WINDMOLENBROEK TOWARDS FOSSIL FUEL INDEPENDENCE

AND THE ROLE OF THE ENERGETIC UNDERGROUND

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Summary

The municipality of Almelo wants the neighbourhood Windmolenbroek to become fully independent from fossil fuels. They want to reach this aim by looking at the potential of the underground and by looking at possible other above ground-renewable energy sources. This report provides the starting point of this aim, by providing a multidisciplinary, academic perspective on possible options, their integration and on their implementation in Windmolenbroek. The main research question this report investigates is: 'What options are available to make optimal use of the energetic potential of the underground to foster the energy transition of Windmolenbroek?'. In order to answer the main research question, four different subdomains have been formulated: technology, hydrogeology, biology/chemistry, and social aspects and the built environment. These domains each contain their own specific sub questions. The methods of this research include literature research and the construction of a hydrogeological groundwater model.

The promising sustainable energy supply systems ATES (Aquifer Thermal Energy Storage), BTES (Borehole Thermal Energy Storage) and PVT (solar photovoltaic-thermal systems) have been investigated in depth. The possibility of applying other innovative sustainable resources related to wastewater has been investigated too, however, less extensively.

It was found that the underground of Windmolenbroek consists of one unconfined aquifer, below which a large aquitard is present. The results of the hydrogeological model showed that ATES could potentially satisfy the entire heating demand of Windmolenbroek. The model shows that the resulting thermal plume will move westward, along with the regional groundwater flow direction. It is unlikely that regional drinking water wells will be thermally affected.

However, the implementation of an ATES system in Windmolenbroek is highly risky, as a large uncertainty exists regarding the possible clogging of the wells. As the chemical characteristics of the underground where not analysed here and therefore the risk of clogging is uncertain, implementing an ATES system is not advised.

Due to this lack of knowledge regarding the characteristics of the subsoil and as BTES systems are closed and therefore are not susceptible to clogging, they provide an overall better option. From the research it is concluded that the optimal solution for using the energetic potential of the underground of Windmolenbroek is to install a grid of BTES systems arranged in a field, with energy supplied by the residential heat excess during summer and thermal energy from the PVT panels. Each house should have a heat pump in order to upgrade the temperature of the water. A BTES borehole field is preferred instead of single BTES systems per house since this would have a large impact at the household level and would also result in greater heat losses in subsoil storage. However, the implementation of single household BTES systems is advised since some houses in the centre of Windmolenbroek would be located too far away from the borehole fields, which would result in heat losses in transmission. Locations of the potential borehole fields and PVT panels are also provided in this report. The possibility to extract energy from the effluent waste water of wastewater treatment plant de Sumpel is a promising option as an additional renewable energy source used for direct home heating. Ultimately, this report is valuable in that it provides a concrete starting point for how Windmolenbroek might achieve its carbon neutrality goals using the potential of the underground. The reader is advised that it might be practical to skip to the given advice in chapter 7.

Our team

This academic consultancy training (ACT) team consists of five students from Wageningen University & Research having a multidisciplinary background. The ACT is a course aimed at contributing at an academic level to the execution of a transdisciplinary project for an external commissioner. Emphasis is put on the process and contents, and integrating all expertise into a final advice for the commissioner. This chapter briefly introduces the five students working on this project.

Hester Koning is in her second year of the master Urban Environmental Management, and follows the track Environmental Policy. She is particularly interested in the social challenges related to the energy transition and the challenges within the built environment.

Nina Sandfort is in the second year of the master program Earth and Environment. Within this master's program she is following the tracks Hydrology and Soil Surface Processes and Dynamics. She is able to contribute to modelling tasks, work in ArcGIS, and can also provide knowledge on the biological and technical elements of this project.

Maurice Mertens is a second year master student in the program Earth and Environment and has a background in Environmental Sciences. He is experienced in working with broad environmental issues and their solutions and is particularly interested in the ecological effects of climate change and changing environmental conditions and is interested in how to make use of natural process in developing solutions to environmental issues.

Peter La Follette is a second year MSc student from California studying Hydrology, with a niche in computational hydrology. He has bachelor degrees in chemistry and maths. He has experience in ArcGIS, as well as a number of hydrological/hydrogeological codes and software. In this project, he contributes to the modelling of the groundwater- and heat flow. He is the secretary, which means he is the default for external communication, and is responsible for aspects of scheduling.

Zhang is from China and is in his first year of the master Environmental Sciences. He has a bachelor's degree in renewable energy professional engineering. Because of his background in- and experiences on engineering design software like AutoCAD, he is committed to the technical part of the research, more specifically about the energy system itself.

List of abbreviations

ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
COP	Coefficient of performance
DEM	Digital elevation model
DHW	Direct hot water
HTH	High temperature heating
LTH	Low temperature heating
PVT	Photovoltaic thermal
RES	Regional energy strategy
RMSE	Root mean square error
UTES	Underground thermal energy storage
WTA	Willingness to adopt
WWTP	Wastewater treatment plant

Table of contents

1. Introduction and objective **1**

2. Research questions **2**

3. Methods **3**

4. Case description of Windmolenbroek **5**

4.1 Neighbourhood characteristics 5

4.2 Hydrogeological conditions of Windmolenbroek 8

5. Potential sustainable heat sources and technologies **11**

5.1 UTES systems 11

5.2 Photovoltaic Thermal panels 22

5.3 Additional sustainable energy sources 25

6. Application to Windmolenbroek **27**

6.1 ATES (model results) 27

6.2 ATES risk of clogging 29

6.3 BTES 30

6.4 Photovoltaic Thermal panels 31

6.5 Additional sustainable energy sources 34

6.6 Social consequences and social support 36

6.7 Final SWOT 38

7. Final advice and conclusion **39**

8. Discussion **42**

9. Recommendations for further research **44**

Appendix I – Application of renewable resources to Windmolenbroek **46**

Appendix II – Hydrological model parameters **47**

Appendix III - TES energy supply: model calculation description **49**

Appendix IV - BTES energy supply approximation **50**

References **55**

1. Introduction and objective

Windmolenbroek, a Dutch neighbourhood with 13,965 inhabitants located in the south of Almelo, strives to become fully independent of fossil fuels (Kennispunt Twente, 2019). An innovative plan is required to achieve this goal, highlighting alternative, sustainable energy sources. A specific plan per neighbourhood to eliminate reliance on natural gas is part of the regional energy strategies (RES), a regional realization of the goals and ambitions determined in the Paris Climate Agreement (RVO, n.d.). A neighbourhood approach is recommended, as every street or part of a neighbourhood has its own characteristics, and might therefore need a specific approach (Van Mierlo & Benayad, 2019). Almelo belongs to the RES Twente. An element of the RES is the so-called 'warmtetransitieplan', a 'heat transition vision', which describes for each neighbourhood which alternative heat sources are most suitable, what their financial effects are, and when the plan should be realized. This should be finished in 2021, so there is an urgent need to come up with an innovative plan. As a result, the municipality of Almelo has reached out to Witteveen+Bos to come up with an innovative plan to explore the energetic potential of the underground. Correspondingly, this research could be seen as a starting point for the 'Warmtevisie', as it will analyse potential alternative, sustainable heat sources for the neighbourhood of Windmolenbroek. In the face of climate change and depleting fossil energy resources, the relevance of contributing to the energy transition is evident. According to numbers from 2018, residential houses are responsible for approximately 16% of the overall societal energy demand (CBS, 2019). Tackling this specific sector within the energy transition is therefore highly relevant. As the Netherlands are striving towards a nearly completely renewable energy supply by 2050 (Ministerie van Economische Zaken, 2019), the municipality of Almelo is currently considering the use of renewable resources to meet its energy demand. Apart from applying the more common methods for sustainable energy generation using wind, sun or biogas, the municipality is especially interested in exploring the potential of the underground as a supplier of sustainable energy. Although scientific research emphasises the high potential of the underground as a source of renewable energy (Juez-Larré, 2019), it is often not directly considered to be able to play an important role in the energy transition (Sanner et al., 2003).

Witteveen+Bos aims to investigate the full potential of the underground for the case of Windmolenbroek in order for the municipality of Almelo to ultimately implement a full-scale and sustainable energy network, possibly integrating various techniques and methods. The main problem for reaching this goal is a lack of knowledge on how to make optimal use of the energetic potential of the underground. The municipality is thus interested in gaining knowledge on promising design options for the case of Windmolenbroek and on strategies for implanting these options in the neighbourhood. In order to tackle this problem, several challenges need to be overcome, such as the implementation of new technologies, the integration with the existing residences and infrastructure, consideration of the hydrogeological conditions, possible additional functions of the proposed options, and their ecological opportunities and consequences. Deep geothermal, taking advantage of the heat towards the centre of the earth, is not considered. This project is limited to investigating the relatively shallow subsurface to assist the energy transition. As there are many challenges to be overcome before the neighbourhood of Windmolenbroek can become fully fossil fuel independent, the municipality of Almelo is in the need of conceptual and interdisciplinary knowledge to act as a starting point for further plans. The study described here provides this starting point by providing a multidisciplinary, academic perspective on possible options, their integration and on their implementation in Windmolenbroek in order to make use of the energetic potential of the underground of Windmolenbroek. The results of this study can be used to base additional plans upon and to guide the municipality through the steps that need to be taken and knowledge that needs to be gained.

2. Research questions

The main research question that will be investigated is: ''What options are available to make optimal use of the energetic potential of the underground to foster the energy transition of Windmolenbroek?''.

In order to adequately answer this question, the project is divided into four subdomains: technology, hydrogeology, biology/chemistry, and social aspects and the built environment. For each aspect, several sub-questions are answered, these are listed below. Eventually, the applicability of the investigated options for Windmolenbroek are analysed and an advice for the optimal implementation plan is provided.

Technology

1. What is the current heat demand and supply for Windmolenbroek?
2. Which technologies are currently most suitable for storing energy in- and extracting energy from the shallow underground, and what is the energy storage and extraction potential of these technologies?
3. Which technologies are most suitable for Windmolenbroek and in what way can they best be implemented?

Hydrology

1. What are the hydrogeological conditions of Windmolenbroek?
2. Do the discussed technologies affect the hydrogeological and thermal conditions of the subsurface of Windmolenbroek, and if so, in what way and to which extent?
3. What is the optimal location within Windmolenbroek for the proposed technologies?

Biology/chemistry

1. What are the biological/chemical effects of the discussed technologies?
2. What are potential biological/chemical side benefits?

Social aspects and the built environment

1. What type of houses are present in Windmolenbroek and how are they insulated?
2. Which options exist to improve the heating efficiency of the houses?
3. What are the possible social barriers for implementing a neighbourhood-wide plan?
4. What are possible options to increase the social support of the advised plan?

3. Methods

In order to provide a multi-disciplinary consultancy advice, various tasks were executed. Scientific literature was reviewed, conversation with several involved stakeholder were held and a hydrogeological modelling study was executed. Below, each task is discussed in more detail.

Information on innovative options for using the energetic potential of the underground was gathered by an extensive review of the available scientific literature. The applicability of these options for Windmolenbroek was analysed by performing an in-depth study on both the hydrogeological situation of the underground, as on the existing infrastructure and built environment. Suitable options were selected and calculations on their energy supply potential were performed. An integrated advice was developed by combining various options and examining their collective value. A visualisation of this advice was made using AutoCAD. Throughout the research phase, stakeholders were interviewed in order to gather the case-specific information necessary for the research. A hydrological model was developed and used for the analysis of the different underground energy supply systems. The exact methods for developing this hydrological model are described below.

Hydrological modelling

A regional hydrogeological model was developed with MODFLOW and covers an area of roughly 500 km^2. The model spatial extents are roughly Goor in the South, the Holterberg in the West, Den Ham in the North, and the western tip of Borne in the East. The boundaries were selected along either no-flow lines or isohypses (lines along which groundwater levels are assumed to be constant). The regional model has a longitudinal resolution of 200 m and a variable vertical resolution, dividing the soil between the surface and the first aquitard (Breda formation) into five layers. The model includes a diffuse drainage network, a transient groundwater recharge time series (generated using an R script, essentially calculating the amount of precipitation that reaches the water table between 1985 and 1995), the five drinking water extraction wells of Vitens, a Digital Elevation Model (DEM) and hydrogeological parameters (specific yield, porosity, saturated hydraulic conductivity, etc.) associated with each layer of soil. All data was provided a professor of the Environmental Sciences department of Wageningen University & Research, during an advanced groundwater modelling course in May 2019.

The regional model was refined in and around Windmolenbroek to provide a more detailed, local representation of groundwater dynamics, to a longitudinal resolution of 25 m. The land use classes (which control drainage and recharge) were also given small-scale detail in Windmolenbroek. The local model was validated near Windmolenbroek by comparing the model with groundwater elevation data from Well ID B28G0406001 on grondwatertools.nl. This was done for two periods: The first between March and May 2010, and the second between January and July 1985. In the first case, the RMSE was found to be 30 cm, and in the second case it was found to be 36 cm. Proposed injection and extraction wells were added, and the longitudinal resolution was decreased to 12.5 m directly around the wells to provide more detailed dynamics in these areas. The effect of the wells on the groundwater levels (heads) was determined.

The temporal resolution of all models is 10 days. A statistically average year of recharge was generated based on the average recharge to groundwater per day of year for 11 years (1985-1995). This average year was then repeated in the model 11 times, though for validation only the original data were used. The averaged dataset provides multiple advantages. It demonstrates the average seasonal distribution of the recharge well, but it still includes a few extremes; that is, the number of years being averaged is large enough to show relatively smooth, average dynamics but still short enough to represent shocks to the system.

Next, a heat flow model was generated using MT3DMS. MT3DMS is typically used for solute transport in groundwater, but because the equations governing solute and heat transport are mathematically identical, MT3DMS can be used for modelling heat distribution in groundwater. This was developed with the same spatial extent as the local groundwater model. The temperature at the boundaries was set to the average groundwater temperature for Windmolenbroek. The thermal properties of the soil can be found in Appendix I – Hydrogeological model parameters.' Then, injection/extraction wells were implemented, representing an Aquifer Thermal Energy Storage (ATES) system. The energy supplied by the groundwater was calculated by multiplying the extraction rate of each well, the change in temperature between the extracted and injected waters for each well, the heat capacity of water, and the density of water (an example calculation is provided in Appendix C – ATES energy supply, model calculation description). Finally, the long-term effect of the ATES system on the distribution of heat in groundwater can be directly observed from MT3DMS.

Basic visualizations of concepts relevant to Borehole Thermal Energy Storage (BTES) placement within Windmolenbroek were also generated using MT3DMS. However, considering time availability and the complexity of BTES modelling, no extensive modelling of BTES was performed.

4. Case description of Windmolenbroek

Here, Windmolenbroek is described in terms of its built environment and hydrogeological characteristics. The first category includes information on housing stock, including a general map, energy demand, and details about insulation; the second category contains information about the geological formations and their hydrogeological conditions.

4.1 Neighbourhood characteristics

Figure 1 shows a general map of Windmolenbroek with the most important buildings, providing a rough idea of the characteristics of the neighbourhood. In the centre of the neighbourhood, the bio installation is located which provides energy to the heat network by burning wood chips. Also there is a hospital located in the neighbourhood. On the west part there can be found a small lake and a wastewater treatment plant, and surrounding the neighbourhood there are mainly farming fields.

Figure 1. Map of Windmolenbroek. Red lines represent the heat network which is already in place. Colours of the neighbourhood represent the energy demand. Red: high demand. Yellow: medium demand. Green: low demand (greenvis.nl and separate google maps figures).

Neighbourhood characteristics and the built environment

Windmolenbroek is a relatively new neighbourhood, 82% of the houses were built between 1980 and 2000, and 18% after the year 2000 (AlleCijfers, 2019). Some general characteristics of Windmolenbroek are described in Table 1, providing a general impression of the neighbourhood. Table 2 describes in the upper row the building year of all buildings in Windmolenbroek. The total number of buildings in Windmolenbroek in this figure is 5964, but only 5489 of them are dwellings. Different periods of construction correspond with different general insulation characteristics, described by Milieu Centraal (n.d.).

Table 1. Neighbourhood characteristics Windmolenbroek (Oozo, n.d.; Bunschoten, 2013; AlleCijfers, 2019)

Surface area Windmolenbroek (hectare)	**Residents**	**Average density (addresses per km²)**	**Total amount of households**	**Types of houses**	**Average surface house (m²)**	**Ownership**
822, of which 782 land and 40 water	13,930	1051 (corresponding with 1781 people)	5489	Mostly single family houses	135	78% privately owned, 17% rental, 5% others

Table 2. Original building characteristics and potential for improving (Milieu Centraal, n.d.; AlleCijfers, 2019).

Building year	**1975-1982**	**1983-1991**	**1992-1999**	**2000-2019**
Approximate number of houses	489	2469	1900	974
Windows	Double or single glass	Mostly double glass, some single	Double glass	Triple or HR++ glass
Improvement options	Triple or HR++ glass	Triple or HR++ glass	Triple or HR++ glass	Not necessary
Walls	Moderate cavity wall insulation	cavity wall insulation	cavity wall insulation	cavity wall insulation
Improvement options	Extra insulation	Extra insulation	Extra insulation	Extra insulation
Roof	Moderate insulation, 5-7 cm.	Moderate insulation, 5-7 cm.	Proper roof insulation	Very good roof insulation
Improvement options roof	Improve roof insulation	Improve roof insulation	Extra insulation only necessary for energy neutral house	Generally not necessary
Floor	Floor insulation is missing	Floor insulation present	Proper floor insulation	Very good floor insulation
Improvement options	Install floor insulation	Improve floor insulation	Extra insulation when installing floor heating	Extra insulation when installing floor heating
Facade	Façade insulation is missing	Façade insulation present	Proper façade insulation	Very good façade insulation
Improvement options	Insulate the inside or outside	Insulate the inside or outside	Extra insulation only necessary for energy neutral house	*Additional insulation generally not required for energy neutral house*

An overview of general insulation characteristics for houses built between 1980 and 2020 is given in Table 2, as well as improvement options for insulation. If these insulation improvements are sufficiently applied to the houses, they will be suitable for Low Temperature Heating (LTH) systems (temperature between 35°C and 55°C), instead of the High Temperature Heating (HTH) systems used currently (temperatures between 75°C and 85°C). However, most current heating systems are not feasible for LTH yet. Older radiators generally do not feature a sufficient heating surface. Therefore, either larger radiators, floor- or wall heating needs to be installed in the houses in order to be compatible for LTH (Verwarminginfo, n.d.).

Natural gas and electricity demand of Windmolenbroek

The average gas consumption in Windmolenbroek in 2017 was 1200 m^3 per year (AlleCijfers, 2019). It is assumed that the gas consumption has not radically changed in the last two years. Table 3 provides more detailed information about the natural gas consumption of Windmolenbroek. Currently, there already exists a heat network for 800 houses (Cogas B.V., n.d.). This is a HTH network, and therefore unfeasible to connect to LTH networks, such as ATES, BTES, or waste heat streams. This will be elaborated on later in the report. The current heat network could co-exist with ATES or BTES systems, but they cannot be connected. The existing heat network is supplied by four wood fired boilers, and one biogas boiler. There are two reserve boilers fired by natural gas, but they are infrequently used. Therefore, their natural gas consumption is not considered. Accordingly, the natural gas consumption of only 4689 households will be considered, as this is the number of houses in Windmolenbroek currently not connected to the network of Cogas B.V..

Table 3. Electricity and natural gas consumption Windmolenbroek (Cogas B.V., n.d.; AlleCijfers, 2019).

