After the boom

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AFTER THE BOOM; EVALUATION OF DUTCH ATES-SYSTEMS FOR ENERGY EFFICIENCY

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ABSTRACT

Aquifer thermal energy storage (ATES) is a technology to sustainably provide space heating and cooling. Particularly in The Netherlands the number of ATES systems has grown rapidly in the past decade, often with the (re)development of urban areas. To meet objectives for greenhouse gas emission reduction the number of ATES systems is expected and required to further rise in future both in The Netherlands and elsewhere. To evaluate the lessons learned and the role of practical aspects in the Dutch development of ATES systems, in this study the geohydrological conditions and well characteristics for 331 (~15% of total) Dutch ATES systems are evaluated with respect to optimal well design for maximal thermal energy recovery. The study shows that well design of most (70%) ATES systems is suboptimal. The well design criteria that have been used thus far in practice, focus on allowing maximum flow/capacity, disregarding the effect of groundwater flow on efficiency and the effect of well design on subsurface space use. Instead, well design should be based on a more representative value for the storage volume that takes into account . Based on monitoring data and analysis of variations and uncertainties of the actual storage volume, a guideline is defined to reflect these in the storage volume used for design. Also a guideline for well design is introduced that accounts for both conduction and dispersion losses as well as advection losses in case of high ambient groundwater flow.

1. INTRODUCTION

Globally, there is a strong drive to meet energy demand sustainably. Seasonal Aquifer Thermal Energy Storage (ATES) systems provide sustainable heating to and cooling to buildings. Although the potential for using ATES systems depends both on climatic and hydrogeological conditions, the application of ATES has potential in many areas worldwide (Bloemendal et al., 2015) and is therefore expected to rise in the future. Although the potential of ATES systems is largely not deployed in many parts of the world, practical experience with ATES systems has been developed in several European countries and elsewhere (Blum et al., 2010; Eugster and Sanner, 2007; Fry, 2009; Verbong et al., 2001). Particularly in The Netherlands the number of ATES systems has grown rapidly in the past decade, often with the (re)development of urban areas. For an optimal development of ATES systems, maximizing the thermal recovery efficiency is crucial as well as minimizing the required subsurface space (Bloemendal et al., 2014; Willemsen, 2016). This depends on hydrogeological conditions, design aspects as well as operational aspects. Although, operational aspects are difficult to predict in detail, typical characteristics for ATES operation should be taken into account in the design and installation phase of a new ATES project As after installation it is relatively costly and complex to change the ATES well design, ATES wells should a-priori consider local hydrogeological conditions and characteristic ATES operational aspects to allow maximizing recovery efficiency and minimizing subsurface space use. The experience with the rapid development of ATES systems so far, may support optimal further development and use of ATES systems for sustainable heating and cooling in the future, both in The Netherlands and elsewhere.

2. MATERIALS AND METHODS

2.1 Theory of heat transport and storage

Thermal energy (cooling or heating capacity) in infiltrated water in the subsurface is subject to several processes which cause loss of the stored energy. The

processes are diffusion[1], advection, conduction and dispersion.

Energy losses due to mechanical dispersion and conduction

Water infiltrated by a an ATES well in an homogeneous aquifer occupies a cylindrical shaped volume in the aquifer. Rather than a sharp thermal interface between the infiltrated water and ambient groundwater, mechanical dispersion and heat conduction spread the heat over the boundary of the cold and warm water bodies around the ATES wells.

Losses due to mechanical dispersion and conduction occur at the boundary of the stored body of thermal energy. So to minimize these losses the surface area of the circumference and the cap and bottom of the thermal cylinder can be optimized by identifying an appropriate filter screen according to storage volume and local conditions. (Caljé, 2010; Gelhar et al., 1992)

Energy losses due to advection

Advection contributes to losses as when injected water is displaced with the natural groundwater flow, it can only partially be recovered. The thermal energy within the injected water volume moves at approximately half the speed of the water as a consequence of thermal retardation. The higher groundwater flow velocity relative to the thermal radius, the more significant the losses to the ATES system will be. To minimize these losses the thermal radius can be optimized by identifying an appropriate filter screen according to storage volume and hydrogeological conditions.

Reducing losses

To recover as much of the stored thermal energy as possible, the ratio between extracted and infiltrated energy per well (Equation 1a) is a measure for the thermal efficiency (η_{th}) of a well. The loss that occurs depends on the geometric shape of the thermal body of ground & groundwater, in this study simplified as a cylinder. The size of the thermal cylinder depends on the storage volume, filter screen length, water and aquifer heat capacity (Figure 1 and Equation 1b). The footprint of an ATES system is the surface area of the top of the thermally influenced cylinder around the well, described by the thermal radius (R_{th}); Equation 1.

