High Temperature Storage in the Dutch subsurface – critical factors and economic feasibility

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ABSTRACT

Many geothermal doublets that are used to produce heat face the problem that the demand is low in summer and high in winter. Hence, the full potential of the doublet is not used in summer, and may fall short in winter. A solution is to store the excess hot water in shallow aquifers when demand is low, and produce it when demand is high. We have assessed the factors that play a critical role, and developed a calculation tool to assess the economic feasibility. The tool uses data, knowledge and models of the subsurface, and data related to drilling and the geothermal installation, in combination with a discounted cash flow model. The latter uses economic variables such as CAPEX, OPEX, project duration, etc. The most important outcome of the tool is the levelized cost of energy.

The permeability of the aquifer, the temperature of the stored water and the number of operational hours are the most important performance indicators for a high temperature storage system. The sensitivity analysis shows that the minimum required transmissivity is about 120 Dm. In the shallow subsurface, between 100 and 200 meters, the minimum required transmissivity is about 200 Dm. The higher the temperature and the number of full load hours, the lower the cost price per unit heat becomes.

The shallow aquifers of the Netherlands were screened for applicability of high temperature storage. Two business cases were evaluated with different subsurface conditions and heat supply and demand.

The calculation tool is available as Excel spreadsheet.

1 INTRODUCTION

Greenhouse and district heating by geothermal energy is becoming more and more recognised as reliable and cheap alternative for conventional, fossil energy powered heating. However, apart from various successful examples as the Paris Basin, the German Molasse Basin and the Netherlands, the development is generally proceeding slowly. This is partly due to the uncertainty in underground parameters, and partly to the large investment costs compared to the anticipated revenues. The subsurface risk, in practice, is limited, given for instance the fact that out of thirteen doublets that were drilled in the Netherlands since 2006, twelve are operational (the remaining one is currently shut in due to a lack of local heat demand). In order to make the operation of the doublet more cost effective, the load factor should be as high as possible. When geothermal energy is used for heating purposes, the demand is usually low in summer, and high in winter. As a consequence, some doublets shut down in summer, or are operated at limited load factor. Furthermore part of the time they may be forced to operate at lower than nominal capacity. Apart from the fact that sub-optimal use is made of the available heat, shut in of a doublet for short or long periods has adverse effects on the doublet performance because of the possibility of clogging, scaling and corrosion. An option to optimise the utilisation of the doublet over its lifetime would be to store the excess hot water in shallow aquifers during periods of low demand, and to re-produce it during periods of high demand. For low temperatures (up to about 30 °C) this is an established method, usually referred to as Aquifer Thermal Energy Storage (ATES). Examples of high temperature storage (HTS) however are relatively scarce. Some are given by Pfiffer et al. (1991), Sanner and Knoblich (1999), Hoyer et al. (1991). The only HTS that is believed to be currently operational is located under the German Parliament building in Berlin (Sanner et al., 2005). Storing and retrieving heat costs energy, consumed by the electrical pump that transports the water from the surface into the reservoir, and later back to the surface. In order for the technique to be economical, the net LCOE (levelized cost of energy) should be competitive with alternative sources over the anticipated lifetime of the doublet.

The performance of subsurface HTS depends on both subsurface and technical cost factors. In order to be able to analyse all of them, a simplified calculation model was constructed. The basis of the model is the probabilistic DoubletCalc software tool for pre-drill

geothermal doublet performance assessment (Van Wees et al. 2012). This software tool uses information about the aquifer (permeability, thickness, depth, geothermal gradient, etc.), the doublet system and pump (return temperature, pump efficiency, etc.) and the wells (casing diameter, roughness, deviation, etc.) to calculate the flow rate, required pump power and coefficient of performance (COP). For the current application, the probabilistic approach used by DoubletCalc was abandoned in favour of a deterministic one in order to economize on calculation time and to keep the model simple. The calculation method was not changed. The model was then extended with an additional economic module which calculates the LCOE, based on given subsurface parameters and flow rate, economic lifetime, subsurface drilling and installation costs, operational costs (mainly the costs of operating the pumps), surface facility parameters (reinjection temperature, load hours, plant cost, etc.), and fiscal-economical parameters (fiscal stimulation, inflation, required return on investment, etc.). The cash flow methodology is largely based on Dutch economic models and spreadsheets developed by the Energy Center Netherlands (ECN, www.ecn.nl).