Gas		**Electricity**	
Number of households connected to natural gas	4689	Number of households connected to electricity grid	5489
Average gas consumption (m^3/household/year)	1200	Average electricity consumption (kWh/household/year)	3300
Total natural gas consumption Windmolenbroek (m^3/year)	5,626,800	Total electricity consumption Windmolenbroek (kWh/year)	18,113,700
Total natural gas consumption (GJ/year)	220,659	Total electricity consumption Windmolenbroek (kWh/day)	49,627
Total natural gas consumption (GJ/day)	605		

4.2 Hydrogeological conditions of Windmolenbroek

In this section the hydrogeological conditions of Windmolenbroek will be discussed. This is of value for this report since a good understanding of the underground is necessary if technologies in the underground are going to be implemented. For example, this information is necessary for assessing the groundwater speed of Windmolenbroek, which is necessary to assess suitability and efficiency of both ATES and BTES. All the information in this section was retrieved from Dinoloket or grondwatertools.nl. First the geological formations of the deeper underground will be discussed, after this the first 35 meters of the underground will be discussed in more detail.

Geological formations

A west-east cross-section indicates the underground layout of geological formations of Windmolenbroek (see Figure 2). The formations are discussed from top to bottom. The surface layer is the Boxtel formation (BX), consisting of sand ranging from very fine to very coarse. The hydraulic horizontal conductivity of this layer usually ranges between 5 until 10 meters per day. Directly underneath the Boxtel formation is the Drenthe formation (DR), which is made up of glacial deposits. Due to glacial activities, this formation holds a lot of different lithologies, ranging from coarse sand to clay. Although this formation contains some clay, it still has a horizontal hydraulic conductivity ranging between 25 and 50 meters per day. Underneath the glacial deposits is the Peize and Waalre formation (PZWA). Both formations contain fluvial deposits. The Peize formation consists of sand ranging from moderately coarse to extremely coarse sand, the Waalre formation consists of sand ranging from extremely fine to extremely coarse sand. The horizontal hydraulic conductivity of this layer ranges from 25 to 50 meters per day. Below the fluvial deposits of the Peize and Waalre formation is the marine Oosterhout formation (OO). The main deposits of this formation are sands ranging from fine to extremely coarse sand. This formation has a hydraulic conductivity ranging from 5 to 10 meters per day.

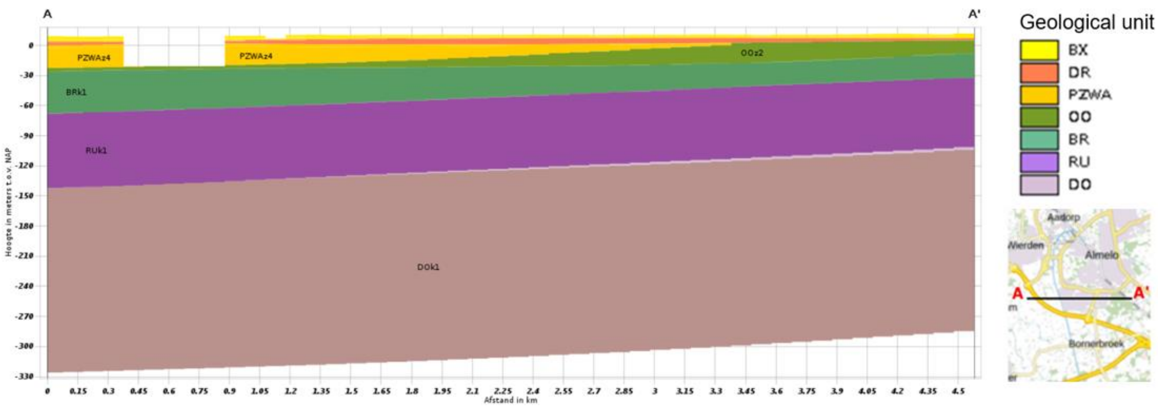

Figure 2. Geological cross-section of the underground of Windmolenbroek (Dinoloket). The gap on the top represents the lake.

The layers described above are all considered to be aquifers, permeable layers that can hold and transport groundwater. However, the underlying Breda formation (BR) is barely permeable for water and can be considered an aquitard. An aquitard is a layer in the soil of which the hydraulic conductivity is so small that no flow through this layer can be considered. The Breda formation consists of marine sands and clayey deposits. The vertical hydraulic conductivity of this formation ranges from $3 \cdot 10^{-3}$ to $5 \cdot 10^{-3}$ meters per day. The next formation, which is the Rupel formation (RU) is also an aquitard formed under marine conditions and consists mainly of clay. The vertical hydraulic conductivity of this layer ranges from $5 \cdot 10^{-4}$ to $10 \cdot 10^{-4}$ meters per day. The deepest formation present in this cross section is the Dongen formation (DO) also deposited in a marine environment. The most dominant deposit is clay. It has a hydraulic conductivity ranging from 0 to $5 \cdot 10^{-5}$ meters per day.

The shallow underground

From the description above, it can be concluded that groundwater flow is restricted to the layers above the Breda formation. This roughly means that directly under Windmolenbroek, there is only one aquifer present and a thickness of soil ranging from 20-35 meters can be used for installing a technology which requires an aquifer to be present (see Figure 2 above).

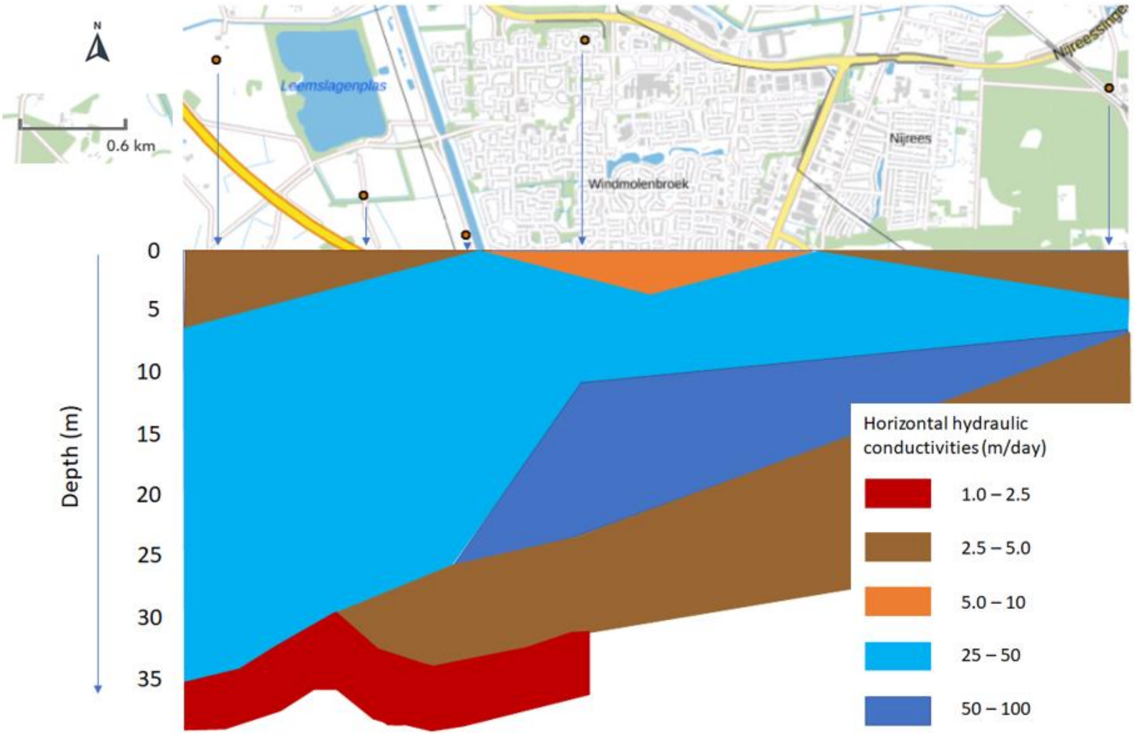

Figure 3. Representation of the shallow underground of Windmolenbroek. Cross section from West to East, based on five borehole points on Dinoloket. Street Map of Windmolenbroek is obtained from google maps.

The figure above is a zoom in on this aquifer. It again shows a cross section of the underground (see Figure 3). However, it only shows the underground up to 35 meters deep, and therefore depicts the aquifer-part of the geological formations in more detail. This cross section is an interpolation of 5 boreholes found on Dinoloket. It is important to note that this is a rough and schematic overview and the depths and that delineations between the different layers are not precise. Also the five boreholes are not all on a straight line from west to east, therefore this also brings uncertainty. The different colours represent the different horizontal hydraulic conductivities. There is quite a big range in hydraulic conductivities; from 1 until a 100 meters per day. However the hydraulic conductivities presented here are approximations and for the hydrogeological model more exact values were used. All these layers have a large enough hydraulic conductivity to be considered part of the aquifer. The red layer consists mainly of loamy and silty sand, and therefore it has the lowest hydraulic conductivity. The brown layers consist mostly out of medium fine sand or medium coarse sand. Medium to fine sand can be found in the orange layer. The light blue layer mainly out of course sand and very coarse sand and the dark blue layer out of very coarse sand and extremely coarse sand.

Although all the layers are aquifers and hydraulically suitable for e.g. an ATES technology, it is important to know the detailed layering of the soil before implementing a technology. From this brief hydrogeological analysis it can be concluded that the first 35 meters of the underground is hydraulically suitable for an ATES system. It can also be concluded that the first 35 meters and deeper are suitable for a BTES system.

Finally, using groundwater elevations from grondwatertools.nl and Darcy's equation, it is calculated that the groundwater speed is 7 m/year on average, moving mostly westward, but it can be as high as 11.5 m/year. The unsaturated zone is fairly thin - about 2 m - which will be further discussed in the modelling results. The average groundwater temperature is assumed to be 12 °C.

5. Potential sustainable heat sources and technologies

In this chapter, different sustainable heat sources and technologies will be discussed in general. At first, UTES systems will be described, consisting of both ATES and BTES systems. Their advantages and disadvantages will be covered, and the environmental effects of implementing these technologies. Furthermore, PVT technology will be elaborated. Eventually, potential waste heat sources and some not yet fully developed technologies will be briefly explained.

First of all, it will be motivated why ATES, BTES, PVT, and potential waste heat sources have been chosen as the main focus within this advice. After having consulted the municipality and Cogas B.V., it seems as if these technologies are likely to be able to assist with the desired energy transition. ATES and BTES systems are investigated, as they represent the current state of the art for underground energy storage. ATES and BTES occur commonly in the Netherlands, and therefore might have potential in Windmolenbroek as well. PVT panels are investigated for their well-known ability to provide sustainable electricity and heat in a variety of environments. Potentially, PVT and UTES systems could be combined in order to supply both heat and electricity for Windmolenbroek. This option will be investigated within this report. Finally, additional (potentially free) energy sources are investigated because they could represent cheap, easy to obtain sources of energy.

5.1 UTES systems

Underground Thermal Energy Storage (UTES) is a seasonal system that continuously heats and cools down buildings by storing and recovering seasonally stored heat and cold (Gao et al., 2009). The use of UTES helps to save greenhouse gases. As a renewable energy technology, UTES systems will effectively reduce greenhouse gas emissions in the application of building heating and cooling (Rosiek et al., 2013). Furthermore, UTES systems have lower operating and maintenance costs than traditional heating systems (Sibbitt et al., 2012). Ideally, the operation of heat pumps in UTES systems can be maintained using green energy, and long-term operating income is higher than that of other fossil fuel-dependent heating systems. Two forms of UTES systems are the most widely used (Nordell, 2000), namely Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES).

General description ATES/BTES

ATES

In an ATES system, the storage and recovery of thermal energy is achieved by using wells to extract and inject groundwater from the aquifer. The most applied form of the ATES system is that two wells (called a doublet) operate in a seasonal mode, with hot wells for storing heat and cold wells for storing cold. In summer, the low-temperature groundwater in the aquifer is extracted to transfer heat in the building to the groundwater through a heat exchanger, thereby achieving a cooling effect. The heated groundwater is then injected back into the aquifer to form a hot groundwater reservoir. In the winter, the stored hot groundwater is pumped up, the heat is extracted by the water source heat pump and used for heating and the cooled groundwater is injected back into the aquifer. Depending on the stored volume, the thermal properties of the aquifer and hydrological conditions (Doughty et al., 1982), the thermal storage retains its temperature for months to years, such that typically between 50 and 90% of the injected energy is recovered (Sauty et al., 1982). Typical storage temperatures are 5-12˚C for cold storage and 14-30˚C for heat storage (Bonte et al., 2011).

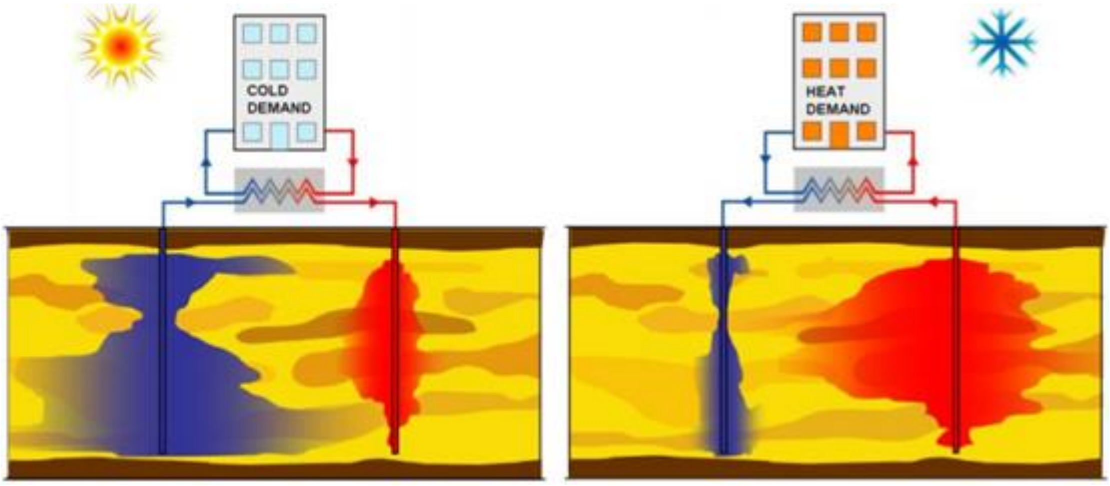

Figure 4. Principle operation of an ATES doublet system in summer (left) and winter (right) (Verburg et al., 2010).

BTES

Unlike the open ATES system, a BTES system is a closed system that stores thermal energy in the bedrock without the need to extract groundwater from the aquifer (Nordell, 2000). The BTES system uses a volume of rock or sediment accessed via an array of borehole heat exchangers (BHEs) (Giordano & Raymond, 2019). BHEs penetrate into the storage medium, and the thermal energy carrier circulating through the BHEs is thermally coupled to the bedrock (Paksoy, 2007). The BTES system works through a series of U-shaped pipes which carry a thermal working fluid that transfers heat to the surrounding soil via conduction. The liquid, carrying thermal energy from sources including the ambient air, solar energy and process waste heat, can either insert or extract thermal energy into or out of the bedrock (Nordell et al., 2007). Unlike ATES systems for large energy storage, the size of BTES systems depends on the number of installed BHEs, and is therefore suitable for both small and large energy applications (Nordell et al., 2007). When operating as a small system, BTES typically provides winter heating and summer cooling for single-family houses (Nordell, 2013). On the other hand, large BTES systems are more suitable for providing seasonal thermal storage for large buildings or communities (Nordell et al., 2007). The figure below shows a schematic of a small- and large size BTES systems (see Figure 5).

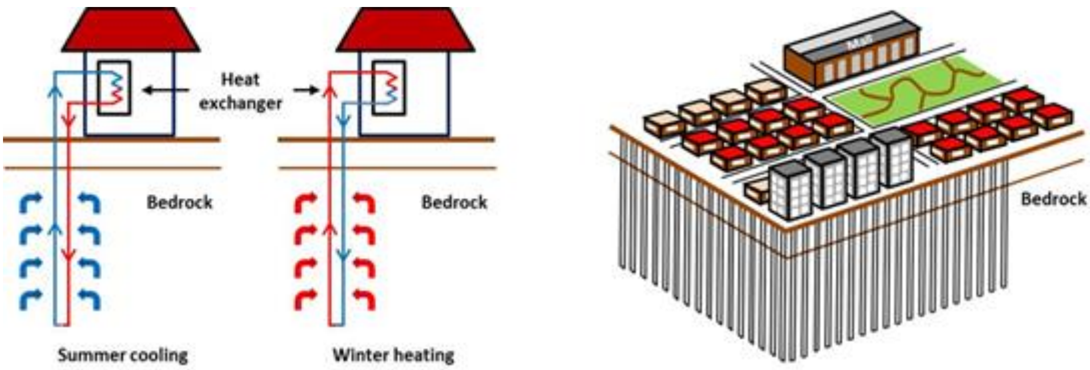

Figure 5. Small- (left) and large-scale (right) BTES systems (Nordell et al., 2007).

BTES systems have the advantage of having relatively low maintenance, though the initial effort and cost for installation can be large (Cruickshank, 2016). They usually require several years of operation before they reach their peak performance, and can therefore not be fully relied upon shortly after their installation. BTES energy recovery typically ranges between 70% and 90% (Lanahan, 2017).

Hydrogeological requirements

The construction of an ATES system must meet certain hydro-geological requirements, of which the main are discussed below. The water flow in the aquifer is predominantly horizontal, and the groundwater temperature varies with the natural geographical environment, geological conditions and depth. The 'unconfined aquifer' is near the surface, and its water temperature is affected by the external climate. It is a variable temperature zone and is susceptible to pollution. The 'confining aquifer' is generally a deeper area and is a relatively constant temperature zone. Therefore, a confining aquifer at a certain depth is preferable for ATES, though an unconfined aquifer can be used (Wang, 2003). ATES requires the presence of a suitable aquifer that is able to hold and supply water. Therefore, thick (>10 m) sandy aquifers are preferred. Natural groundwater flow may transport (part of) the stored energy outside of the capture zone of a well during the storage phase (Sommer et al., 2013). To reduce such advective energy losses, aquifers with a low hydraulic gradient are preferred. Secondly, the selected aquifer should comprise of a low natural groundwater flow rate. The flow rate should not exceed 50 m/year and should preferably be less than 20 m/year. In this way, energy loss through groundwater flow is minimised (Bloemendal & Hartog, 2018). The aquifer should comprise of a high hydrological conductivity and thickness, to ensure sufficient groundwater recharge. Also, the hydrological conductivity of the confining bed should be minimal, so thermal short-circuiting with the adjacent aquifer is avoided (Kim & Parizek, 1997). In addition, the connection of water sources between wells in different energy storage aquifers will cause thermal conduction and water short-circuiting, resulting in reduced energy storage efficiency and even loss of energy storage system (Lage et al., 1997). Therefore, a single aquifer should be selected, containing both hot and cold reservoirs.

Table 4. Required aquifer conditions for ATES systems.

Required aquifer conditions
Low natural flow rate of groundwater, less than 50m/year, preferably less than 20m/year
High aquifer hydrological conductivity
Thick aquifer layer
Small aquitard hydrological conductivity
No thermal short-circuiting with adjacent aquifer

BTES systems have relatively few hydrogeological restrictions. There are two factors impacting whether high groundwater speeds are suitable for BTES systems. First, borehole heat recovery can be drastically reduced with fast groundwater, as groundwater flow will transfer heat far away from its desired location (Skarphagen et al., 2019). On the other hand, if the BTES systems cool the soil to a temperature below the ambient groundwater temperature, then fast groundwater serves to replenish the heat around the borehole. See the Appendix IV – BTES energy supply approximation for a more detailed discussion of the effect of groundwater speed on BTES performance. Still, the actual performance loss due to high groundwater speed depends on the borehole size, extent of positive interference between adjacent boreholes and borehole geometry (Lanahan, 2017). Conventional BTES boreholes generally extend to a maximum depth of 30-200 meters (Cruickshank, 2016), and as such they often penetrate bedrock. Heat storage in both rock and soil are feasible, so the presence or absence of bedrock is not a hydrogeological requirement for BTES. However, it is important to understand the geological profile, especially the thermal properties and hardness of the rock or sediment, so one can know what to expect for system performance and drilling costs.

