High temperature storage at TU Delft campus

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ABSTRACT

In this article, the possibility to apply a high temperature storage (HTS) at the TU Delft campus is investigated. The TU Delft is trying to improve its energy efficiency by 30% till 2020 when compared to 2005 (TU Delft., 2016). A geothermal well will be implemented on the campus to provide a constant thermal energy supply. In combination with a HTS, energy surplus can be stored in an aquifer. The stored energy can later be reused during shortages. The campus heat demand in 2016 is compared with the supply of the geothermal well to determine the amount of thermal energy surplus. This is converted to a required storage volume in the aquifer. The aquifers near the campus are identified and compared on criteria needed for HTS. A total volume of 740000 m^3 of water needs to be stored in the De Lier Member, the most suitable aquifer. The aquifer is large enough to store this amount of water. It can therefore be concluded that it is possible to apply a HTS at the TU Delft campus.

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1. Introduction

The increasing climate change puts extra pressure on our energy production. The production of non-renewable energy by burning fossil fuels can't go on forever (Shafiee & Topal, 2009). Therefore, sustainable energy sources need to be used to supply our future energy needs. Different techniques have already been developed to utilize wind and solar power. These sources are, however, not enough to meet our ever rising energy demand (Lee, 2013; Ölz *et al.*, 2007). Additional to power, heat takes account for a substantial amount of the world energy demand. A sustainable source for heat production is geothermal energy, which uses the earth subsurface' heat to produce energy. The subsurface can also be used to store energy to overcome discrepancies in time between availability and demand for heat.

The TU Delft and other Dutch universities have agreed to improve their energy efficiency by 30% till 2020 compared to 2005 levels (TU Delft., 2016). In the near future a geothermal energy well will be added to the energy infrastructure at the campus, the Delft Geothermal Project (DAP) (DAP, 2014). This well will produce a constant amount of heat from the earth's subsurface (GEA, 2014). Due to the changing heat demand of the campus, the geothermal well may produce a surplus of heat at a certain time, while not be able to meet the demand some other periods. To utilize this surplus to its maximum capacity a storage facility is needed. Due to the reuse of heat when the heat demand is higher than the well production, the energy efficiency will be improved.

Therefore, the objective of this research is to investigate the possibility to apply HTS at TU Delft district heating network. This will be done by determining the required size of the HTS depending on the amount of heat which needs to be stored. Also possible aquifers, which are able to store such amount of thermal energy, will be identified.

2. Background information

2.1 Aquifer Thermal Energy Storage

Different methods are available to store excess energy in the subsurface, after which it can be extracted when needed. This is currently used in the Netherlands to heat and cool buildings (Drijver, 2012). In the summer excess heat is produced and stored in the subsurface, which can be used in the winter.

Thermal energy can be stored or abstracted from the ground and groundwater by altering its temperature (Bloemendal *et al.*, 2014). The use of aquifers to store thermal energy is called Aquifer Thermal Energy Storage (ATES). Pairs of groundwater wells are installed, which can be used for both abstraction and infiltration of water to the aquifer (Lee, 2013). This technique is used to heat or cool larger buildings.

In ATES, high temperature storage (HTS) stores and recovers heat with a temperature larger than 60 °C, which can be used directly for heating purposes (Drijver, 2012). In the Netherlands, three HTS projects were realised: at University of Utrecht, the

Hooge Burch and in Beijum. The first two projects are already inactive while the project in Beijum is still active (Boer *et al.*, 2013).

2.2 Heat production at TU Delft campus

The current total heat demand of the TU Delft campus is supplied by a Combined Heat and Power (CHP) plant, which is divided into boilers and a cogeneration part. The cogeneration uses heat which is produced during electricity production. The boilers currently provide 75% of the heat demand and 25% is being produced by cogeneration (TU Delft., 2016).

3. Methodology

3.1 High temperature storage size

To determine the storage size of the HTS, the surplus of heat produced needs to be known. This is done by calculating the heat demand of the TU Delft campus and the heat production of the geothermal well. The data concerning the heat demand of the TU Delft campus is derived from TU Delft Energy Monitor (TU Delft., 2016). The heat consumption is expressed in m^3 natural gas equivalent, which is the amount of natural gas needed to supply the demand, assuming 100% boiler efficiency (TU Delft., 2016). This is converted to the unit MWh: 31.65 MJ = 1 m^3 gas; 1 MJ = 0.278 kWh; 1 MWh = 1000 kWh (TU Delft., 2016). It represents the heat consumption of the TU Delft campus in 2016. Unfortunately, only heat consumption data of 2015 and 2016 is available, of which the one from 2016 is more representable. From the heat demand of the campus, 2015 was on average a milder year.

