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Seasonal thermal energy storage for large scale district heating

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Abstract

Seasonal thermal energy storage (STES) systems in combination with heat pumps can significantly reduce the impact of peak loads in large scale district heating systems and allow for the application of renewable heat sources in these networks. This paper investigates technologies with the highest potential for implementation in large scale district heating networks and identifies high temperature aquifer thermal energy storage (HT-ATES) as the most suitable technology. The HT-ATES has been applied at the primary side of the network (90 to 110 °C) and at the secondary side (72 to 92 °C). Suitable locations for the STES have then been identified. A control volume approach is used in Matlab to predict heat transfer and pressure drop in the HT-ATES wells considering porosity, permeability, grain size and geometry of the aquifer. The temperature distribution and extraction temperature are predicted as function of time. The yearly heating demand of a network has been used in combination with different operating modes to identify the required size of the HT-ATES. The simulations indicate that it will take 5 years to reach steady temperature supply.

Keywords: heat pump; high temperature aquifer energy storage; district heating.

1. Introduction

In the Netherlands, the built environment creates about 20% of the entire national energy demand. The heat consumption of the sector amounted 574 PJ in 2015 [12] and the majority of this heat is produced by gas-fired boilers. The national and international climate agreements together with policies concerning gas production in Groningen (the Netherlands) require substantial changes in the thermal energy supply of the built environment. A significant increase of the use of district heating networks (DHN) is one of the measures proposed to move away from gas-fired heating systems. Several studies predict that by 2050 a large share of the heating supply in the built environment will make use of DHNs. Hoogervorst [8] predicts a share of 57%, Roelofsen et al. [15] of 27% and Wielders et al. [27] of 61%.

Currently, most of the heat delivered by DHNs does not originate from renewable sources. Although DHNs are suitable to transport renewable energy, the thermal energy is currently mostly produced by fossil-fueled plants such as combined heat and power plants (CHP) and backup boilers (BUB). According to Schoots et al. [18], 75% of the thermal energy supplied by large scale DHNs in the Netherlands is based on fossil fuels. Renewable heat production units, such as solar heat, industrial waste and geothermal energy plants, need to be added to the thermal energy supply. The increasing variety of heat production units causes a decrease in flexibility of the heat supply. Waste heat from industrial processes does not fluctuate over the seasons but is determined by industrial activity. Solar thermal energy and energy from geothermal plants are determined by the amount of sun hours and limitation in pumping rates. For all heat sources, long operating times have a strong impact on the levelized cost of energy (LCOE). LCOE quantifies the cost of unit energy produced including the investment and operational costs of the system.

Nomenclature

Roman symbols	V	Volume	m^3	hot	Hot well

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A	Area	m^2	z	Coordinate	m	in	At inlet
c_p	Specific heat	$kJkg^{-1}K^{-1}$	*Greek symbols*			out	At outlet
E	Thermal energy/year	$kJyear^{-1}$				r	At radius r
			Δ	Difference	-		
h	Heat transfer coeff.	$kWm^{-2}K^{-1}$	η	Efficiency	-	sto	Storage
m	Mass	kg	ρ	Density	kgm^{-3}	th	Thermal
Q	Heat	kJ	*Subscripts*			tot	Total
$\dot{Q}$	Heat flow	kW				w	Water
r	Radial coordinate	m	aq	Aquifer		well	Well
T	Temperature	°C or K	ave	Average		z	At position z
t	Time	s	cold	Cold well			

Seasonal thermal energy storage systems (STES) are able to store surplus heat. In winter, when the demand is higher than the supply, STES can function as an extra heat source. STES allows DHNs to operate in a sustainable and efficient way. In order to balance the heat demand and renewable heat supply at all times, thermal energy storage systems in DHNs seem inevitable. Fig. 1 shows the heat demand of the DHN of Utrecht in 2017 and 2018. The blue area shows the effect of STES on the required thermal energy production. In the summer the heat supply can be increased and the surplus heat (above the thermal energy demand curve) is stored.

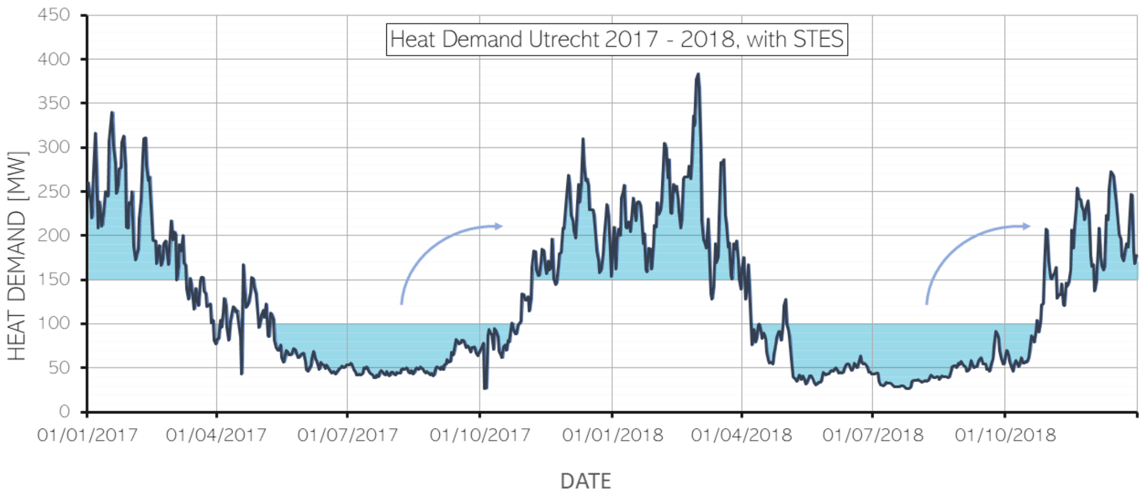

Fig. 1. Daily heat demand of the DHN of Utrecht in 2017 and 2018. The blue filled areas indicate the effect of STES on the installed capacity. In summer the heat production is increased so that the surplus can be stored to be used during winter as an extra heat source.

