Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Simulation and Data Based Optimisation of an Operating Seasonal Aquifer Thermal Energy Storage

Stefan Kranz[1], Jörn Bartels[2]

[1]Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany

[2]Geothermie Neubrandenburg GmbH, Seestraße 7a, D-17033 Neubrandenburg, Germany

[1]kranz@gfz-potsdam.de, [2]gtn@gtn-online.de

Keywords: Aquifer Thermal Energy Storage, optimization, simulation

ABSTRACT

Seasonal Aquifer thermal energy storage (ATES) systems have the potential to contribute significantly to reduce the primary energy consumption in energy provision systems. Energy is stored in periods when surplus heat is available and provided to the consumer when energy is demanded. The energetic efficiency of such heat storages in the groundwater determines the environmental and economic performance and is considerably affected by the storage operational mode. Therefore, the analysis and improvement of the actual storage operation is crucial. Combining measured data analysis and the application of numerical ATES models leads to a performance-enhancing storage operation strategy, thus to an overall improved energy utilisation. In this context, a case study of an existing aquifer storage system combined with the identification of general parameter dependencies is discussed. The example presented here is the energy supply system of the German Parliament Buildings in Berlin. Measured operational data from the last 6 years of the heat storage operation were analysed. The analysis shows that the energy recovery factor varies significantly between the annual storage cycles. Since the number of parameters influencing the storage efficiency is too large to be identified by data analysis only, a detailed simulation model based parameter study is carried out. Simulation results show that for the existing storage system the energy recovery factor can be improved with (a) increasing storage temperature at the warm well, (b) lowering the injection temperature at the cold well, (c) increasing the circulated total ground water volume, and (d) increasing the amount of stored thermal energy.

1. INTRODUCTION

In ATES systems water bearing sandstones are used as storage medium for thermal energy resulting from combined heat and power plants (CHP), solar energy or industrial waste heat. The groundwater serves likewise as heat transfer medium and storage medium. Common ATES systems consist of two well groups or at least two wells (well doublet), “cold” wells and “warm” wells (Figure 1). This indication refers to the temperature level in the aquifer used. Due to the large storage capacity of water bearing sandstones, ATES systems are used to store thermal energy seasonally, mainly for the provision of room heat and cold in buildings. When charging the ATES system with heat, the groundwater is produced from the cold well, heated at the surface by means of heat exchangers and injected into the aquifer via the warm well. During discharging the operation is reversed and the still heated groundwater is produced from the warm well, cooled off while passing through heat exchangers and injected again into the aquifer via the cold well.

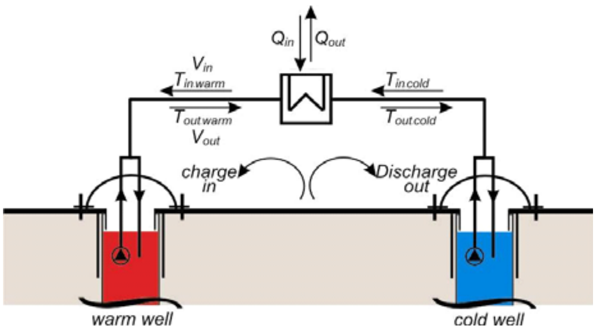

Figure 1: Scheme of a ATES doublet and notation

Many of these ATES systems that are designed for heating purposes are linked to heat pumps. But also direct use of the stored thermal energy is possible if the extracted ground water provides sufficiently high temperatures. For all applications the achieved energetic storage efficiency reflects the quality of the storage system which differs depending on the type of application. Since the energetic performance of ATES systems has a decisive impact on the economic viability and environmental benefit, estimating the storage efficiency is an important task for sound planning of such storage systems. In previous investigations, the calculation of the storage efficiency was based on accounting for only one well. In this context, comprehensive parameter studies of Doughty (1982); Sauty (1982) and Dwyer (1987), for example, have shown how mainly geological parameters affect the storage efficiency. Other investigations focused on the temperatures at the wells only or the temperature distribution in the aquifer Shaw-Yang (2008).