The ultimate goal of HTS is to store and produce heat against competitive costs. This is only possible if the optimal subsurface (reservoir permeability, depth, temperature, etc.) and installation parameters (well completion, pump, etc.) can be determined. To that extent, a sensitivity analysis was performed on the relevant parameters.

Finally, the methodology was applied to two locations in the Netherlands using the results of a national subsurface mapping program for which depth, thickness and hydraulic properties of the relevant shallow aquifers were mapped..

2 HTS CALCULATION TOOL

2.1 Boundary conditions

The boundary conditions for DoubletCalc have been described in Van Wees et al. (2012). The additional boundary conditions of the HTS model are as follows (Doughty et al. 1982):

- The subsurface installation consists of a production and an injection well.
- The efficiency of the system per season cycle is 75% - only three quarters of the amount of stored heat is thought to be recoverable. This means that the amount of production hours is 75% of the amount of storage hours.
- The amount of production hours of the system is at most 3760 per year. This is calculated as the number of hours per year 8760 / (1 + 1 / 0.75).
- The operational costs depend on the electricity consumption of the pumps that are used for storage and production. This is the product of the pump power and the amount of operating hours.
- The required pump power P_{pump} is calculated from the pressure losses in the wells and the reservoir. The reservoir resistance is calculated according to Verruijt (1970) and Dake (1978).

The COP is defined as

$$COP = \frac{\dot{m}(T_p - T_o) \times C_p}{\left(\frac{P_{pump} \times \left(1 + \frac{1}{0.75}\right)}{P_{eff}}\right)} \quad [1]$$

Having:

$\dot{m}$ mass flow rate [kg/s]
T_p temperature of the produced water [°C] (corrected for temperature decrease during production)
T_o return temperature of the cooled water [°C]
C_p heat capacity [J/kg K]
P_{pump} required pump power [MW]
P_{eff} pump efficiency [%]. The pump efficiency was assumed to be 63%, based on a rough estimate for the pump itself (85%), and the pump motor (75%)

The calculation tool was implemented in an Excel environment to allow maximum flexibility.

2.2 Performance

The transmissivity is the most important performance indicator for a successful HTS system. It is defined as the product of thickness and permeability[1] of the reservoir. Other important factors are the net-to-gross ratio and the well radius. Together with the pump pressure, the transmissivity largely determines the flow rate and the COP.

The maximum pump pressure that can be applied to the reservoir depends on the depth of the aquifer. A very large pressure difference between the well and the reservoir may endanger the integrity of the reservoir. It was therefore decided to apply a maximum of 10% of the hydrostatic pressure as the maximum pump pressure (1 bar / 100 meter).

In order to have a better understanding of the minimum required permeability for an economically profitable HTS system, the effect of depth on minimum required flow rate for the given pressure loop was calculated. The maximum allowed pressure is defined as 110% of the reservoir pressure, or 2 bar per meter for the driving pressure loop (producer and injector). This applied pressure difference determines the power consumption of the pump, and hence the variable cost of running the doublet system. The benefit of the doublet is determined by the power production, which is linearly related to the flow rate. For the techno-economic calculation the parameter values specified in Table 1 were used. The economic profitability was defined in terms of a maximum acceptable LCOE of 6 €/GJ. The economical parameters are given by ECN/DNV KEMA (2013).

[1] Permeability is generally expressed in Darcy, where one Darcy equals about 9.87E-13 m². Transmissivity is often reported in Dm (Darcy-meter).

The permeability, and as a result the flow rate, was then changed until the 6 €/GJ (well and pump operating cost) was reached, resulting in the minimum required permeability and associated COP.