The transformation of a large scale mainly fossil-fueled DHN into a mainly renewable heat based system will generally reduce the flexibility of the DHN. Optimally sized STES can balance demand and supply of heat and to a certain extent provide flexibility to the DHN. The renewable heat sources can then always operate at optimal conditions while the surplus heat can be stored for later use.

The supply temperatures of most of the existing DHNs in the Netherlands is between 70 and 90 °C [27]. Low temperature DHNs, with supply temperatures <70 °C, perform thermally better since heat losses are lower [2]. While more heat sources become available when the DHN makes use of low temperatures, in the current built environment infrastructure high temperature DHNs can have a better economic performance. The existing infrastructure has been designed to deliver heat at high temperature and does not require end-user investments. Also, the high temperature DHN requires smaller distribution pipes leading to lower costs [26]. This study focuses on large scale (>2,000 consumers) high temperature supply (>70 °C) DHNs similar to the DHN of Utrecht.

The DHN of Utrecht is the third largest in the Netherlands [8]. It supplies thermal energy to more than 40,000 users. Presently the network is entirely supplied by fossil-fueled heat sources and needs to transition to renewable energy sources in the coming years. Internal scenarios from the owner, Eneco, indicate that seasonal storage is required from an economic perspective. The district heating network of Utrecht can be divided into two networks: the transport network and the distribution network. The transport network carries hot water generated at the heat source to the heat transfer station (HTS). The heat source and the HTS both have heat exchangers to transfer the heat from and towards the transport network. At the HTS the hot supply water transfers thermal energy to the distribution network. The colder water leaving the HTS is sent back to the heat source to be reheated. The supply temperature of the water is determined by the maximum thermal energy demand of the day [6]. This ensures a constant daily supply with an average lower supply temperature. As the heat demand is higher in the winter than in the summer, the temperature of the water in the transport network is higher in the winter to provide enough thermal energy. The DHN always needs to deliver safe and sufficient heat to the end-users. Safe means that the water temperature should always be high enough to prevent legionella to develop. These two characteristics determine the supply temperature of the DHN. The daily set-point is determined by a dedicated prediction software [5]. The BUBs can supply extra heat to the distribution network if the power from the source is insufficient. In the HTS the heat is transferred to the distribution network making use of heat exchangers. The distribution network's supply temperature is determined by the ambient temperature. The hot water exchanges heat at the end-user before it returns to the HTS. Fig. 2 shows left the relation between the delivered thermal power and the supply temperature in the transport network and right the relation between environmental temperature and supply temperature of the distribution network. The major heat sources are located in the transport network and consist of two CHP plants of 180 MW each and a BUB of 105 MW. Additionally a few BUBs are installed in the distribution network with capacities in the range 58 to 90 MW. Goal is to substitute these fossil-fuel driven heat sources by renewable heat sources. In the first phase mainly bio heat and green gas combustion systems will be implemented. In the second phase renewable heat sources without combustion will be implemented.

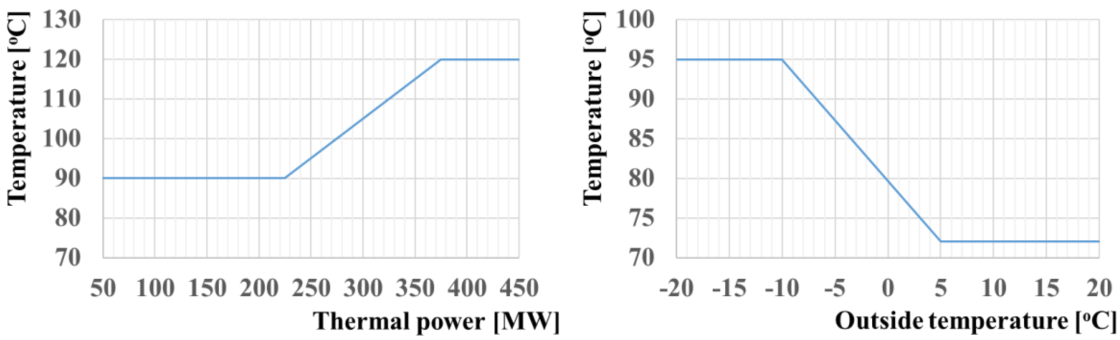

Fig. 2. Temperature levels of the supply water in the network: left in the transport network as a function of thermal power requirement and right in the distribution network as a function of the environmental temperature.