$$\eta_{th} = \frac{E_{out}}{E_{in}} = \frac{\Delta T_{out} \cdot V_{out}}{\Delta T_{in} \cdot V_{in}} \quad (a)$$

$$R_{th} = \sqrt{\frac{c_w \cdot V_{in}}{c_{aq}} \cdot \pi \cdot L} \quad (b)$$

$$R_h = \sqrt{\frac{V_{in}}{n \cdot \pi \cdot L}} \quad (c)$$

$$R_{th} = \sqrt{\frac{n \cdot c_w}{c_{aq}}} \cdot R_h \approx 0,6 \cdot R_h \quad (d)$$

Equation 1, Thermal efficiency (a), thermal radius (b) the relation between thermal and hydraulic radius (c,d). R_{th}=Thermal radius [m], V=Storage volume groundwater [m³], η_{th}=Thermal efficiency [-],T =Temperature [°K], c_w =Specific heat capacity of water 4,2·10⁶ [J/kg/K], c_{aq}=Specific heat capacity of saturated porous medium 2,8·10⁶ [J/kg/K], n=porosity [-],L=Filter screen length [m]

Topview = footprint

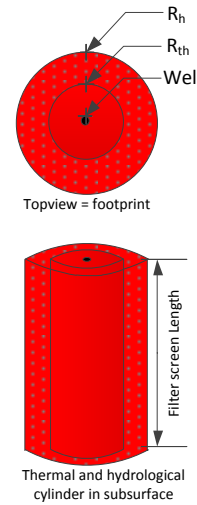Thermal and hydrological cylinder in subsurface

Figure 1: Schematic presentation of footprint and subsurface space use of thermal and hydrological cylinder

2.2 Data used

Permit data from Provinces

The data on the characteristics of ATES systems in The Netherlands used in this study, was obtained from provincial databases. Provinces are the local authorities with the task of permitting and enforcing ATES systems, they keep a database with characteristics of the ATES systems for which they issued a permit. Not all provinces register the same characteristics in their databases, and out of the twelve Dutch provinces only five (Gelderland, North-Brabant, North-Holland, Utrecht, Drenthe) keep data on the location, permitted yearly storage volume and filter screen length, resulting in a total of 331 systems suitable for evaluation.

Operational data

At an aggregated level, operational data of ATES systems has been used in regional and national studies and evaluations (CBS, 2005; SIKB, 2015; Willemsen, 2016) all showing that ATES systems yearly use 40-

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[1] Diffusion losses are negligible and therefore not discussed in this paper

60% of their permitted capacity. Local authorities keep a record of the yearly pumped groundwater, but cannot share that detailed information due to privacy regulations.

Geohydrological Data

Local geohydrological conditions affect the applied design ATES wells. For instance; when an aquifer has a limited thickness it is not possible to install a longer filter screen, or when the groundwater velocity is high, it may be more beneficial to have shorter filter screen lengths. Therefore the applied well design is evaluated with respect to the local geohydrological situation; the groundwater flow velocity, horizontal conductivity of aquifer and the aquifer thickness. This data is not available together with the characteristics of ATES systems in the provincial databases and collected separately from the Dutch Geologic databases (TNO, 2002a, b, c) based on the ATES locations. For a geographically representative subset of 204 ATES systems it was possible to retrieve local hydrogeological data for all ATES systems.

For the following hydrogeological parameters data was abstracted and processed for the aquifer regionally targeted for ATES systems:

- Hydraulic conductivity. (TNO, 2002a, c)
  Hydraulic conductivity values are for each location provided as a range defined by a minimum and maximum value. The average of both extremes was used.
- Groundwater head gradient. (TNO, 2002b)

- Aquifer thickness. (TNO, 2002a, c)
  The aquifer thickness is used to identify how much filter screen length can reasonably be expected to installed for each ATES system.

2.3 Numerical modeling tools

To realistically simulate subsurface groundwater flow and heat transport, a geohydrological model was developed using MODFLOW (USGS, 2000) and MT3DMS (Zheng and Wang, 1999) (Hecht-Mendez et al., 2010). MODFLOW and MT3DMS are finite-difference element packages and well-established models, widely used for the simulation of groundwater flow and transport.

3. RESULTS AND DISCUSSION

3.1.2 Size and design of ATES systems

The permitted capacity of the ATES systems ranges up to 5000,000 m3/year but most (~70%) are smaller than 500.000 m^3/year (Figure 2).

The regional differences in ATES system characteristics are limited (Table 1), only Drenthe has relatively small systems with limited variation. The standard deviation of the other permit capacity varies between 80% and 95% of average capacity. The installed filter screen lengths are again similar again with Drenthe a bit off, as a consequence of the relatively small systems there. Noord-Holland shows a bit larger installed filter screens, which may be caused by the relatively large systems in combination with the known thick aquifers which are present there.