Environmental effects

The implementation of an UTES system in any given location will inevitably affect the belowground and in some cases even the aboveground environment (Boer et al., 2012).These effects range from effects on the overall groundwater quality, ecology and on the functioning of the system itself, it is important to be aware of these possible effects and to take them into account when designing the specific UTES system. In this way, the harmful effects the envisioned system has on its surroundings can be minimised. The environmental effects of belowground energy storage systems can be classified into three main domains; geochemical effects, ecological effects and physical effects. All possible environmental effects are either directly or indirectly linked to the two primary effects UTES systems can have on the subsoil. These primary effects are either the mixing of water bodies with different chemical compositions or the alteration of local soil and groundwater temperatures. Because ATES and BTES systems function in an inherently different way, the specific environmental effects of both systems can differ substantially. ATES systems are based on the storage of hot and cold water in separate wells. Therefore, large quantities of either relatively hot or cold water are being moved through the subsoil on a seasonal base. This large-scale water movement results in both local changes in subsoil temperature and possible mixing of water bodies with different chemical compositions. In a BTES system, no large-scale movement of groundwater occurs, because the borehole does not inject or extract water from its surrounding as only thermal energy is transferred. Because of the absence of groundwater movement, the environmental effects of BTES systems are mainly linked to induced changes in subsoil temperature. These are similar to the thermal effects of the ATES system, but the effects are likely to be increased. This is due to the fact that BTES systems have only a small radius of temperature impact on the subsoil. The soil material within this radius experiences large changes in temperature, that enlarge the extent to which temperature-related environmental effects occur. The various effects discussed below are summarised in the below (see Table 5).

*Table 5. Environmental effects of UTES systems (*only for ATES systems).*

Environmental effects	**Geochemical**	**Ecological**	**Physical**
Groundwater mixing	Changes in groundwater quality	Transport of microorganisms	Clogging of wells*
	Precipitation of solid substances	Altered microbial activity and compositions	
	Transport of contaminants		
Changes in subsoil temperature	Altered chemical equilibria	Changed biological reaction rates	Clogging of wells*
	Changed chemical reaction rates	Altered microbial compositions	

Due to the complexity of the underground, the large collection of possible environmental effects UTES systems can have on the underground and the possible detrimental consequences of these effects, it is highly important to execute an extensive hydrogeochemical analysis of the subsoil during the design phase of any proposed UTES system. In this way, negative environmental effects and their consequences on system efficiency can be minimised.

Geochemical effects

In the case of UTES systems, considering particularly the possible geochemical effects is of major importance as alterations to the subsoil and groundwater chemistry can cause various severe negative effects. Firstly, alterations in groundwater chemistry can pose risks to drinking water supply, especially in non-confined aquifers (Possemiers, 2014). Secondly, changes in subsoil and groundwater chemistry can cause substantial losses in system efficiency through well clogging (see Textbox 'The risk of clogging in ATES systems). in the case of ATES systems (Lee 2013; Veldhoen, 2010). Thirdly, underground geochemistry is tightly linked to belowground ecology. Geochemical effects of UTES systems can therefore in turn have detrimental effects on the local ecology. Geochemical effects in the belowground soil material or groundwater can be caused by either changes in the local temperature or by the mixing of water bodies with different chemical compositions.

Geochemical effects related to changes in subsoil temperature can occur in both ATES and BTES systems and can affect both geochemical equilibria and -reaction rates. However, these effects are generally neglectable in low-temperature ATES systems that are thermally balanced between the hot and the cold well, because the effects in the hot well are compensated by opposing effects in the cold well (Boer et al., 2012; Hartog et al., 2013). In unbalanced low-temperature ATES systems however, or in high-temperature ATES or BTES systems that operate above 25˚C, the effect of temperature on both mineral equilibria and reaction rates becomes increasingly important (Hartog et al., 2013).

In low-temperature ATES systems, the mixing of groundwater from different depths having different chemical compositions is the main factor affecting groundwater chemistry (Boer et al, 2012; Hartog et al., 2013 and Van Oostrom et al, 2010). Groundwater is stratified in the underground and shows gradients in chemical characteristics. Differences in the chemical characteristics of groundwater originating from different aquifers are even more pronounced in open- or enclosed aquifers as they have very different characteristics. The extent to which ATES systems mix different water types depends on both the vertical length of the well screen as the reactivity of the aquifer sediments (Van Oostrom et al, 2010). The well screen comprises of the part of the well through which water is extracted or injected. The main gradients that are reported to cause alterations in the chemical composition of the groundwater through mixing of alien groundwater bodies are gradients in salinity, pH or redox-potential (Van Oostrom et al, 2010). These will shortly elaborated on in the paragraphs below.

Salinity

Salinization of groundwater through mixing mainly occurs in areas that are located close to the sea or when deep and relatively saline groundwater is mixed with more superficial groundwater. Whether this groundwater salinization plays a role thus depends on the location. Furthermore, when salinization is prone to occur, it may not always be problematic as a slight salinization of urban surface waters may not cause direct problems when it is not used for human purposes such as drinking water supply.

pH

The main risk of mixing groundwater bodies having a different water hardness, mainly lies in the possible precipitation of carbonates which may play a role in well clogging. To avoid substantial carbonate-induced clogging to occur, it is important to keep the system pressurised. This way, the groundwater does not become carbonate-unsaturated and the precipitation of carbonates on the well screen and aquifer is minimised (Van Oostrom et al., 2010; Hartog et al., 2013).

Redox potential

The main geochemical effect of ATES systems regarding the mixing of water bodies is related to the gradient in redox potential. When groundwater of different redox potentials is mixed, precipitation of chemical substrates is likely to occur, which can have detrimental effects on system efficiency through well clogging (Lee 2013; Veldhoen, 2010). Precipitation of iron(hydr)oxides is the main chemical process related to mixing that causes well clogging. In order to minimise the risk of chemical clogging, it is highly important to prevent the mixing of different water bodies, especially the mixing of shallow oxic groundwater with deeper anoxic groundwater (Van Oostrom et al., 2010). Therefore, an extensive hydrogeochemical analysis of the aquifer at different depths should be executed to optimise well design and well screen placement to minimise the risk of clogging.

The risk of clogging in ATES systems

Due to the inherent character of ATES systems, in which large quantities of water are being moved through the subsoil on a seasonal base, possible clogging of the wells can have a large impact on the energy efficiency of the systems. This can subsequently lead to high costs related to decreased energy supply, well generation or the instalment of additional wells. As ATES systems are designed for a lifespan of at least 20 years (van Oostrom et al., 2010) and clogging is currently still problematic (Vermaas, 2008), it is important to be aware of both the processes and conditions that can cause clogging as well as existing methods to minimise the risk of clogging. Well clogging is caused by the accumulation of clogging substances in either the well itself, or in the direct vicinity of the well, as large quantities of water extracted or injected by the well are directed through a relatively small volume of soil. Clogging can occur in both the extraction as injection well and clogging substances either accumulate at the border of the borehole or on the well screen itself (see Figure 6).

Although clogging itself is an entirely physical process, the substrates that cause this clogging can originate from either physical, biological or chemical processes and even a combination between the three. Physical clogging is mainly caused by particles or gas bubbles that are caught between the soil matrix (van Oostrom et al., 2010). As groundwater naturally contains soil particles, the groundwater pulling- and pushing motion of the well can cause these particles to become trapped within the soil matrix. Clogging by soil particles mainly poses a problem during the first year of operation, as the transported groundwater loses its particle content to the soil matrix after some cycles. The risk of severe particle clogging can be reduced by frequently switching between injection or extraction rates and directions (van Oostrom et al., 2010). Also, the extraction and discharge of relatively small amounts of groundwater during overall injection operation removes accumulated soil particles. Gas clogging can occur when deep and thus pressurised groundwater is depressurised during extraction and pumped back into the injection well. The depressurisation of the groundwater causes dissolved gasses to escape from the liquid itself and clog the soil matrix of the injection well as the groundwater is returned to the aquifer. To prevent gas clogging from occurring, the systems should continuously be kept under pressure (van Oostrom et al., 2010).

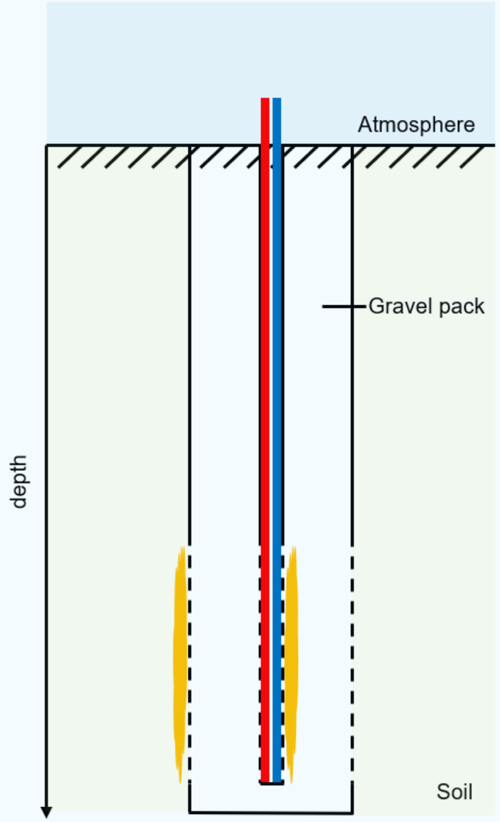

Figure 6. Clogging of an ATES well. Clogging of the border of the borehole on the left. Clogging of the wel screen on the right (based on Veldhoen, 2010).

Biological clogging can either occur as microorganisms can greatly increase the reaction speeds of chemical processes that produce clogging substances (Stuyfzand, 2007) or by producing a biofilm (BTS, 2006). Biological clogging is mainly caused by mixing groundwater with varying chemical compositions and requires the presence of biologically degradable organic matter. The high flow rates in the direct vicinity of the well can increase the nutrient availability, which can lead to increased microbial growth (van Oostrom et al., 2010). The risk of biological clogging can be minimised by avoiding the mixture of different groundwater bodies.

Chemical clogging occurs when chemical processes produce solid substances that hamper extraction and infiltration flows. As with biological clogging, chemical clogging is mainly caused by mixing groundwater bodies origination from different depths that comprise of different redox potentials and thus different chemical compositions (van Oostrom et al., 2010). In the more superficial water layers, relative high concentrations of oxygen, nitrate and sulphate occur due to aboveground input. As these oxidising substances are being reduced in the soil, their concentration decreases along with aquifer depth (Appelo & Postma, 2004). The figure on the right illustrates this chemical gradient (see Figure 7).

From the figure, it can be seen that certain chemical substances do not occur simultaneously at certain depths. When groundwater from different depths is mixed, the introduction of non-cooccurring chemical substances can cause precipitation of solid substances. The most occurring form of chemical clogging is through precipitation of iron(hydr)oxides when the iron present in deep groundwater is oxidised by the oxygen or nitrate present in shallow groundwater (van Oostrom et al., 2010). As with biological clogging, the risk of chemical clogging can best be minimised by preventing the mixing of different types of groundwater. Also, keeping the system air-tight prevents oxygen to be introduced to deep groundwater during extraction. Chemical clogging can also occur when changes in temperature cause decreased chemical solubilities. At high temperatures, clogging though precipitation of carbonates could occur leading to a need for additional water treatment (van Oostrom et al., 2010). However, as most ATES systems operate under relatively small temperature differences, the risk of carbonate clogging is minimal (van Oostrom et al., 2010).

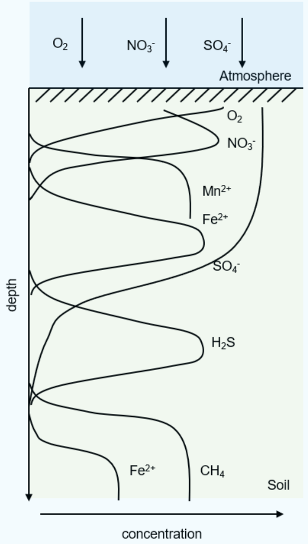

Figure 7. Redox potential gradient of the subsoil (based on Appelo & Postma, 2004).

Although various methods exists for well regeneration, preventing clogging from occurring is the preferred and more cost-efficient solution. To prevent clogging from occurring, it is important to be aware of the different processes and circumstances that cause well clogging. It is highly necessary to execute a thorough analysis of the local groundwater quality at different depths to minimise the clogging risks associated with mixing. In this way, system and well design can be optimised according to the local conditions.

Besides the clogging effect that the mixing of chemical gradients can have, the mixing character of ATES systems can also cause environmental harm through contaminant transport. Due to human activities, the subsoil of the Netherlands is severely polluted at various locations (Milieu Centraal, 2019). When ATES systems are installed at polluted locations, the extraction and injection of polluted groundwater can transport these contaminations, putting a greater area at risk. However, current research indicates the potential for removal of these contaminants by combining the pumping characteristics of ATES systems with the treatment of these contaminants through bioremediation (Sommer et al., 2013; Ni et al., 2015).

Bioremediation

Many urban areas are dealing with contaminated soils and groundwater (Milieu Centraal, 2019). Because of this, ATES systems are not allowed to be installed in contaminated areas as they are thought to cause contaminant dispersal. However, recent studies indicate the potential for using the groundwater-moving character of ATES systems for treating contaminated sites (Sommer et al., 2013; Ni et al., 2015). These innovative methods would be relevant to explore as they combine sustainable energy supply with improvement of the environmental quality. Chlorinated hydrocarbons comprise of the types of contaminants mostly found at the depths at which ATES systems occur (Sommer et al., 2013). Originating from dry cleaners and industries, these chemicals are known to be a threat to groundwater quality and human health (Bradley, 2000) and due to their recalcitrant nature, they are extremely difficult to treat. These compounds are naturally removed from the environment through natural attenuation processes. However, these natural biodegradation rates are very low as other substances present in the oxygen-poor subsoil are more preferable to reduce. Due to the mixing and temperature-changing character of ATES systems, natural bioremediation can be speeded up substantially. When adding nutrients to the injection flow, treatment efficiencies can further increase as iron and sulphate present in the groundwater is reduced, clearing the way for complete dechlorination. A recent study modelling the bioremediation potential of ATES systems for chlorinated compounds indicates the potential of the combination. Reported biodegradation rates where 13 times higher than natural attenuation (Sommer, 2015). As combining bioremediation with ATES systems is a relatively new field of study, practical results that confirm the modelled potential are limited. Therefore, if a combination method of ATES and bioremediation is to be implemented at a specific contaminated location, it is highly important to be aware of the risk of contaminant diffusion. Also, an extensive hydrogeochemical analysis should be executed to match nutrient addition to the amount of contaminants and hampering subsoil oxidants present in the groundwater.

Ecological effects

Although alterations to the ecological state of the subsoil do not pose direct risks to system efficiency, it is important to include possible ecological effects into the systems design. Subsoil ecology provides several important ecosystem services such as a healthy soil fertility, degradation of contaminants and provides food for higher trophic levels (Wagelmans & Roeloffzen, 2009). It also affects the quality of the groundwater, which in turn may affect the quality of the local drinking water (Hartog et al., 2013). In the same way that UTES systems can affect geochemistry, changes in belowground temperature and the possible mixing of different water bodies can affect subsoil ecology.

Again, both ATES and BTES systems can affect the subsoil temperature and thereby affect the subsoil ecology. However, the specific effects can change between ATES and BTES systems, as BTES systems generally cause more severe changes in subsoil temperature close to the well itself (Skarphagen et al., 2019). The main ecological effects related to changes in subsoil temperatures are local changes in biological reaction rates and alterations of the microbial communities. In the case of ATES systems, although higher temperatures related to the injection of hot water generally result in increased microbial reaction rates (Arrhenius, 1889), the overall larger scale effect of thermally balanced ATES systems on microbial reaction kinetics is minimal. This again is due to the dual character of ATES systems, in which increased microbial reaction kinetics in the vicinity of the hot well are compensated by decreased kinetics in the cold well (Boer et al., 2012; Hartog et al., 2013). Therefore, when considering the ecological effect of ATES systems on a larger scale, effects are small. As BTES systems generally induce more severe temperature changes in close vicinity to the borehole itself, thermally induced effects on biological reaction rates can be expected to be higher compared to those of ATES systems. However, as BTES systems also comprise of the seasonally changing heat extraction or injection character, the large-scale ecological impact of BTES systems are expected to be minimal if thermally balanced. Changes in temperature can also impact the occurrence of microbial populations. As different microbial populations perform best under different temperatures, alterations in subsoil temperature will affect subsoil microbial populations. When temperature changes increase beyond the growth curve of a specific microbial community, it is unable to grow and thus becomes locally absent. However, this temperature effect generally does not have a significant effect on the microbial functions of the underground as different populations with different optimal temperatures can perform the same ecological functions. Temperature-induced alterations to subsoil ecology and functioning could however become relevant when storing water warmer than 40 ˚C (Dinkla et al., 2012).

In low-temperature ATES systems, the mixing of different types of groundwater is the most determining factor in observed changes in subsoil ecology (Dinkla et al., 2012). Microorganisms are transported through the soil together with the large quantities of water. This mixing can introduce microbial communities to locations where they were previously absent. Changes in redox conditions can affect the occurrence and functioning of subsoil microbiology. When water with a high temperature is stored (above 40˚C), organic matter can become freely available, which acts as a nutrient and can thus increase the activity of the subsoil ecology when distributed by the underground water movement (Boer et al., 2012).

Physical effects

UTES systems can affect the physical state of the subsoil in several ways. In the case of ATES systems, the extraction and injection of groundwater causes changes in water table height and groundwater flow. This can have serious effects for nearby agriculture or soil stability. Changes in groundwater temperature can also affect groundwater flow by causing density-driven groundwater flow or by altering the viscosity of the groundwater itself. These effects are however only considerable in systems that cause temperature changes of several tens of degrees (van Oostrom et al., 2010). In the situation in which ATES or BTES boreholes run through multiple aquifers, the physical puncturing of the aquitards can have substantial consequences in the form of aquifer leaking.

Comparison of ATES and BTES

	ATES	BTES
Strengths	1. High energy capacity through large storage capacity of the subsoil. High storage efficiencies of seasonal energy used for combined heating and cooling (Tomasetta et al., 2015) makes ATES systems meeting the needs of many large buildings or communities. 2. The ATES system does not consume groundwater, it only stores and recovers energy from groundwater. 3. High energy efficiency. The coefficient of performance (COP) is a parameter describing the utilization efficiency of the heat pump unit for thermal energy. That is, the ratio between the unit's thermal energy supply and power demand for operation. ATES water source heat pump has a COP of over 4. 4. Possibility of combining with bioremediation.	1. Less hydrogeological limitations compared to ATES systems. Presence of aquifer is not required as BTES systems are able to use soil layers as medium for thermal energy storage. 2. Suitable to be used in combination with additional sustainable energy sources to deliver thermal energy to borehole. 3. Lower contamination risk that ATES systems due to absence of groundwater exchange.
Weaknesses	1. Required hydrogeological conditions more stringent than ATES systems due to the use of groundwater for energy storage. Aquifer thickness and groundwater flow rate have strict requirements (Sommer et al., 2013). Due to seasonal operation mode, certain climatological requirements are in place. 2. Low outflow temperatures due to legal injection limit of 25 degrees require retrofitting of houses and the addition of external energy for upgrading temperature to be used for tap water. 3. Optimal capacity only achieved after a few years as wells need several seasonal cycles to become either hot or cold.	1. Higher construction investment required compared to ATES systems. Horizontal piping requires substantial excavation and leads to substantial energy losses due to close proximity of the surface (Omer, 2008). Vertical piping requires deep boreholes and often brings along various technical challenges . 2. Optimal capacity only achieved after a few years as quantity of thermal energy stored increases over time.
General Challenges and Risks	1. Large uncertainty in thermal recovery due to uncertainty in thermal interference (Sommer et al., 2013). Spacing between hot and cold wells should be large enough to avoid negative interference and subsequent energy loss. However, over-sizing of spacing may limit the amount of ATES that can be applied in a certain area (Sommer et al., 2015). 2. In certain conditions, thermal pollution of nearby drinking water wells by thermal plume (Visser et al., 2015) may occur. 3. Clogging of the wells may occur depending on the chemical and physical conditions of the aquifer, strongly affecting energy efficiency. 4. Possible negative environmental effects due to groundwater mixing and changes in subsoil temperatures.	1. Scaling of BTES systems important design component to consider. Small-scale BTES systems may lead to suboptimal energy efficiencies due to their high heat losses per unit of stored energy, compared to ATES systems (Başer et al, 2015). 2. Due to energy storage through diffusion, system performance is directly impacted by a large array of parameters such as soil porosity, conductivity, soil moisture and groundwater flow (Catolico & McCartney, 2016). 3. Possible negative environmental effects due to changes in subsoil temperature. 4. Leaking of borehole liquid can cause substantial environmental harm.