Recent investigations, presented in this article, of an existing ATES system which is integrated in the energy provision system of the German Parliament buildings show that, in addition to geological parameters, also operational parameters such as temperatures at both wells have a significant influence on the storage efficiency. The calculation of the storage efficiency in this paper is therefore extended by defining a heat recovery factor (HRF) which accounts for the two connected wells simultaneously, considering the temperatures at both wells and the volume of charged and discharged ground water. In order to identify the determining parameters, a detailed simulation model based parameter study was carried out. Based on the simulation results it can be concluded that a site-specific optimum operation strategy exists for each ATES application. For future projects, a method must be developed to integrate these aspects already in the planning process.

2. BACKGROUND

The energy supply system of the German Parliament Buildings in Berlin comprises several components that allow an energy efficient and environment-friendly energy provision. Apart from energy conversion components, there are two seasonal ATES systems involved. One ATES system is used as heat storage and is located at a depth of app. 300m. The second ATES serves as cold storage and uses an aquifer at a depth of 40 to 70m. The heat storage is charged with surplus heat from a biofuel driven cogeneration plant (CHP) in summertime. In wintertime, the ATES is discharged to supply the buildings with low temperature heat. The temperatures are 45°C and 30°C for flow and return respectively. The cold storage is cooled down by means of dry cooling in case of the ambient temperatures being low. In summertime, the cold groundwater is used to cool the buildings Kabus (2000).

The investigations presented here are focused on the heat storage. The heat storage system is based on one cold well and one warm well (well doublet). The design temperature at the warm well is 70°C while charging. This temperature is limited because of geochemical aspects (solubility of silicates at higher temperatures). While discharging and direct heat use, the groundwater is cooled down to 30-35°C and injected at the cold side into the aquifer again. The design heat storage capacity is 2650MWh/a.

3. METHODS

In order to evaluate the achieved efficiency of the investigated ATES, measured operational data are analysed based on an extended definition of a heat recovery factor. Since the number of parameters influencing the efficiency is too large to be identified by data analysis only, a detailed parameter study based on a simulation model was carried out. For the improvement of further storage operation, reliable recommendations are derived.

3.1 Measured data based analysis

The evaluation of the storage efficiency is based on the heat recovery factor (HRF), which accounts for the energy balance around the heat storage including the warm and the cold well. The HRF is defined as the ratio of charged to discharged thermal energy per storage period and is calculated according Equation (1).

$$HRF = \frac{Q_{out}}{Q_{in}} = \frac{\int_{t,out} [V_{out}(t)\,\rho\,c_p\,(T_{out,warm}(t) - T_{out,cold}(t))]\,dt}{\int_{t,in} [V_{in}(t)\,\rho\,c_p\,(T_{in,warm}(t) - T_{in,cold}(t))]\,dt} \qquad (1)$$

where *HRF, Q, V,* ρ, c_p, *T, t* are heat recovery factor, thermal energy (kJ), water volume circulated (m³), density of groundwater (kg/m³), specific heat capacity of groundwater (kJ/kgK), temperature (°C) and time. The subscripts *out* and *in* indicate discharging energy and charging energy and *warm, cold* stands for warm well and cold well respectively.

To apply this equation the temperatures, flow rates, density and specific heat capacity of the groundwater during the analysed operation period need to be known. For the temperatures at each well and the volume flow rates the measured data are used. The temperature $\boldsymbol{T_{out,\,cold}}$ is related to the cooling of the groundwater while discharging and is defined by the temperature of the secondary side of the heat exchanger which depends on the heating circuit temperatures (Figure 1).

3.2 Modelling and simulation of the storage operation

Two different numerical ATES models were created. The simplified ATES model takes into account the thermal behaviour and a flow field of a single well only whereas the detailed 3D-model calculates the thermal and hydraulic field of a well doublet and allows for heterogeneities in the subsurface.

The detailed 3-dimensional finite-element model based on the flow and heat transport simulator FEFLOW, Diersch (2002) was fed with operational data and verified with measured recovery temperatures. Since comprehensive parameter studies using the detailed model would be highly time consuming, also the simplified and fast model TRNAST Hellström (1986); Schmidt (2005), applicable within the simulation environment TRNSYS Klein (1976), was applied. TRNAST is an ATES-model containing two in the subsurface thermally and hydraulically independent wells. It uses the finite-difference method and an axial symmetric model geometry. The surface connection of the wells incorporating temperatures and volume flow rates was implemented using TRNSYS. It has been verified with measured operational data and with results from the detailed 3-dimensional aquifer model to ensure reliability.

