d.). The same holds for aquifer thermal energy storage and further research is recommended to investigate these options.

Also, since solar thermal and PV collectors on the roofs buildings have not been taken into account in this research, the effects that this has on the heat demand have to be investigated further.

This study is based on the situation in 2016, which was an average year. In follow-up studies, the effects of a cold year and a year with low solar irradiation has to be investigated further.

The cultivation of energy maize on the lands which cannot be used for the installation of solar collectors and generating biogas from the harvested maize has been investigated in this study, but the costs incorporated with the storage of biogas made this option not viable. Instead of producing biogas, green gas can also be produced and stored in the gas network, but the viability of this alternative has to be investigated further. Also, another storage system might be more feasible than the storage in large tanks under pressure. The same holds for the hydrogen storage, which was one of the main reasons why the hydrogen storage system was considered not to be feasible to be implemented. Also, AkzoNobel and Gasunie are investigating the option to produce hydrogen by electrolysis in Delfzijl (DvhN, 2018), which might be able to be combined with the excess electricity production in the municipality of Groningen. Furthermore, taking the electricity supply of the off shore wind turbines into account will cause the NLDC in figures 5-6, 5-9 and 5-12 to shift to the right, reducing the amount of time with an electricity deficit and making the solar PV option more viable.

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APPENDICES

Appendix 1

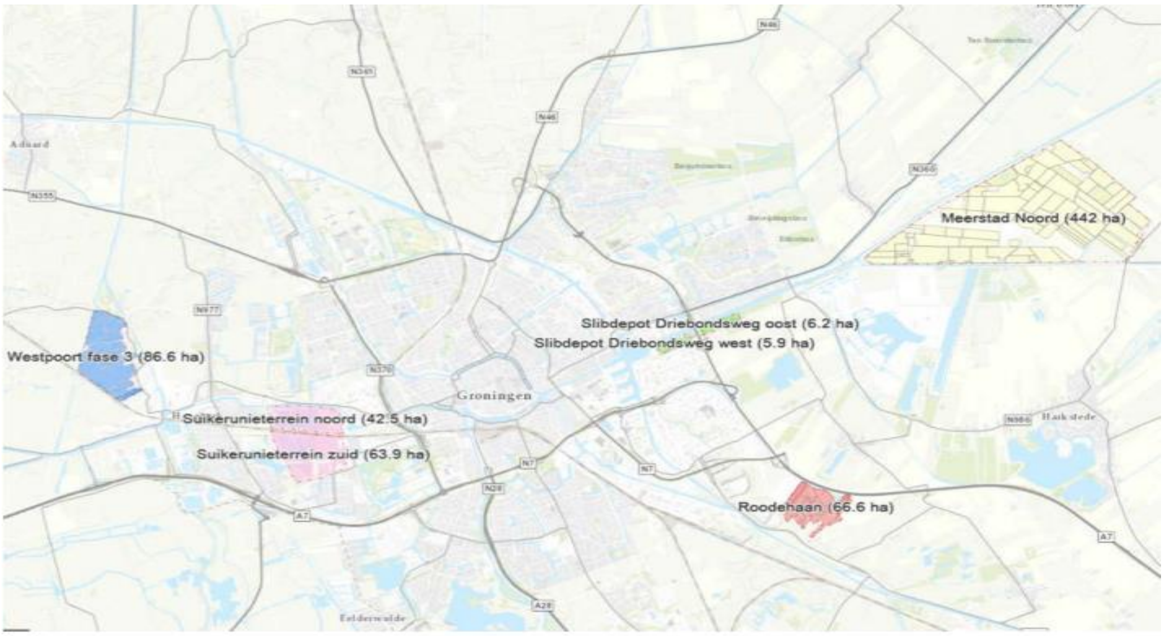

Figure 0-1: Assessment of available lands in the municipality of Groningen in 2015 (Gemeente Groningen, 2016)