Table 1: Reference values for the performance analysis.

parameter	value	Unit
maximum acceptable LCOE	6	€/GJ
effective production temperature	70	°C
project duration	15	Year
return temperature	35	°C
well cost	1000	€/m
pump investment cost	0.1	M€
pump workover cost / interval	0.1	M€/5 year
electricity price for pump	140	€/MWhe
effective production hours	3000	Hrs
storage hours	4000	Hrs
heat exchanger investment	150	k€/MWth
heat exchanger fixed operational cost	1	% of CAPEX
interest on loan	6	%
return on investment	15	%
percentage own capital	20	%
loan duration	15	Year
depreciation period	15	Year

Figure 1 shows the results of the performance analysis. The investment costs increase with increasing depth (drilling cost). The required heat production and hence flow rate will also increase with depth in order to satisfy the 6 €/GJ constraint. The minimum required transmissivity and associated COP can be calculated from the required flow rate.

The minimum required transmissivity is about 120 Dm at 400 - 800 meter depth. Above 400 meter the required transmissivity increases because of the lower allowable maximum pump pressure (10% of the reservoir pressure). The increase of the required transmissivity below 800 meters depth is caused by the high pressure losses due to tubing friction, and the lower efficiency of the system at larger depth.

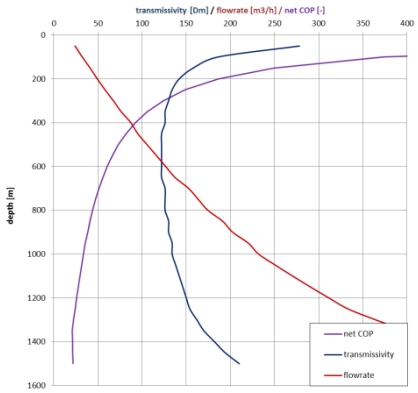

Figure 1: Minimum transmissivity, flowrate and COP required for attaining 6 €/GJ LCOE. Reference parameters as in Table 1.

2.3 Sensitivity analysis

In order to obtain a better understanding of the economic sensitivity of the HTS system, a further sensitivity analysis was performed with respect to variation in:

- well diameter
- temperature of the buffered water
- full load hours
- electricity price
- maximum cost price (LCOE)

Figure 2 (a-d) shows the results of the sensitivity analysis. Each of the graphs shows the base case required transmissivity in grey, and the variation in minimum required transmissivity as a result of the sensitivity analysis in (dashed) black. In general, the increase in the shallow domain (<200m) is related to the low pressure allowance. The increase in the deep domain (>800m) is related to increased drilling costs and pressure loss due to tubing friction.

a) The influence of a varying well diameter on the performance of the system is limited up to a depth of about 800 meter. Small well diameters (7-8") are only a limiting factor when high flow rates (>200 m³/h) are required. This is mainly caused by the high friction losses narrow tubings suffer.
b) The influence of different temperature of the buffered water on the performance is very large. The higher the temperature of the buffered water, the better the performance, resulting in a low required transmissivity. At a buffer temperature of 90 °C the minimum required transmissivity is reduced to less than 70 Dm, compared to 120 Dm at the reference case 70 °C. A low buffer temperature of 60 °C has a significantly lower performance. The minimum required transmissivity (at a depth of about 500 meter) is 180 Dm.
c) A varying electricity price is of limited influence on the performance, except at larger depths (>1200 meter). The number of full load hours of the system has a large influence on the performance. A lower number of hours is unfavourable.
d) The influence of the minimum required transmissivity on LCOE is logically high. An increase in transmissivity of 80 to 170 Dm at the most favourable depth (400-600 meter) results in a decrease of the LCOE from 8 to 5 €/GJ.

It is concluded that the transmissivity of the reservoir, the temperature of the buffered water and the number of full load hours are the major performance indicators of the HTS system. The minimum required transmissivity for the base case is about 120 Dm. The minimum required transmissivity in the shallow (100-200 meter) and deep (>1000 meter) domains is significantly higher.