The parameter study accomplished focuses on the dependency of the HRF on parameters determined by the mode of operation. These parameters are: the injection temperature at the warm well while charging $\boldsymbol{T_{in,\,warm}}$, the temperature at the cold well while discharging $\boldsymbol{T_{out,\,cold}}$, the water volume circulated while charging $\boldsymbol{V_{in}}$ and discharging $\boldsymbol{V_{out}}$, their ratio $\boldsymbol{V_{out}/V_{in}}$, and the thermal energy stored $\boldsymbol{Q_{in}}$.

All other HRF relevant geological and site specific parameters were kept constant (Table 1).

Table 1: Parameters of the ATES models

Property	Value
Thickness (m)	25-30
Temperature gradient (K/100 m)	3.0
Temperature (°C)	app. 20
Volumetric heat capacity (J/m³K)	$2.5 \cdot 10^6$
Thermal conductivity (W/mK)	3.0 (horizontal and vertical)
Longitudinal dispersion length (m)	1.2
Porosity (-)	0.3
hydraulic conductivity horizontal (m/s)	$3{,}1 \cdot 10^{-5}$
hydraulic conductivity horizontal (m/s) (damage zone around cold well)	$1.2 \cdot 10^{-5}$ (radius 2.3 m)
hydraulic conductivity vertical (m/s)	$0.8 \cdot 10^{-5}$

3.3 Model vVerification

The 3-dimensional detailed ATES model was applied to simulate the hydraulic and thermal aquifer state and storage behaviour for all years of operation. The calculated and measured temperatures for one storage period at the warm well while discharging energy and at the cold well while charging energy are shown in Figure 2. The model results reproduce the measured temperatures closely in times where a continuous operation took place and, therefore, heat loss in the well is negligible. In periods with no or frequently interrupted operation, heat loss in the well can not be neglected and an agreement can not be expected. Consequently, the correct model temperature curve has to mark the upper limit of the measured curve.

By means of the detailed ATES model the simplified ATES model was verified and adjusted. Several relevant ATES operation modes were defined and calculated with both models focusing on the heat recovery factor. The results obtained by the simplified model correspond with the results obtained by the detailed model (Table 2).

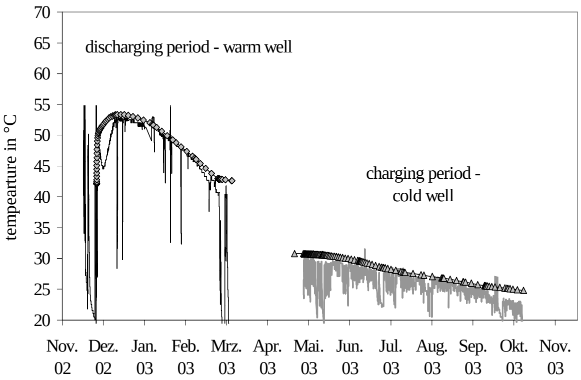

Figure 2: Comparison between modeled (symbols) and measured temperatures (lines) for the warm and cold side, respectively

$T_{in, warm}$ / $T_{out, cold}$ °C	Capacity Mwh/a	HRF TRNAST	HRF FEFLOW
50 / 15	5000	0.864	0.857
90 / 35	1000	0.487	0.471
50 / 35	1000	0.356	0.383
90 / 20	1000	0.630	0.610
50/ 20	1000	0.721	0.707
90 / 15	1000	0.668	0.648
50 / 15	1000	0.788	0.795

Table 2: Comparison of the heat recovery factor calculated with TRNAST and FEFLOW for selected parameter settings

4. RESULTS AND DISCUSSION

In the following chapter the results of the measured data analysis and the results of the simulation study are presented and discussed. The parameters this investigation is focused on reflect the operational modes of the ATES system and have significant influence on the energy efficiency.

4.1 Data Based Analysis of the ATES Operation

The storage operation was started in 1999. Since 2002 a continuous monitoring has been accomplished that comprises the measurement of temperatures, flow rates, well head pressure, chemical composition and biological characteristics. The energy balance using Equation (1) was calculated for 4 storage periods (Table 3). The stored thermal energy and the heat recovery factor vary significantly from year to year. Apart from the period 2006/2007 a regular operation of the storage system was realized. In the period 2006/2007 almost no thermal energy was discharged because of a breakdown of the submersible pump as well as general maintenance work. The stored thermal energy varies between 1400 and 3100MWh/a and has levelled to 1400 - 2000MWh/a in the last 3 periods. The amount of thermal energy stored is lower than expected since the actual surplus heat in summer of these periods is lower than the design condition. This is caused by the higher heat demand in buildings than originally expected. The higher heat demand is caused by increasing demand for cooling which is provided by absorption chillers and Desiccative & Evaporative Cooling (DEC). Neglecting the last storage period the heat recovery factor (HRF) ranged from 0.53 to 0.76 and the average value being 0.64.