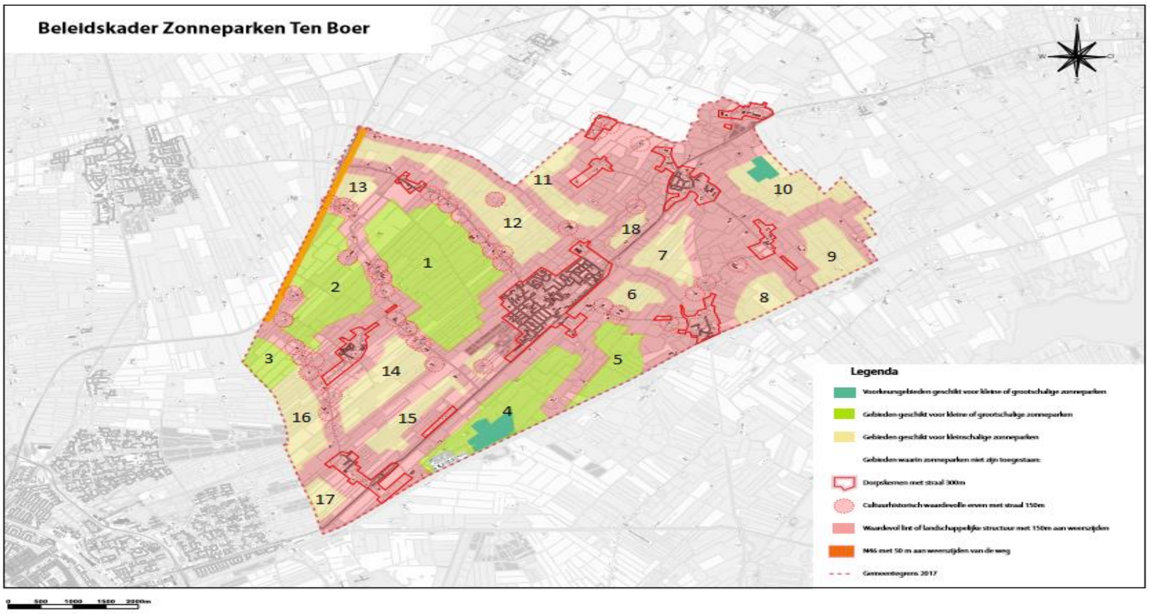

Figure 0-2: Assessment of available lands in the municipality of Ten Boer (Ten Boer, 2017)

Table 0-1. Surface area of the numbered lands as shown in figure 0-2 in the municipality of Ten Boer.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Surface area (ha)	340	180	46	170	72	28	77	50	73	120	70	190	27	110	60	91	30	11	1,745

Appendix 2

The other sources that have been compared with the data obtained from Energieinbeeld (Energieinbeeld, 2017) and the assumptions that have been made are elaborated below. This has been done for Groningen, since the data for Ten Boer is incomplete in these sources. Especially agriculture, water treatment and gas extraction have a large share in the energy consumption, but the exact division of the energy consumption between these sectors is unknown, because these are commercial secrets (Energiemonitor, 2017). Energieinbeeld does not take these bulk consumers into account and the heat demand of Ten Boer is only a small fraction of the heat demand of Groningen, so therefore only different sources for Groningen have been compared to the data found at Energieinbeeld.

According to the Energiemonitor (Energiemonitor, 2017), the total energy demand in the municipality of Groningen was 4,203 GWh in 2016. Around 30% of the total energy demand was consumed by households, around 50% by the industry and services and around 20% by transport. The total energy consumption of households was 1,273 GWh in 2016, of which 81% was supplied by gas, 17% by electricity and 2% by renewable heat. Assuming that the total demand for heating in households is low temperature heat and is supplied by gas and renewable heat, the total low temperature heat demand of households is therefore 1,051 GWh.

The total energy consumption of the industry and services was 1,998 GWh in 2016. A distinction has been made between industry (40%), others (30%), governmental institutions (5%), educational institutions (10%) and healthcare institutions (15%), but the Energiemonitor does not make a distinction between energy carriers. Assuming that the industry consumes high temperature heat and electricity and that the rest (referred to as services from now on) consumes low temperature heat and electricity, gives an energy consumption of 799 GWh for the industry and 1,199 GWh for services.

Assuming the same division between the commercial electricity and gas consumption as given by Energieinbeeld (Energieinbeeld, 2017), 38,5% and 61,5% respectively, and applying that to the assumed energy consumption for services as given by the Energiemonitor, this gives a total low temperature heat consumption of 737 GWh. Adding this to the total low temperature heat demand of the households, this gives a total low temperature heat demand of 1,789 GWh.

In the report 'Groningen aardgasloos in 2035' (Noorman & Noordenburg, 2016) an estimation has been made of the total heat consumption in 2014. The total energy consumption in 2014 (4,262 GWh), is around 1.5% higher than in 2016 and the estimated total low temperature heat consumption is 1,793 GWh according to this report.