Table 1, ATES system and geohydrological characteristics in provincial datasets selected for this study

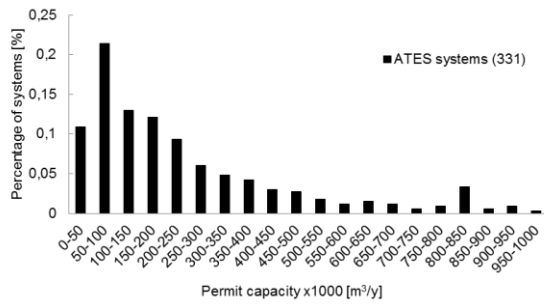| Province	Number of ATES systems	Average permit capacity	St. deviation of Per. capacity	Average of L installed	Average Aqiufer Thickness	Average Hydraulic conductivity	Average Groundwater flow
unit	*[-]*	*[m³/y]*	*[m³/y]*	*[m]*	*[m]*	*[m/d]*	*[m/y]*
Drenthe	11	87.627	49.340	18	144	20	24
Gelderland	28	197.982	167.715	28	79	42	49
N-Brabant	172	210.754	199.244	28	60	28	23
N-Holland	95	282.946	228.893	43	144	33	6
Utrecht	25	349.620	296.958	33	121	21	10
Total	**331**	**236.790**	**216.988**	**32**	**96**	**30**	**18**

Figure 2, Frequency distribution of selected dataset according to yearly storage volume

3.1.2 local conditions

ATES systems are spread over the whole of The Netherlands, but are concentrated in urban areas. Table 1shows the geohydrological characteristics of the ATES systems location. Both hydraulic conductivity and groundwater flow velocity vary little, only the

groundwater flow in Gelderland is higher as a consequence of pushed/inclined aquifers. The variation is larger for the aquifer thickness, caused by local differences in aquifer thickness.

3.1.3 Practical considerations; consequences of dynamic pumping regimes

To make a thorough assessment of the well design of the ATES systems in the selected data it should be evaluated based on the actual storage volume. The storage volume of groundwater for each well depends on the energy demand of the building over time, which in turn depends on use, type and quality of building and weather conditions. To anticipate on climate changes, extreme seasons and allow future growth in future the permitted capacities are generally larger than the actual stored capacities during operation .

Table 1, ATES system and geohydrological characteristics in provincial datasets selected for this study

Province	Number of ATES systems	Average permit capacity	St. deviation of Per. capacity	Average of L installed	Average Aqiufer Thickness	Average Hydraulic conductivity	Average Groundwater flow
unit	[-]	[m³/y]	[m³/y]	[m]	[m]	[m/d]	[m/y]
Drenthe	11	87.627	49.340	18	144	20	24
Gelderland	28	197.982	167.715	28	79	42	49
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Utrecht	25	349.620	296.958	33	121	21	10
Total	331	236.790	216.988	32	96	30	18

Several evaluations of ATES systems at an aggregated level, show that ATES systems use 40-60% of their permitted capacity (CBS, 2005; SIKB, 2015; Willemsen, 2016). What further reduces the total maximum stored volume during the year is that the storage volume is not injected in once. Particularly in spring and fall an ATES system may operate alternating in heating and cooling mode. However small, this also has a reducing effect on the maximum stored volume during a year. In contrast, the permitted stored volume may be incidentally exceeded due to seasonal extremes which may cause temporal imbalances. Demand for heating and cooling does not balance every year, e.g. excess heat may accumulate in warm wells during a couple of warm winters until a very cold winter depletes the warm well. The effect of these aspects is illustrated by different scenarios for the   cumulative build-up of injected volume for a

warm well of a fictitious ATES system and monitoring data of several ATES systems;

1. All in once pattern. This energy demand profile is often used to assess ATES-systems; the total yearly storage volume is infiltrated and extracted during a relatively short period, with a period of rest in between.
2. Gradual pattern. The yearly storage volume is infiltrated and extracted gradually over the year, during spring and fall infiltration and extraction alternate.
3. Weather dependent demand pattern based on the storage volume variation expected based on the monitored outside air temperature (2020-2010) of the weather station of De Bilt in The Netherlands (KNMI, 2013). The energy demand pattern is derived from the relative deviation of the daily temperature from the average outside air temperature of

the evaluation period. So at the end of the evaluation period there is energy balance, but due to seasonal variations, imbalances occur over the years.

The effect of these patterns on the storage volume over time is shown in Figure 3, and shows that, for the different demand patterns, the maximum storage volume of weather dependent energy demand profile uses 70% of the permit capacity. This is confirmed by Willemsen (2016), who also looked at imbalances and found that the standard deviation of imbalances over 5 year periods is around 30%.Thus, to make a fair comparison, the well design will be evaluated based on the expected maximum storage volume; which is approximately 75% of the permitted capacity, or around 150% of the expected yearly average storage volume.
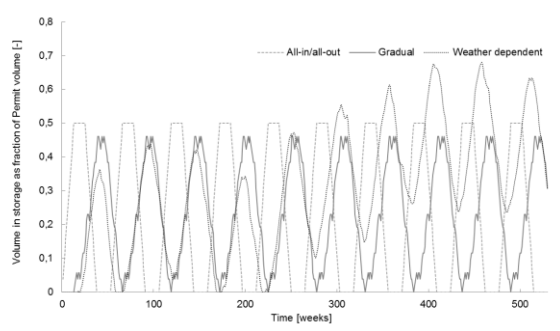