Referring to Equation (1) the injection temperatures at both wells (***$T_{in, warm}$; $T_{out, cold}$***) and the volume circulated (***V_{in}; V_{out}***) affect the HRF. These data are listed in Table 3 for the observed storage periods. The average temperatures calculated are weighted by the corresponding volume flow rate. Considering constant aquifer properties the fluctuating heat recovery factor is caused by parameters reflecting the mode of operation. A simulation based study was therefore carried out in order to detect the important parameters which are influencing the heat recovery factor.

4.2 Results of modelling and simulation

Simulations with the simplified ATES-model were carried out using the parameters listed in Table 1. The operation time assumed is 10 years. All results presented in the following paragraphs denote average values for this operation time.

Table 3: Results of the measured data analysis for the years 2003 to 2007

Storage period	$T_{in, warm}$ °C (average)	$T_{out, cold}$ °C (average)	V_{in} m³	V_{out} m³	V_{out} / V_{in}	Q_{in} MWh	Q_{out} MWh	*HRF*
03 / 04	64.6	32.7	71350	89189	1.25	3141	1918	0.61
04 / 05	53.1	32.4	51090	73862	1.44	1396	742	0.53
05 / 06	55.8	31.3	60439	90928	1.50	1842	1404	0.76
06 / 07	58.5	28.9	58191	914	0.016	1949	14.4	0.007

4.2.1 Effect of Injection Temperature at Warm Well ($T_{in, warm}$) and Cold Well ($T_{out, cold}$) on the HRF

The effect of injection temperatures at both wells were investigated taking into consideration reasonable conditions of operation. The results in Figure 3 show different impacts of $T_{in, warm}$ on the HRF depending on the temperature $T_{out, cold}$. Considering the specific case investigated here, the HRF increases with increasing $T_{in, warm}$ when $T_{out, cold}$ is above 20°C. When $T_{out, cold}$ is 20°C, no effect of $T_{in, warm}$ on the HRF can be identified. For a temperature $T_{out, cold}$ below 20°C the effect of $T_{in, warm}$ on the HRF inverts in such a way that the HRF decreases with an increasing temperature $T_{in, warm}$. Since the undisturbed natural aquifer temperature $T_{aquifer}$ of the ATES is 20°C the inverting effect seems to be dependent on the relation of the temperature $T_{out, cold}$ to the natural aquifer temperature. This assumption is supported by the following analytical approach.

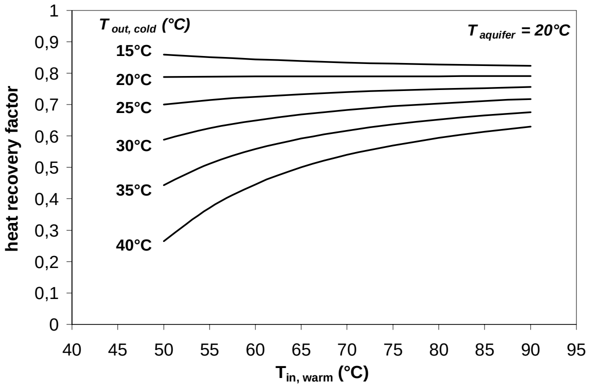

Figure 3: Effect of injection temperature at warm well ($T_{in, warm}$) and cold well ($T_{out, cold}$) on the HRF (volume flow rate 33,3 m³/h, each charging and discharging length 3000hr, V_{out}/V_{in}=1)

Using the definition stated in Doughty (1982) and the notation used in this article, the individual heat recovery factors for the warm well ε_{warm} and for the cold well ε_{cold} can be written as:

$$\varepsilon_{warm} = \frac{\overline{T}_{out,warm} - T_{aquifer}}{T_{in,warm} - T_{aquifer}} \tag{2}$$

$$\varepsilon_{cold} = \frac{\overline{T}_{in,cold} - T_{aquifer}}{T_{out,cold} - T_{aquifer}} \tag{3}$$