5.2 Photovoltaic Thermal panels

Basic description

Combined solar photovoltaic-thermal systems convert solar radiation into heat and electricity simultaneously. Not all incoming radiation is used for electrical output, as only a certain wavelength is suitable for electricity production. Therefore, it is efficient to use the other wavelengths for heat production (van Helden et al., 2004). A typical efficiency of solar cells ranges from 5-20%, corresponding with the amount of useful solar irradiation that can be used to produce electricity. Whether the solar irradiation is useful to produce electricity, depends on its wavelength. This means that approximately 80% of the remaining solar irradiation, with different wavelengths, could be harvested as heat for a LTH system (Santbergen et al., 2010). Accordingly, per unit area, it is more efficient to use a PVT panel than a separate PV panel and solar thermal collector (van Helden et al., 2004). Accordingly, with PVT panels, a higher share of renewables could be generated in the built environment, which is in line with the renewable energy targets.

However, efficiencies compared to conventional PV panels or thermal collectors are 14% and 19% (relative) lower respectively. This is the case because of the loss of electrical efficiency due to the high fluid temperatures and loss of thermal efficiency due to high emissivity. Both of these losses could be significantly reduced by the use of anti-reflective coatings, but trade-offs have to be made favouring either electricity or thermal production (Santbergen et al., 2010).

For the Netherlands, it is suggested that a one-cover glazed sheet-and-tube design is most efficient, providing a good compromise between thermal and electrical yield (see Figure 8). Also, the European PVT Roadmap concludes that a one-cover PVT collector using liquid as transport fluid, has the most potential at the market. These panels could be used for space heating as well as for providing hot tap-water. The PV part of these panels is directly connected to the grid. The solar collectors are connected to a storage tank, having an average size of 100 to 200 litres. This heat storage tank is separating the water running through the PVT panels and the fresh tap water with a collector loop and a heat exchanger, which is located outside of the tank. The storage tank is stratified, and a pump control strategy ensures that with unfavourable weather, no water is being pumped through the collector. When the heat supply is higher than the heat demand, the storage tank temperature could even reach the boiling temperature, but this situation will be prevented by mechanical interventions (Zondag et al., 2005).

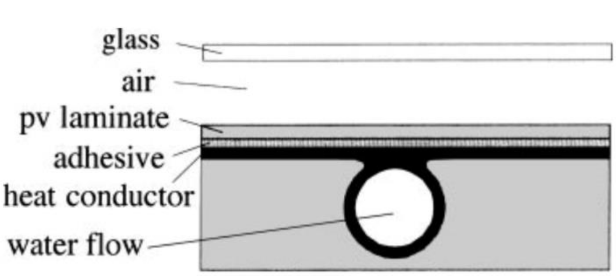

Figure 8. Overview PVT basic panel (van Helden et al., 2004).

SWOT-analysis

The main advantages of a PVT system are its efficient use of area, easy installation, and its integration of functions. The weaknesses are that the reliability is not yet optimised, and that the economics are not completely clear yet. Opportunities consist mainly of the large potential to increase its efficiency and to optimise the system design. Also, there are opportunities for combined subsidies. The main challenges concern its markets, because the market channels for PV and thermal collectors are still different, and standards are lacking. Also, practical experience from demonstration projects is still lacking (Zondag et al., 2005). See the table below for an overview of the SWOT-analysis.

Table 6. SWOT analysis PVT (Zondag et al., 2005).

Strengths	Efficient use of area
	Easy to install
Weaknesses	Reliability not optimised yet
	Coupling of two dissimilar needs; heating and electricity generation
	Economics not clear yet
	Reduced thermal model efficiency
Opportunities	Optimise system design
	Combine study
	Interesting, new niche markets
Threats	Two separate industries are required
	Market channels for PV and thermal collectors are different
	Standards are lacking
	Practical experience is lacking

The heat and electricity yield of PVT collectors depends mainly on the irradiance, ambient temperature, wind speed, and the average fluid temperature (de Keizer et al., June 2016). Therefore, it highly depends on the external circumstances how much heat and electricity could be produced. As a result, different studies show different numbers. A study from the RVO, a governmental service for entrepreneurial Netherlands, came with specifications of electrical and thermal yield per PVT panel for a situation in the Netherlands, described in table 7 below. It is assumed that these numbers are also applicable for Windmolenbroek (Timmerman, 2009).

The performance of a GSHP-PVT has been calculated for an average family dwelling in the Netherlands with a floor surface of 132 m^2, which is very close to the assumed average of 135 m^2 floor area in Windmolenbroek. The research showed that if the PVT collector area is 52 m^2, the total heating demand and almost the entire electricity demand could be covered. Simultaneously, the average long-term ground temperature could be kept constant (Xia et al., 2017).

Table 7. Specifications PVT panel suitable for the Netherlands (Timmerman, 2009).

Design of a PV-Thermal panel	
Electrical yield per m^2 PVT panel	96 kWh/year
Thermal yield per m^2 PVT panel	0.95 GJ/year = 265 kWh/year
Panel cost	€400,- to €500,- (excl. installation and VAT) €350,-
Return time on investment	~ 15 years

Add-on PVT system; combination with a ground source heat pump (GSHP-PVT)

Currently, there is a large interest in PVT systems in combination with a (ground source) heat pump (de Keizer et al., 2016). An optimal design could be achieved when solar heating is used to produce hot tap water in summer, and to recharge the boreholes of the BTES system in wintertime. The proposed design for this system is shown in Figure 9. Table 8 describes the operation modes of this system. As can be seen in the figure, this system requires two tanks. The first tank is used to produce direct hot water (DHW), the second tank is used to heat water that can be used to recharge the ground to achieve the thermal balance of the underground. The auxiliary heater, which will be an electrical heater, will only be used when the thermal energy generated by the PVT collections is not sufficient to keep the water in tank 1 at the right temperature (Xia, Ma & Kokogiannakis, 2017).

Table 8. Operation modes of GSHP-PVT system (Xia, Ma & Kokogiannakis, 2017).

Mode	Description
PVT for space heating	Use the heat generated by the PVT panels for space heating
GSHP for space heating and cooling	Use the GSHP for both space heating and cooling
PVT for ground recharging	Use the thermal energy collected with the PVT for to recharge the ground
PVT for DHW	Use the thermal energy collected with the PVT for DHW

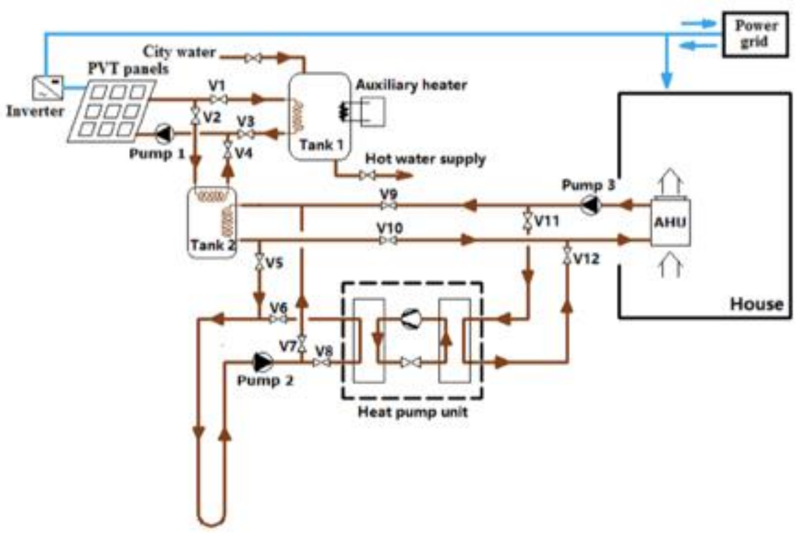

Figure 9. Schematic overview of a GSHP-PVT system (Xia, Ma & Kokogiannakis, 2017).

5.3 Additional sustainable energy sources

Energy from the sewer system

Waste water has quite some potential in providing thermal energy. Numerous sources suggest that heat can be extracted from waste water in the sewer system when it is transported to waste water treatment plants (WWTP) (Frijns et al., 2013, Meggers et al., 2011, Kollmann et al., 2017). The temperature of waste water leaving the houses into the sewer system varies over the day, but has an average of 27 degrees. Heat exchangers installed in the sewer system can extract thermal energy from the waste water. The extracted heat can then be supplied to residential houses as thermal energy. This form of recovering energy has already been applied in for example Zurich and Hamburg (Frijns et al., 2013). In Hamburg this has been put into practice by Hamburg Wasser and 215 houses are partly heated in this way (van der Hoek, 2011). It has been calculated that the theoretical maximum potential heat in waste water for a Dutch household is 21.3 megajoules per home per day. However, it should be considered that extracting heat from the sewer system results in the waste water having a lower temperature and this might affect the efficiency of the wastewater treatment processes (Frijns et al., 2013). It can have negative effects on the process of nitrification in the WWTP. The nitrification capacity will be reduced as a result of lower influent wastewater temperatures, which results in higher concentrations of ammonium in the effluent water. However, when temperatures of the incoming water are reduced for just a couple of hours the process of nitrification is not affected (Wanner et al., 2005).

Circular household heat recovery

Apart from extracting heat from waste water in the sewer system, heat can also be extracted from the waste water which is produced in the residential houses. For example, the heat of the shower waste water and clothes washer waste water could be extracted by a heat recovery tank. Next, a heat exchanger could supply this extracted heat to a heat pump. This heat pump generates a higher temperature. The recovered heat can be used to warm up water again (Frijns, et al., 2013). This idea is already applied in some new housing projects in the Netherlands. It was found that these shower heat exchangers save around 50 Nm^3 gas per household per year (SenterNovem, 2006). The maximum potential of heat which can be recovered using this technology is estimated to be 140 Nm^3 gas per household per year. An advantage of this system compared to heat extraction system in the sewer is that here the water is much warmer, and therefore more heat energy can be extracted. It should be noted that this system is more complex to implement compared to typical hot water systems used today. Also the costs will be higher at first. However, the overall benefits are going to weigh up against the costs and the total costs will come down (Meggers, et al., 2011).

Chemical energy from the wastewater treatment plant

Besides the thermal potential of the waste water, the chemical energy potential could be used as well. Wastewater contains a lot of organic matter and therefore is a significant carrier of carbon energy. Part of the chemical energy is lost as metabolic heat during oxidation, but a part of it can also be recovered by digestion of the sludge. This recovering produces biogas. Many wastewater treatment plants already digest sludge, however more energy could be recovered with anaerobic treatment (Frijns, et al., 2013). At this moment, there are some wastewater treatment plants which are producing enough energy by anaerobic sludge digestion to be self- sufficient.

There are sources which also suggest that WWTP should be able to provide a surplus of energy, which could then be used for heating households (Frijns, et al., 2013). There are still different possibilities for providing this surplus. One of those is the anaerobic treatment named above. Another possibility is called up-concentration processes. This is a process taking place at the wastewater treatment plant which allows maximal recovery of resources from domestic water (Verstraete et al., 2009). However, this process is not described in detail in this consultancy paper because it is out of the scope. A third possibility would be sludge incineration, which means to incinerate dried sludge for power generation. Furthermore, co digestion could also be an extra way to recover energy, which means that energy rich organic waste material is added to the wastewater digesters. These methods will not be discussed further here since the exact functioning is outside the scope of this project. However, these are all possibilities which can be considered when searching for ways to make a wastewater treatment plant produces energy.

Effluent of wastewater treatment plant

Also the water leaving the WWTP is a potential source of thermal energy which could be used to heat up residential houses. In the report 'Thermische energie op de RWZI' of the Stowa it is suggested that thermal energy of the effluent water of the WWTP can be used for heating residential houses in the neighbourhood with the use of a heat pump. Also, this energy could be used to supply the WWTP itself with energy. This report also states that the temperature of the effluent in winter has an average of 10 ˚C and in Summer an average of 20˚C.

Lake for cooling water

Climate change might result in higher temperatures of surface waters. This makes that shallow lakes have the potential to provide heat which can be recovered. However, since our summers are probably getting warmer due to climate change, the cooling demand of buildings rises. With deeper lakes there is more potential to extract cool water (Frijns, et al., 2013). In Amsterdam, such a system already exists. The water from the lake 'Ouderkerkerplas' cools the offices in Amsterdam South-East, which results in a reduction of 20 kton of CO_2-eq/year when compared to using separate cooling machines (van der Hoek, 2011). The Ouderkerkerplas deepest depth is 43 meters and it has an area of 0.73 km^2. Figure 10 below shows a representation of such a system.

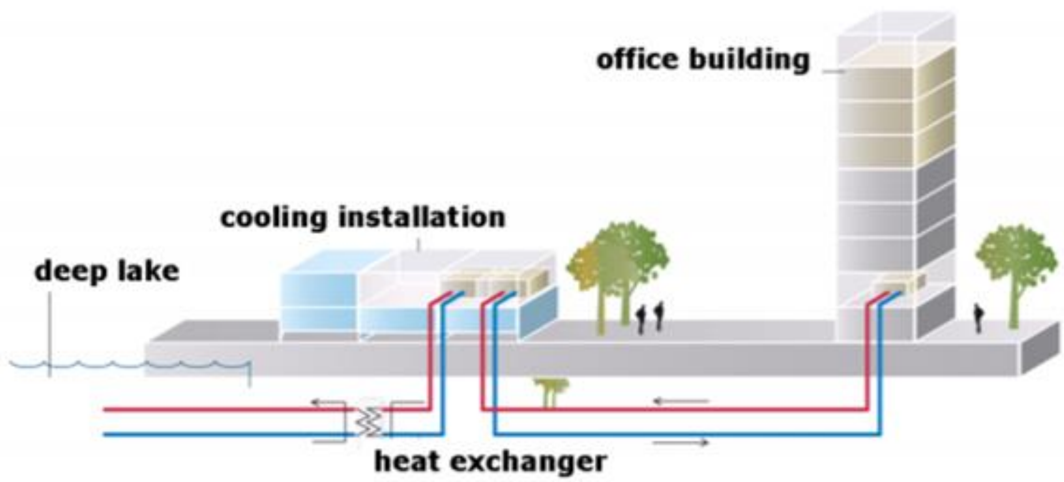

Figure 10. Representation of a cooling system (Van der Hoek, 2011).

6. Application to Windmolenbroek

Here, there is a description of how the aforementioned technologies could be applied in Windmolenbroek in order to satisfy the heating demand. First the application of an ATES system to Windmolenbroek will be elaborated on. Next, BTES and its application to Windmolenbroek is discussed. After that, PVT and other renewable energy resources will be discussed. At the end of this chapter a SWOT analysis is provided, which gives an overview of the most important aforementioned findings.

6.1 ATES (model results)

This section contains the results of the hydrogeological and heat flow models, answering the questions related to ATES energy supply/storage, effects of ATES on groundwater levels, and the development of the heat plume of a potential ATES system. The description of the model parameters can be found in Appendix II – Hydrogeological model parameters.

First, the visual model results are presented. Here is an oblique view of the regional groundwater head model at a single time step, along with a bird's eye view with a street map attached. An oblique view is provided in order to demonstrate the 3D nature of the model (see figure below).

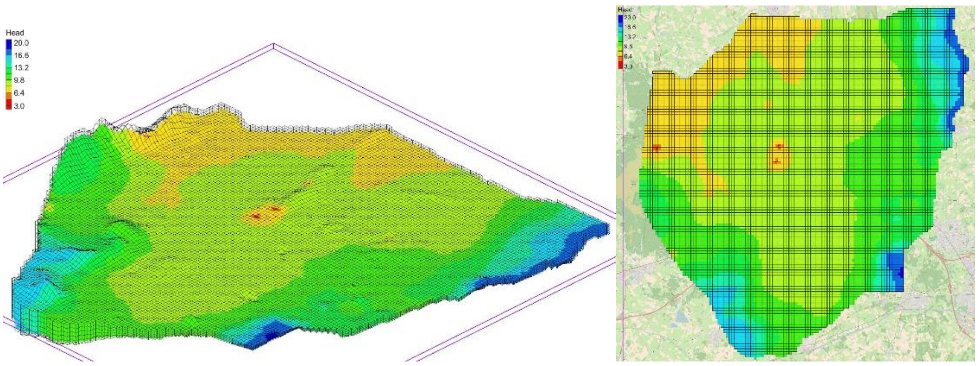

Figure 11. Oblique (left) and birds-eye view (right) of the regional hydrogeological model.

Next, the local model results are presented. Here is how the proposed wells will affect groundwater heads: https://www.youtube.com/watch?v=r0ox5lgbSFU&feature=youtu.be

And here is how the proposed wells will affect the temperature distribution:

https://www.youtube.com/watch?v=xcwQEtqkzi4&feature=youtu.be

Over the course of 11 years, the development of westward groundwater temperature plumes is evident. As the hot and cold wells are spaced at a distance of approximately 3 times the thermal radius of the hot body of water (see Appendix II – Hydrogeological model parameters), there is minimal interference between the hot and cold water bodies. This spacing is determined as a result of a numerical study with the purpose of optimizing spacing of wells in ATES systems (Sommer, 2015). Further, the wells are oriented along the direction of regional flow - mostly west with a slight southward component in this location - and as such positive interference between directly neighbouring wells is increased (see Appendix II – Hydrogeological model parameters).

Energy supply

First, the energy supply is explained. This is done in the method of the calculation in section 6.1. For the first year, the system is not yet working at full capacity, due to the initial water extraction only having a temperature of 12°C. After this period, the system of 10 wells provides $28.3 \cdot 10^3$ GJ/year on average; this accounts for 13% of the annual heat demand of Windmolenbroek. The calculation method is explained in the Appendix III – ATES energy supply, model calculation description. Therefore, 8 such systems could cover the demand entirely, which would easily fit within Windmolenbroek. It is prudent to build more; in the event of an exceptionally cold year, there would be extra supply. There would be less energy lost by having more than 5 wells per system in a row, due to a greater amount of positive interference (Sommer, 2015) – however, in this case, energy losses related to distribution would increase. Therefore, there is a trade-off between positive interference of adjacent wells and efficiency of distribution of heat. The efficiency of heat distribution is outside the scope of this research. Finally, it is interesting to note the increase in performance of this system over the conventional one that spaces all wells (hot and cold) at a distance of approximately 3 times the thermal radius. In these cases, neither hot nor cold wells benefit from positive interference. With such a well placement pattern, it is possible that the heating demand can be met via ATES, but it would require more wells or a larger pumping rate per well.