Figure 3, Volume in storage of well for different energy demand patterns

3.2 Analytical evaluation of ATES
3.2.1 Loss of thermal energy due to dispersion and conduction

Relation between storage volume and optimal filter screen length

Since heat dispersion and conduction occur at the boundary of the thermal cylinder (Figure 1), minimizing its total surface area (*A*) should improve the recovery efficiency. Figure 4 shows the relative contribution of the circumference and cap and bottom to the total surface area of the thermal cylinder in the aquifer. This reveals that the surface area has a flat minimum around L/R_{th}=2. Because dispersion dominates around the circumference while conduction dominates at the "cap & bottom" of the cylinder (section 2), optimizing well design requires to distinguish between the two to account for the reduced conduction losses to confining layers after several storage cycles (Doughty et al., 1982). Doughty et al.(1982) showed that efficiency increases with the number of storage cycle to an equilibrium, they found

that the optimal ratio between filter length and thermal radius (L/R_{th}) has a flat optimum around 1,5. The optimal L/R_{th}-ratio is lower because over multiple cycles, the conduction losses to "cap & bottom" reduces. Applying this rule to larger storage volumes increases the overall efficiency because the surface area of the "thermal cylinder" relative to the storage volume decreases with increasing storage volume.
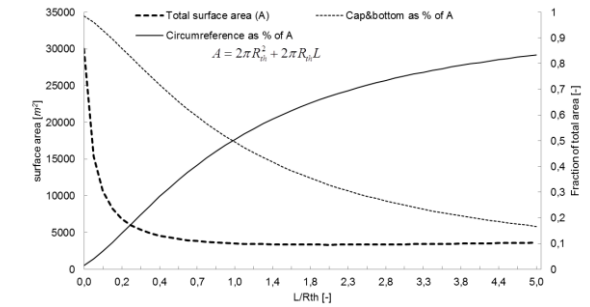

Figure 4: Relation between surface area of cap & bottom and circumference area of thermal cylinder for different filter screen lengths (1-25m and a storage volume of 500 m^3

Substituting the expression for the thermal radius (R_{th}) in the optimal relation of L/R_{th}=1,5 gives the optimal filter screen length (*L*) as a function of storage volume (*V*), Equation 2 (a-c). Substituting the expression for thermal radius in the formula for the surface area of the thermal cylinder (Figure 4), and equating its derivative to zero results in a similar expression for optimal filter screen length according to Doughty et al. Equation 2 (d-f) shows that the solution for the filter screen length results in the same third root of the storage volume, only with the constant 1,23 instead of 1 for (Doughty's) optimal solution. From the relation between surface area of circumference and cap & bottom (Figure 4) can be seen that this effect implies that shorter filter screens are more beneficial than simply minimizing the thermal cylinders' surface area.

$$L = \sqrt[3]{2.25 c_w V \Big/ c_a \pi} \quad (a)$$

$$L = c_{doughty} \sqrt[3]{V} \quad (b)$$

$$c_{doughty} = \sqrt[3]{2.25 c_w \Big/ c_a \pi} = 1.02 \quad (c)$$

$$A = 2 \frac{c_w V}{c_a L} + 2\pi \sqrt{\frac{c_w V}{\pi c_a L}} L \quad (d)$$

$$A' = \frac{-2\pi c_w V}{c_a L^2} + \pi \sqrt{\frac{c_w V}{\pi c_a}} \frac{1}{\sqrt{L}} \quad (e)$$

$$L = c_{analytical} \sqrt[3]{V} \quad (f)$$

$$c_{analytical} = \frac{2c_w}{c_a\pi\sqrt{\dfrac{c_w}{\pi c_a}}} = 1.23 \quad (g)$$

Equation 2, (a-c) Optimal filter screen length as a function of storage volume (Doughty et al., 1982). (d-f) filter screen length for minimizing the surface area of the thermal cylinder. L=Filter screen length [m], V=Storage volume groundwater [m³], c_w =Specific heat capacity of water 4,2·10⁶ [J/kg/K], c_{aq}=Specific heat capacity of saturated porous medium 2,8·10⁶ [J/kg/K]

The Dutch guidelines for design of ATES wells do not give a clear guideline or formula to determine the filter screen length with respect to storage volume (NVOE, 2006). In the guidelines determination of filter screen length is mainly based on maximum desired flow rate. The relation between filter screen length, storage volume and thermal losses is briefly discussed and concluded with the advice to choose a filter screen length which creates a relatively "flat cylinder". From this guideline we conclude that Dutch ATES systems are supposed to have a filter screen length equal or shorter than the optimal filter screen length with respect to the expression for filter screen length given in Equation 2 (a-c). Although no formula is given, this approach corresponds with Doughty's rule.

Evaluation of the installed filter screen lengths
Equation 2 (l) is now used to assess the installed filter screen lengths of the ATES systems in the dataset. From the results of the analysis in Table 2 can be seen that on average filter screen lengths are designed too short, the average value for L/R_{th} of the installed systems is 74% of what they should be according to Equation 2; 1,1 instead of 1,5. When the optimal and installed filter screen lengths are plotted with respect to storage capacity (Figure 5) it becomes clear that most systems (~76%) have a too short filter screen. As is shown in Figure 4, also Doughty found a flat optimum for L/R_{th}-value, thus it can also be accepted when the L/R_{th}-value is between 1 and 4 (Doughty et

al., 1982). In that case 53% of the systems has a too short filter screen and three systems have a too long filter screen, Figure 5.