Assuming the same geological parameters for each well, the same volume injected into both wells (V_{out}/V_{in} =1) as well as the same injection time for each well (3000hr) yield:

$$\varepsilon_{warm} = \varepsilon_{cold} = \varepsilon \tag{4}$$

With the definition of ε_{cold} and ε_{warm}, considering that ε_{cold} and ε_{warm} are independent from the corresponding injection temperature Doughty (1982) and using the average values for $T_{out, warm}$ and $T_{in, cold}$, Equation (1) can be stated as follows:

$$HRF = \frac{(\varepsilon\, T_{in,warm} + (1-\varepsilon)\, T_{aquifer}) - T_{out,cold}}{T_{in,warm} - (\varepsilon\, T_{out,cold} + (1-\varepsilon)\, T_{aquifer})} \tag{5}$$

The differentiation of Equation (3) with respect to $T_{in, warm}$ and a case differentiation regarding the slope of the HRF yields:

$$\frac{dHRF}{dT_{in,warm}} = 0 \quad \text{if} \quad T_{out,cold} = T_{aquifer}$$

$$\frac{dHRF}{dT_{in,warm}} < 0 \quad \text{if} \quad T_{out,cold} < T_{aquifer}$$

$$\frac{dHRF}{dT_{in,warm}} > 0 \quad \text{if} \quad T_{out,cold} > T_{aquifer}$$

Therefore this analytical approach corroborates the results obtained from the numerical study. The slope of the heat recovery factor against $T_{in, warm}$ depends on the relation of $T_{out, cold}$ to $T_{aquifer}$.

In order to identify how sensitively the HRF depends on the injection temperatures at both wells, the curves representing the derivative of the HRF with respect to $T_{in, warm}$ and $T_{out, cold}$ were determined (Figure 4). The derivative of the HRF with respect to $T_{out, cold}$ has a negative sign due to an increasing HRF with a decreasing temperature. The results show that for each case investigated the HRF is more sensitive to a changing $T_{out, cold}$ than on a changing $T_{in, warm}$. Considering the HRF improvement of the ATES investigated, it is recommended to reduce $T_{out, cold}$ as low as technical and economical possible before changing $T_{in, warm}$. A lower $T_{out, cold}$ can be achieved with lower temperatures of the heat demanded and/or with lower temperature differences inside heat exchangers between the groundwater circuit and the heating circuit.

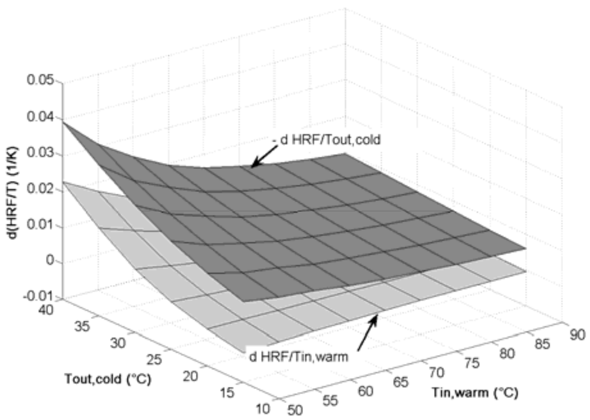

Figure 4: Derivative of HRF with respect to the temperature at warm well ($T_{in, warm}$) and cold well ($T_{out, cold}$), the derivative of HRF with respect to Tout, cold is shown with negative sign in order to compare the sensitivity

4.2.2 Effect of Volume Circulated and Volume Ratio (V_{out}/V_{in}) on the HRF

Because of heat conduction and the dispersion of heat the thermally influenced area within the aquifer is larger than the area considering convective heat transfer only. Consequently, it might be advantageous to circulate more volume while discharging than while charging since the level of the production temperature at the warm well enables further heat transfer to the heating circuit ($T_{out, warm}$ > $T_{out, cold}$). Identifying the effect of a higher volume circulated while discharging, the volume ratio V_{out}/V_{in} was varied from 1 to 1.5. The operation conditions for the charging period were a flow rate of 33.3m³/h and a duration of charging and discharging of 3000hr. The temperatures taken into consideration were varied between 50°C and 80°C for $T_{in,\ warm}$ and between 15°C and 35°C for $T_{out,\ cold}$.