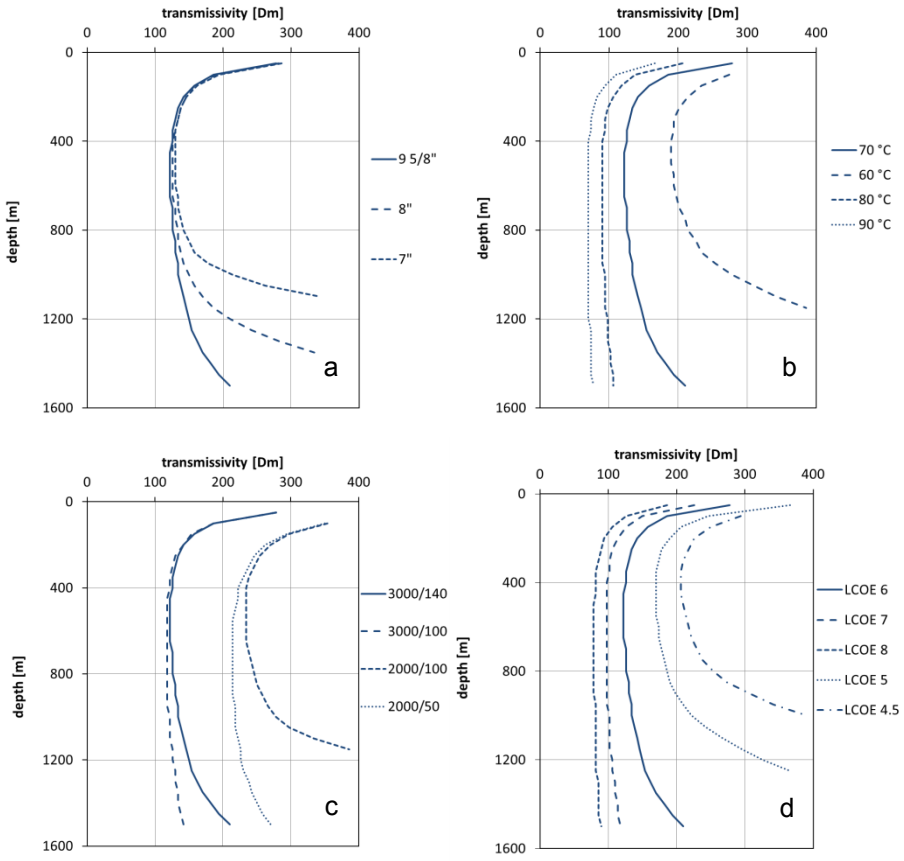

Figure 2: Performance analysis showing the minimum required transmissivity for varying a) well diameter b) temperature buffered water c) full load hours and electricity price d) maximum allowed cost price (LCOE).

3 MAPPING

The subsurface of the Netherlands has been mapped in detail. For shallow depths (0-500 meter) this has been done using abundant borehole information (Regional Geo-hydrological Information System REGIS, Van Vernes and Van Doorn, 2005). For larger depths (>1000 meter) 2D and 3D seismic and borehole information was used (Pluymaekers et al. 2012). For both realms, the depth of the top and bottom of the aquifers was mapped. Hydraulic properties for all layers were mapped using well test data, core plug measurements and log-derived permeability data (Pluymaekers et al. 2012). This implies that for all aquifers permeability maps exist. The mapping of the intermediate interval, which suffers from poor data coverage, especially for the hydraulic properties, which are of major importance for HTS, is currently ongoing, hence the permeability maps should be considered preliminary.

The boundary conditions for areas that are potentially suitable for HTS are:

- Minimum depth 150 meter in order to prevent heating of shallow subsurface;
- Maximum depth 1500 meter in order to limit the drilling cost;
- Minimum aquifer thickness 20 meter;
- Minimum aquifer transmissivity 100 Dm (≈ 100 m²/day).

Furthermore, groundwater protection areas and sweet water aquifers are ruled out. Aquifers containing stacked layers of low transmissivity were joined.

For a selection of suitable aquifers only aquifers belonging to the Tertiary North Sea Supergroup were considered because they approximately cover the required depth range over the largest part of the Netherlands (TNO 2013).

Figure 3 shows the stacked suitability of all aquifers that were considered. Suitable aquifer areas correspond to areas where there is high likelihood of encountering aquifers for HTS, meeting the requirements as listed above, potentially available corresponds to a medium likelihood.