Effect of geohydrological conditions on well design
The design and practical aspects discussed above were used to compare the applied filter screen length with thickness available in the aquifer. After analysis of the local aquifer thickness it appears that 40% of the ATES systems with a too short filter screen have space available to make it longer, of which 82% have space available to meet the optimal length. So in total about one third of the ATES systems has a too short filter screen but with enough space available to make it longer.
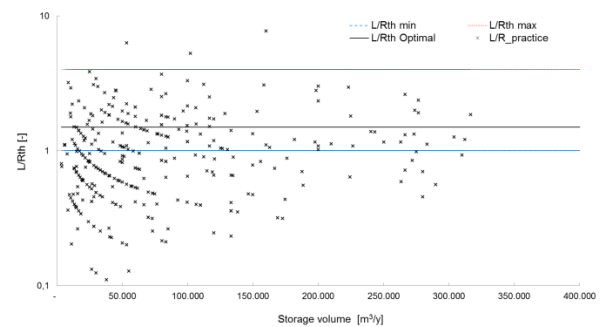

Figure 5, L/R_{th} relative to storage volume

The aquifer thickness found in the data was corrected to have sufficient clearance between filter screen and confining aquitards and to take account for variations in aquifer thickness, considering that the source data only gives a rough indication of aquifer thickness. Legal boundaries were also included, for instance in Noord-Brabant it is not allowed to install ATES systems deeper than 80 m below surface level, so any aquifer available below 80 is disregarded in the evaluation. As a result of this correction the space available for filter screen length used for evaluation may in some cases be underestimated.

Table 2, ATES system filters screen length in practice compared to optimal design, L optimal is Doughty

	Capacity / well	L installed	L optimal	L installed / L optimal	L/Rth
	[m³/y]	[m]	[m]	[m]	[-]
10th percentile	16.000	12	25	0,4	0,4
average	80.000	33	43	0,74	1,1
90th percentile	200.000	56	59	1,26	2,1

3.2.2 The effect of ambient groundwater flow on recovery efficiency

Relation between groundwater flow and energy losses
Additional to the thermal losses that occur through conduction and dispersion, ambient groundwater flow may increase thermal energy losses significantly, as it displaces the stored volume before recovery. Under these conditions, a body of water in a flowing aquifer can only be partly extracted by the well which was used for infiltrating that water body (Bear and Jacobs, 1965). The overlapping surface area of the thermal footprints before and after the volume of thermal energy has moved with the groundwater flow is equivalent to the storage efficiency relative to groundwater flow, Figure 6.
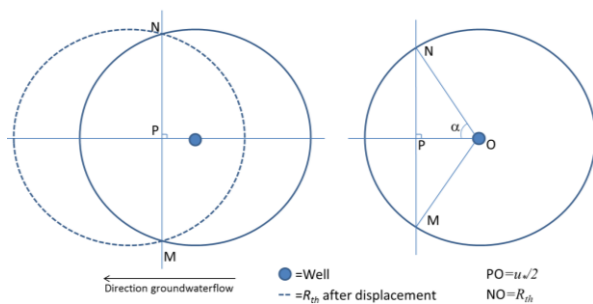

Figure 6, calculating the overlapping surface area of 2 identical cylinders.

To obtain maximum efficiency the overlapping area of the thermal footprint must be maximized, in areas with high groundwater flow velocity this can be achieved by increasing the thermal radius; thus reducing the filter screen length. This simple approach is used to assess well design of ATES systems in areas with ambient groundwater flow. So for any groundwater flow velocity it is required to identify a minimal thermal radius to obtain a sufficient recovery efficiency during operation of an ATES system in that specific aquifer. Goniometric rules allow to express thermal radius as a function of groundwater flow velocity, substituting a desired minimum efficiency condition results in a design condition dependent on flow velocity (u) and the thermal radius; Equation 3. The velocity of the thermal front (u_*) is QO in Figure 6. Equation 3 shows that the relation between groundwater flow and efficiency only depends on thermal radius, so for any storage volume and filter screen length there is a single R_{th}/u-value indicating the expected losses through groundwater flow. Therefore the R_{th}/u-value is used to evaluate the ATES systems design.

Equation 3 shows that for each desired efficiency (η_{th}) there is a minimum value for the ratio of R_{th} and u.