The International Energy Agency (IEA) gives an overview of previous high temperature storage systems [16]. Existing high temperature storage systems connected to district heating are predominantly located in the north of Europe. Wolfgramm [28] reports that in Neubrandenburg (Germany) a geothermal installation has been converted to a 4 MW high temperature aquifer thermal energy storage (HT-ATES) system. In the winter the system supplies heat to a low temperature district heating network. In the district heating of Braedstrup (Denmark) several pit thermal energy storage (PTES) and tank thermal energy storage (TTES) have been successfully implemented [20-21]. Several caverns are under construction to store 120 MW of hot water of the DH of Helsinki [23]. The Drake Landing project (Canada) provides almost the entire heat demand of a district by combining solar thermal heat with thermal storage [19]. The European project HeatStore plans to demonstrate underground thermal energy storage in five different countries [10].

The objective of this paper is to investigate the technical feasibility of the implementation of a seasonal heat storage system in an existing large scale DHN. The approach followed is schematically illustrated in Fig. 3. First the most suitable technology is identified, then suitable geographical locations are determined. A model for an HT-ATES system combined with a heat pump to load and unload the storage is developed in Matlab. The performance of the storage system in combination with the load profile of the DHN of Utrecht is then predicted and analysed.

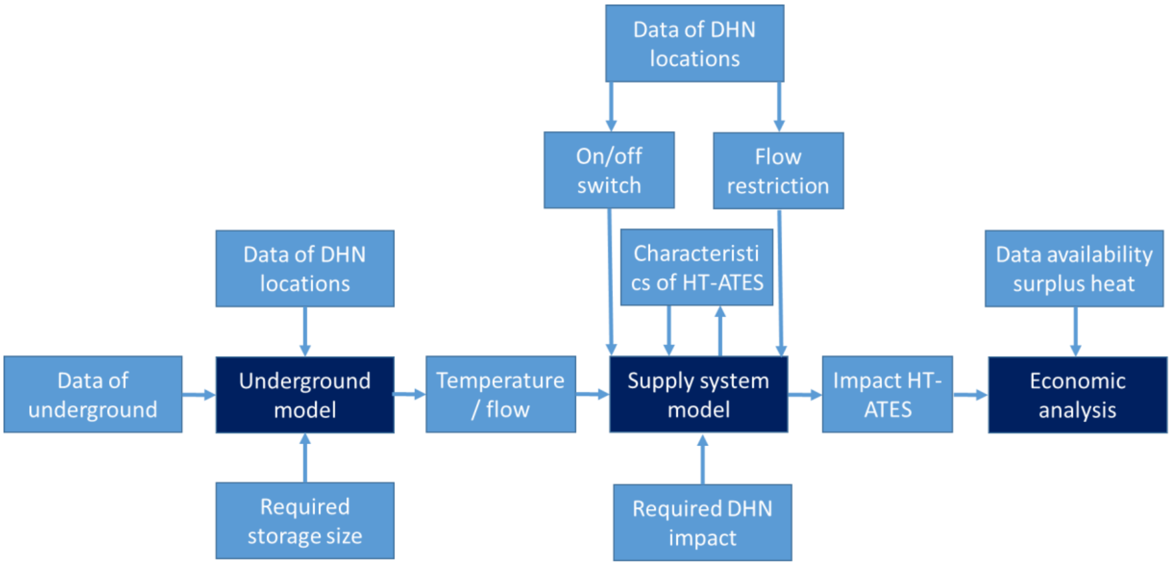

Fig. 3. Schematic of the approach used. A model was first developed for an HT-ATES taking the underground data for the different possible locations and the required storage size into account. This model allows for the prediction of inlet or outlet well temperatures and flow as a function of time. Then a supply system model including a heat exchanger and a heat pump was developed which is coupled to the HT-ATES model and allows for the prediction of the storage conditions as a function of time. Finally these results were used to estimate the economic performance of the storage facility.

2. Seasonal thermal energy storage (STES) systems

Three different groups of storage can be adopted for thermal energy storage (TES): sensible heat storage, latent heat storage and thermochemical heat storage. Fig. 4 (left) illustrates the three groups with corresponding storage capacities and temperature range [17].

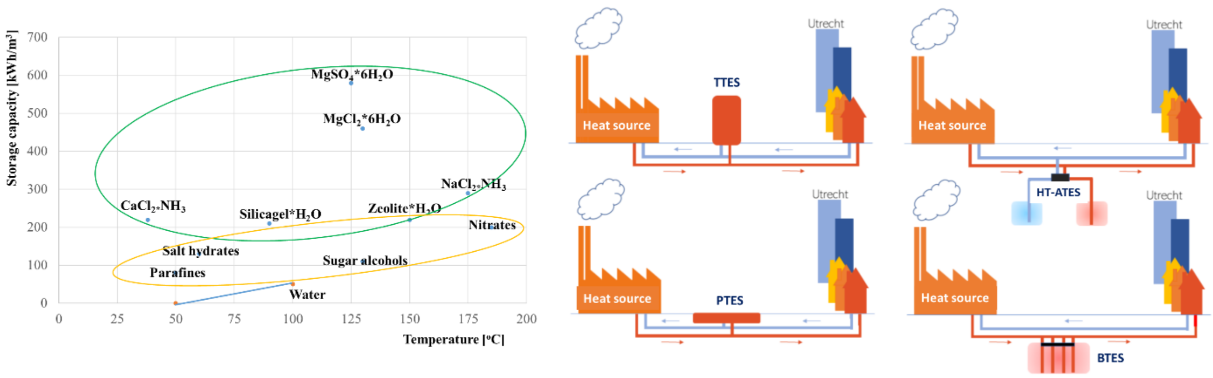

Fig. 4. Left the three groups of TES with sensible heat in blue, latent heat in yellow and thermochemical in green showing that latent heat storage can be twice compacter and thermochemical heat storage up to 7 times compacter. Right the four promising STES systems for district heating integration.