According to the Klimaatmonitor, the total heat consumption was 2,616 GWh in 2014. The amount of gas consumed by industry was 89.3 Mm^3, equivalent to 775 GWh. Assuming that this gas is used for high temperature heat, the total low temperature heat consumption was 1,841 GWh in 2014 (Agentschap NL, 2017).

Table 0-2. Comparison of the low temperature heat demand of the municipality of Groningen for different years and from different sources.

Source	Year	Low temperature heat demand (GWh)
Energieinbeeld	2016	1,923
Energiemonitor	2016	1,789
Energieinbeeld	2014	1,903
Noorman & Noordenburg	2014	1,793
Agentschap NL	2014	1,841

Appendix 3

From the website of the KNMI, hourly global horizontal irradiance data can be obtained. But since the collectors will be under an angle, this data need to be converted. There are some free websites on which this data is available, like Renewables.ninja for 2014 (Renewables.ninja, n.d.) and SoDa for 2005 (SoDa, n.d.), which are making use of sattelite data. Since demand patterns for 2010-2016 from the GasUnie have been obtained, the initial idea was to use the website of renewables.ninja, but since 2014 was a warm year and had a soft winter (KNMI, n.d.(b)), this would not give a representative demand pattern.

Therefore, another solution has been found. In the book Solar Engineering of Thermal Processes (2013) by John A. Duffie and William A. Beckman, different methods are described to calculate the global insulation under an angle from the global horizontal insulation. From this book, the Hay, Davies, Klucher, Reindl model (HDKR) gives for the total radiation on the tilted surface (Duffie & Beckman, 2013):

$$I_t = (I_b + I_d A_i) R_b + I_d (1 - A_i) \left(\frac{1 + \cos\beta}{2}\right)\left[1 + f \sin^3\left(\frac{1 + \cos\beta}{2}\right)\right] + I\rho_g \left(\frac{1 - \cos\beta}{2}\right)$$

Where (the symbols and the corresponding formulas are explained below in the order of appearance),

$\boldsymbol{I_b}$ Beam horizontal insulation (direct): $I_b = \left(1 - \frac{I_d}{I}\right) I$

$\boldsymbol{I_d}$ Diffuse horizontal insulation: $I_d = \left(\frac{I_d}{I}\right) I$

$\boldsymbol{I}$ The hourly value for the global horizontal insulation as measured

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09\, k_T & for\ k_T \leq 0.22 \\ 0.9511 - 0.1604\, k_t + 4.388\, k_T^2 - 16.638\, k_T^3 + 12.336\, k_T^4 & for\ 0.22 < k_T \leq 0.80 \\ 0.165 & for\ k_T < 0.80 \end{cases}$$

$\boldsymbol{k_T}$ The hourly clearness index, defined as: $k_T = \frac{I}{I_0}$

$\boldsymbol{I_0}$ The extra-terrestrial radiation on a horizontal surface for an hour period, given by

$$I_0 = \frac{12\ x\ 3600}{\pi} G_{sc}\left(1 + 0.033 \cos\frac{360n}{365}\right) \times \left[\cos\Phi \cos\delta\,(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin\Phi \sin\delta\right]$$

Where,

$\boldsymbol{G_{sc}}$ The solar constant: $G_{sc} = 1367\ \frac{W}{m^2}$

$\boldsymbol{n}$ The number of the day in the year

$\boldsymbol{\phi}$ Lattitude, angular location north or south of the equator, north positive: $-90° \leq \phi \leq 90°$

δ Declination, the anglular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive: $-23.45° \leq \delta \leq 23.45°$

$$\delta = \left(\frac{180}{\pi}\right)(0.006918 - 0.399912 \cos B + 0.070257 \sin B - 0.006758 \cos 2B$$
$$+ 0.000907 \sin 2B - 0.002697 \cos 3B + 0.00148 \sin 3B$$

Where,

$$B = (n-1)\frac{360}{365}$$

ω Hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive

$\boldsymbol{A_i}$ Anisotropy index, which is a function of the transmittance of the atmosphere for beam radiation

$$A_i = \frac{I_b}{I_0}$$

$\boldsymbol{R_{b.ave}}$ The ratio of the total radiation of the tilted surface to that on the horizontal surface

$$R_{b.ave} = \frac{a}{b}$$

Where,

$$a = (\sin\delta\ \sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma) \times \frac{1}{180}(\omega_2 - \omega_1)\,\pi +$$
$$+ (\cos\delta\cos\phi\cos\beta + \cos\delta\sin\phi\sin\beta\cos\gamma) \times (\sin\omega_2 - \sin\omega_1)$$
$$- (\cos\delta\sin\beta\sin\gamma) \times (\cos\omega_2 - \cos\omega_1)$$

and

$$b = (\cos\phi\cos\delta) \times (\sin\omega_2 - \sin\omega_1) + (\sin\phi\sin\delta) \times \frac{1}{180}(\omega_2 - \omega_1)\,\pi$$

