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Abstract

Aquifer Thermal Energy Storage (ATES) systems contribute to reducing fossil energy consumption by providing sustainable space heating and cooling for buildings by seasonal storage of heat. ATES is important for the energy transition in many urban areas in North America, Europe and Asia. Despite the modest current ATES adoption level of about 0.2% of all buildings in the Netherlands, ATES subsurface space use has already grown to congestion levels in many Dutch urban areas. This problem is to a large extent caused by the current planning and permitting approach, which uses too spacious safety margins between wells and a 2D rather than 3D perspective. The current methods for permitting and planning of ATES do not lead to optimal use of available subsurface space, and, therefore, prevent realization of the expected contribution of the reduction of greenhouse gas (GHG) emissions by ATES.

Optimal use of subsurface space in dense urban settings can be achieved with a coordinated approach towards the planning and operation of ATES systems, so-called ATES planning. This research identifies and elaborates crucial practical steps to achieve optimal use of subsurface space that are currently missing in the planning method. Analysis from existing ATES plans and exploratory modeling, coupling agent-based and groundwater models were used to demonstrate that minimizing GHG emissions requires progressively stricter regulation with intensifying demand for ATES. The simulations also quantified both the thresholds beyond which such stricter rules are needed as well as the effectiveness of different planning strategies, which can now effectively be used for ATES planning in practice.

The results provide scientific insight in how technical choices in ATES well design, location and operation affect optimal use of subsurface space, and what trade-offs exist between the energy efficiency of individual systems

and the combined reduction of the GHG emissions from a plan area. The presented ATES planning method following from the obtained insights now fosters practical planning and design rules suitable to ensure optimal and sustainable use of subsurface space-- that is, maximizing GHG emission reductions by accommodating as many ATES systems as possible in the available aquifer, while maintaining a high efficiency for the individual ATES systems.

Keywords: Aquifer thermal energy storage (ATES), ATES planning, optimal use of subsurface space

Nomenclature

A_{Ap}	=	Surface area of ATES plan under consideration [m^2]
A_b	=	Surface area of buildings in ATES plan [m^2]
c_{aq}	=	Volumetric heat capacity of saturated porous medium; 2.8 x 10^6 [$J/m^3/K$]
c_w	=	Volumetric heat capacity of water; 4.2 x 10^6 [$J/m^3/K$]
COP_{hp}	=	COP heat pump; 4 [-]
COP_c	=	COP chiller; 3 [-]
COP_b	=	COP boiler; 0.9 [-]
D_{same}	=	Multiplier for thermal radius for well distance between same type of wells [-]
$D_{opposite}$	=	Multiplier for thermal radius for well distance between opposite type of wells [-]
Δp	=	Hydraulic resistance or required pressure increase [$kg/m/s^2$]
E	=	Energy [J]
e_{fg}	=	Emission factor for electricity; 0.157 (Harmelink et al., 2012) [tCO_2/GJ]
e_{fe}	=	Emission factor for gas; 0.056 (Harmelen and Koch, 2002) [tCO_2/GJ]
FSI	=	Floor space index [-]
F_A	=	Allocated surface area fraction for ATES [m^2/m^2]
F_s	=	Allocated aquifer space fraction for ATES [m^3/m^3]
g	=	Gravitational acceleration; 9.81 [m/s^2]
L	=	Filter screen length [m]
L_a	=	Aquifer thickness [m]
n	=	Porosity [-]
η_{th}	=	Thermal efficiency [-]
η_p	=	Pump efficiency; 0.25 [-]

P	=	Thermal or electrical power [J/s]
ρ	=	Water density; 1,000 [kg/m^3]
Q	=	Hourly pumping rate of ATES wells [m^3/hr]
R_{th}	=	Thermal radius [m]
T	=	Temperature [°C]
V	=	Yearly storage volume of groundwater [m^3/y]

1. Introduction

ATES contributes considerably to GHG emission reductions

Many governments and companies set targets to reduce greenhouse gas (GHG) emissions (EU, 2010; Ministry-of-Economic-affairs, 2016; SER, 2013; UN, 2015). To meet these goals, the heating and cooling demand in the built environment is important because it consumes about 40% of the total fossil energy worldwide (EIA, 2009; Jong, 2016; RHC, 2013). Aquifer Thermal Energy Storage (ATES) systems contribute to reducing energy consumption by providing sustainable space heating and cooling for buildings through seasonal storage of heat in aquifers (e.g. (Cabeza et al., 2015; Kranz and Frick, 2013)). ATES potential is present in areas with moderate climate and suitable aquifers (sandy layers with groundwater). Bloemendal et al. (2015) showed that such areas can be found around the world in the eastern part of North America, Europe and Asia. The potential contribution of ATES systems to the reduction of fossil fuel consumption by the built environment is estimated at 11% in the Netherlands (Naber et al., 2016), a country with high potential for ATES. This potential warrants exploring this technology in depth to allow utilization to its full technical and societal potential (MacKay, 2008).