The geothermal well data is obtained from multiple sources. The discharge of the well will be between 80 – 150 m^3/h (Bakker, 2008; den Boer, 2012). The production and injection temperatures are 80˚C and 35 ˚C respectively (den Boer, 2012). Using the difference in temperature, the amount energy needed to heat or cool an object can be expressed as:

$$Q = m * c * \Delta T \quad (1)$$

Where Q represents the energy in kilojoule (kJ), c the specific heat of water (kJ/kg/K), ΔT the difference in temperature and m the mass of water in kg. The mass of 1 m^3 of water is assumed to be 1000 kg. The energy production of the geothermal well is calculated at 80 and 150 m^3/h, the minimum and maximum flow rate respectively. The energy is converted from kilojoule to megawatt hour (MWh) and multiplied by the amount of hours per month to be comparable with the heat consumption of the TU Delft campus. By comparing the energy demand and supply in each month a certain surplus or deficit is calculated.

3.2 Conditions of HTS aquifer

The conditions a HTS aquifer should meet is described below:

Temperature and depth are important characteristics when selecting an aquifer. The temperature can be predicted from the average geothermal gradient which is about 31 ^{0}C per km for the subsurface of the Netherlands (Pluymaekers *et al.*, 2012). Aquifer temperature will be artificially increased during storage due to the continuous injection temperature. The ambient temperature is also an important criterion to consider. A larger difference between injection and ambient temperature will cause bigger thermal energy losses. Losses are assumed to be in the range of 25 – 40% , depending on operational properties such as injection temperature, injection volume, ambient temperature, production temperature, conduction, dispersion, regional groundwater flow, density-driven flow (Schout *et al.*, 2014). Moreover, subsurface properties such as the permeability and thermal conductivity of the aquifer and confining layers, aquifer heterogeneity and changes in aquifer thickness also affect the energy losses (Schout *et al.*, 2014).

Furthermore, the thickness of the aquifer needs to be investigated. An aquifer should have a minimum thickness of 20 m over a large distribution area. Besides, aquifers thinner than 20 m might not meet the minimum transmissivity of 10 Dm (Pluymaekers *et al.*, 2012). Transmissivity, which is the mathematical product of the aquifer thickness and permeability has to be taken into account since it determines the flow rate which can be achieved due to the pressure difference applied to the wells (Pluymaekers *et al.*, 2012). Additionally, porosity and permeability are also key parameters. The aquifer should be porous to be able to sustain a large volume of water. It should be highly permeable, the pores should be interconnected so that water can easily flow within the respective rocks of the aquifer (TNO, 2013).

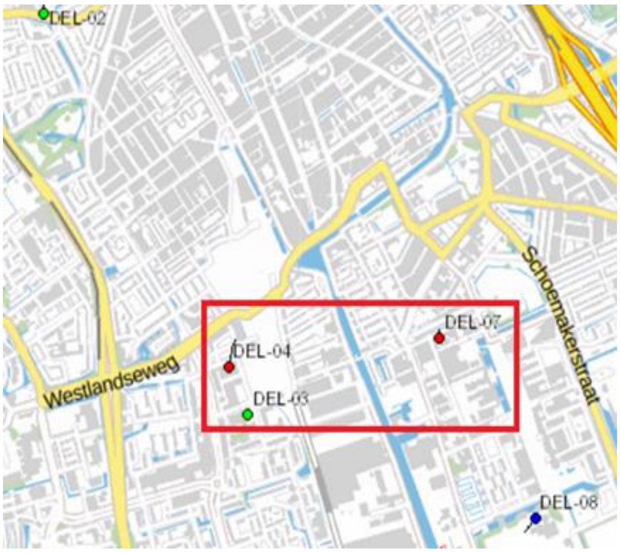
Also a continuous rock layer is needed with minimal number of natural barriers such as faults which prevents water to continue to flow between injection and production well. Therefore, a continuous rock layer provides a good flow of fluids within the aquifer. Besides, the rock layer should be as homogeneous as possible (TNO, 2013).