Where,

γ Surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive;

$-180° \leq \gamma \leq 180°$

β Slope, the angle between the plane of the surface in question and the horizontal

$0° \leq \beta \leq 180°$

f Modulating factor to account for cloudiness: $f = \sqrt{\frac{I_b}{I}}$

All these formulas have been put in Excel and the global irradiance under an angle has been calculated and compared with the horizontal values given for the different angles for each hour of 2005. Data gaps have been replaced by data from the week after, which was the case for 6 days (around hour 5,660) and for 1 day (around hour 7,916).

It became clear that for the hours containing sunrise and sunset, the values deviated a lot. This has been solved by taking the horizontal values for the hours containing sunrise and sunset. Sunrise and sunset times have been obtained from the NOAA Solar Calculations (GMD, n.d.).

There were some negative and values that were too high, but since for the different angles there were only between 10-30 of these wrong values, these have been filtered and the horizontal values have been taken for these values.

However, the excel sheet that has been made, only shows small deviations for tilted surfaces facing south. Tilted surfaces facing east or west deviate too much to be useful in the model made, probably because taking horizontal values at sunrise or sunset and for other deviating values, has a bigger impact if the surface is orientated to east or west compared to the surface orientated to the south. Due to time limitations, this problem has not been solved and only surfaces orientated to the south have been used.

The deviations with the calculated values and the obtained values from the SoDA database are shown in table 0-3.

Table 0-3. Deviations with the calculated values and the obtained values from the SoDA database

Angle	**10°**	**15°**	**25°**	**30°**	**35°**	**40°**	**60°**
Deviation (%)	-1.44	-2.06	-2.77	-3.01	-2.84	-2.28	+3.70

Appendix 4

The power output of the solar collector following the steady state collector model (Trier, 2012; Fan et al., 2009).

$$P_c = A_c \cdot K_\theta \cdot (\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2)$$

has the boundary condition of G>800 W/m2. Therefore, this model will not be used in this research, but the Quasi Dynamic collector model will be used instead.

The Quasi Dynamic collector model is an extended model and the generated heat per unit area can be found in the formula below.

$$\frac{Q}{A} = F'(\tau\alpha)_{en} K_{\theta b}(\theta)G_b + F'(\tau\alpha)_{en} K_{\theta d}(\theta)G_d - c_6\, u\, G^* - c_1 \cdot (T_m - T_a) - c_2 \cdot (T_m - T_a)^2$$
$$- c_3\, u\, (T_m - T_a) + c_4(E_L - \sigma T_a^4) - c_5 dT_m/dt$$

The single incidence angle modifier used in the steady state collector model has been divided into incidence angles for direct and for diffuse irradiance. The incident angle modifier for diffuse irradiance($K_{\theta d}$) is taken as a constant, while the incident angle modifier for the direct irradiance ($K_{\theta b}$) is calculated for each hour. Instead of only considering the global irradiance on the collector, the diffuse and direct irradiance are used in this model. Also, a thermal capacitance term is added. Terms for the heat loss dependence on long wave irradiance (c_4), wind speed (c_3) and wind speed dependence on the zero loss coefficients (c_6) have been added. All parameters are based on whole day measurements (Kovacs, 2012; Osorio, 2011). However, for covered solar collectors, the coefficients c_6, c_3 and c_4 can be assumed to be without statistical significance (Zambolin & Del Col, 2010). Since the in- and outlet temperature in the collector are assumed to be constant, dT_m/dt is equal to 0 as well, resulting in the formula used in this research.

$$P_c = A_c \cdot (\eta_0 \cdot (G_b \cdot K_\theta + G_d \cdot K_d) - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2)$$