The results show a flat optimal volume ratio depending on the temperatures $T_{out,\ cold}$ and $T_{in,\ warm}$ (Figure 5). The optimal volume ratio shifts to higher values with decreasing $T_{out,\ cold}$ and with increasing $T_{in,\ warm}$. The optimal volume ratio amounts to between 1.1 and 1.2 at a temperature $T_{out,\ cold}$ =35°C for each $T_{in,\ warm}$ investigated whereas the optimal volume ratio amounts to between 1.4 and 1.5 at a $T_{out,\ cold}$ =25°C. The optimal volume ratio which is higher than 1, disagrees with the conclusion given in Sauty (1982) valid for one well. Sauty has stated the highest efficiency for symmetrical (V_{out}/V_{in} = 1) storage cycles. Focusing on the results that represent a temperature $T_{out,\ cold}$ = 15°C the curves do not show an optimal volume ratio in the manner of an extremum. Considering an extended range of the volume ratio the curves increase continuously without reaching a extremum since the temperature $T_{out,\ cold}$ is below the natural aquifer temperature $T_{aquifer}$=20°C. Therefore the aquifer acts as an energy source.

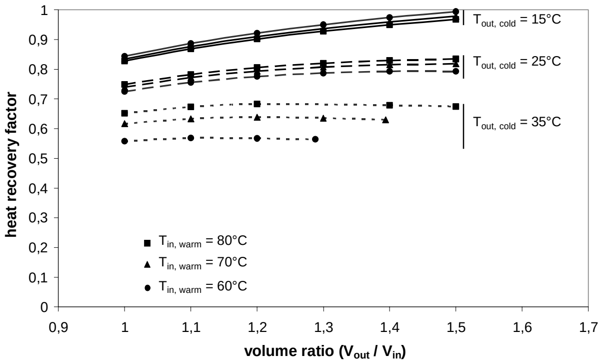

Figure 5: Effect of the volume ratio (V_{out} / V_{in}) on the HRF taking into account different injection temperatures at both wells for constant volume flow while charging (charging and discharging length 3000hr, charging volume flow rate 33,3m³/h)

Taking into account a volume ratio of 1 and varying the circulated volume per storage period between 25000m³ and 210000m³, the HRF increases with increasing water volume. This general characteristic can be observed for all temperature pairs $T_{in,\ warm}$ / $T_{out,\ cold}$ investigated (Figure 6) and is caused by the decreasing surface area to volume ratio ***A/V*** of the aquifer heated. The volume specific heat losses to the confining layers as well as to the aquifer are determined by the geometrical shape. Assuming the heated aquifer is cylindrical and has a given thickness ***H***, the surface area to volume ratio decreases with an increasing injected groundwater volume.

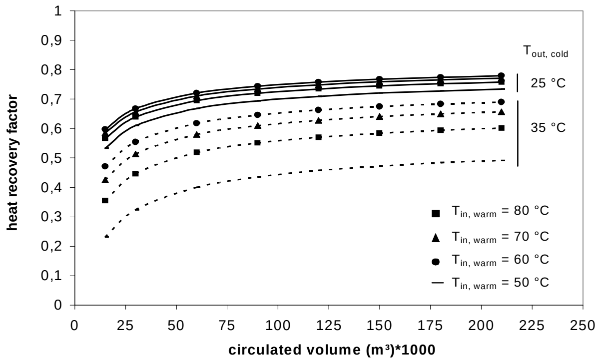

Figure 6: Effect of circulated volume on the HRF considering different injection temperatures at both wells (charging and discharging length 3000hr, V_{out} / V_{in} = 1)

4.2.3 Effect of Charged Energy on the HRF Considering Different Injection Temperatures at Both Wells

Taking into account a realistic ATES operation the charged thermal energy depends on the amount of surplus heat provided e.g. by CHP. Therefore, the effect of thermal energy charged was investigated considering reasonable amounts of surplus heat. The surplus heat considered ranges from 1000MWh/a to 5000MWh/a. Injection temperatures from 50°C to 90°C were considered at the warm well, and temperatures from 25°C and 35°C at the cold well (Figure 6). In general, the results show that the HRF increases with an increasing amount of stored thermal energy at constant injection temperature at the warm well. This characteristic is caused by the increasing volume circulated with an increasing amount of thermal energy (see 4.2.2). Considering now a constant amount of thermal energy (Figure 8) and a temperature $T_{out,\ cold}$ = 35°C, the HRF increases with increasing $T_{in,\ warm}$ even though the volume circulated decreases. In contrast, the equivalent curve representing $T_{out,\ cold}$ =25°C does not show any significant effect of $T_{in,\ warm}$ on the HRF. That means, considering a specific amount of thermal energy the effect of $T_{in,\ warm}$ on the HRF seems to be negligible at a temperature $T_{out,\ cold}$ slightly higher than the natural aquifer temperature.