3.3 Available aquifers at the campus

The suitable aquifers for geothermal energy storage near Delft, are the Lower Cretaceous (145.5 -100.5 million years ago (Ma)) and Upper Jurassic (161.2 – 145.5 Ma) aquifers (Pluymaekers et al., 2012). The aquifers available at the campus are as follows: Maassluis Formation, Oosterhout Formation, Breda Formation, Landen Clay Member, Ommelanden Formation, Texel Marlstone Member, Texel Greensand Member, Upper Holland Marl Member, Middle Holland Claystone Member, Lower Holland Marl Member, De Lier Member, Vlieland Claystone Formation, Rijswijk Member, Rodenrijs Claystone Member, Delft Sandstone Member, Alblasserdam Member.

A map of the borehole wells from NLOG in the surroundings of the campus is shown in figure 1, with the red box showing the wells of interest.

Figure 1.
Borehole wells in the surroundings of the campus



Log data from the three borehole wells in the red box from figure 1, DEL-03, DEL-04 and DEL-07 respectively, are used to analyse the stratigraphy of the campus because they are the closest borehole data which can be used to analyse the geology of the subsurface at the campus. An overview of the depth, layer thickness and stratigraphy of the wells analysed is shown in table 4 in the appendix. An overview of the stratigraphy from the borehole wells is shown in figure 2.

The stratigraphy's found from the borehole wells DEL-03, DEL-04 and DEL-07 respectively are summarised in table 1 (DINOloket, 2013).