Sensible heat storage is the simplest to apply. The stored amount of energy is obtained with eq. (1).

$$Q = m \cdot c_p \cdot \Delta T \qquad (1)$$

Where m is the mass of storage medium (frequently water), c_p its specific heat and ΔT the temperature difference between initial and final temperature of the storage medium. The most frequently used methods of storage of sensible heat are illustrated in Fig. 4 (right): tank thermal energy storage (TTES), pit thermal energy storage (PTES), high temperature aquifer thermal energy storage (HT-ATES) and borehole thermal energy storage (BTES). The optimal STES system stores heat at low cost and high efficiency and can be implemented in dense urban areas without too many constraints.

The bigger the storage volume, the smaller the relative area through which heat losses can take place. Increasing the size generally increases the construction costs. Especially for TTES and PTES the costs increase significantly. The increasing costs for HT-ATES are however smaller as the subsurface itself functions as the insulating material. Fig. 5 shows that the costs reduce with increasing storage volume [11].

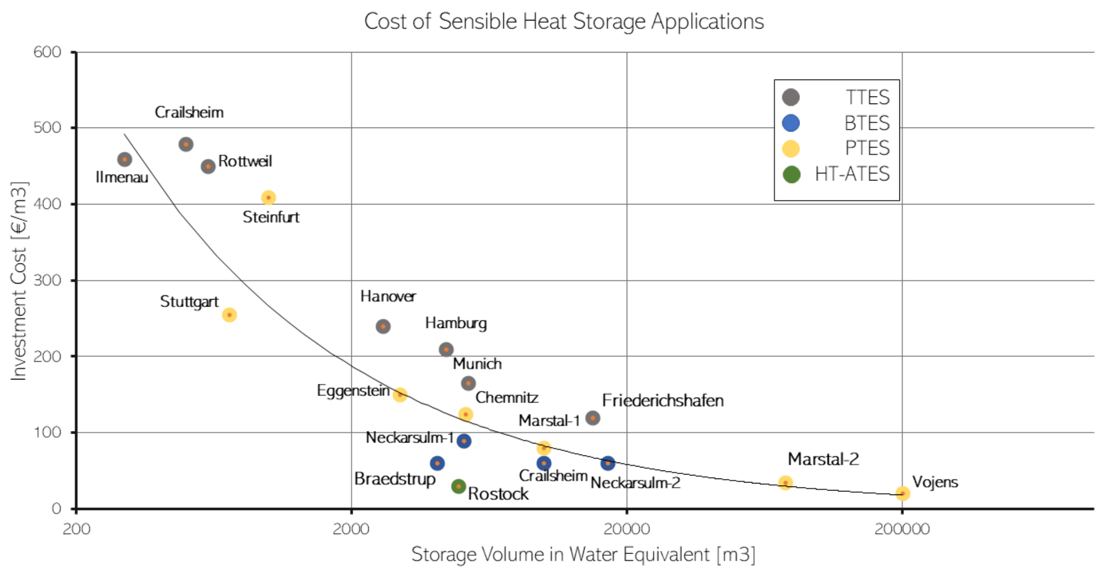

Fig. 5. Relation between specific investment costs and volume of TES based on existing plants in Denmark and Germany [11].

The largest TES, the PTES of Vojens, has a volume of 200,000 m^3 and supplies heat to 2,000 consumers [24]. According to the Danish Energy Agency [3] the costs of this plant are 113 €/GJ. The larger the STES systems, the more economic attractive the systems become. According to de Wit-Blok [7] TTES is expected to have the highest large scale investment costs (139 €/GJ) while HT-ATES is expected to have the lowest costs (14 €/GJ).

Latent heat storage uses the phase change energy of a material to store heat. The melting enthalpy is significantly larger than the sensible change of enthalpy so that the same amount of energy can be stored in a much smaller volume, see Fig. 4 (left). Additional advantage is that the phase change takes place at almost isothermal conditions which depend on the material and can be selected in the temperature range of the DHN (50 ºC to 150 ºC). The most important drawback of latent heat storage is its costs which are currently significantly higher than for sensible heat storage. According to the IEA [9] the costs are 2,778 €/GJ and need to reduce significantly before latent heat storage becomes competitive. A reduction of at least 50% is required for applications in DHNs [22].

Thermochemical energy storage uses chemical energy preserved in the bonds of molecules to store heat [13]. The energy added to the system is used to dissociate a material into other components [1]. Thermochemical storage systems have very high energy densities, see Fig. 4 (left), and are optimal for dense urban areas. Yu et al. [29] claim that storage volumes can be up to 30 times smaller than for sensible heat storage systems and the IEA [9] claims that theoretically storage efficiencies of 100% can be attained. The challenges of applying this storage system for large DHNs are the low technical readiness level and the system costs. The lowest reported potential cost is 2,222 €/GJ [9]. Remmelts [14] has compared the largest PTES storage in Vojens (200,000 m^3) assuming a storage efficiency of 60% for the sensible PTES and a storage efficiency of 100% for the thermochemical storage. The storage costs for Vojens are 113 €/GJ while the costs for the thermochemical storage are 2,222 €/GJ or 1,111 €/GJ, assuming a 50% cost reduction. As the cost of heat increases, a storage technique with a higher storage efficiency (thermochemical) will have a faster increasing economic potential. However, assuming a relatively high cost of heat (the current consumer market price of 24 €/GJ), the total yearly costs of the thermochemical storage are still 2.3 and 1.4 times higher than for the PTES.