ATES systems put pressure on subsurface space use in urban areas

ATES systems typically concentrate in urban areas. ATES wells have to be placed close to their associated building to limit connection costs and heat losses during transport. In addition, neighboring wells of different temperatures should be placed at a given minimum distance from each other to reduce thermal losses. These spatial constraints lead to scarcity of and competition for the available subsurface space. Bloemendal et al. (2015) show that such problems associated with implementation of ATES in dense urban settings in the Netherlands will also arise in cities around the world.

ATES demand continues to exceed available subsurface space

Around 2,000 ATES systems were operational in The Netherlands by the end of 2015 (Graaf et al., 2016; Willemsen, 2016). This number, however, represents only a modest adoption level at about 0.2% of the 1.1 million non-domestic/utility buildings present in the country (CBS, 2016). Even with this limited level of application, the number of ATES systems has grown to congestion levels in many city districts. The expected adoption level of ATES in 2050 is, however, about 100 times larger (Naber et al., 2016), which implies that this problem will grow considerably in the coming decades.

Under current practice and rules, ATES systems are granted too much subsurface space

Like in other countries, ATES planning and permitting in the Netherlands strongly focuses on protecting existing interests; the precautionary principle is followed (Haehnlein et al., 2010; Schultz van Haegen, 2013), due to which a spacious safety margin around the wells is obligatory so as to prevent mutual interaction. On top of that, monitoring data shows that ATES systems generally use less than 50 % of their permitted capacity (Willemsen, 2016); ATES users generally claim too much subsurface space in their permit requests. The current rules do not lead to maximum beneficial use of available aquifer space because it is currently still based on 2D allocation of space, while this allocation is in fact a 3D planning problem. The distance between ATES systems is logically based on the thermal radii of wells, i.e. the radius around wells in which subsurface temperature is significantly affected. But this thermal radius depends on the well screen length, which is minimized to limit drilling costs in practice. These practical planning and permitting aspects result in a large under-utilization of available subsurface space in dense urban settings while optimal use is highly needed there. This leads to the question of how the use of subsurface space for the purpose of ATES can be optimized.

ATES plans are made to facilitate more ATES systems in an area

The trade-off between individual well efficiency on the one hand, and overall savings of GHG emissions on the other, has been demonstrated for areas that are densely populated with ATES systems (Jaxa-Rozen et al., 2015; Li, 2014; Sommer, 2015). These studies indicate a large potential for improvement of aquifer space utilization by ATES systems and, hence, for the reduction of GHG emissions. The existing struggle to facilitate an increasing number of ATES systems in the Netherlands has resulted in a coordinated approach towards their planning, aiming at reducing required mutual well distances and coordinating well locations, see

. The goal of these ATES plans is to maximize GHG emission reductions by facilitating more ATES systems within the plan area, as compared to when current standard rules are applied.

Standard rules and ATES planning methods need to be improved

In 2017, 45[1] districts in the Netherlands required an adapted regulatory framework to allow optimizing the use of subsurface space to accommodate their (future) demand for ATES. A method to make ATES plans exists (Arcadis et al., 2011), but application of this method is not enforced. A benchmark of the 24 ATES plans available in the Netherlands (Appendix A), revealed that the available method was not or only partly used. Furthermore, none of these plans substantiated why the plan was needed in the first place, neither was their benefit quantified in terms of reduced GHG emissions. This lacking substantiation is reflected in the low fraction of aquifer space that these plans allocated to ATES, namely between 3 and 37%. Analysis of this ATES planning method (Appendix B) showed that these critical elements (substantiation and benefit) are also missing in the ATES planning method set up by Arcadis et al. (2011).

Before making an ATES plan, it is important to acknowledge that change of the expected conditions and developments over time, tend to gradually invalidate these plans. In fact, existing ATES planning rules may hinder further ATES adoption, when it is not updated to meet changes in real-estate developments in the area at hand (e.g. the ATES plan in Utrecht, Appendix A).

Currently, there are 45 ATES plan areas, but this number is likely to grow to 4,500, given the required increase in ATES adoption level to meet GHG reduction targets. The rules to which these plans abide are, however, customized for the area under consideration. Under current practice rules differ considerably among ATES plans (e.g. Figure 1Figure 1A cut out of the ATES plan maps in Delft (left) and Amstelveen (right), indicating search areas for warm and cold well (the red and blue areas) and existing well locations (green, red and blue markers).), while the current general rules are uniform for the whole country, which was desired by the legislator to stimulate ATES adoption (Schultz van Haegen, 2013). So despite the fact that rules in each individual ATES plan area may be clear, the diversity introduced by numerous spatial ATES plans complicates permitting and lowers the speed and efficiency of design and construction of ATES systems, which becomes an obstacle for the large growth of ATES systems required to meet the official energy saving goals.

The issues discussed above, show that ATES planning practice and method need to be improved. However, even proper ATES plans made with good cause have their downside: they cost money, time and effort to draw up and to maintain their validity. At the same time they also lead to undesired fragmentation in ATES rules. Therefore, it is important to apply general planning rules as long as possible, and only make ATES plans when absolutely necessary -- and when this is required, make them robust and substantiated.