This relation is plotted in Figure 7 and can be used to identify minimum desired thermal radius (i.e. maximum desired filter screen length for a given storage volume) at a location with a given groundwater flow velocity.

$$A_{overlap} \geq \eta_{th} \cdot A_{footprint}$$

$$A_{footprint} = \pi \cdot R_{th}^2$$

$$A_{overlap} = 2 \cdot R_{th}^2 a\cos\left(\frac{u_*}{2R_{th}}\right) - u\sqrt{R_{th}^2 - \frac{1}{4}u_*^2}$$

$$\frac{2}{\pi} a\cos\left(\frac{u_*}{2R_{th}}\right) - \frac{u_*}{\pi \cdot R_{th}^2}\sqrt{R_{th}^2 - \frac{1}{4}u_*^2} \geq \eta_{th}$$

Equation 3, Calculating the overlapping surface area of 2 cylinders. A **=Surface area [-],**η_{th}**=Thermal efficiency [-],** R_{th}**=Thermal radius [m],** u_***=Velocity of the thermal front [m/y]**

To verify this approach numerical MODFLOW simulations were used to reproduce the relation of thermal radius, groundwater flow velocity and efficiency. For different sizes of systems with different groundwater flow velocities the recovery efficiency was calculated. The numerical simulation results are also plotted in Figure 7, which shows that the analytical relation over-estimates the efficiency significantly. This makes sense because the numerical model also includes losses due to dispersion and conduction which are not taken into account in the analytical approach to evaluate losses due to groundwater flow. To take account for this effect the numerical results were normalized to obtain the efficiency loss as a consequence of the groundwater velocity only. This was done by relating the efficiency of the simulation with groundwater flow to the associated simulation without groundwater flow (e.g. normalized result for u= 5 m/y; $\eta_5 = \eta_0/\eta_5$). The normalized efficiencies show a better resemblance with the analytical relation; RMSE=0,14. The difference is caused by dynamical aspects; the analytical solution evaluates the advection of an completely filled storage well, while in practice and in the numerical model the losses already start to occur at first injection of (warm/cold) water.

The relations in Figure 7 show that for high flow velocity and/or small thermal radius ($R_{th}/u < 2$) losses through background groundwater flow are dominant. While at low velocity and or large thermal radius ($R_{th}/u > 4$) conduction and dispersion is dominant; efficiency is constant. In between ($2 < R_{th}/u < 4$) both are important.
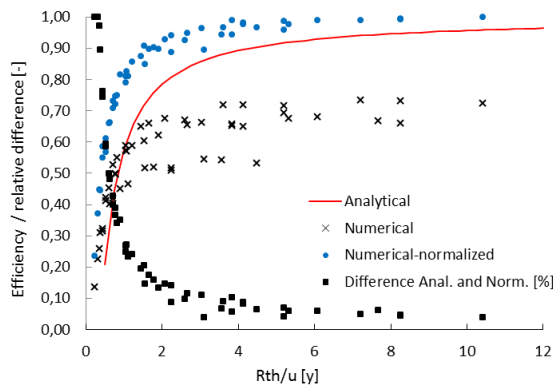
Figure 7, Relation between thermal radius and groundwater flow velocity for different desired efficiencies

Evaluation of the installed filter screen lengths
For each of the ATES systems in the data the R_{th}/u–value was determined, the relation given in Figure 7 and Equation 3 are used to indicate lines of expected thermal efficiency, Figure 8. From this can be seen that many systems (44%) have an expected efficiency lower than 80% ($R_{th}/u<2,3$) only taking into account losses due to ambient groundwater flow. In addition, depending on the optimality of L/R_{th} the actual efficiency is further reduced (Figure 7).
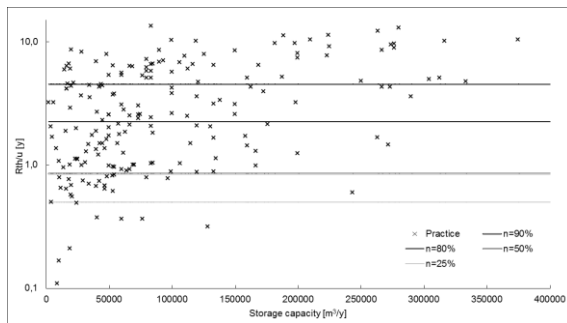

Figure 8, R_{th}/u-values for ATES systems in the dataset with thresholds for different efficiencies

Losses incurred by ambient groundwater flow are in addition to those by conduction and dispersion. There is no guideline (NVOE, 2006) or method available to take account for these losses in well design. Defining a minimum acceptable efficiency allows to find an appropriate (maximum) filter screen length, Equation 3. From simulations and monitoring data we know that thermal efficiency from ATES well ranges from 70-90% (Figure 7, Willemsen, 2016, Sommer, 2015, Caljé, 2010, NVOE, 2006).These efficiencies also include losses due to groundwater flow velocity, therefore an acceptable thermal efficiency due to groundwater flow is assumed to be in the same order of magnitude; 80%. To identify the minimum thermal radius a 20% loss due to groundwater flow velocity is used as threshold.

The analysis shows that 66%of the systems has an appropriate filter screen length. Table 3 shows the systems characteristics and groundwater flow velocity of the systems which do and do not meet the desired size of the thermal radius. This shows that groundwater flow velocities around 29 m/y start to cause problems and mostly smaller systems suffer from losses due to ambient groundwater flow. The results from the analysis confirm what logically follows from Figure 7, smaller thermal radii (i.e. smaller ATES systems) are most vulnerable for significant losses as a consequence from ambient groundwater flow.