These ATES systems should be able to handle peak energy demand; if the wells pump water at a faster rate, then the demand can be met. This is due to the fact that the energy extracted from ATES is directly proportional to the pumping rate. Given that the peak demand is estimated to be 3.7 times the average demand (personal communication with Menno van Dijk of Cogas B.V., 8 October 2019), and the above system describes the average demand, then a pumping rate of roughly 2000 m^3/d per well (rather than 500 m^3/d) would suffice. Because this flow rate will only be needed for a relatively brief time and shouldn't change the average yearly dynamics of the well extraction or injection rate, one might assume that they also wouldn't cause flooding, though further modelling would be required to determine this. While peak energy demand of the neighbourhood is known, no data was accessible regarding the specific timing of peak demand.

ATES effect on groundwater heads

Next, the modelled pumping rates did not cause flooding at any time in the 11-year run; that is, the unsaturated zone was always present. When the model was run where each well had double the flow (1000 m^3/d rather than 500 m^3/d), flooding occurred, but only localized to active injection wells, rather than on a large scale. Therefore, with the current well configuration, the maximum flow rate per well that will not cause flooding is somewhere between 182000 m^3/year and 365000 m^3/year, corresponding to the flow rates of 500 m^3/d and 1000 m^3/d, respectively. The unsaturated zone is thin here (consistent with the fact that Windmolenbroek is in a low-lying area), which restricts the well flow rates as described above.

Plume development

The heat plume is evident after 11 years. Consistent with the earlier calculation of regional groundwater velocity (7 m/year, moving due west), one can see the development of a westward moving heat plume (see Figure 12 below).

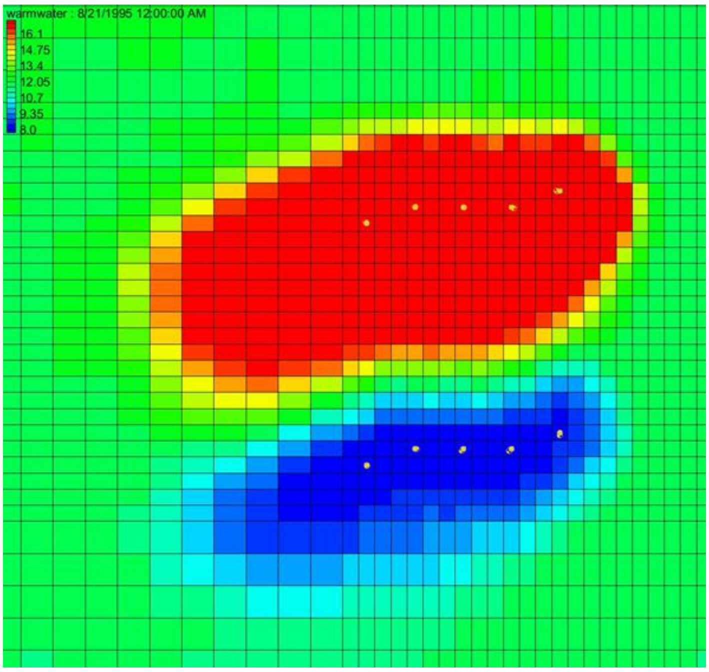

Figure 12. Each small cell around the wells has a side length of 12.5 meters, the large cells (for example in the upper right) have a side length of 25 m, the elapsed time is about 11 years, and the hot wells are injecting at the presented time step (which is in August).

The plumes develop in a mostly westward direction with a small southward component. So, the hot plume has moved about 125 m in 11 years (via advection and diffusion). Therefore one can easily conclude that the plume is not in danger of reaching the groundwater protection zones, approximately 5 km away from this location.

6.2 ATES risk of clogging

However, implementing ATES systems in Windmolenbroek is highly risky. This is due to the large uncertainties related to possible well clogging. The subsoil of Windmolenbroek consists of only one, unconfined, aquifer. Is it highly likely that this aquifer presents a clear gradient of redox potential in which the more superficial layers are oxidised and the deeper groundwater layers are anoxic and rich in iron. Mixing this chemical gradient can cause clogging of ATES wells due to the precipitation of iron(hydr)oxides. As the belowground chemical conditions were not assessed here, and the presence of this gradient in redox potential is highly likely, implementing ATES systems in Windmolenbroek is not currently advised.

6.3 BTES

Heat storage or supply

Regarding the scope and timeframe of this research, only a rough estimation of potential energy supply from BTES systems is provided. Boreholes arranged closely in a field can store energy more efficiently that single boreholes (Skarphagen et al., 2019). In this case, the estimated energy recapture rate of boreholes optimally spaced in a field is 80%, whereas the energy recapture rate of single boreholes is estimated at 70%. A detailed description of the method by which we arrived at these conclusions can be found in Appendix IV – BTES energy supply approximation. Further, BTES below the aquifer is most practical. This is due to relatively large advection in the aquifer, which dominates over diffusion; in the Breda formation beneath the aquifer, groundwater speed is essentially zero, so diffusion can dominate. See Appendix IV for a more detailed discussion of the effect of groundwater speed on BTES performance. A borehole field with roughly 4900 boreholes, each with a usable borehole length of 150 m, and with a power input of 30 W/m for a 4 month heating period (corresponding to 4500 W), would be able to provide the heating demand of Windmolenbroek.

Surface area or volume required

Via a basic calculation, it can be shown that the area required of a BTES borehole field satisfying exactly the energy demand of Windmolenbroek should require somewhere between 1.3 and 10.5 hectares, which depends on borehole temperature, depth, and optimal distance between boreholes. This relationship is explained in Appendix IV.

Implementation and social impact

A borehole field is likely to have a smaller impact than individual BTES systems at the household level. BTES boreholes can occur under parking lots or agricultural land (Paksoy, 2009), and many agricultural fields are adjacent to Windmolenbroek. Installing boreholes per home perhaps represents an overall larger effort, as it involves destroying part of the property, and it is unlikely that all homeowners will agree to this. If the housing stock in Windmolenbroek is going to be replaced at any point (note that the neighbourhood was built in the 1980s), it might be an attractive option to install BTES systems per house if and when the housing stock is replaced or retrofitted.

Distance heat source to houses

Evidently, the BTES systems installed per home are very close to each home, whereas the borehole fields could be relatively far away. There is some heat lost in transmission to the homes from the borehole fields, but it might be the case that the added efficiency due to positive interference between boreholes in a field accounts for more than the heat lost in transmission. That optimization problem is outside the scope of this report and is included later as a recommendation

Suitability with current houses in Windmolenbroek

BTES is highly suitable for Windmolenbroek. The typical concern with BTES systems is that they penetrate aquitards and water mixes between aquifers. In Windmolenbroek, this problem does not apply, as there is just one aquifer. Also, the thick Breda formation below the aquifer is ideal for storing energy, because the aquifer is relatively shallow and due to a lack of convection losses due to groundwater movement (Skarphagen et al., 2019).

6.4 Photovoltaic Thermal panels

Potential heat supply and required surface area

As shown in Table 3 (p.8), the total natural gas demand per year in Windmolenbroek is 220,659 GJ. The PVT panels have an area of about 2,5 m² on average and – as described in chapter 5 in Table 9 (p.21) a yearly thermal yield of about 0.95 GJ and a yearly electrical yield of about 96 kWh. These calculations assume that 100% of the heat yield can be directly used for heating after having been stored in a BTES system. However, BTES systems do not perfectly recapture heat. Therefore, an efficiency of 80% is assumed considering heat recover from a BTES system, this calculation is also elaborated on Appendix IV (Timmerman, 2009).

It needs to be determined to what extent the houses in Windmolenbroek are suitable for installing PVT panels. Having visited the neighbourhood of Windmolenbroek, it can be concluded that there are predominantly houses with sloped roofs. A rule of thumb is that approximately 75% of the sloped roof houses have a southeast or southwest oriented roof, corresponding with about 3500 houses. The average roof surface of a Dutch house is approximately 50 m², and generally for row houses and semi-detached houses 33 or 38 m² is suitable for solar panels respectively (Timmerman, 2009; Homedeal, n.d.).

Table 9 shows that if the entire heat demand were to be covered with heat harvested from the PVT panels, about 32 panels of 2.5 m² each are required, corresponding with a total PVT area of almost 80m² per house. Assuming an average roof area suitable for PVT of about 33 m², this means that only using the roof surface is not sufficient if the entire demand has to be covered by the PVT panels. Accordingly, about 60%, corresponding with about 66,000 panels, needs to be placed at other places than the roofs. Garage roofs however are not included and could potentially be used for PVT panels as well. Another option is to make PVT fields just outside Windmolenbroek, or to have floating PVT panels at the Leemslagen lake. However, the heating demand could significantly be decreased by improving the insulation of all houses. This would drastically decrease the amount of PVT panels required.

Table 9. Total demand Windmolenbroek and amount of panel required (own elaboration).

	Heat	Electricity
Demand Windmolenbroek	220,659 GJ/year = 61,343,202 kWh/year	18,113,700 kWh/year
Demand Windmolenbroek per house	47.05 GJ/year = 13,066 kWh/year	3300 kWh/year
Yield per panel per m^2	0.95 GJ/year = 265 kWh/year	96 kWh/year
M2 PVT panels required to cover demand	232,272	188,684 (electricity demand automatically covered)
Number of panels required in Windmolenbroek (assuming 2,5 m² panels)	92,909	
Number of panels required in Windmolenbroek compensating for the 80% efficiency after heat recovery form BTES	111,491	
Number of houses suitable for PVT (southeast or southwest oriented roof)	3516	
Number of panels required per house	31.7	

Approximate costs

The approximate costs of a hybrid PVT collector system are about 8,000 and 16,000 euros for an average household. One panel costs approximately 900 euros. However, the costs vary significantly per brand and type of panel or collector. The lifespan of panels is approximately 30 years, which is profitable considering the payback time of 15 years (Zonne-Paneel.net, n.d.; Timmerman, 2009).

Actual heat delivery solar panels and the need of storage vessels

Conventional solar thermal collectors are designed and dimensioned to supply roughly 50% of the hot tap water demand, corresponding with storage vessels of approximately 100 to 200 litres and a collector surface of about 2.7 m^2 (Timmerman, 2009). However, the houses in Windmolenbroek are likely to have a much larger collector surface, as the results of the calculations in table 9 show that about 31 panels of 2.5 m^2 are required in order to cover both hot water and space heating demand. So in practice, the houses will have the potential to cover the entire hot water demand if the suggested amount of PVT panels will be installed in Windmolenbroek. However, it is assumed in this report that the PVT panels will deliver about 50% of the domestic hot water demand. This assumption is made as most hot water will be harvested during the summer months, and therefore storage of hot water is essential. Besides, most houses in Windmolenbroek are row houses, and therefore storage vessels larger than 100 or 200 litres might be unfeasible. An important conclusion is that each house should have at least a couple of square metres of solar panels in order to harvest sufficient heat to supply at least 50% of the domestic hot water demand. The research of Timmerman suggest 2.7 m^2 of panels, but they assume conventional solar thermal collectors which have a 19% higher efficiency than the PVT panels (Santbergen et al., 2010; Timmerman, 2009). Therefore, the houses in Windmolenbroek should each have at least about 4 m^2 of PVT panels. If PVT panels will be placed at the Leemslagen lake, it is suggested to install large storage vessel near to the lake to store the DHW harvested from the panels. This DHW could subsequently be transported to the households for direct use.

In the Netherlands, 80% of the natural gas is used for space heating, and 20% is used for the domestic hot water demand, for example showering and hot tap water (Milieu centraal, n.d.). Assuming that half of the domestic water demand will be covered by PVT, this means that about 22,000 GJ has to come from other sources in Windmolenbroek on a yearly base. For example, electrical heaters could be installed at the household level, which could upgrade the domestic hot water temperature in the winter months to the desired temperature. The existing heat pumps could be used to upgrade the temperature to about 50˚C (Sanner et al, 2003). Having a COP of 4, these are fairly efficient in doing so. Subsequently, the electrical heaters only have to be used for upgrading the water from 50 ˚C to the desired temperature. In the Netherlands, the maximum temperature of hot water is usually about 60 to 70 degrees, so the electrical heaters will only need to upgrade the temperature with 10 or 20 ˚C (milieu centraal n.d., 2) Therefore, the actual amount of energy required for domestic hot water heating is likely to be less than 22,000GJ per year, presented in Table 10 below. However, considering the worst case scenario, we assume that 22,000 GJ per year will be required.

Table 10. Allocation of natural gas consumption and quantity hot water supplied by PVT and external sources (AlleCijfers, 2019; Milieu centraal, n.d.; own elaboration)

Total natural gas consumption Windmolenbroek (GJ/year)	Total natural gas consumption for domestic hot water demand in Windmolenbroek (GJ/year)		Total natural gas consumption for space heating in Windmolenbroek (GJ/year)
220,659	44,132		176,527
	Supplied by PVT (GJ/year)	**Supplied from external source (GJ/year)**	
	22,066	22,066	

6.5 Additional sustainable energy sources

The first three additional sustainable energy sources described in chapter 5; energy from the sewer system, circular household heat recovery and chemical energy from the WWTP are not elaborated on in this chapter. This is because they are not seen as technologies to be implemented in Windmolenbroek in the close future. They are still rather new, undeveloped technologies at this point in time. However, since they are technologies which might become important in the future they have still been discussed in chapter 5 and they are still being described further in Appendix I – Application of renewable resources to Windmolenbroek, considering the application to Windmolenbroek. This means in this section only the effluent water of the WWTP and the possibility to use the lake for cooling are discussed.

Effluent of wastewater treatment plant

The effluent water from the WWTP could be a potential energy source for Windmolenbroek. The waste water is normally discharged into streams and rivers nearby, but instead, heat could be recovered and could be used for spatial heating in the house. Here, the temperature should be upgraded by a heat pump which is installed at the house and it can be used for wall/floor heating. The WWTP De Sumpel is just on the border of Windmolenbroek and therefore this WWTP has a close enough proximity to be of potential to the neighbourhood. De Vissedijk is located further away, which means more transportation distance. Therefore, De Vissedijk could be a potential energy source for neighbourhoods located in its vicinity.

The Waterschap Vechtstromen has provided the discharge of the effluent water and the temperature of the digesting sludge of De Sumpel. In Table 11 below, the averages for winter and summer can be found, and also the potential amount of energy this effluent water could deliver to Windmolenbroek. The averages of temperature and discharge are calculated over approximately one year of data. It should be noted that the temperature of the sludge is not necessarily the same as the temperature of the wastewater. The wastewater will be a couple of degrees lower than the sludge, also this will differ per season (G.C Speek, Waterschap Vechtstromen). Subsequently, therefore it is still unclear what the temperature of the wastewater will be exactly. In this calculation therefore an assumption is made; the wastewater will be two degrees lower in temperature compared to the sludge temperature (see Table 11). Furthermore it was found in a report that the general average temperature of the effluent of WWTPs is 20 ˚C in Summer and 10 ˚C in Winter (Stowa, Thermische energie op de RWZI). These numbers are in the same order as the calculated numbers below.

The thermal energy that could be retrieved from the waste water is calculated based on a basic equation, and therefore it rather provides a rough estimation. The equation used here is a similar equation used to describe the rough amount of energy the ATES system could generate and can be found in Appendix III – ATES energy supply, model calculation description. In the equation, it is assumed that we can cool down the waste water to ˚C. This means that in summer the heat pump should extract 9 ˚C from the water, and in winter 1 degree. This results in quite large energy amounts which could be extracted from the waste water. It should be noted that probably still some energy gets lost due to transportation of the water and other efficiency matters. However, in this example we assume the heat pump can cool down the water to 8 ˚C, but in reality the heat pump might be able to cool the water down to even lower temperatures. If this is the case, more energy could be extracted. From Table 11 below, it can also be seen that the energy which can be obtained per day by decreasing the temperature with 1 ˚C is 86 GJ. Although this calculation only provides a rough estimate, it can still be concluded that the WWTP is a potential source of energy. Cooling the effluent waste water by just 1 ˚C will provide 14% of the average daily demand of Windmolenbroek.

Table 11. Summarisation of the effluent discharge, average temperature of the sludge and wastewater effluent and the energy potential. Data obtained from G.C. (Berry) Speek, Adviseur Civiele Techniek, Waterschap Vechtstromen.

	Average Effluent (m^3/d)	Average temperature sludge (°C)	Assumed temperature of wastewater (°C)	Energy potential (GJ/d)
Winter	20,580	11	9	86
Summer	13,881	19	17	524

Lake for cooling

There is a small lake bordering the neighbourhood of Windmolenbroek, the Leemslagenplas. This lake has a maximum depth of 30 m and an area of approximately 0.24 km^2. It was formed by the excavation of sand. At this moment the lake is only used for diving, furthermore it is not open for public use. This lake could have the function of a cool water reservoir during the summer. Especially when taking into account that the summers will probably become warmer, and therefore the demand for cooling is expected to increase. By creating a heat exchanger network from the lake to the houses in Windmolenbroek, the cooling demand can partly be supplied by the lake and partly by the underground.

6.6 Social consequences and social support

The above described technologies cannot be installed without affecting the social environment. Therefore, it is important to consider the social consequences of implementing certain technologies. Furthermore, it is important to consider the willingness to adopt (WTA) of residents for renewable energy technologies. The WTA is an important factor to investigate as human choice of technologies is a critical factor in adoption rates. Besides, it is a decisive factor for encouraging social acceptance and to create market opportunities (Hai, 2019). The social consequences and acceptance of both BTES and PVT panels will be discussed in this paragraph, as these technologies appeared to have most potential in Windmolenbroek.

Factors affecting PVT and BTES implementation

Different factors affect the WTA of PVT and BTES systems, which can be subdivided into personal and contextual factors. Personal factors include for example age, income, knowledge, and interest. Contextual factors could be the community and market situations. These factors are important to analyse, as they can direct people towards adoption or non-adoption of technologies (Hai, 2019). Table 12 describes for both PVT and BTES some critical aspects likely to affect the social acceptance of these technologies. It is expected that the WTA of PVT is lower than BTES. BTES has mostly barriers during its installation, as boreholes may need to be drilled in the garden. However, when they are installed, the system is invisible. The implementation of PVT is therefore expected to be accompanied with larger barriers inhibiting adoption and implementation, mainly because they remain visible. Residents might perceive and consider the panels as unattractive and disturbing for the street scene in Windmolenbroek. This is a barrier that needs to be considered and overcome.

For both technologies, significant changes will need to occur at the household level. The most important change is the transition towards a LTH systems, requiring sufficient insulation and potentially an alternative heating system. For example, radiators with a larger surface, or floor- or wall heating systems need to be installed to heat up the houses sufficiently. As most houses are probably not sufficiently insulated yet, this will be the absolute starting point. This should be prevented, as it is important to at least maintain the current comfort level of the residents. Residents should be educated on how to use such a LTH system. It will take longer to heat up a house, so therefore maintaining a relatively constant temperature over day and night is suggested. Although this is not complex to manage, it is important that the residents have knowledge of it.

Table 12. Factors affecting the WTA and social acceptance of proposed design.

PVT	BTES
Installation and costs of panels	Impacts of drilling (impact on garden)
Change in regulating the inside climate	Change in regulating the inside climate
Switch to LTH; potentially another heating system needs to be installed and the house needs to be sufficiently insulated	Switch to LTH; potentially another heating system needs to be installed and the house needs to be sufficiently insulated
Visibility of PVT panels	After installation, the BTES system is invisible

Potential business case

It is suggested to put effort in setting up an attractive business case concerning the implementation of any proposed design. Generally, people do not like changes, as it requires time and effort to get used to a new situation. Therefore, the proposed design should be presented and made as attractive as possible. It is recommended to do in-depth research on composing an attractive business case, but some starting points are provided below.