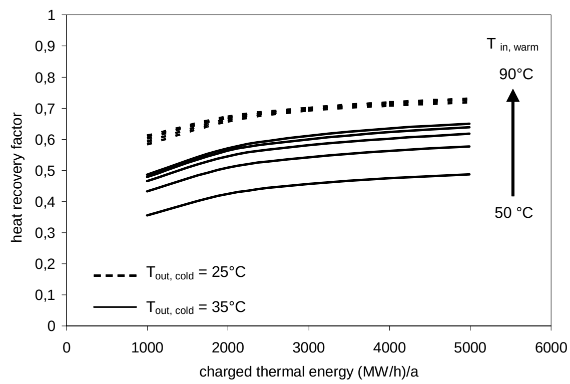

Figure 7: Effect of charged energy on the HRF considering different injection temperatures at both wells (charging and discharging length 3000hr, volume ratio V_{out}/V_{in} = 1)

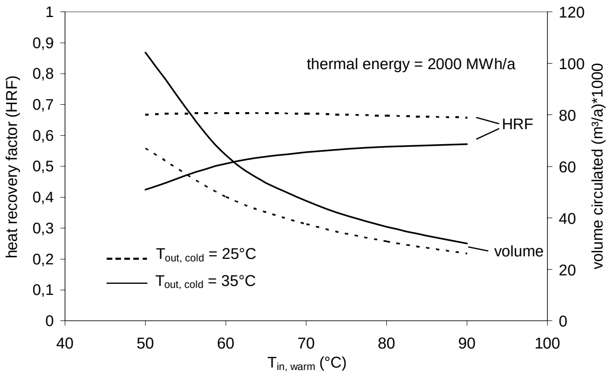

Figure 8: Effect of $T_{in,\ warm}$ on the HRF considering a constant thermal energy of 2000 MWh/a and a temperature $T_{out,\ cold}$ of 25°C and 35°C (charging and discharging length 3000hr, volume ratio V_{out}/V_{in} = 1)

SUMMARY AND CONCLUSION

The operation of the ATES system that is incorporated in the energy supply system of the German Parliament Buildings was analysed using measured operational data and two numerical ATES models. The dependency of the heat recovery factor on parameters reflecting the operation mode was investigated. These parameters are the volume circulated, the volume ratio, the temperature at the cold well while discharging, the temperature at the warm well while charging, and the amount of thermal energy stored. In general, the heat recovery factor increases with (a) an increasing circulated volume (b) an increasing amount of thermal energy stored and (c) a decreasing temperature at the cold well while discharging. Focusing on the temperature at the warm well while charging two different cases have to be taken into account. If the temperature at the cold well while discharging is lower than the natural aquifer temperature, the heat recovery factor increases with a decreasing temperature at the warm well. However, if the injection temperature at the cold well is higher than the natural aquifer temperature, the energy recovery factor increases with increasing storage temperatures at the warm well. For the operation of the investigated storage, a lower temperature at the cold well while discharging as well as a higher temperature at the warm well while charging will lead to an improved heat recovery factor.

Considering prospective ATES systems designed for direct heat provision, the injection temperature at the cold well should be as close as possible to the natural aquifer temperature. In this case the effect of the storage temperature at the warm well on the heat recovery factor is negligible and this storage temperature can be determined with focus on operation reliability and storage capability. With a lower temperature at the warm well e.g. the risk of storage damage due to dissolution and precipitation can be reduced.

Focusing on district heating systems, for which ATES systems are well applicable due to the large storage capacity, the conclusion means: the higher the temperatures needed in the heating system the higher should be the natural aquifer temperature, thus the aquifer depth.

ACKNOWLEDGEMENT

This research project is financially supported by the Federal Ministry of Economics and Technology under Grant No. BMWi 0329809C.

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