Where,

P_c: Power output of the collector	[W]
A_c: Effective collector area	[m^2]
η_0: Maximum efficiency if there is no heat loss	[–]
G_b: Beam radiation (direct) on collector plane	[W/m^2]
K_θ: Incident Angle Modifier for the incidence angle at the given time step	[–]
G_d: Diffuse radiation	[–]
K_d: Incident Angle Modifier for diffuse radiation	[–]
a_1: 1st order heat coefficient	[W/(K·m^2)]
a_2: 2nd order heat coefficient	[W/(K·m^2)]
T_m: Mean collector fluid temperature	[°C]
T_a: Temperature of the ambient air	[°C]

Instead of the global inclined irradiation, the diffuse and direct inclined irradiation are needed to calculate the power output of the solar thermal collectors. The ratio between the horizontal diffuse and the total irradiation has been calculated and the same ratio is assumed for the inclined diffuse and the total irradiation. In this way, the inclined diffuse and direct radiation can be calculated.

Also, the incident angle modifier for direct radiation has to be calculated. This has been done by calculating the angle of direct radiation on the tilted surface, with the following formula (Duffie & Beckman, 2013):

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega$$
$$\text{s}\cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega$$

An explanation of the parameters can be found in Appendix 3.

For sunrise and sunset hours, this gave deviating values, and therefore an angle of 85° has been taken.

The solar thermal collector that will be considered is the HTHEATstore 35/10 and has been tested under quasi-dynamic conditions (Acron-Sunmark, 2016). This solar collector is manufactured by Arcon-Sunmark, which developed the large scale solar thermal collector parks in Silkeborg, Vojens and others (Acron-Sunmark, n.d.) and has the following parameters, as displayed in table 0-4 and 0-5.

Table 0-4. HTHEATstore 35/10 (Acron-Sunmark, 2016).

Performance parameters	η_0	c_1	c_2	c_3	c_4	c_6	K_d
Units	-	W/(m^{2}K)	W/(m^{2}K)	J/(m^{2}K)	-	s/m	-
Test results	0.745	2.067	0.009	0.000	0.000	0.000	0.930

Table 0-5. Incident angle modifier, from (Acron-Sunmark, 2016).

Angle θ (°)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
K_θ	1.00	0.99	0.97	0.94	0.90	0.82	0.65	0.32	0.00

In order to obtain the value of the incidence angle modifier at any calculated angle for the direct irradiation, a fifth order polynomial formula has been fitted to the values for the incidence angle modifier at the given angle θ:

$$K_\theta = 0.795 + 0.03928357 \cdot \theta - 0.00248447 \cdot \theta^2 + 0.6568473 \cdot 10^{-4} \cdot \theta^3 - 7.718531 \cdot 10^{-7} \cdot \theta^4 + 3.141026 \cdot 10^{-9} \cdot \theta^5$$

With this formula, the incident angle modifier for direct irradiation has been calculated for each hour. The assumption that the ratio between the diffuse horizontal irradiation and the global horizontal irradiation is the same as the ratio the diffuse inclined irradiation and the global inclined irradiation is the same, is an uncertain assumption. Checking this for the SoDA data for 2005 (SoDa, n.d.) gives that the diffuse inclined irradiation as calculated is 20% higher than given diffuse inclined irradiation. The direct inclined irradiation as calculated is 20% lower than the given direct inclined irradiation. But, as said in the discussion, the results are in line with the results found by Noussan et al. (Noussan et al., 2017).

Appendix 5

There are three types of thermal energy storage technologies; latent heat storage, chemical heat storage and sensible heat storage.

Latent heat storage

With latent heat storage, thermal energy is stored in materials that changes phases during the storing process, therefore called phase change materials (PCM). The only phase change used for thermal storage is the solid–liquid change. Due to the high energy storage density and the therefore relatively small storage volume, it is an attractive way to store solar heat. Also, it stores the energy at a constant temperature which widens the scope for the application of a latent heat storage system. However, this technology has not been applied for long-term storage and is still in the research phase (Mishra et al., 2015; Xu et al., 2014).

Chemical heat storage

Chemical reaction heat storage is a thermal storage method which has distinctive advantages of high energy storage and low heat losses. Chemical storage has also the capability to conserve energy at ambient temperature as long as desired without heat losses. This technology is based on the reversible reaction between two substances (chemical reaction heat storage) or from absorption or adsorption processes (sorption heat storage). Although the studies on thermochemical storage materials (TCM) are at the theoretical and laboratory testing stages, it is considered a promising thermal storage technique (Xu et al., 2014).