From the previous discussion it becomes clear that presently sensible heat storage seems to be the most competitive STES and, taking into account the required size of the DHN storage, the HT-ATES solution seems the most appropriate. It occupies the least surface area of all the sensible heat storage solutions. Presently, in the Netherlands, subsurface regulations only allow pilot high temperature storage projects and allowance for commercial projects is being investigated.

The HT-ATES can be installed in the transport network (centralized) or at several locations of the distribution network. This is illustrated in Fig. 6. The largest difference between the two locations is that the centralized location affects all distribution networks while the decentralized affects only the respective distribution network. The centralized location requires higher supply temperatures then the decentralized locations.

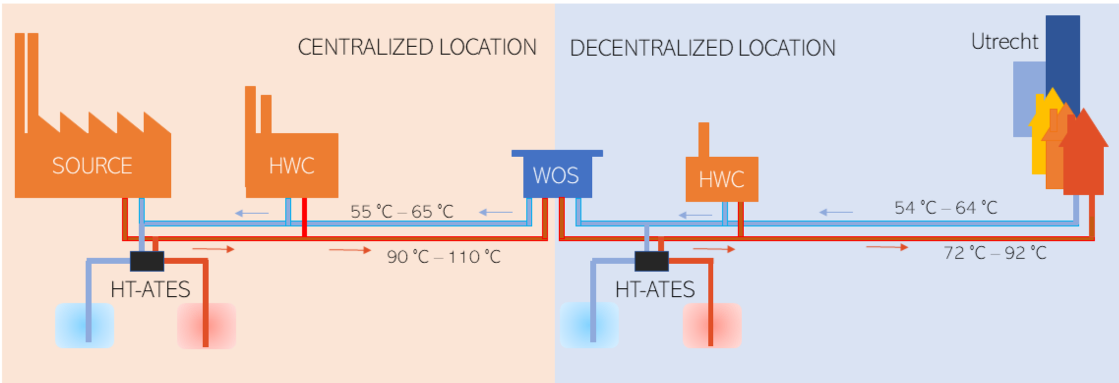

Fig. 6. Possible locations for the HT-ATES STES. At the surface, heat pumps bring the guarantee that heat can be delivered to the network (discharging phase) or to the heat storage (charging phase).

ATES system should not interfere with drinking water or other protected sub-ground areas so that those areas are excluded as possible HT-ATES locations. To prevent conflicts with protected areas the usable aquifers are more than 150 m below the surface. Below 500 m under the surface the mining law applies and the installation costs of the wells increase so that the usable aquifers must be above this level. HT-ATES systems consist of at least three layers: two confining impermeable layers and a permeable aquifer. The confining layers function as an insulator for the stored heat. The heat is stored in the aquifer layer which consist of water and sand. In the subsurface of Utrecht the impermeable and aquifer layers are stacked alternatively.

Remmelts [14] has identified suitable underground layers. These aquifers have suitable permeabilities in the range 5 m/day and 20 m/day [4]. The ground water flow is 3.5 m/year so that it will hardly affect the heat recovery of the storage.

3. Modelling of STES system

3.1. Underground thermal performance model

The thermal performance of an aquifer can be evaluated by determining its thermal recovery efficiency. This efficiency gives the ratio of extracted and injected thermal energy, see eq. (2). The non-recovered heat is the heat loss of the aquifer. This heat loss results in a higher efficiency for the next cycle.

$$\eta_{th} = \frac{T_{out,ave} \cdot V_{out}}{T_{in,ave} \cdot V_{in}} \tag{2}$$

Where T_{ave} is the average temperature during the charging or discharging period. The thermal recovery depends on the heat transport phenomena in the aquifer and impermeable layers (aquitards). Fig. 7 (left) illustrates the forms of heat transfer that have been taken into account.

The right hand side of Fig. 7 shows how the energy conservation equations have been locally used to determine the temperature. Further details of the underground model can be found in Remmelts [14]. Fig. 8 illustrates the results obtained with the underground model.

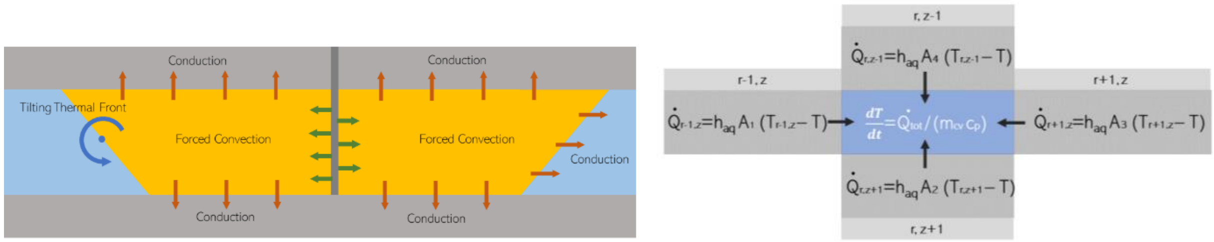

Fig. 7. Heat transfer phenomena considered in the modelling of the aquifer: convection, conduction and tilting of the thermal front. The vertical line indicates the position of the well while the yellow area represents the hot water stored in the aquifer. Right the control volume approach to determine the local temperatures in the aquifer.