Figure 2.
Stratigraphy's of the boreholes

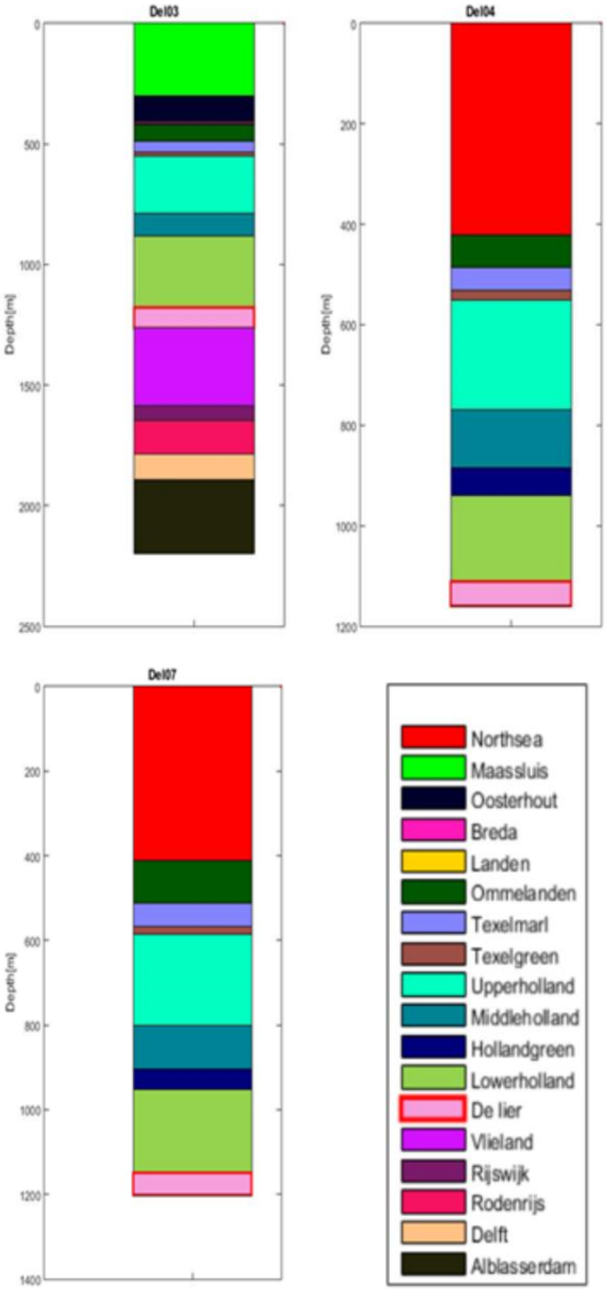


Table 1.
Description of stratigraphy

Stratigraphy	Description
North Sea Supergroup	Group of formations consisting of an alternation of sands and sandstones and clays
Maassluis Formation	Shelly, fine-grained to coarse-grained sand with sparse clay alternations
Oosterhout Formation	Succession of sands, sandy clays, and clays
Breda Formation	Sequence of marine, glauconitic sands, sandy clays and clays
Landen Clay Member	Hard, flaky clay, somewhat silty, containing glauconite, pyrite and mica
Ommelanden Formation	Succession of fine grained limestones. The formation comprises mainly hard, dense limestones (as result of compaction and cementation)
Texel Marlstone Member	Limestones and marly chalks
Texel Greensand Member	Glauconitic, calcareous sandstones with alternated marls
Upper Holland Marl Member	Marls
Middle Holland Claystone Member	Calcareous shaly claystone
Lower Holland Marl Member	Marl or calcareous, fissile claystone, frequently with intercalated bituminous claystone beds
De Lier Member	Very fine- to fine-grained sandstones and sandy claystones
Vlieland Claystone Formation	Claystone with intercalated siltstone and very fine sandstone beds
Rijswijk Member	Sandstones with a very fine to medium and locally gravelly grain size; mica, lignitic matter and siderite concretions
Rodenrijs Claystone Member	Silty to sandy lignitic claystones with common laminated or contorted bedding, and lignite/coal beds.
Delft Sandstone Member	Massive sandstone sequence, fine to coarse-gravelly
Alblasserdam Member	Variegated clay- and siltstones, fine to medium grained massive and thick-bedded sandstones

4. Results and discussion

4.1 High temperature storage size

The total heat consumption of the TU Delft campus is compared with the geothermal well heat production, shown in figure 3. These results can also be found in table 2 and 3. The possible geothermal well production is based on the minimum and maximum flow, 80 and 150 m^3/h respectively. Equation 1 is used to calculate different heat production. Using the specific heat of water $c = 4.18\ kJ/kg/\Delta T$ and a difference in production and injection temperature of 35 ˚C (den Boer, 2012). With a flow of 150 $m^3\ h^{-1}$ the well produces 7.84 MWh, while the well with a flow of 80 m^3/h produces 4.18 MWh. These values are extrapolated to the monthly production, shown in figure 3.

The total consumption of the campus is shown by the blue bar in figure 3. The difference between the consumption and production, the well production minus the total consumption, shows the supply and demand, displayed in figure 4. Negative values in figure 4 represent a deficit in heat production by the well and thus extra heat is required. Positive values show the surplus heat which can be stored in the high temperature storage. When the geothermal well produces 150 m3/h it provides enough heat to supply the campus, except for January, February,

Figure 3.