Sensible heat storage

With sensible heat storage, the material does not change state during heating. The amount of energy stored is proportional to the material's temperature and to the material's properties like density and heat capacity. Storing materials can be for example water, soil or rock. Sensible heat storage is considered to be a simple, low-cost and relatively mature technology for seasonal energy storage compared to the other alternatives and has been implemented in a significant number of projects (Xu et al., 2014). Therefore, only this type of thermal energy storage will be considered in this study.

Thermal energy storage options

There are a number of different types of sensible heat storage possibilities available and a number of well-functioning examples exist. The main four concepts for seasonal thermal energy storage, as shown in figure 0-3, include (Maripuu & Dalenbäck, 2011):

- Borehole thermal energy storage (BTES)
- Pit thermal energy storage (PTES)
- Tank thermal energy storage (TTES)
- Aquifer thermal energy storage (ATES)

Tank thermal energy storage(TTES)

With TTES the tank is filled with water to store thermal energy. The structure can be made of steel, concrete or of glass fibre reinforced plastic and can be located on the ground, partially buried or completely underground. Insulation is fitted outside the tank to reduce thermal losses to the environment. Due to the relatively high investment costs, TTES is most commonly used as a short-term thermal energy storage option and can also serve as a buffer in combination with other thermal energy storage options (Guidalfajara et al., 2014; Schmidt & Miedaner, 2012).

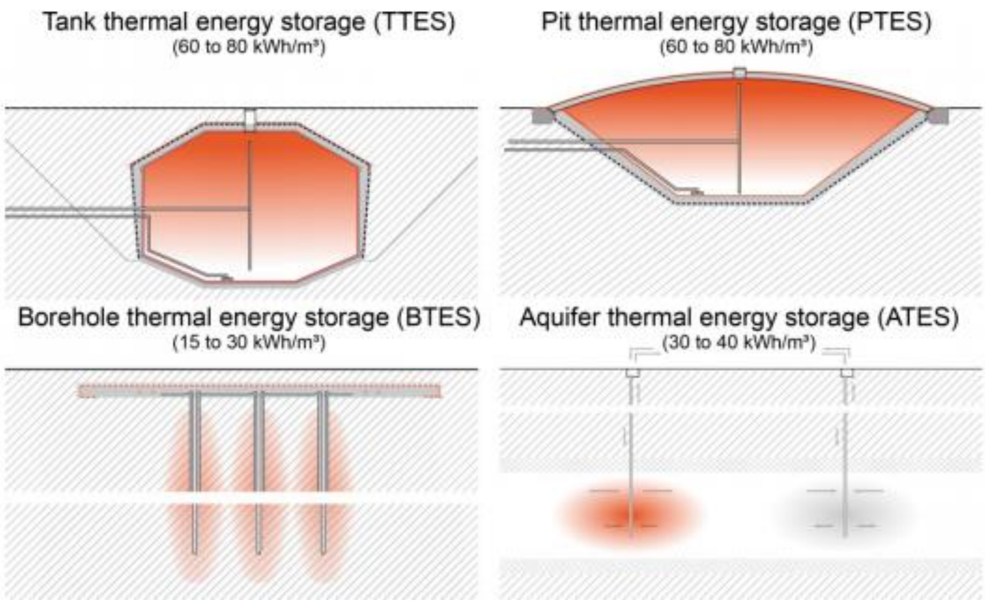

Figure 0-3: Different thermal energy storage options and their heat capacities (Schmidt et al., 2015).

Pit thermal energy storage (PTES)

PTES consist of an artificial pool which is closed on top. The pool is filled with storage material, which can be water or a gravel-water mixture (gravel fraction 60-70%). The tilted walls of the pool and the bottom are heat insulated. The roof over the artificial pool can be floating on the water or can be built as a self-supporting structure as a rugged roof. If the pit storage is filled with a gravel-water mixture, the heat capacity decreased from 60 to 80 kWh/m^3 to 30-50 kWh/m^3. This means that in order to reach the same storage capacity, a pit storage filled with the mixture must be 1.3 times to twice the size of a pit storage filled with water. However, this also means that the roof of the pit will be more solid and the space over the storage can easily be used. The maximal stored temperature is about 80-90°C (Mangold & Deschaintre, 2015). A typical lifetime of the polymers used for insulation depends on the temperature of the storage and is around 20 years (SHC,2016).