First of all, it is important to provide people with a clear overview of the overall transition plan and the idea to switch to another energy carrier than natural gas. Next, information per household should be provided, describing what type of insulation is required to install, and corresponding costs. Lastly, information should be provided concerning what will happen for the connection to the BTES system, and what needs to happen for the installation of the PVT panels. The overall financial picture should be clear. Perhaps long-term loans could be offered to make the transition affordable, and an inventorisation of possible subsidies should be executed. The offer should be made as financially attractive as possible, and it should be made clear what the payback time is and what the profits will be in the long-term.

Secondly, the transition could be combined with an appealing moral message. This could be realized by setting up a campaign with a slogan such as 'Live life cleaner by making Windmolenbroek fossil free' or 'Make Windmolenbroek green so there will be a tomorrow'. This way, residents could become aware of their responsibility to contribute to a more sustainable energy system. Motivating residents to change is an important factor to increase the adoption of sustainable technologies.

Lastly, time and effort could be put in setting up or stimulating neighbourhood initiatives. These have to aim to stimulate residents to simultaneously adopt, install, and invest in new technologies. Support is likely to increase if people know that their neighbours are going through the same process and need to make the same investments. The investment and installation costs might decrease as well if they are directly implemented at a large scale instead of per household. Also, residents will be more likely to install PVT panels when the entire street has them, mainly concerning visibility considerations. Such an initiative could start with a single street, and subsequently the initiative can be upscaled.

6.7 Final SWOT

This chapter presents the final SWOT analysis, applied specifically to Windmolenbroek using the conclusions derived from chapter 6. It describes relevant factors when choosing which technologies to implement in Windmolenbroek. The final advice in the next section is developed based on the table below.

Table 13. Final SWOT-analysis (own elaboration).

	ATES	BTES	Additional sources	PVT
Strengths	- Low initial cost - Minimally impactful on residents - Can easily provide all of energy demand, from a flow rate perspective - Low energy storage loss	- Presence of relatively shallow base impermeable layer allows for heat storage with minimal losses due to advection -can theoretically provide all of heating demand, given enough heat input from PVT and other sources - Low energy storage loss - Theoretically very long-lived system	- Use of local sources of waste heat or cold that would otherwise have been wasted -Potentially large amount of energy available from wastewater	- Generates both electricity and heat - Potential to supply entire heat and electricity demand - Easy to install at the roof
Weaknesses	- Low outflow temperature requires retrofitting and external energy to be used for tap water - Potentially high maintenance costs - System requires a few years before it starts working at optimal capacity	- High initial cost - System requires a few years before it starts working at optimal capacity - Low outflow temperature requires retrofitting and external energy to be used for tap water -High impact of well placement at the household level	-probably the WWTP needs renovation.	- Expensive to install - Many panels are required to cover the entire demand - Requires a lot of surface area - Require hot water storage tanks - Their visibility might be considered unattractive
Opportunities	- Potential of combination with bioremediation			- Future efficiencies might improve, requiring less PVT panels - If houses will be rebuilt or retrofitted, the panels might be integrated in the roof
Threats	- Possible high risk of clogging - Potential distribution of subsoil contaminants - Physical well clogging may occur in the long-term occur through injected sediments	- (Low) risk of leaking fluid - Complex optimization problem; heat recapture not 100% effective	- Limited knowledge on implementation - Cooling from the lake: possible ecological concerns - certainty of wastewater heat stream needs to be investigated	- Not widely implemented yet, so slightly uncertain performance - Uncertain market

7. Final advice and conclusion

The optimal solution for using the energetic potential of the underground of Windmolenbroek is to install a grid of BTES systems arranged in a field, with energy supplied by the residential heat excess during summer and thermal energy from the PVT panels. Also, certain parts of Windmolenbroek could have individual BTES systems, depending on the trade-offs between energy lost due to storage inefficiency of single boreholes versus energy lost due to transmission from BTES fields. This proposed design does not incorporate the current heat network, as that network operates at a high temperature, while the BTES and PVT would be connected to a LTH system. Therefore, they are not compatible and they cannot be connected.

Storage

The BTES boreholes should be placed in a grid in a field. These boreholes should be fairly deep - reaching well into the Breda formation - to take advantage of this layer's lack of groundwater flow. The part of the borehole running through the aquifer should be insulated to minimise advective losses in heat storage due to groundwater flow. The borehole depth could be around 180 meters, and borehole spacing could be between 1.5 and 3 meters, though these numbers must be refined as the result of a much deeper modelling study before any concrete plans can be made. Between 1.3 and 10.5 ha of borehole field space is required in order to provide the heating demand using PVT and residential summer heat excess as energy sources. Further, the system should incorporate water storage tanks at the household level to directly supply hot tap water to the households, accompanied with an auxiliary electric heater during the times for which PVT heating is insufficient. Large water tanks should also be implemented to store energy in times of peak supply.

Individual boreholes implemented per house are also acceptable though not preferable due to greater heat losses when compared to a borehole field. In these cases the insulation around the borehole running through the aquifer becomes relatively more important, and one should expect these systems to have a lower heat recapture rate than the BTES systems placed in a grid. Still, the suitability of single boreholes becomes greater closer to the centre of Windmolenbroek, as these homes are farther from the proposed borehole fields and so more heat would be lost in transmission.

ATES could potentially store a comparable amount of energy to BTES. However, the implementation of an ATES system is absent from the final advice, because of its inherent risk of clogging. The risk of chemical clogging strongly depends on the chemical gradient of the subsoil in which the wells are placed. Given the fact that the aquifer below Windmolenbroek is unconfined and probably thus composes of a strong gradient in redox potential, the risk of clogging through groundwater mixture could be substantial. In the case that the aquifer does not comprise of a strong gradient in redox potential and ATES implementation would thus not mix groundwater layers with different characteristics, clogging is less likely to occur and implementing ATES systems in Windmolenbroek could be promising.

Supply

The energy sources for this system should consist of the residential summer heat excess and the thermal energy captured by PVT panels. The PVT panels could occur on the surface of the lake, above the BTES boreholes, or on top of the houses. As the residential summer heat excess can provide approximately 20% of the heating demand, 23 ha of PVT panels would be required to satisfy the remaining 80%. A reasonable system would supply more than what Windmolenbroek requires, so the required area of solar panels numbers should be scaled up to the desired supply percentage.

It should be noted that heating from BTES and a household level heat pump can achieve a temperature of about 50°C, which is less than the required temperature for hot tap water. Therefore, the remaining hot water demand needs to be supplied via another method. Because this remaining demand is a fairly small percentage of the total demand (estimated to be 10% or less), it is recommended that electric heating is used for this purpose.

A large amount of thermal energy is potentially available from the wastewater treatment plant De Sumpel. While the exact amount of energy obtainable from the wastewater plant is not calculated here, 14% of the average heating demand can be extracted by cooling the treated wastewater effluent by each 1°C. Given that it is possible that the effluent can be cooled down by more than 1 °C, wastewater could be an even larger source of heat. The temperature of the wastewater effluent should be upgraded with heat exchangers at the household level. The use of waste heat from wastewater effluent is recommended in the homes relatively close to the wastewater plant, depending on the actual amount of energy available.

Location

Given that the lake has an area of about 27 ha, there is potential to install many of the PVT panels on the lake. Further, the fields directly south and west of Windmolenbroek have an area of 92 ha, so it is recommended that solar panels should be installed here too. Some of the panels must be on the roofs of houses, so that they can heat water to a high temperature for domestic use. Further, maximising the number of rooftop PVT panels is suggested to preserve the green spaces around Windmolenbroek. Given that the fields South and West of Windmolenbroek have an area of 92 ha, and given that BTES boreholes can operate under agricultural land, the area requirement for boreholes can be more than satisfied with these fields. Thus the proposed BTES fields and solar panels can fit well within the proposed area.

Figure 13. Locations of proposed technologies in and around Windmolenbroek. The orange areas are suitable for both BTES borehole fields and/or PVT (if possible), the yellow area is suitable for solar panels only, and the purple area is suitable for BTES borehole fields only. The total orange area is 92.2 ha, the yellow area is 26.7 ha, and the purple area is 23.0 ha. Solar panels could also occur on the roofs of houses.

Implementation and adoption of technologies

The proposed technologies impact their (social) environment, and therefore social aspects and the physical environment are important to consider. Also, some factors affecting the rate of adoption of technologies and interventions are emphasized in this proposed design.

It turns out that the starting point of the implementation of the proposed design is to retrofit or better insulate the current houses in Windmolenbroek. Triple or HR++ glass should be installed, walls and roofs should be extra insulated, and floor insulation could be combined with installing floor heating. This is important for two reasons. First, without sufficient insulation and appropriate heating systems, the low temperature might not heat up the houses to the desired temperature. This should be prevented, as the proposed design should not be at the expense of the comfort of residents. Second, the heating demand will be significantly decreased when the insulation of all houses is improved. This would drastically decrease the amount of PVT panels required. This way, both the financial and visibility barriers will be decreased.

Several suggestions are provided to improve the willingness of adoption of PVT panels. This is important, as both their visibility and relatively high investment costs might pose barriers to residents to adopt them. First, sufficient information should be available about the panels, such as their payback time, the investment, and their long-term benefits. Another promising way is to set up neighbourhood initiatives, as adoption rates are likely to increase if neighbours install them simultaneously.

It has been calculated that with the current heat demand, if all roofs suitable for PVT panels are fully covered with PVT panels, another 41,000 panels need to be placed elsewhere in or around the neighbourhood. Garage roofs, the lake, or borehole fields are recommended to install the remaining number of required PVT panels. The amount of panels placed on roofs could be reduced by relying more heavily on the lake or fields for PVT panel placement.

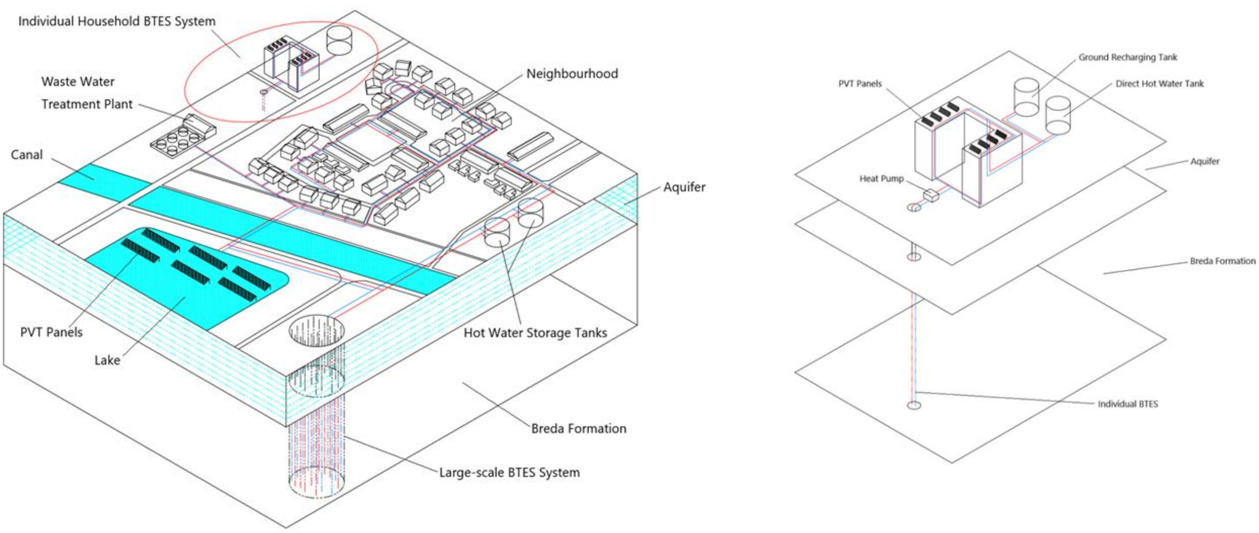

Figure 14. Visualisation of proposed design for Windmolenbroek.

8. Discussion

Value of this advice

The value of our proposed design is to provide a comprehensive plan of how Windmolenbroek could switch to an alternative heating system, having potential to leave the natural gas era behind. This research does so by not solely considering technological challenges, but by directly linking those to ecological side effects, hydrogeological conditions, and required changes at the household level. This research has a holistic approach, emphasizing the interconnectedness of the entire system, thereby making sure that no aspects are neglected or marginalized. If the proposed design will be implemented, Windmolenbroek will generate more sustainable, renewable energy, which is in line with the heat transition vision of the municipality of Almelo and their long-term sustainability goals.

Uncertainties and assumptions

During the execution of the research, several assumptions have been made concerning the potential thermal storage in the soil and thermal yield from technologies, resulting in some uncertainties. However, these uncertainties are minimized, as the most reliable and appropriate numbers we were able to find have been used. However, it is important to keep in mind that not all findings might be perfectly representative for Windmolenbroek. The largest uncertainties will be described below, and it is recommended to examine these during further research.

First of all, the current natural gas demand of Windmolenbroek is considered as a starting point. However, if all houses will be retrofitted or insulated, the heating demand will significantly decrease, decreasing the required BTES capacity and amount of PVT panels as a result. This is likely to significantly alter the energy demand in the proposed design, but in a positive way, as it will decrease the overall heating demand. Considering assumptions about the houses, an average roof surface suitable for PVT of 33m² is assumed. Although these numbers are from Dutch statistics and specifically for semi-detached houses, which is the case in Windmolenbroek, the suitable surface might slightly deviate from this. This will affect the number of panels that could be installed at the roofs, and the number of panels that should be installed at for example the Leemslagerplas. Furthermore, it is assumed that 50% of the hot water demand could be supplied by the PVT panels, based on the current characteristics of solar collectors at roofs. In this case, storage vessels of approximately 100-200 litres are required at the household level. However, the potential hot water delivery of the proposed design is significantly higher than 50%, so it is likely that less heating needs to come from another heat source.

Also, the houses built in Windmolenbroek are already approximately 30 to 40 years old. It might be decided that the houses will be demolished, rebuilt, or retrofitted in the short- or long-term. If this is the case, the future houses might be way more efficient and better insulated, resulting in significant consequences for the heating- and cooling demand. It is also possible that alternative or new technologies might become more suitable to install in Windmolenbroek rather than PVT panels and BTES systems. Innovations are currently introduced at the market at a rapid pace, associated with large future uncertainties.

Some assumptions considering hydrogeological aspects should be highlighted as well. The hydraulic conductivities are aggregated in such a way that the top 6 meters of the model all have the same value, while the rest of the model down to the Breda formation has another single value. Representing small-scale heterogeneities in hydraulic conductivities could influence the flow pattern and groundwater elevations throughout Windmolenbroek. It is worth noting that the model has been well validated, with a RMSE of about 36 cm, but this applies to a single point rather than to the whole model. Further, no losses of heat are assumed to happen through the top of the aquifer to the environment, nor through the bottom of the aquifer to the Breda formation. These are reasonable assumptions, as the heat capacity of air is small, and there is no advection in the Breda formation to transfer heat, but could be refined in an even more in-depth model.

Furthermore, it is assumed throughout the report that no heat losses in transmission occur. This report roughly estimates a borehole field heat recapture rate of 80%. While this number is supported by literature, including numerical and field studies, it is not precise.

Concerning the hydrogeological model and the subchapter 4.1 on the description of the underground, it must be noted that different hydraulic conductivities are mentioned for the Boxtel formation. In the underground description it is mentioned that the range is from 5 to 10 meters per day, however the value used in the model is 31 meters/day. The value of 31 meters/day is obtained from ing. a professor at WUR, and his value was assumed to be more reliable.

Another uncertainty worth mentioning concerns future climate change. As a result of more severe weather circumstances, the heating and cooling demand might change per household. It is important to consider future scenarios for the climate in Windmolenbroek in order to anticipate on the requirements for the heating- and cooling system. Correspondingly, also the resilience and flexibility of the infrastructure is an important consideration, due to expected increased severe weather circumstances. The required capacity of the system might change due to a growing number of residents in Windmolenbroek as well.

Accordingly, this research provides a starting point to compose a complete and reliable plan of how to realize the transition off natural gas in Windmolenbroek. More precise field research, calculations, and model simulations need to be performed to validate, confirm, or update the findings in this report.

9. Recommendations for further research

High priority recommendations

While numbers for borehole length and spacing are provided above (about 180 m and ranging from 1.5 m and 3 m, respectively), these numbers are based on rough estimations and literature values. A much more in-depth modelling study of BTES in Windmolenbroek needs to be conducted to make these numbers truly optimal. This study should also incorporate the suggestion of insulated boreholes in the aquifer to precisely determine the associated energy storage savings. Further, the optimal placement of the BTES field(s), within our suggested areas, should be determined, incorporating the loss of energy due to distribution to homes. Finally, this should result in where or if single boreholes per home are preferable over homes relying on the BTES field.

The municipality of Almelo should conduct an extensive analysis of the geochemical conditions of the aquifer for the entire aquifer depth. This should be done in order to determine the gradient in redox potential which is strongly related to the clogging risk of ATES and to gain knowledge in the possible environmental effects of both BTES and ATES systems. Also, the risk of possible contaminant diffusion or bioremediation could in this way be analysed.

The municipality of Almelo should get detailed information of the temperature of the wastewater effluent at De Sumpel, rather than just the sludge temperature. This, together with the discharge data, will provide a precise amount of energy that can be extracted from the wastewater. This is consistent with the RES goals as well.

Analyse if the proposed design fits with the spatial planning of the municipality and whether it is allowed to e.g. put solar panels at the lake and install storage vessels at the lake. This is recommended as the advice is to partially install the panels in public, recreational areas. Therefore, extensive consultation with involved stakeholders and spatial planners is essential. Besides, legal and spatial restrictions need to be taken into account.

Correspondingly, investigate potential back-up systems, in case failure might occur or (waste) heat streams might be lacking for a while. To ensure sufficient space heating and hot water supply, the natural gas connection could be maintained for the first decades as back-up or in case the heat supplied by our proposed design is not sufficient. Other back-up systems could be more and larger heat storage vessels outside Windmolenbroek, for example near the Leemslagen lake or placed underground. This has not elaborately been analysed in this research, but the presence of reliable back-up systems are crucial.

An in-depth financial analysis of operation and maintenance costs of proposed technologies is suggested, as that was out of the scope of this research. However, it is important to have all installation, operation, and maintenance costs of the proposed designs clear in order to provide a thought out advice.

Low priority recommendations

It is advised to investigate options for delivering cold to e.g. the shopping mall, the hospital, or to industries. It is likely that there will be an excess of cold with the proposed design, and there is potential to use this excess of cold for cooling purposes of industries or facilities with a cooling demand, thereby decreasing the need for air conditioning. However, this opportunity has not been analysed in this report due to time constraints, but it is expected to yield valuable results.

It should be investigated what the long-term certainty is of the heat delivery from the WWTP - or potential other waste heat delivering industries. Perhaps, the heat delivery from the WWTP is only five years. It could be that the WWTP delivers heat for a longer time span, but the (un)certainty of waste heat suppliers should be anticipated. However, even if industries could supply heat only for a relatively short time period, they could be very useful. Still, the heat delivery system should be reliable, and if heat will be delivered from several sources, the system should be sufficiently flexible and resilient to cope with a potentially unstable input. Therefore; investigate opportunities to improve the flexibility of the system, in order to make it possible to connect potential other heat sources.

Further research is recommended about personal and contextual factors directing people towards adoption or non-adoption. It is recommended to have a specific look at the education level of residents, and correspondingly their knowledge and interest concerning the implementation and purchase of solar panels. This is important, as it might be the case that these turn out to be inhibitory factors in the process of adoption. Some of these factors, such as knowledge, could be relatively easy to overcome.

An important contextual factor to investigate is the market situation of existing PVT panels. The market is still relatively uncertain, so it is recommended to explore the best opportunities, taking into account financial, efficiency, and reliability aspects of the panels.