Heat demand and consumption of the TU Delft campus

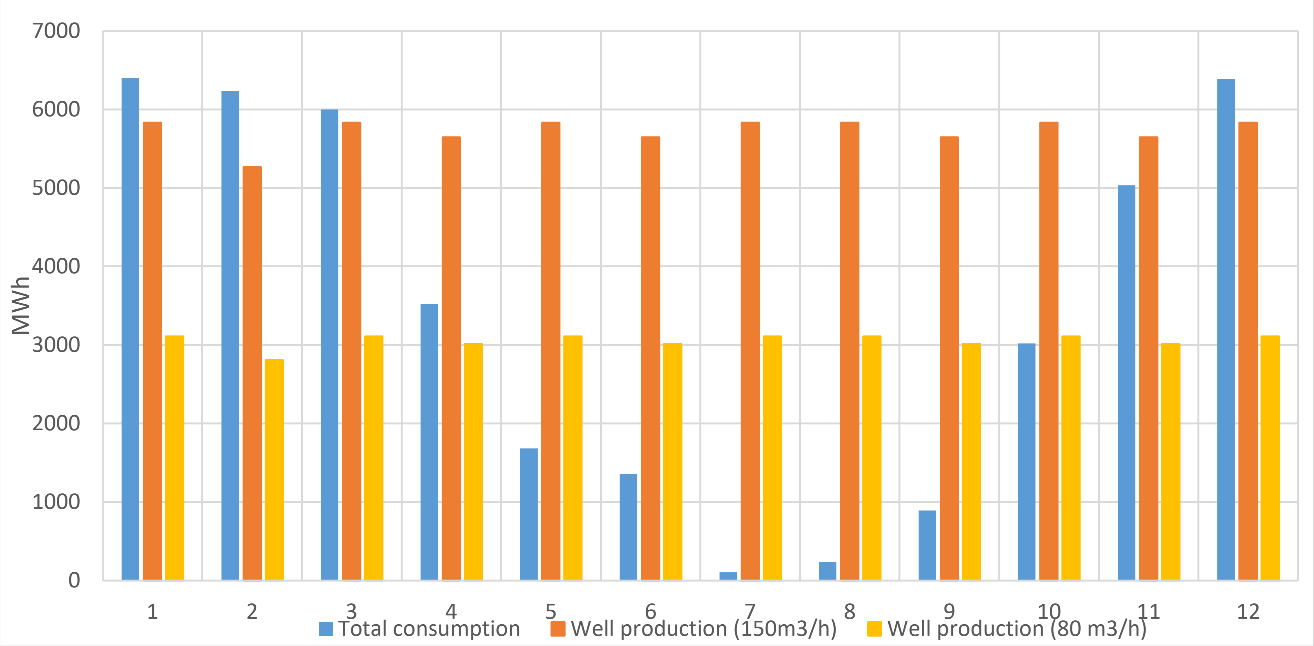
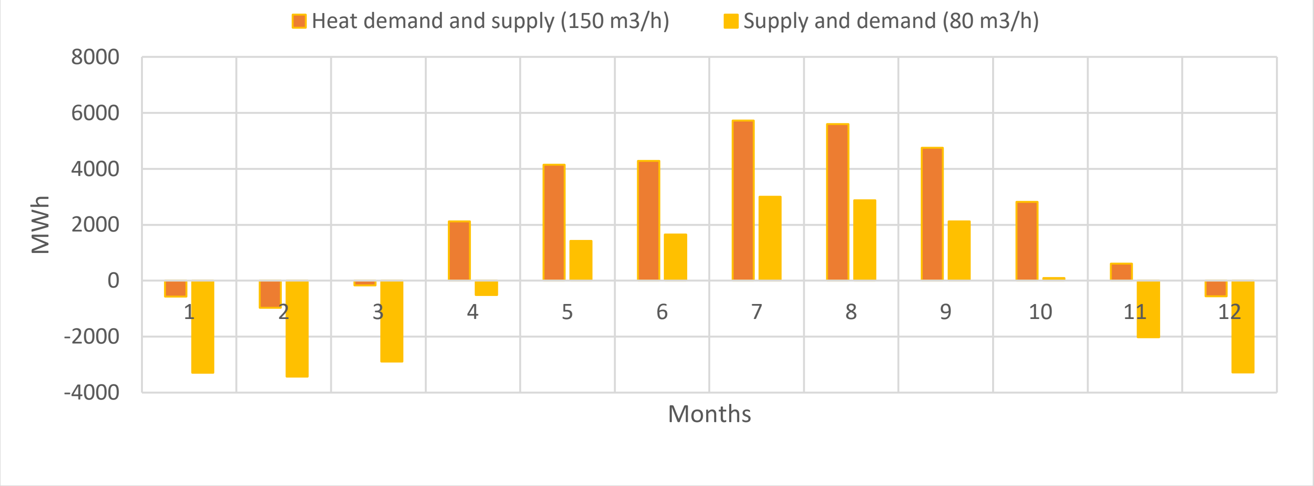


Figure 4.

Heat supply and demand

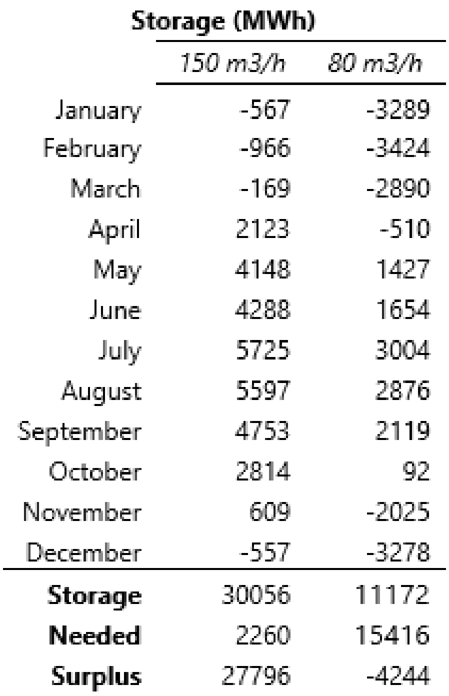


March and December, extra heat will be required. During the other months it will be possible to store the excess heat to meet the heat demand during periods of deficiencies. When the well produces at a flow of 80 m^3/h, in the months May to September surplus heat can be stored. This stored heat, however, is not enough to supply the shortage of the other months, shown in table 2. There will be a total deficit of 4244 MWh. The HTS won't be able to deliver a 100% recovery efficiency, therefore extra heat production by the Combined Heat and Power will be required. Table 2 and 3 show that the well production at 150 m^3/h will exceed the heat demand by 27796 MWh.