Borehole thermal energy storage (BTES)

Thermal energy can also be stored in the ground directly. BTES consists of U pipes that are located in vertical boreholes in order to create a heat exchanger with the soil, typically 30 to 100 m below the surface. Suitable geological formations for this kind of storage are rock, or water-saturated soils without any natural groundwater flow. In the charging period, hot water is flowing from the centre to the boundaries creating a radial temperature distribution in the storage. (Guidalfajara et al., 2014; Schmidt & Miedaner, 2012). The subsurface of Groningen is very suitable for this kind of storage up to 50°C (IF Technology, 2012; Gemeente Groningen, n.d.).

Aquifer thermal energy storage(ATES)

At some locations it is possible to make use of underground caverns or aquifers for the storage of thermal energy. An useable aquifer is a permeable sand, gravel, sandstone or limestone layer with high hydraulic conductivity, surrounded by impervious layers above and below. There is no or a low natural groundwater flow in the aquifer. Two wells are drilled into the aquifer layer, one serving for the extraction of water and one for the injection of water. During charging periods, the cold ground water is extracted, heated up and injected into the aquifer layer again. During discharging periods the flow direction is reversed (Mangold & Deschaintre, 2015).

Appendix 6

Table 0-6. Storage capacity (including 10% yearly losses) vs utilized generated solar heat (Solar thermal scenario 80-40).

Storage Capacity (GWh)	0	1	2	5	10	50	100	250	400	500	600
Solar Utilized (%)	20	35	39	43	45	48	53	64	76	84	92
Solar Utilized (GWh/y)	230	400	450	500	520	560	610	740	880	970	1060

Table 0-7. Storage capacity (including 10% yearly losses) vs utilized heat (Solar thermal scenario 91.5-61.5).

Storage Capacity (GWh)	0	1	2	5	10	50	100	250	400	450
Solar Utilized (%)	20	38	43	45	49	54	58	73	87	92
Solar Utilized (GWh/y)	190	350	400	430	460	500	540	680	810	860

Table 0-8. Transmission line capacity (MW) for import and export vs the yearly electricity export (GWh) (Solar PV scenario 2).

Transmission lines (MW)	200	250	300	350	400	450	500	550	600	650
Electricity export (GWh)	390	440	480	510	540	550	560	560	560	560

Table 0-9. Transmission line capacity in MW for import and export vs the electricity export in GWh (Warmtestad scenario 4).

Transmission lines (MW)	50	100	150	200	250	300	350	400	450	500
Electricity export (GWh)	130	220	290	340	380	400	410	420	420	420

Table 0-10. Storage capacity (including 10% yearly losses) vs utilized generated solar thermal heat (Warmtestad scenario 4).

Scenario	No st.		low					medium			high
Storage Capacity (GWh)	0	0.25	0.5	1	2	5	10	50	75	100	130
Solar Utilized (%)	20	36	40	44	48	48	52	64	72	80	93
Solar Utilized (GWh/y)	50	90	100	110	120	120	130	160	180	200	230
Biogas consumption (GWh/y)	280	240	230	220	220	210	200	170	150	130	100

Table 0-11. Transmission line capacity in MW for import and export vs the electricity export in GWh (Optimized scenario 5).

Transmission lines (MW)	25	50	100	150	200	250	300	350
Electricity export (GWh)	70	120	200	250	290	300	310	310

Table 0-12. Storage capacity vs utilized generated solar thermal for the different scenarios (Optimized scenario 5).

Scenario	No st.		low					medium			high
Storage Capacity (GWh)	0	0.25	0.5	1	2	5	10	50	100	200	225
Solar Utilized (%)	24	35	41	45	49	51	52	59	69	88	92
Solar Utilized (GWh/y)	120	170	200	220	240	250	255	290	340	430	450
Biogas (GWh/y)	650	600	570	550	530	520	515	480	430	240	220

Appendix 7

Table 0-13. Summary of all the costs (System description chapter 4).

	Lower boundary (k€)	Upper boundary (k€)	Lifetime (years)	Group
Solar thermal collector *(per hectare)*	510	710	25	Generation
Solar PV collectors (per hectare)	650	650	25	Generation
PTES (200.000 m^3 water) *(per MWh)*	0.172	0.271	25	Storage
TTES (5.000 m^3 water) (per MWh)	1.85	3.45	25	Storage
Large scale heat pump (per MW)	300	300	25	Storage
Hydrogen storage tank *(per tonne)*	240	380	25	Storage
Elektrolyser *(per MW)*	80	870	13 (upper) 20 (lower)	Storage
Fuel cell *(per MW)*	80	1,000	13 (upper) 20 (lower)	Storage
Biogas storage (per 1,000 m^3)	30	30	25	Storage
Biogas AD system *(per kilotonne)*	53.64	53.64	25	Generation
Feedstock pre-treatment *(per kilotonne)*	3	3	25	Generation
Biogas boiler *(per MW)*	60	60	25	Generation
Air source heat pump *(per building)*	8	8	25	Buildings
Electricity grid reinforcement *(per heat pump)*	3.94	3.94	40	Network
District heating network *(per connection)*	10	25	50	Network
District heating network *(per km)*	980	1,650	50	Generation