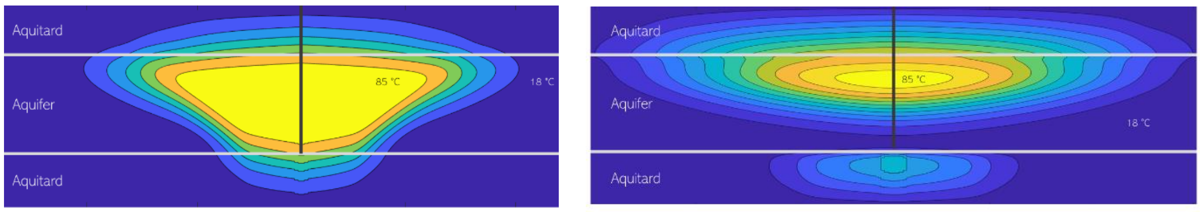

Fig. 8. Typical temperature profiles predicted by the underground model. Left at the end of the injection stage (charging) and right at the end of the extraction stage (discharging). An aquitard is an impermeable layer.

3.2. HT-ATES size

The heat available for storage originates from heat that otherwise would be wasted and from heat produced by increasing the base load of the heat sources of the DHN during the summer. Goal is to size the HT-ATES to deliver 400,000 GJ/year. The HT-ATES should be able to deliver heat for a period of 120 days with a maximum power output of 50 MW and an average of 38 MW. It is expected that there will be approximately 185 days charging time, 30 days buffer time, 120 days extraction time and again 30 days buffer time, depending on the thermal energy demand. The desired size of the HT-ATES is given by eq. (3).

$$V_{sto} = \frac{E}{\rho_w \cdot c_p \cdot (T_{well,hot} - T_{well,cold})} \approx \frac{400{,}000{,}000{,}000}{983 \cdot 4.185 \cdot (73 - 18)} = 1{,}767{,}862 m^3 \qquad (3)$$

The hot well is charged with water at 85 ºC but its temperature drops to 55 ºC during the discharging period. The HT-ATES has been designed with a storage volume of 1,300,000 m^3 since the compressor of the heat pump delivers part of the required heating capacity. The volume extracted from the hot well should be equal to the injected volume. Otherwise the recovery efficiency for the next cycle will be lower. Also the discharging must be limited to a maximum of 180 days so that there is enough time left to recharge the HT-ATES.

The maximum allowable flow velocity in an aquifer so that the well filter does not get blocked determines its total capacity [25]. This implies that several wells are required for the required size of the storage.

3.3. Connection to DHN

The water from the HT-ATES system cannot be directly used in the DHN. It has a different chemistry than the DHN water and it must be pumped back into the same ground layer. In order to transfer the heat from the HT-ATES to the DHN a heat exchanger and a heat pump are used. Due to the large temperature difference between cold and hot wells, a heat exchanger is not sufficient. To return the flow at the desired temperature a heat pump must be used. For each doublet (pair of cold and hot wells) a pump is required to overcome the pressure difference between both wells. Fig. 9 illustrates the system connections for a decentralized supply system.

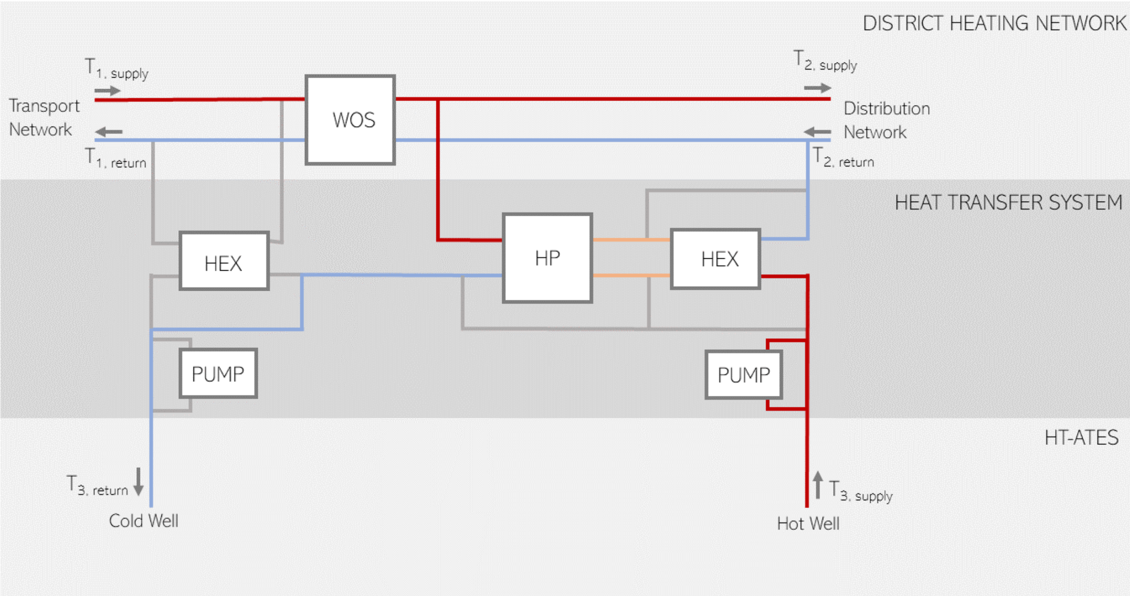

Fig. 9. Schematic of decentralized heat transfer system. The HT-ATES is operating in the beginning of the winter so that both heat exchanger (HEX) and heat pump (HP) are in operation. In red the hot water streams, in blue the cold water streams and in grey the inactive lines.