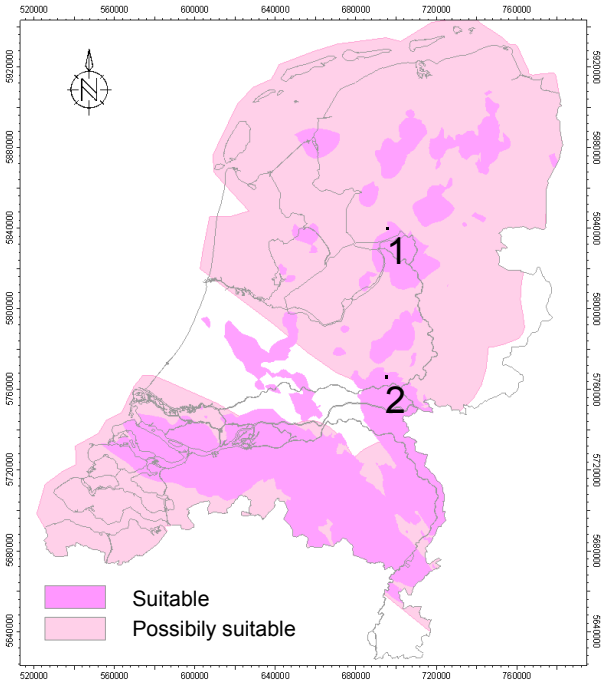

Figure 3: Suitability for HTS. Purple is suitable, pink is potentially suitable. Numbers refer to cases.

4 CASES

Two locations having a heat supply shortage were examined using the developed HTS tool and the mapped aquifer properties. Their locations are shown in Figure 3. Subsurface temperature data were obtained from Bonté et al. (2012).

4.1 Case 1

Case 1 concerns a geothermal doublet producing water of 71 °C from an aquifer at a depth of about 2000 meter. It has the annual energy profile shown in Figure 4. The summer surplus heat (35700 GJ) could be stored in shallow aquifers to be used in winter to cover the shortage (26800 GJ).

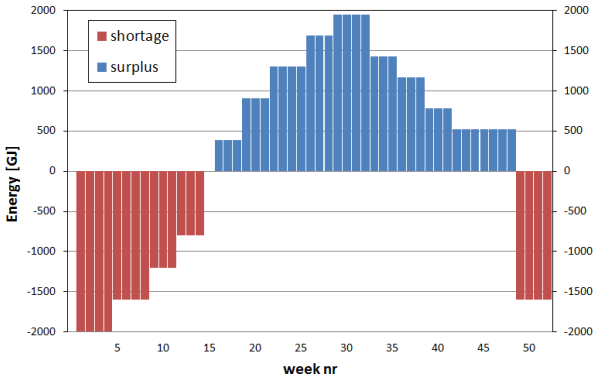

Figure 4: Case 1 energy profile showing shortage in winter and surplus in summer.

At the location a shallow aquifer with a transmissivity of about 440 Dm is present around 200 meters depth. The maximum flow rate that can be achieved here, at a pump pressure not exceeding 10% of the reservoir pressure (2 bar) is 32 l/s (115 m³/hr). It assumed that the stored water does not significantly cool during the storage, and that 75% of the stored heat can be retrieved. Therefore 35700 GJ must be injected to produce 26800 GJ. An average injection rate of 16.5 l/s (59 m³/hr) at a pump pressure of 1 bar is required to meet this demand per season.

Table 2 shows that economic boundary conditions that were used. Table 3 shows the results of the techno-economical calculation. The cost of storing and reproducing the water is 4.89 €/GJ (taking into account the 75% efficiency). This is about equivalent to the cost of a gas-fired boiler (0.15 €/m³ gas equivalent). However, the cost of producing the water to be stored from the deep reservoir in the first place is also 4.19 €/GJ. The current base level feed-in tariff for geothermal energy in the Netherlands is 0.056 €/kWh (15.55 €/GJ), which would make this case economical.