Table 0-14. Summary of all the costs in millions of euros for the different scenarios (Warmtestad scenario 4)

	Scenario	Lower boundary (M€)	Upper boundary (M€)	Group
Electric system:				
Maximal insulation	all	738	738	Buildings
Air source heat pumps	all	642	642	Buildings
Electricity grid reinforcements	all	198	198	Network
Solar PV collectors (720 hectares)	all	468	468	Generation
Storage options electric:				
Electrolyser (50 MW)	low	5	46	Storage
Hydrogen Storage (1,400 tonnes)	low	336	532	Storage
Fuel cell (24 MW)	low	2.4	25	Storage
Electrolyser (250 MW)	medium	25	229.5	Storage
Hydrogen Storage (4,104 tonnes)	medium	984	1,558	Storage
Fuel cell (162 MW)	medium	12.3	170	Storage
Electrolyser (400 MW)	high	40	372	Storage
Hydrogen Storage (4,536 tonnes)	high	1,085	1,718	Storage
Fuel cell (259 MW)	high	19.5	203	Storage
District heating system:				
Extensive insulation (all buildings DH)	all	44.4	44.4	Buildings
Solar thermal collectors (225 hectares)	all	116	161	Generation
District heating network (all connections)	all	71.5	179	Network
Heating network from site to DH (5 km)	all	2.5	4.2	Generation
Biogas storage (10,1 Mm³)	all	303	303	Storage
Biogas AD system + feedstock pre-treatment (136,350 tonnes)	all	7.7	7.7	Generation
Biogas boiler (135 MW)	all	6.8	6.8	Generation
Storage options DH:				
TTES (500 MWh)	low, medium, high	0.9	1.7	Storage
PTES (49,500 MWh)	medium	8,5	13.4	Storage
Large scale heat pump (10 MW_{el})	medium	3	3	Storage
PTES (129,500 MWh)	high	22.3	35	Storage
Large scale heat pump (26 MW_{el})	high	7.8	7.8	Storage

Table 0-15. Summary of all the costs in millions of euros for the different scenarios (Optimized scenario 5)

	Scenario	Lower boundary (M€)	Upper boundary (M€)	Group
Electric system:				
Maximal insulation	all	506	506	Buildings
Air source heat pumps	all	382	382	Buildings
Electricity grid reinforcements	all	118	118	Network
Solar PV collectors (518,5 hectares)	all	337	337	Generation
Storage options electric:				
Electrolyser (25 MW)	low	2.5	23	Storage
Hydrogen Storage (756 tonnes)	low	181	286	Storage
Fuel cell (13 MW)	low	1.3	14	Storage
Electrolyser (150 MW)	medium	15	139	Storage
Hydrogen Storage (2,700 tonnes)	medium	684	1,026	Storage
Fuel cell (77 MW)	medium	7.7	89	Storage
Electrolyser (400 MW)	high	40	367	Storage
Hydrogen Storage (3,240 tonnes)	high	778	1,231	Storage
Fuel cell (129 MW)	high	13	135	Storage
District heating system:				
Extensive insulation (all buildings DH)	all	98	98	Buildings
Solar thermal collector (426,5 hectares)	all	220	305	Generation
District heating network (all connections)	all	201	501	Network
Heating network from site to DH (3 x 3 km)	all	4.4	7.5	Generation
Biogas storage	all			Storage
Biogas AD system + feedstock pre-treatment (136,350 tonnes)	all	7.7	7.7	Generation
Biogas boiler (362 MW)	all	18.2	18.2	Generation
Storage options DH:				
TTES (500 MWh)	low, medium, high	0.9	1.7	Storage
PTES (49,500 MWh)	medium	8.5	13.4	Storage
Large scale heat pump (10 MW_{el})	medium	3	3	Storage
PTES (224,500 MWh)	high	38.5	60.8	Storage
Large scale heat pump (45 MW_{el})	high	15	15	Storage