The electrical power consumed by the well pump is obtained from the extraction volume flow rate and the total pressure difference that the pump has to overcome. This pressure drop consists of the pressure drop in HEX and HP, the pressure drop between the doublet, the pressure drop in the vertical wells and the pressure drop in the transportation lines. A pump efficiency of 74% and an electric efficiency of the electric motor drive of 88% are further assumed. For the heat exchangers, the minimum temperature difference between the hot inlet and the outlet is assumed to be 5 K. If the temperature of the extracted flow becomes too low for the heat exchanger, the flow is guided through a by-pass directly to the heat pump.

Butane (R600) has been selected as the working fluid of the heat pump. An isentropic efficiency of 70% has been assumed for the compressor of the heat pump. The heat rejection from the heat pump takes place in three steps: de-superheating, condensation and sub-cooling. The condensation takes place at a 3 K higher temperature than the supply temperature to the DHN. Also at the sub-cooling side, the condenser outlet temperature is 3 K higher than the water returning from the DHN. Table 1 gives the design conditions of the heat pump and its corresponding COP.

Table 1. Design operating temperatures of heat exchanger and heat pump.

	$T_{source,out}$ [ºC]	$T_{source,in}$ [ºC]	$T_{sink,in}$ [ºC]	$T_{sink,out}$ [ºC]	$T_{condensation}$ [ºC]	$T_{evaporation}$ [ºC]	*COP*
Decentralized	18	60	60	76	75	15	3.99
Centralized	18	60	62	105	98	15	3.27

3.4. Heat load in DHN

The daily thermal energy demand data of the DHN and the corresponding supply and return temperatures have been linked to the thermal model of HT-ATES side of the system. The switching point for the discharging of the HT-ATES follows from the required thermal energy of the DHN. The ATES model predicts the time dependent extraction temperature. As discussed in section 1, the supply temperature of the DHN follows from its operating conditions so that the temperature delivered by the heat pump is also time dependent. The injection temperature into the cold well is fixed at 18 ºC so that the evaporating temperature of the heat pump is also fixed. The extraction temperature and the temperature of the return flow from the DHN determine if the bypass of the heat exchanger is activated.

4. Results

4.1. Performance of ATES

The properties of aquifers at different locations in the area covered by the DHN of Utrecht have been used to determine the corresponding recovery efficiency. Charging and discharging cycles as discussed in section 3.2 have been applied for a total of 15 cycles for each of the possible locations. The most promise ATES in a decentralized network area had a recovery efficiency of 80% at the end of the 15th cycle and in the centralized area of 77%.

During the first years of operation the aquifers have a lower recovery efficiency because the soil needs to heat up. Fig. 10 shows the temperature of the water injected into the hot well / extracted from the hot well as a function of time for a period of 15 years. The extracted temperature at the end of the discharging period increases every year. The constant parts of the temperature line correspond to the injection period at constant temperature (85 ºC).

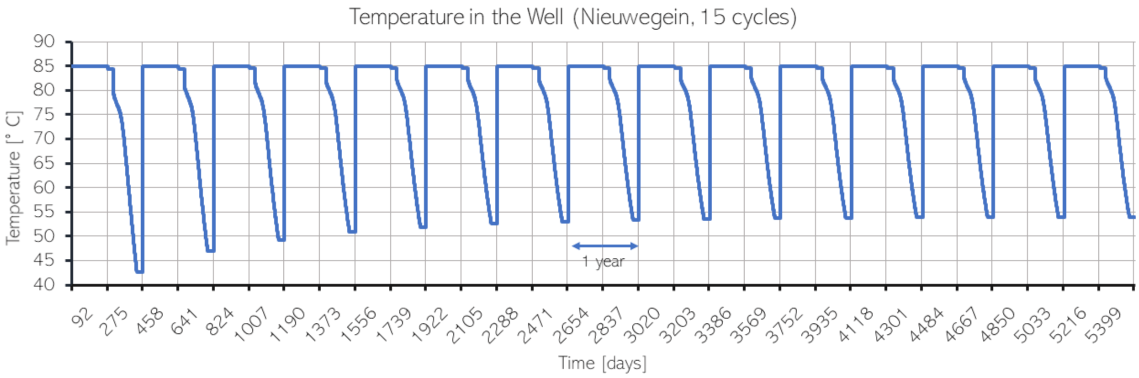

Fig. 10. Change of the extraction temperature from the HT-ATES during a period of 15 years.

4.2. Performance of STES in combination with the DHN

The locations with best performing aquifers have been tested to determine its potential for three different operating strategies:

- "Peak shaving" where the peak thermal energy demand during the winter is supplied from the HT-ATES;
- "Winter base load" where a constant base load is delivered by the HT-ATES during the winter season;
- "Total winter coverage" where the entire winter thermal energy demand is supplied by the HT-ATES.