3.2.3 Combined results loss of thermal energy by, advection, conduction and dispersion
For a particular storage volume, increasing the thermal radius (decreasing filter screen length) will lead to reduced losses by ambient flow. However, at $R_{th}/u >4$ the benefit of increasing R_{th} decreases and care should be taken not to decrease L/R below 1-2 (Figure 4) as this would result in a strong decrease in the loss by conduction (and dispersion). Assessing the ATES systems to both relations, 6 types of systems can be identified as shown in Table 4 and Figure 9. From this can be seen that 27% of the systems (types C, E and F) have a too long filter screen mainly because of high groundwater flow velocity, in Figure 9 can be seen that these are mainly small systems. Of the 24% of the systems which need a longer filter screen (type B), 68% has space available to do so (17% in total). Type D systems meet both requirements. The most challenging systems are the type A systems, which should have a longer filter screen to minimize conduction and dispersion losses, while the groundwater flow velocity would require a shorter filter screen.

Table 3, Results of analysis of filter screen length with respect to groundwater flow velocity

	average u	average V
	[m/y]	[m^3/y]
$\eta < 80\%$	5	154.307
$\eta > 80\%$	29	62.617

From this can be seen that depending on the size of ATES system and groundwater flow velocity, efficiency of ATES wells is dominated either by conduction and dispersion, advective transport due to ambient groundwater flow or a combination of the two. To get grip on the thresholds and transition area from one rule to another, both rules can be combined.

Figure 10 shows the relations for optimal filter screen length for Doughty and groundwater flow velocity combined and plotted together with the ATES systems characteristics associated with the required L/R_{th}-value for different ambient groundwater flow velocities. The obtained relations are a weighted average of the two rules with the ambient groundwater flow velocity as weighing factor; because the higher the groundwater flow velocity, the higher its impact on the desired L/R_{th}-value.
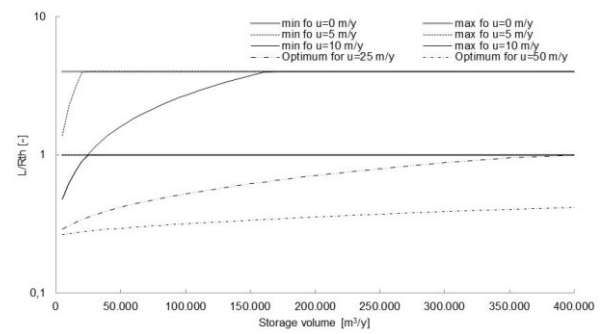
Table 4, Results of combined requirements for optimal filter screen length

Doughty condition	Ground-water flow condition	$\eta < 80\%$	$\eta > 80\%$
	Condition	L is too long	L is ok
$L/R_{th} < 1$	L is too short	A = 18% **L is.. #unknown#**	B = 24% **L is too short**
$1 < L/R_{th} < 4$	L is ok	C = 26% **L is too long**	D = 29% **L = ok**
$L/R_{th} > 4$	L is too long	E = 0% **L is too long**	F = 1% **L is too long**

Figure 9, Different types of ATES systems with respect to requirements for optimal filter screen length

3.2.4 Conclusions from analytical analysis

In this analysis, analytical solutions were used and combined to assess the ATES well design, therefore the ATES storage was simplified as a cylinder during operation. Rules and relations available in literature were used and where necessary new rules were derived. In at least 52% of the cases the filter screen length is not optimal, for another 18% it is not clear. For only 29% of the assessed ATES system it is safe to assume that based on the expected storage volume the installed filter screen is optimal. Incorporating the (thermodynamic) processes which occur in the aquifer in more detail, may give a better insight in the aspects influencing thermal efficiency and how to deal with the type A, B,C and F system types. This however is future research.

Figure 10, Optimal L/R_{th} for Doughty and groundwater flow combined

3.5. Discussion

In practice however, more complex hydrological and thermodynamic processes occur which are not taken into account in this analytical analysis. To verify the validity of the (combined) analytical rules and the conclusions drawn from them in this work, it is required to incorporate the operational aspects like uncertainty and variations in seasons and assess the effect of well design on efficiency accordingly. Therefore next steps in this research is to carry out a Monte-Carlo analysis using multiple secnario's to simulate ATES efficiency with a numerical geohydrological model.
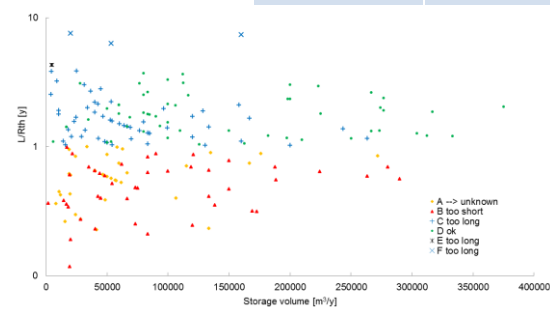
Storage volume as a cylinder

In this research the thermal energy storage in the subsurface was simplified as a thermal cylinder. However in practice ATES wells may have a more ellipsoidal shaped footprint instead of circular as a consequence of ambient groundwater flow and/or neighboring systems. The effect of this on the method followed in this research is limited because the losses due to groundwater flow are taken into account.