Although this research provides a starting point for composing an attractive business case for residents, further research is required to compose this advice. This is highly recommended, as offering an attractive alternative for natural gas is decisive for residents in their process of adoption and implementation.

Residents might perceive and consider the panels as unattractive and disturbing for the street scene in Windmolenbroek. This is a barrier and ethical concern that needs to be analysed. It is recommended to do a survey in the neighbourhood to investigate the social support for installing panels at the roof. Perhaps, it turns out to not be a barrier for the citizens. But in case it is, they could be promoted in a more attractive way or their long-term financial benefits could be better emphasized.

Another interesting technology that could be considered is on-site treatment of wastewater to make biogas. This is interesting to investigate, as such installations (e.g. anaerobic sludge digesters) have potential to turn faeces and kitchen waste into heat and biogas, which could be supplied to households and decrease the amount of heat that needs to be harvested by PVT panels.

Perhaps uninsulated boreholes that only extract heat could be installed only on the houses on the eastern border of Windmolenbroek. If they only extract heat, and are capable of cooling the groundwater below the ambient temperature of 12 C, they could take advantage of the moving groundwater, which would constantly provide relatively warm groundwater. This would cool down the rest of the soil of Windmolenbroek, which would make insulation more important there, but could still provide some energy to the houses on the eastern border of the neighbourhood.

Appendix I – Application of renewable resources to Windmolenbroek

Energy from the sewer system

This technology has the potential to be implemented in Windmolenbroek, but ideally at a later stage in time. This is suggested since it is still uncertain what the implications will be for the process of nitrification in the wastewater treatment plant (Wanner et al., 2005). It might be that reduced influent wastewater temperatures slow down the efficiency of the functioning of the wastewater treatment plant. Furthermore, for implementation of this technology, the sewer system will need construction. However, there is a lot of energy in the wastewater system (21.3 MJ/home day) so when aiming to become independent of fossil fuels it can be useful to retrieve this energy.

Circular household heat recovery

This proposed technology operates closer to the source, which is an advantage since the water will still be warmer here. Using a heat recovery tank in a residential house could save up to 50 Nm3 gas per household per year (SenterNovem, 2006). However, incorporating this technology into houses requires large reconstructions. This technology is being applied now only in new housing developments in the Netherlands (Meggers, et al., 2011). Therefore, especially when the neighbourhood will be demolished and then rebuilt, this technology will be an option for implementation at Windmolenbroek.

Chemical energy from the wastewater treatment plant

At Windmolenbroek there is one WWTP plant, which is called 'de Sumpel'. There is another wastewater treatment plant a bit further away from the neighbourhood: 'de Vissedijk'. Currently there is a big project going on in which the Vissedijk is being renovated. What is being renovated exactly is not clear. However, the possibilities of WWTPs to produce energy suggested in chapter 5, might be already part of this renovation. If the Sumpel is going to be renovated in the future, then it will be worthwhile to look at whether the possibilities for this wastewater plant to become self-sustaining or even energy providing are feasible or not. However, this will probably be an idea related to the longer scope.

Appendix II – Hydrological model parameters

The model contains 10 wells in total; five hot and five cold, with the hot wells North of the cold wells. Neighbouring hot or cold wells are placed approximately 0.75 times the thermal radius apart from each other. The thermal radius is given by:

$$R_{th} = 0.66 \cdot \sqrt{\frac{v}{\pi \cdot c \cdot L}}$$

where v is the volume of the thermal body, c is the porosity, and L is the well screen length (Bloemendal, 2018).

The optimal spacing to ensure positive interference between wells is 0.5 times the thermal radius (Bloemendal, 2018), but the wells were placed slightly farther apart to reduce the risk of flooding during injection periods (the unsaturated zone is relatively thin in Windmolenbroek). Extraction and injection flow rates oscillate between 500 and -500 m^3/d, depending on the season. Ideally, the flow regime varies with the energy demand (for example, peak flow to match peak demand), but the flow regime used here should still be able to basically address the questions related to this model. The well screens go from an elevation of 3 m to -15 m NAP. Typically, the well screen in ATES systems covers the entire aquifer, but in this model the well screens extend from close to the bottom of the aquifer to a few meters from the top. This is because the aquifer in Windmolenbroek is unconfined, and as such might be sensitive to changing heads over time. If the eastern Netherlands gets drier as a result of climate change, it would be ideal if the well screen remained completely submerged. The groundwater speed is 7 m/year on average in Windmolenbroek, though this model includes variations in this speed (it can be as fast as 11.5 m/year). The direction of the groundwater flow is mostly westward, but in this specific location, we find that there is a slight southward component of the velocity. Thus, to minimize negative interference, the wells are placed in a South-West-West-West orientation. The temperature injected into the hot wells is 20°C, and 8°C for the cold wells. It could be the case that these values could realistically be more extreme, such that somewhat more energy can be obtained from the same pumping rate.

In the local hydrogeological model the solute transport modelling code MT3DMS was implemented in order to see model heat flow as a result of injection and extraction of warm and cool water. Certain values of thermal soil properties needed to be implemented. The table below gives an overview of these properties and their values and the sources from which these values were retrieved.

Soil properties	**Values**	**Source**
Porosity [-]	0.354	https://www.geotechdata.info/parameter/soil-porosity.html
Bulk density (kg/m^3)	1740	Hamdhan & Clarke, 2010
Specific heat capacity (J/kg K)	1513	Hamdhan & Clarke, 2010
Horizontal conductivity top 6 m of model (m/day)	31	Professor of the WUR
Horizontal conductivity below 6 m from top (m/day)	33	Professor of the WUR
Longitudinal dispersion (m)	1	Sculze-Makuch, (2005)
Bulk thermal diffusivity (m^2/day)	0.16	Bloemendal & Hartog, (2018)
Thermal conductivity of aquifer (W/mC)	2.55	Bloemendal & Hartog, (2018)
Effective molecular diffusion (m^2/day)	$1 \cdot 10^{-10}$	Bloemendal & Hartog, (2018)
Thermal distribution coefficient (m^3/kg)	$2 \cdot 10^{-4}$	Bloemendal & Hartog, (2018)

Appendix III - TES energy supply: model calculation description

The energy supply for each well is calculated simply by multiplying the density of water, its heat capacity, the change in temperature between the extracted hot water temperature and the injected cold water temperature, and the extraction rate. The COP of the heat pumps and their required electricity are incorporated, in the style of the calculation below. This is done for each of the 10 wells, so 10 different temperature time series are used in the calculation. The below calculation is an example, showing the concept of the calculation for a single (large) well.

The amount of water required by the system depends mainly on the thermal load, cooling load and groundwater temperature of the project. Heating demand takes an average of 617 GJ/d. Because the typical storage temperatures are 5-12°C or cold storage and 14-30°C for heat storage (Bonte et al., 2011), select heat pump input temperature 20°C, output temperature 8°C. The commonly used water source heat pump has a coefficient of performance (COP) value between 4 and 5, so 4.5 is selected for calculation. Based on the above conditions, calculate the average water demand for the operation of the ATES system.

According to the working principle of groundwater source heat pump, when the water source heat pump is used for heating, the heat production:

$$N_{production} = N_{water} + N_{input} \tag{1}$$

According to the law of conservation of energy, the above formula can be transformed into:

$$N_{production} = Q_{water} \cdot \rho \cdot c \cdot \Delta T + N_{input} \tag{2}$$

$$Q_{water} = \left(N_{production} - N_{input}\right) / \left(\rho \cdot c \cdot \Delta T\right) \tag{3}$$

The parameters in the formula: $N_{production}$ is the total heat production of the system; N_{water} is the energy of groundwater extracted or released; N_{input} is the input electricity of the system; Q_{water} is the flow rate of water during heating; ρ is the density of water, ie 10^3kg/m^3; c is the specific heat capacity of water, ie 4.2KJ/(kg· ℃); ΔT is the temperature difference between intake and recharge water; COP_{heat} is the coefficient of performance of heat pump.

$$N_{input} = N_{production} / COP_{heat} = \left(617 GJ/d\right) / 4.5 = 137.1 GJ/d \tag{4}$$

$$\therefore Q_{water} = \frac{\left(617 GJ/d - 137.1 GJ/d\right)}{\left(10^3 kg/m^3 \times 4.2 KJ/(kg \cdot °C) \times 12°C\right)} = 9521.6 m^3/d \tag{5}$$

Therefore, to meet the heating demand of 617GJ/d, the average water demand is 9521.6m^3/d.

Finally, given that this pumping will only occur for about half the year, the water demand will be 19042 m^3/d for the heat extraction period.

Appendix IV - BTES energy supply approximation

Here, one can find explanations of methods by which the BTES storage efficiencies and required areas are determined.

First, consider a single borehole, for example serving one home, that goes from the surface to the bottom of the aquifer in Windmolenbroek, with a length of 30 m. If a reasonable power of 900 W (Skarphagen et al., 2019) can be input to this borehole for 4 months (representing the excess residential heat over summer), then the soil around the borehole will contain about 9.4 GJ after the 4-month heating period. Given that the peak heating demand per house is 0.49 GJ/day/house, (extrapolated from personal communication with Menno van Dijk of Cogas B.V., 8 October 2019) and assuming that the borehole would be able to recover input heat perfectly, then the energy in the borehole could theoretically provide a home with peak heating for 19 days. Given the average heating demand of 0.13 GJ/day/house (assuming the domestic hot water demand is included in this demand), and again assuming perfect recovery, the heating would last 72 days. This quantity of energy can also be seen as roughly 20% of the total annual heating demand.

However, two factors make these supply numbers unrealistically high. First, this calculation neglects the regional groundwater speed of roughly 7 m/year. In the 4 months it takes to heat the ground around the BTES system, the groundwater will move slightly more than 2 meters. Skarphagen et al (2019) found that, after 122 days of heating, the soil temperature will attenuate to the ambient temperature at about a distance of 2 meters from the borehole axis, without any groundwater flow. Therefore, much of the energy that would have otherwise been stored in the soil will instead be advected away by groundwater flow. So, while the heat loss due to the relatively high groundwater speed was not calculated here, it is expected to be quite large; advection clearly dominates over diffusion. Therefore, if placement of boreholes extending only to the bottom of the aquifer was to occur for individual homes, a careful analysis of the local groundwater flow and spacing between neighbouring boreholes would be required to assess the performance of each BTES system. Given that the spacing of houses in Windmolenbroek is much larger than 2 meters, and the relatively quick attenuation of temperature from the borehole, most houses probably wouldn't benefit from positive interference from a neighbouring borehole. The concept of advective heat losses is displayed in the figure below. Note that much of the heat has advected away from the borehole and is thus unrecoverable:

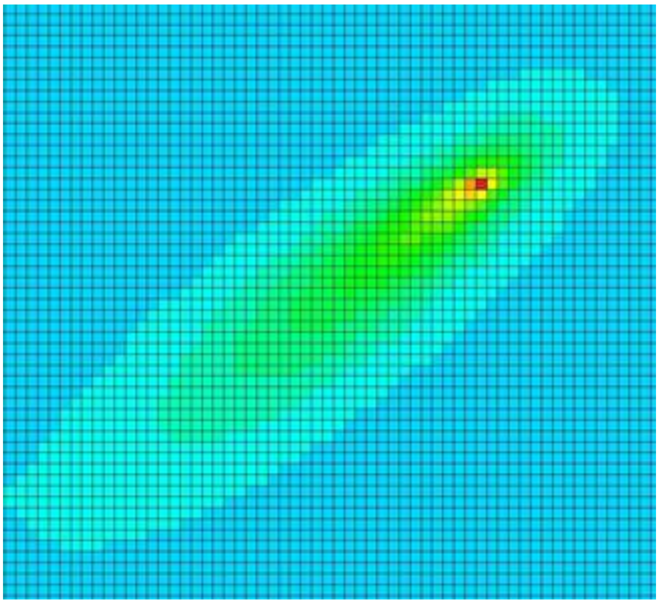

Figure 15. Conceptual illustration of BTES heat distribution after 120 days, with the relatively fast groundwater flow of Windmolenbroek.

Second, even in the absence of groundwater flow, BTES systems do not recapture energy perfectly; they usually operate around 70-90% efficiency (Lanahan, 2017). This is due to diffusive losses of thermal energy. The exact energy loss is determined by the relationship between the borehole power density, the borehole length, the borehole temperature, and the thermal properties of the surrounding soil. While the exact dynamics of this system are complex and outside the scope of this research, the figure below depicts a conceptual visualization of the temperature distribution around a borehole after heating for 120 days in Windmolenbroek, with no prior heating or cooling period. While there are no advective losses, some of the energy will not be recoverable due to diffusive losses.

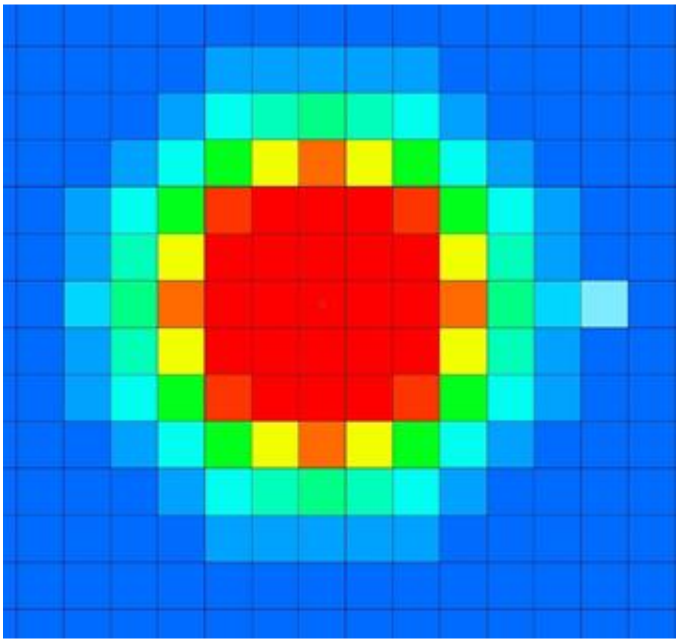

Figure 16. Theoretical temperature attenuation profile around a BTES borehole with no groundwater flow. Cell side length is 12.5 cm.

Methods to increase efficiency of energy storage

The above problem of energy loss due to groundwater speed can be mitigated by drilling deeper boreholes. Below the relatively shallow aquifer of Windmolenbroek, there is a thick (up to at least 350 m) marine sandy clay deposit, which has an extremely low hydraulic conductivity (0.003-0.005 m/d). Therefore, in this layer, it is reasonable to assume the groundwater speed is effectively 0. Diffusion dominates over advection; there would be no advective losses of heat (as demonstrated in Figure 17). For a 30 m borehole heating at 900 W (as in Skarphagen et al, 2019), the BTES system heats at a rate of 30 W/m. If this power density is maintained for a deeper borehole, assuming perfect heat recapture, then the borehole would have to be 150 m to supply all of the heating demand. However, this would require a power input of 4500 watts for the 4 month heating period. Also, the heat recapture would not be perfect due to diffusion losses. Still, deeper boreholes will recapture heat more efficiently due to the absence of groundwater flow.

The problem of energy loss due to groundwater speed can also be mitigated by insulating the part of the deep borehole that is in the aquifer. For example, if a 200 meter borehole had its top 30 meters insulated, there could be no energy storage in the top 30 meters of soil, but there also wouldn't be any advection losses. So, in the case of Windmolenbroek, BTES storage for individual boreholes is maximised when it happens below the aquifer.

To mitigate losses due to groundwater advection in the part of the borehole in the aquifer, as well as temperature attenuation in any part of the borehole, BTES systems can be placed in a grid, at a distance such that each borehole benefits from positive interference from its neighbours. In this way, there will be less losses due to diffusion. The concept is demonstrated in Figure 17, below. This option means that each house can't have its own BTES system; however the benefit from positive interference might be worth the heat lost when transferring to houses, though that optimization problem is outside the scope of this report.

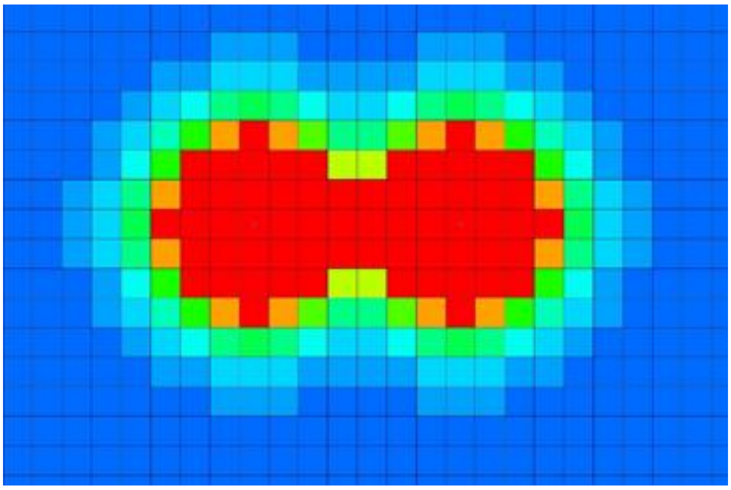

Figure 17. Less heat is lost to the environment in the soil between closely spaced BTES systems. Advective and diffusive losses are minimized with a grid of closely spaced boreholes. These boreholes are probably spaced too closely, at a distance of less than 1 meter - this is just meant to demonstrate the concept.

So, BTES systems in Windmolenbroek can store a significant amount of heat, though attention must be paid to advective and diffuse losses. These losses can be mitigated by drilling deeper borehole or placing boreholes in a field, as well as by insulating boreholes in the top 30 meters (though this insulation might be less necessary if the borehole spacing was close enough, such that advection actually contributed to positive interference; again, this is an optimization problem outside the scope of this report). With no advective losses and a tight borehole spacing in a borehole field, we see no reason that BTES couldn't operate at a relatively high efficiency. Given the heat recapture rate range of 70-90% of BTES systems (Lanahan, 2017), we place the dense borehole field at around 80%; it could be even more efficient, but here 80% is used as a 'worst case scenario' for this field. For individual boreholes, one might assume an efficiency of 70%. BTES systems are an integral component of heat storage in Windmolenbroek in this plan.

Finally, a discussion of how groundwater speeds negatively impact BTES performance in this case is provided. It is well-documented that large groundwater speeds can increase BTES heat exchanging performance; indeed, moving groundwater will enforce a steeper thermal gradient and thus allow for quicker heat transfer (Claesson, 2000). However, the issue of energy recovery is something else entirely. The amount of energy recovered can be drastically impacted by groundwater speed, as the heat can be advected far away from the borehole and thus become unrecoverable (Skarphagen et al., 2019). While large groundwater speeds can assist in the performance of BTES heat extraction from aquifers, this is only in the case where the soil around the borehole has been cooled to below the ambient groundwater temperature, and thus the ambient groundwater replenishes the heat around the borehole. So, whether or not groundwater positively impacts BTES performance depends on how much heat is stored from surface sources in the borehole and how cool the soil around the borehole becomes after extraction. In the proposed case, there is a large amount of energy input to the soil; the PVT panels can heat up the BTES exchange fluid to about 90 degrees C, so the losses due to advection will be significant (see Figure 17 above). Further, because this plan assumes all energy sources for BTES come from the surface - from PVT and the residential summer cooling demand - this design does not assume that the soil temperature will be cooled significantly below its average temperature, rather heated to store energy and cooled to extract energy. Finally, cooling the soil below its ambient temperature is undesirable in the case of single, house based boreholes; boreholes downstream of other boreholes will have reduced performance as a result of cold water moving towards the downstream borehole.