Fig. 11 (top) shows the results of the three operating strategies for a decentralized district of the DHN with local thermal energy demand that is close to the size of the HT-ATES (1,300,000 m^3 storage). It is clear that the "total winter coverage" can nicely fit the demand of this district. Part of the storage capacity would remain unused if the "peak shaving" and "winter base load" strategies would be applied. Fig. 11 (bottom) shows that for the transport network side (centralized) of the DHN the "total winter coverage" strategy would lead to a very short operating period. Both the "peak shaving" and "winter base load" strategies could be applied at central level. However the "peak shaving" option leads to very high mass flow fluctuations in both HT-ATES and DHN sides. Such operation may lead to problems in the wells and should be prevented. For this reason the "winter base load" strategy would be the preferred one for the centralized storage. In both applications, at the end of the discharging period, the mass flow from the HT-ATES increases to provide the desired thermal power as the temperature of the extracted water decreases.

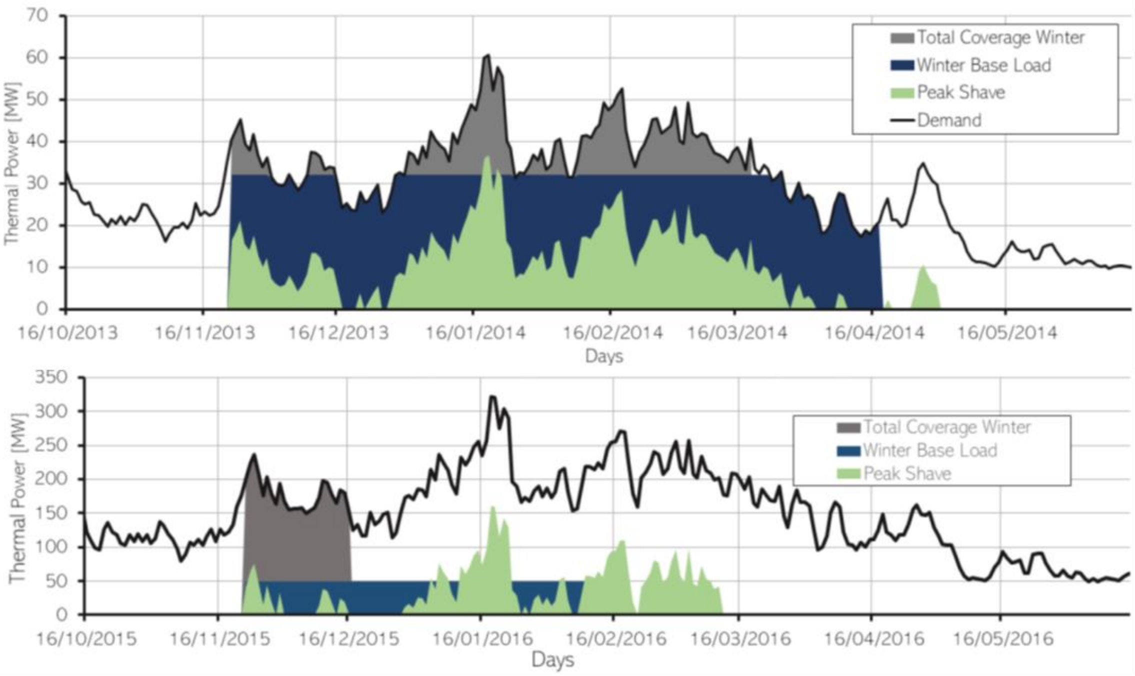

Fig. 11. Supplied thermal energy during the winter of 2015-2016 making use of an HT-ATES with 1,300,000 m^3 storage volume making use of different strategies: "peak shaving" (green), "winter base load" (blue) and "total winter coverage" (grey). Top: decentral location; Bottom: central location.

Fig. 12 shows the contribution of the heat exchanger (blue) and of the heat pump (green) during the discharging period of the winter of 2013 – 2014. Left the results for the decentral application and right for the central application. Due to the higher temperature required at the transport side, the contribution of the heat exchanger is smaller for the centralized solution. The heat exchanger can only deliver a small share of the total delivered heat. Without a heat pump the system would not be feasible.

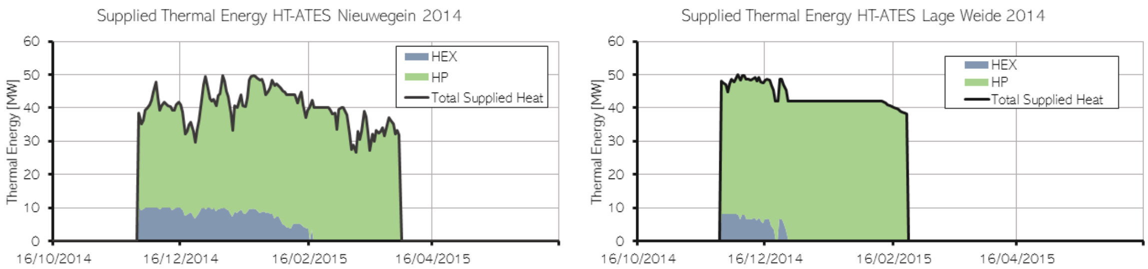

Fig. 12. Contribution of heat pump and heat exchanger to the total supplied heat to the DHN. Left: decentral location; Right: central location.

5. Conclusions

This study confirms that it is technically feasible to implement a seasonal thermal energy storage system in an existing large scale district heating network. Both application at the transport side (centralized) and distribution side (decentralized) result in solutions with comparable advantages for the whole DHN.

- The storage volume of the HT-ATES should be selected taking the local energy demand and the availability of surplus heat into account.
- The maximum thermal power should be selected in agreement with the storage volume available.
- The heat pump plays a major role in the feasibility of the concept. Just using a heat exchanger would significantly limit the energy that can be recovered from the storage.

Acknowledgements

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