This surplus heat can, for example, be sold to surrounding houses. Assuming an average annual heat demand of 20000 kWh per household and a recovery efficiency of 70% almost 1000 households can be supplied with sustainable heat.

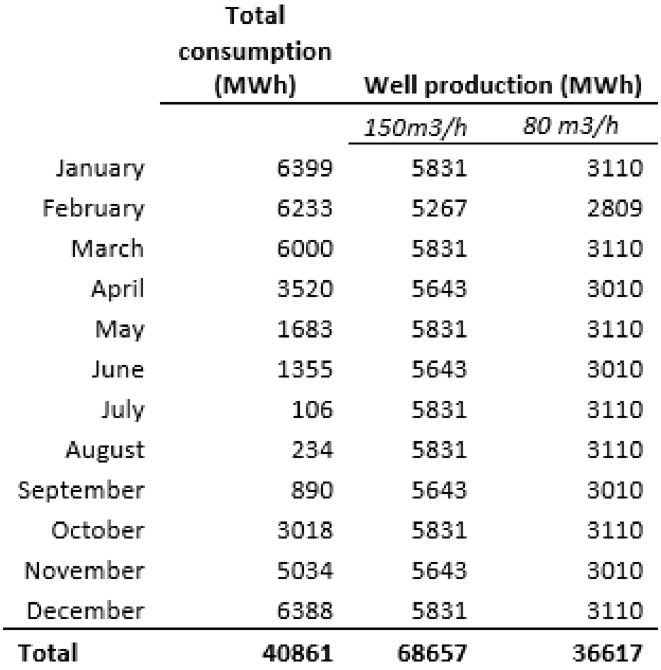
The highest possible total annual heat storage calculated is 30056 MWh. Based on this the size of the HTS is determined using equation 1. The temperature of the HTS is assumed to be 45˚C, which leads to a temperature difference of 35˚C. The 30056 MWh can be converted $1 * 10^{14}$ kJ energy. The mass of the water body is calculated and converted to volume in m^3. This results in a maximum annual

Table 2.
Surplus and deficit per month



	Storage (MWh)	
	150 m3/h	*80 m3/h*
January	-567	-3289
February	-966	-3424
March	-169	-2890
April	2123	-510
May	4148	1427
June	4288	1654
July	5725	3004
August	5597	2876
September	4753	2119
October	2814	92
November	609	-2025
December	-557	-3278
Storage	30056	11172
Needed	2260	15416
Surplus	27796	-4244

Table 2.
Heat consumption and production



	Total consumption (MWh)	**Well production (MWh)**	
		150m3/h	*80 m3/h*
January	6399	5831	3110
February	6233	5267	2809
March	6000	5831	3110
April	3520	5643	3010
May	1683	5831	3110
June	1355	5643	3010
July	106	5831	3110
August	234	5831	3110
September	890	5643	3010
October	3018	5831	3110
November	5034	5643	3010
December	6388	5831	3110
Total	**40861**	**68657**	**36617**

storage volume of 740000 m^3. During the maximum surplus a maximum injection rate of 190 m^3/h is required, which could be divided over several wells to reduce the flow rate. This flow rate however, is able to fluctuate over time.

4.2 Suitable aquifers

From table 1, the possible suitable layers can first be analysed. Besides, based on the NLOG (NLOG, 2014) data the suitable layers with sufficient thickness, porosity, etc. can be identified and compared with the required properties that the aquifer has to fulfil. The selected aquifer for HTS in this case is the De Lier Member. Firstly, from the geological point of view it is a very fine to fine-grained sandstone and sandy claystone, which means it is porous enough for the storage of geothermal energy. The data from table 4 in the appendix, shows that the thickness of the De Lier Member varies between 49 to 86 m, which satisfies the thickness requirement of at least 20 m. Moreover, data from the three wells of NLOG (NLOG, 2014), show that the De Lier Member is present at a depth of 1111 – 1264 m. This means that the De Lier Member is a continuous rock layer that runs all over the subsurface of the campus. Besides, because it is mostly sandstones it is homogeneous aquifer.