Approximation of area required for BTES field

Here, there is a consideration how the energy demand, borehole temperature, depth, and optimal spacing affect the required area for BTES fields. First one assumes a borehole spacing of 2 m in a grid, so each borehole takes 4 m^2. Next, one assumes that the total heating demand for a single home can be stored in a soil column in this grid with an area of 4 m^2 and a depth of 200 m. This is a possible assumption; for this, the average soil column temperature, borehole temperature, and change in average temperature within the column must satisfy:

$$A \cdot L \cdot c \cdot \frac{\Delta T}{n} = 0.129 \; GJ/day$$

where c is the product of the heat capacity of the saturated solid and the density of the saturated solid (in this case, 3.2E6 J/(C · m^3)), ΔT is the difference between the average soil column temperature from the start to end of the heating period, L is the borehole length around which energy is stored, A is the area of the column around the borehole, n is 365 days, and 0.129 GJ/d is the average heating demand per household per day.

This is based on the neighbourhood demand (including the domestic hot water demand, which in reality will be supplied by about half other sources; excluding this reduces the average heating demand per household per day from BTES to 0.116 GJ/d, or by about 10%). So, if one says say A = 4 m^2, and set L = 170 m (a 200 m deep borehole with the first 30 m insulated to minimize advective losses, for example), then ΔT is 21.6˚C. While the groundwater temperature has a maximum ΔT of 20 ˚C, because the lower bound is 5 C and the upper bound is 25 ˚C, the marine sandy clay below the aquifer is not subject to this restriction and thus a ΔT of 21.6 ˚C is possible. Given that 4659 homes need to be heated, and assuming perfect heat recapture, this would require 4659 · 4 m^2, or 1.86 ha. However, as discussed above, a borehole field is likely to operate towards the higher end of the efficiency spectrum of 70%-90%, so if one assumes an efficiency of 80% (justified in 'BTES energy supply approximation, also in the Appendix), the area demand increases to 2.33 ha. Then, the capacity should be increased by another amount to ensure that the supply is always more than the demand, as the above calculation considers the average yearly demand. So, if the area requirement was doubled, the energy stored would be 200% of the annual demand; and this would still only take 4.66 ha. This would be more likely to be able to handle the peak supply of 0.49 GJ/d/house, though this also depends on the choice of heat exchange fluid in the borehole.

Of course, if a lower ΔT is desired, or a shorter borehole was desired, then A would have to increase, and so the borehole field(s) would necessarily require more space. For example, changing the length of the non-insulated part of the borehole to 85 m (halving it) would yield an area requirement of 9.32 ha. Further, the biggest source of uncertainty in this calculation must be addressed: the optimal spacing, which is complexly related to the temperature of the fluid in the BTES system and its energy transmission rate, the borehole length, and the borehole power density (Skaphagen, 2019). If the borehole spacing is too small, then the energy absorbed from the BTES fluid will be too small due to lack of a sufficient thermal gradient. While the temperature should attenuate to the ambient temperature after 2 m from the borehole, in the "worst case" that a spacing of 3 m was required, even in the case of the 200 m borehole, the BTES field would require 10.5 ha. On the other hand, the area requirement could be smaller than 4.66 ha; if the borehole spacing was optimized at 1.5 m (implying a ΔT of 38˚C, and an area per borehole of 2.25 m^2), and the borehole depth of 200 m was possible, then the same calculation yields a necessary area of 2.6 ha. These calculations neglect heat loss in transmission to homes.

References

AlleCijfers (2019). Informatie Wijk 19 Windmolenbroek. Retrieved at 8-10-2019, from https://allecijfers.nl/wijk/wijk-19-windmolenbroek-almelo/

Appelo, C.A.J. en Postma, D., 1999 - Geochemistry, groundwater and pollution. Editie: Fourth corrected print. ISBN-nummer: 90 5410 106 7. Uitgever: A.A. Balkema. Rotter-dam/Brookfield.

Başer, T., Lu, N., & McCartney, J. S. (2015). Operational response of a soil-borehole thermal energy storage system. Journal of Geotechnical and Geoenvironmental Engineering, 142(4), 04015097.

Bloemendal, M., & Hartog, N. (2018). Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics, 71, 306-319.

Bloemendal, M., & Hartog, N. (2018). Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics, 71, 306-319

BOEG: bodemenergie en grondwaterverontreiniging, NVOE, Editor. 2010: Den Bosch.

Boer, S., Dinkla, I., Drijver, B., Hartog, N., Koenders, M., & Mathijssen, H. (2012). Meer met bodemenergie. (2012). Retrieved Oktober, 2019, from https://soilpedia.nl – Bibliotheek – SKB Cahiers

Bonte, M., P.J. Stuyfzand, A. Hulsmann, and P. Van Beelen, Underground thermal energy storage: environmental risks and policy developments in the Netherlands and European Union. Ecology and Society, 2011. 16(1): p. 22.

Bradley, P. M. (2000). Microbial degradation of chloroethenes in groundwater systems. Hydrogeology Journal, 8(1), 104-111.

BTS (2006). Voorkomen en verwijderen van putverstopping door deeltjes op de boorgat-wand - Richtlijnen voor ontwerp, realisatie, bedrijfsvoering en regeneratie van pompputten.

Bunschoten, B (2013). Centraal Bureau voor Statistiek. Twee derde van alle woningen eengezinswoning. Retrieved at 8-10-2019, fromhttps://www.cbs.nl/nl-nl/achtergrond/2013/04/twee-derde-van-alle-woningen-eengezinswoning

Catolico, N., Ge, S., & McCartney, J. S. (2016). Numerical modeling of a soil-borehole thermal energy storage system. Vadose Zone Journal, 15(1).

CBS. (2019, June 24). Energiebalans; aanbod en verbruik, sector. Retrieved on October 16, 2019 from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83989NED/table?ts=1571214217012

Claesson, J., & Hellström, G. (2000, August). Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers. In Proc. of the 8th International Conference on

Cogas B.V.. Stadsverwarming Almelo. Retrieved September 11, 2019 from https://www.cogas.nl/Wat-we-doen/Duurzame-energie/Stadsverwarming/Stadsverwarming-Almelo

Cruickshank, Cynthia Ann, and Christopher Baldwin. "Sensible thermal energy storage: diurnal and seasonal." Storing Energy. Elsevier, 2016. 291-311.

de Keizer, C., de Jong, M., Katiyar, M., Folkerts, W., Rindt, C., & Zondag, H. (2016, June). Performance analysis and yield assessment of several uncovered photovoltaic-thermal collectors: results of field measurements and system simulations. In 32nd European Photovoltaic Solar Energy Conference and Exhibition (pp. 2649-2652).

de Keizer, C., de Jong, M., Mendes, T., Katiyar, M., Folkerts, W., Rindt, C., & Zondag, H. (2016). Evaluating the thermal and electrical performance of several uncovered PVT collectors with a field test. Energy Procedia, 91, 20-26.

Dinkla, I., Lieten, S., Hartog, N. and Drijver, B. (2012). Effecten op de ondergrond Meer met Bodemenergie, Effecten van bodemenergiesystemen op de geochemie en biologie in praktijk. Resultaat metingen op pilotlocaties en labtesten. Bioclear, Deltares, IF Technology and Wageningen University.

Doughty, C., G. Hellström, C.F. Tsang, and J. Claesson, A dimensionless parameter approach to the thermal behavior of an aquifer thermal energy storage system. Water Resources Research, 1982. 18(3): p. 571-587.

Frijns, J., Hofman, J., & Nederlof, M. (2013). The potential of (waste) water as energy carrier. Energy Conversion and Management, 65, 357-363.

G.C. (Berry) Speek, Adviseur Civiele Techniek, Waterschap Vechtstromen.

Gao, Q., Li, M., Yu, M., Spitler, J. D., & Yan, Y. Y. (2009). Review of development from GSHP to UTES in China and other countries. Renewable and Sustainable Energy Reviews, 13(6-7), 1383-1394.

Giordano, N., & Raymond, J. (2019). Alternative and sustainable heat production for drinking water needs in a subarctic climate (Nunavik, Canada): Borehole thermal energy storage to reduce fossil fuel dependency in off-grid communities. Applied Energy, 252, 113463.

Googlemaps pictures of Almelo, retrieved on 16/10/2019, https://www.google.nl/maps/place/Almelo/@52.3609531,6.5892454,12z/data=!3m1!4b1!4m5!3m4!1s0x47b80621c73bb0f5:0x754b2911047bb446!8m2!3d52.3670267!4d6.6684919

Hai, M. A. (2019). Rethinking the social acceptance of solar energy: Exploring" states of willingness" in Finland. Energy Research & Social Science, 51, 96-106.

Hamdhan, I. N., & Clarke, B. G. (2010, April). Determination of thermal conductivity of coarse and fine sand soils. In Proceedings of World

Hartog, N., Drijver, B., Dinkla, I., & Bonte, M. (2013). Field assessment of the impacts of Aquifer Thermal Energy Storage (ATES) systems on chemical and microbial groundwater composition. In Proceedings of European Geothermal Conference, Pisa (Italy) (p. 8).

Homedeal (n.d.). Nieuw dak kosten. Retrieved at 11-10-2019 from https://www.homedeal.nl/dakbedekking/nieuw-dak-kosten/

Hospital picture from presentation of Almelo municipality, retrieved on 16/10/2019

J Wang. (2003). Analysis, application and control of aquifer energy storage systems[D] (Doctoral dissertation)

Juez-Larré, J., van Gessel, S., Dalman, R., Remmelts, G., & Groenenberg, R. (2019). Assessment of underground energy storage potential to support the energy transition in the Netherlands. First Break, 37(7), 57-66.

Kennispunt Twente. (April 2019). Cijfers & trends – Almelo – Inwoners. Retrieved September 11, 2019, from https://kennispunttwente.nl/cijfers-trends/almelo/demografie/inwoners-brp

Kim, J. M., & Parizek, R. R. (1997). Numerical simulation of the Noordbergum effect resulting from groundwater pumping in a layered aquifer system. Journal of Hydrology, 202(1-4), 231-243.

Kollmann, R., Neugebauer, G., Kretschmer, F., Truger, B., Kindermann, H., Stoeglehner, G., ... & Narodoslawsky, M. (2017). Renewable energy from wastewater-Practical aspects of integrating a wastewater treatment plant into local energy supply concepts. Journal of cleaner production, 155, 119-129.

Lage, J. L., Antohe, B. V., & Nield, D. A. (1997). Two types of nonlinear pressure-drop versus flow-rate relation observed for saturated porous media. Journal of Fluids Engineering, 119(3), 700-706.

Lee, K. S. (2013). Underground thermal energy storage. In Underground Thermal Energy Storage (pp. 15-26). Springer, London.

Meggers, F., & Leibundgut, H. (2011). The potential of wastewater heat and exergy: Decentralized high-temperature recovery with a heat pump. Energy and Buildings, 43(4), 879-886.

Milieu Centraal (n.d.) Isoleren en besparen. Retrieved at 8-10-2019, fromhttps://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/

Milieu centraal (n.d., 2). Cv-ketel onderhoud en instelling. Retrieved at 15-10-2019 from https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/verwarmen-op-gas-of-hout/cv-ketel-onderhoud-en-instelling/

Milieu centraal (n.d.,1). Gemiddeld energieverbruik. Retrieved at 15-10-2019 from https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/gemiddeld-energieverbruik/

Milieu Centraal. Bodemverontreiniging. Retrieved from https://www.milieucentraal.nl/in-en-om-het-huis/gezonde-leefomgeving/bodemverontreiniging/ on October 14th, 2019.

Ministerie van Economische Zaken. (2019). Energierapport: Transitie naar duurzaam. The Hague, The Netherlands.

Ni, Z., van Gaans, P., Smit, M., Rijnaarts, H., & Grotenhuis, T. (2015). Biodegradation of cis-1, 2-dichloroethene in simulated underground thermal energy storage systems. Environmental science & technology, 49(22), 13519-13527.

Nordell, B. (2000). Large-scale thermal energy storage. In WinterCities' 2000: Energy and Environment 12/02/2000-16/02/2000.

Nordell, B. (2013). Underground Thermal Energy Storage (UTES). In International Conference on Energy Storage: 16/05/2012-18/05/2012.

Nordell, B., Grein, M., & Kharseh, M. (2007, May). Large-scale utilisation of renewable energy requires energy storage. In Proceedings of the International Conference of Renewable Energys and Suistainable Development, Tlemcen, Algeria (pp. 21-24).

Omer, A. M. (2008). Ground-source heat pumps systems and applications. Renewable and sustainable energy reviews, 12(2), 344-371.

Oozo.nl (n.d.). Wetenswaardigheden, cijfers en statistieken over Windmolenbroek. Retrieved at 8-10-2019, from https://www.oozo.nl/cijfers/almelo/windmolenbroek

Overizchtskaart Windmolenbroek Almelo, retrieved on 16/10/2019, https://www.greenvis.nl/nl/uitbreidingskansen-warmtenet-windmolenbroek-almelo/

Paksoy, H. Ö. (Ed.). (2007). Thermal energy storage for sustainable energy consumption: fundamentals, case studies and design (Vol. 234). Springer Science & Business Media.

Paksoy, H., Snijders, A., & Stiles, L. (2009). Aquifer thermal energy cold storage system at richard stockton college. EFFSTOCK 2009 (11th International)-Thermal Energy Storage for Efficiency and Sustainability.

Possemiers, M. (2014). Aquifer Thermal Energy Storage under different hydrochemical and hydrogeological conditions.

Rosiek, S., & Batlles, F. J. (2013). Renewable energy solutions for building cooling, heating and power system installed in an institutional building: Case study in southern Spain. Renewable and Sustainable Energy Reviews, 26, 147-168.

RVO (n.d.). Transitievisie warmte en wijkuitvoeringsplan. Retrieved at 9-10-2019 from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/aardgasvrij/aan-de-slag-met-aardgasvrij/transitievisie-warmte-en-wijkuitvoeringsplan

Sanner, B., Karytsas, C., Mendrinos, D., & Rybach, L. (2003). Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics, 32(4-6), 579-588.

Santbergen, R., Rindt, C. C. M., Zondag, H. A., & Van Zolingen, R. C. (2010). Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors. Solar Energy, 84(5), 867-878.

Sauty, J.P., A.C. Gringarten, A. Menjoz, and P.A. Landel, Sensible energy storage in aquifers: 1. Theoretical study. Water Resources Research, 1982. 18(2): p. 245-252.

SenterNovem, Watergebruik in Woningen en Warmteterugwinning uit Huishoudelijk Afvalwater (water use in houses and heat recovery from domestic wastewater). Report of TU Delft and Cauberg Huygen, SenterNovem, Utrecht; 2006.

Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., & Kokko, J. (2012). The performance of a high solar fraction seasonal storage district heating system–five years of operation. Energy Procedia, 30, 856-865.

Skarphagen, H., Banks, D., Frengstad, B. S., & Gether, H. (2019). Design Considerations for Borehole Thermal Energy Storage (BTES): A Review with Emphasis on Convective Heat Transfer. Geofluids, 2019.

Sommer, W. T. (2015). Modelling and monitoring of Aquifer Thermal Energy Storage: impacts of soil heterogeneity, thermal interference and bioremediation. Wageningen University.

Sommer, W. T., Drijver, B., Verburg, R., Slenders, H., de Vries, E., Dinkla, I., ... & Grotenhuis, J. T. C. (2013). Combining shallow geothermal energy and groundwater remediation.

Sommer, W., Valstar, J., Leusbrock, I., Grotenhuis, T., & Rijnaarts, H. (2015). Optimization and spatial pattern of large-scale aquifer thermal energy storage. Applied energy, 137, 322-337.

Sommer, W., Valstar, J., van Gaans, P., Grotenhuis, T., & Rijnaarts, H. (2013). The impact of aquifer heterogeneity on the performance of aquifer thermal energy storage. Water Resources Research, 49(12), 8128-8138.

Stuyfzand, P., 2007. Naar een effectievere diagnose, therapie en preventie van chemische put- en drainverstopping. H2O 2007, nr. 8.

Timmerman, M.B. (2009). Ontwerp van fotovoltaïsch-thermische zonnepanelen / Design of a PV-Thermal panel. Rijksdiesnt voor Ondernemend Nederland. Retrieved at 10-10-2019 from https://www.rvo.nl/sites/default/files/Ontwerp%20van%20fotovoltaisch-thermische%20zonnepanelen.%20Design%20of%20a%20PV-Thermal%20panel.pdf

Tomasetta, C., Van Ree, C. C. D. F., & Griffioen, J. (2015). Life cycle analysis of underground thermal energy storage. In Engineering Geology for Society and Territory-Volume 5 (pp. 1213-1217). Springer, Cham.

van der Hoek, J. P. (2011). Energy from the water cycle: a promising combination to operate climate neutral. Water Practice and Technology, 6(2).

van Helden, W. G., van Zolingen, R. J. C., & Zondag, H. A. (2004). PV thermal systems: PV panels supplying renewable electricity and heat. Progress in Photovoltaics: Research and Applications, 12(6), 415-426.

Van Mierlo, E., Benayad, S. (2019). Concept programmacontract Duurzaamheid. Gemeente Almelo. Retrieved from internal sources.

Van Oostrom, N., Drijver, B., Van Baarsen, E., Lieten, S., Van Nieuwkerk, E., De Vries, E., Bakr, M., Hartog, N., Krajenbrink, H., Mathijsen, H., Meindertsma, W., Oude Essink, G., Wennekes, R. and Woning, M. (2010). Literatuurstudie Meer Met Bodemenergie, Overzicht van kennis en onderzoeksvragen rondom warmte- en koudeopslag. Bioclear, IF Technology, Deltares and Wageningen University

Veldhoen, A. (2010). Shedding light on the risk of clogging in combined ATES and soil remediation technology. Internship report. Received on September 17th, 2019 from Tim Grotenhuis (Wageningen University & Research).

Verburg, R., H. Slenders, N. Hoekstra, E. van Nieuwker, R. Guijt, B. van der Mark, and J. Mimpen, Handleiding

Vermaas, D., 2008. Inventarisatie van mogelijke knelpunten in koude-/warmteopslag. Stageverslag, Witteveen+Bos - Wageningen Universiteit.

Verstraete, W., Van de Caveye, P., & Diamantis, V. (2009). Maximum use of resources present in domestic "used water". Bioresource technology, 100(23), 5537-5545

Verwarminginfo.nl (n.d.). Lage temperatuurverwarming: info en prijsadvies. Retrieved at 18-10-2019, at https://www.verwarminginfo.nl/lage-temperatuur-verwarming

Visser, P.W., H. Kooi, and P.J. Stuyfzand, The thermal impact of aquifer thermal energy storage (ATES) systems: a case study in the Netherlands, combining monitoring and modeling. Hydrogeology Journal, 2015: p. 1-26.

Wagelmans M., Roeloffzen, A. (2009). Bodemecologie: wat is het en wat kun je ermee? Stichting Kennisontwikkeling Kennisoverdracht Bodem. SKB, Gouda.

Wanner, O., Panagiotidis, V., Clavadetscher, P., & Siegrist, H. (2005). Effect of heat recovery from raw wastewater on nitrification and nitrogen removal in activated sludge plants. Water Research, 39(19), 4725-4734.

Xia, L., Ma, Z., & Kokogiannakis, G. (2017). Performance Simulation of a Ground Source Heat Pump System Integrated with Solar Photovoltaic Thermal Collectors for Residential Application.

Zondag, H. A., Van Helden, W. G. J., Bakker, M., Affolter, P., Eisenmann, W., Fechner, H., ... & Tripanagnostopoulos, Y. (2005). PVT roadmap. A European guide for the development and market introduction of PVT technology (No. ECN-RX--05-170). Energy research Centre of the Netherlands ECN.

Zonne-Paneel.net (n.d.). Hybride zonnepanelen. Retrieved at 10-10-2019 from https://www.zonne-paneel.net/hybride-zonnepanelen/