Table 2: Case 1 economic boundary conditions.

parameter	value	unit
project duration	15	year
well cost	1000	€/m
pump investment cost	0.1	mln €
pump workover cost / 5 year	0.1	mln €
pump electricity price	80	€/MWhe
effective production hours	3000	hours
storage hours	4000	hours
heat exchanger investment	150	k€/MWth
heat exchanger fixed operating cost (% of CAPEX)	1	%
interest on loan	6	%
return on investment	15	%
equity	20	%
loan duration	15	year
depreciation period	15	year

Table 3: Case 1 calculation results.

parameter	value	unit
effective production temp.	71	°C
return temperature	35	°C
flow rate	16.5	l/s
yearly energy production	26800	GJ
investment in doublet	0.5	mln €
investment heat exchanger	0.37	mln €
operational cost	10	k€/year
energy price produced heat	4.89	€/GJ
energy price produced heat	0.15	€/m³ gas eq.
cost extra geothermal production	4.19	€/GJ
energy price including extra cost	0.28	€/m³ gas eq.

4.2 Case 2

Case 2 concerns seasonal buffering of a co-generation installation. In this case, excess heat is available due to electricity production of the CHP installation. Figure 5 shows the annual energy profile. Similar to case 1, there is a heat surplus in summer and a shortage in winter, although the shape is different from. The

summer surplus is 82600 GJ, the winter shortage 55500 GJ. In order to produce this amount of heat in winter, 74000 GJ should be stored in summer, which is less than the amount available.

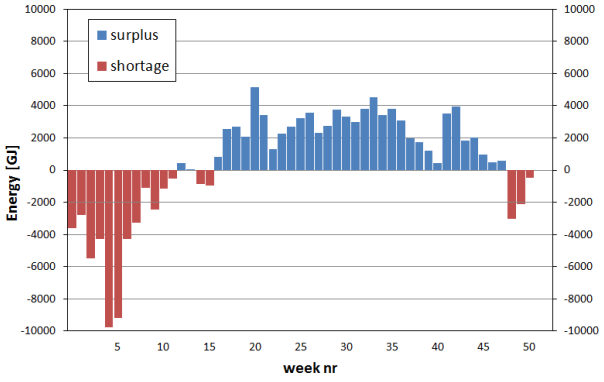

Figure 5: Case 2 energy profile showing shortage in winter and surplus in summer.

Table 4: Case 2 economical boundary conditions.

parameter	value	unit
project duration	15	year
well cost	1000	€/m
pump investment cost	0.1	mln €
pump workover cost / 5 year	0.1	mln €
pump electricity price	50	€/MWhe
effective production hours	2900	hours
storage hours	4866	hours
heat exchanger investment	150	k€/MWth
heat exchanger fixed operating cost (% of CAPEX)	1	%
interest on loan	6	%
return on investment	15	%
equity	20	%
loan duration	15	year
depreciation period	15	year

Table 5: Case 2 calculation results.

parameter	Value	unit
effective production temp.	84	°C
return temperature	35	°C
flow rate	26	l/s
yearly energy production	55600	GJ
investment in doublet	1.0	mln €
investment heat exchanger	0.8	mln €
operational cost	21	k€/year
energy price produced heat	4.59	€/GJ
energy price produced heat	0.14	€/m³ gas eq.

At the project location, the only qualifying aquifer is located at a depth of about 450 meter. It has a transmissivity of about 153 Dm. Given the production efficiency of 75%, an average flow rate of 42 l/s (150 m³/hr)and a pump pressure of 4.5 bar (10% of the reservoir pressure) is required.

Table 4 shows that economic boundary conditions that were used. Table 5 shows the results of the techno-economical calculation. The cost of storing and reproducing the stored heat is 4.59 €/GJ (taking into account the 75% efficiency). This again is about equivalent to the cost of a gas-fired boiler (0.14 €/m³ gas). In contrast to case 1, there is no additional cost for producing the hot water. This would render the second case economic, even without a feed-in tariff.

5 CONCLUSIONS

Seasonal storage of high temperature water may help in increasing the profitability of a doublet system when summer demand is low. An economic assessment tool was built to calculate the profitability of high temperature seasonal storage in terms of LCOE. It combines subsurface information and an economic model. The tool was applied to two candidate locations. The cost of storing and retrieving high temperature heat is competitive with conventional sources. However the economic viability is difficult unless the cost of the source heat is very low. The current Dutch feed-in tariff for geothermal energy still makes the operation competitive.

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