Furthermore, data from well DEL-03 in table 4 in the appendix shows that the De Lier Member is bounded by two clay supported layers, which is an advantage in terms of reduction of the thermal energy losses for the storage of geothermal energy.

4.3 Size of the aquifer

De Lier Member, however, needs to be large enough to be able to store the maximum heat surplus. Several other wells were used to calculate the size of the De Lier Member. Wells DEL-02 and DEL-08 (NLOG, 2014) produced data that confirmed the existence of the De Lier Member on a larger scale. Using the distance between the wells an area of at least 4 km^2 is calculated, which results in a volume of at least 240*10^6 m^3 when multiplied by an average depth of 60 m.

5. Conclusion

This research has investigated the possibility to apply a high temperature storage (HTS) at the TU Delft campus. The total heat demand of the campus in 2016 is compared with the maximum and minimum thermal energy production by a geothermal well. From this, periods of heat surplus and heat deficit are recognized. In the months of heat surplus HTS can be used to reclaim the heat for the months of shortage. A maximum storage capacity is calculated, assuming the maximum production by the geothermal well. This results in a total annual storage of 30056 MWh which equals a volume of 740000 m^3. This volume needs to be stored in an aquifer near the campus. Therefore, an inventory of all the different aquifers near the TU Delft campus is made. The different aquifers are compared based on the following criteria: temperature, depth, thickness, transmissivity, porosity, permeability and the presence of a continuous rock layer. At a depth of 1111 – 1264 m the De Lier Member is the most suitable aquifer for HTS.

To conclude, it is possible to apply a HTS at the TU Delft campus. In combination with a geothermal well production the TU Delft campus will be able to store heat surplus. At a minimum production rate of 80 m^3/h the total deficit in 2016 would have been 4244 MWh. This can be produced by the Combined Heat and Power. At a maximum production rate, at least a surplus of 27796 MWh could have been stored. This heat surplus can be sold to provide sustainable heat to about 1000 households.

6. Recommendations

For future developments some aspects require further research and one of those aspect where more research could be done is the recovery efficiency of the energy storage in the subsurface of the campus. Moreover, gamma ray logs and the cone penetration test results of the borehole wells can also be used to get better detailed information of the soil layers of the subsurface of the campus. Porosity logs can also be used in order to facilitate the choice for suitable aquifers. Furthermore, scaling of wells and how it can be prevented also requires further research. Further research is required regarding the amount of wells needed to inject the surplus heat in the HTS.

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8. Appendix

Table 4.

Borehole well data

DEL-03			DEL-04			DEL-07		
Depth (m)	**Thickness (m)**	**Stratigraphy**	**Depth (m)**	**Thickness (m)**	**Stratigrapy**	**Depth (m)**	**Thickness (m)**	**Stratigraphy**
0 - 300	300	Maassluis Formation	0 - 422	422	North Sea Supergroup	0 – 412	412	North Sea Supergroup
300 – 406	106	Oosterhout Formation						
406 – 414	8	Breda Formation						
414 – 420	6	Landen Clay Member	422 – 487	65	Ommelanden Formation	412 – 513	101	Ommeland Formation
420 – 490	70	Ommeland Formation	487 – 532	45	Texel Marlstone Member	513 – 566	53	Texel Marlstone Member
490 – 532	42	Texel Marlstone Member	532 – 550	18	Texel Greensand Member	566 – 585	19	Texel Greensand Member
532 – 552	20	Texel Greensand Member	550 – 769	219	Upper Holland Marl Member	585 – 800	215	Upper Holland Marl Member
552 – 786	234	Upper Holland Marl Member	769 – 884	115	Middle Holland Claystone Member	800 – 904	104	Middle Holland Claystone Member
786 – 882	96	Middle Holland Claystone Member	884 – 939	55	Holland Greensand Member	904 – 951	47	Holland Greensand Member
882 – 1178	296	Lower Holland Marl Member	939 – 1111	172	Lower Holland Marl Member	951 – 1149	198	Lower Holland Marl Member
1178 – 1264	86	De Lier Member	1111 – 1160	49	De Lier Member	1149 – 1202	53	De Lier Member
1264 – 1587	323	Vlieland Claystone Formation						
1587 – 1647	60	Rijswijk Member						
1647 – 1784	137	Rodenrijs Claystone Member						
1784 – 1892	108	Delft Sandstone Member						
1892 – 2200	308	Alblasserdam Member						