Also the effect of neighboring wells is limited because of the reciprocal principle; in one season a neighboring ATES well may cause increased losses, but the next season it will push back the lost water because it will then also load its well again with thermal energy. This is under the assumption that both systems have a more or less energy balance, which is a Dutch legislative requirement for ATES systems.

ATES systems in aquifer with high groundwater flow velocity

Where groundwater velocity is high, filter screen lengths should be shorter to limit losses due to advection. This simultaneously results in larger thermal radii. It might be a better strategy to identify how two warm and two cold wells can be used to optimize the overall efficiency by infiltrating in an upstream and extracting from a downstream well

(Groot, 2014). In many areas however this might not be possible or desirable because of other buildings in the close vicinity who also have or want to install an ATES system. In such areas it makes sense to use planning and organizational procedures to optimize ATES well positions, to prevent negative interaction, which is likely to result in the fact that filter screens can be longer or a vertical separation of filter screens over the depth of the aquifer.

<u>ATES systems in densely built areas</u>

Planning of subsurface space occurs based on the thermal footprint (Figure 1) of an ATES well projected at surface level. As a consequence, the subsurface space use depends on the presence of neighboring systems, storage volume (operational aspect) and filter screen length (design aspect). In areas with many ATES systems mutual interaction is likely to occur, and an integrated approach like was proposed by Bloemendal et al. (2014) or masterplans (Arcadis et al., 2011; Li, 2014) are a more appropriate way to organize optimal use of the subsurface. However, also in these situations the recommendations from this study will be useful; in such areas it is very wise to make optimal use of the available aquifer thickness and reduce thermal radii, which requires longer filter screens.

Because of accumulation of ATES systems in urban areas, scarcity of space in urban aquifers is occurring (Bloemendal et al., 2014; Hoekstra et al., 2015). Recently it was shown that scarcity of space for ATES is expected to occur in the near future in many cities in Asia and the United States, among others (Bloemendal et al., 2015). Several studies showed that there is a tradeoff between individual well efficiency and overall greenhouse gas emission savings in an area densely populated with ATES systems (Jaxa-Rozen et al., 2015; Li, 2014; Sommer, 2015). With that in mind, the question arises to what extent subsurface space designated for ATES systems is optimally taken advantage of, in current ATES planning and operation practice, which is focused on protecting existing permitted ATES systems (Schultz van Haegen, 2013). The facts that ATES systems use only 75% of the permitted volumes, the safety margin around the wells and that in many cases the filter screens are shorter than optimal as shown in this study, results in a underutilization of roughly 30% of the available subsurface space in urban areas with many ATES systems. These observations indicate that subsurface space use (i.e. the projected thermal footprint at surface level) of ATES systems is much bigger that would be the case when taking into account optimal storage volume and filter screen length.

Practical aspects
- Longer filter screens may have another advantage worth mentioning; a longer filter screen results in lower groundwater flow velocity around the well. This reduces the mobilization of particles in the aquifer and with that risk of clogging of the well (Beek, 2010; NVOE, 2006). This will have a positive effect on the life time and maintenance requirement for the wells.
- In tube wells often the infiltrated and extracted water is not evenly distributed over the filter screen (Houben, 2006; Korom, 2003; Sommer, 2015). When relying on longer filter screens for efficiency or planning purposes, practical operation must ensure even distribution over the filter screen otherwise this effect may frustrate the ATES well efficiency and/or subsurface space use. Ensuring evenly employment of the filter screen may be ensured by using multi partially penetrating screens, special filter screens or pump inflow tubes at different depths.

6. CONCLUSION

Well design

Thus far, well design is mainly based on the tradeoff between maximum capacity (flow rate) of the wells and drilling cost. This research provided simple methods to design wells taking into the wells thermal efficiency. This research also showed that with respect to the recovery efficiency, the optimal filter screen length has a flat optimum which limits this problem. Because of the flat optimum and the effect of short filter screens on the thermal footprint of the ATES system it is recommended to make them longer in areas with low groundwater flow velocity and/or scarcity of space in the aquifer.

Ambient groundwater flow

In case of high groundwater flow velocity it is recommended to apply the analytical rule for well design derived in this paper. Groundwater flow is summarily taken into account while designing ATES wells in the Netherlands because design guidelines were not available. This lack on insight is reflected in the ATES well design of installed systems in areas with groundwater flow, in most cases the well design is not optimal.

Storage volume

The estimated storage volume which is used as a basis for well design is of crucial importance. Variation in yearly storage volume, groundwater flow, conduction and dispersion need to be taken into account. Climate data and aggregated monitoring data indicate that a proper yearly storage volume to base well design on,

is 75% of the permitted value. Using the permitted volumes as a basis for well design would not result in the best/highest efficiencies and would also lead to too big spatial claims.

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