[1] At the time of this research, in The Netherlands, 24 districts are indicated on www.wkotool.nl. This website however is not complete, an internet search and consultation of local authorities resulted in an additional 24 areas for which ATES plans were made. Three of those areas overlap, so in total 45 busy areas. It is however likely that not all areas were found, so that there will probably be more.

Goal of this paper

The goal of this paper is to provide a method for ATES planning in practice. This is done by providing elements to the currently applied method.

A. Development of general planning/placement rules for wells that prevent the need to draw up a formal ATES plan, for an as high as possible fraction of the available aquifer space that is expected to be allocated to ATES in the future.
B. Determination of a threshold for use of aquifer space beyond which additional planning is necessary
C. Identification of effective practical planning methods
D. Development of an assessment framework that allows for scenario evaluation and quantification of the benefits of the applied planning rules.

The first three elements suggest a practical stepped approach towards ATES planning, i.e. intensifying planning rules with increasing demand of ATES, which is translated to the fraction of subsurface space to be allocated to ATES. Quantifying these elements yields practical general rules that ensure optimal use of subsurface space and clear indicators under which conditions local authorities need to apply ATES planning.

The development of such practical methods requires the following scientific insights and understanding: I) quantification of well design and placement strategies on subsurface space use and efficiency. II) The inherent uncertainties associated with building energy use and ATES well placement options in urban areas, and the identification of methods to deal with those uncertainties in practice. III) The trade-off between individual and overall performance. IV) Identification and quantification of the stakeholders' interests to allow identification of an adequate assessment framework.

Figure 1A cut out of the ATES plan maps in Delft (left) and Amstelveen (right), indicating search areas for warm and cold well (the red and blue areas) and existing well locations (green, red and blue markers).

2. Background information

2.1. Working principle of ATES Technology

Buildings in moderate climates tend to have a heat surplus in summer, combined with a heat shortage in winter. Where aquifers of sufficient capacity exist, this discrepancy can be overcome by seasonal storage and recovery of summer heat and winter "cold" in the subsurface (Bloemendal et al., 2015). ATES systems have been operating in the Netherlands since the early 1990s. They are applied in buildings of any type, but larger office and utility buildings dominate their use (Graaf et al., 2016). An Aquifer Thermal Energy Storage (ATES) system generally consists of one or more pairs of tube wells that simultaneously pump groundwater to extract or store thermal energy in the subsurface, thereby changing subsurface temperature (Figure 2).

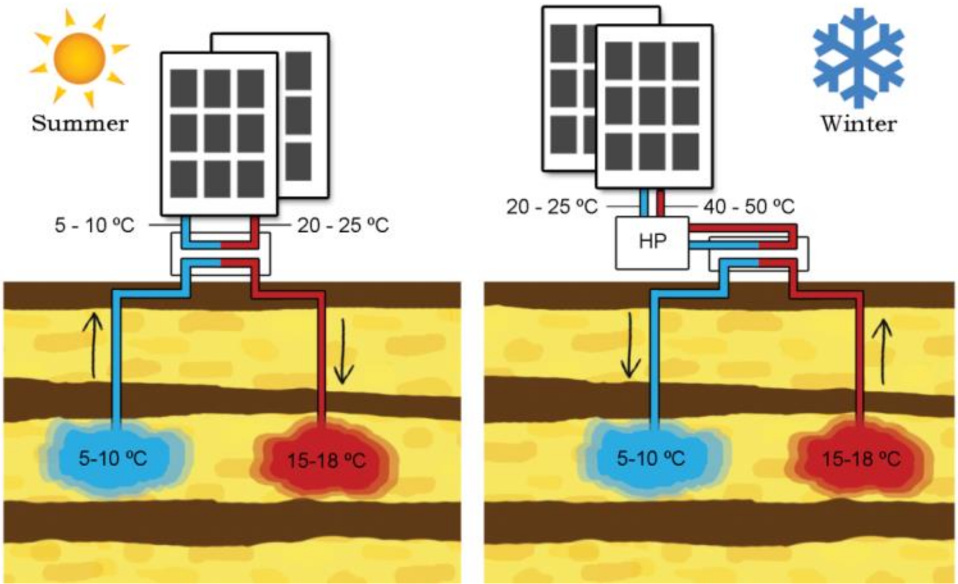

Figure 2. ATES-doublet working principle

Buildings can be efficiently cooled during summer using groundwater from the cold well. This water, heated during this cooling to about 14-18°C, is simultaneously stored through the warm well to be used for heating in the following winter season. This is illustrated in Figure 2. This cooling requires no facilities next to the low-temperature groundwater stored in the previous winter season; this is called free cooling. When during the summer season the temperature of the cold well rises above approximately 10°C, this free cooling is no longer possible; the heat pump, which is always required for space heating during winter, is then used as a back-up cooling machine. During winter, groundwater is extracted from the warm well. The heat pump boosts the temperature to the level required to heat the associated building, around 40°C. When heating the building, this heat pump cools the pumped groundwater to between 5-8°C, which is stored through the cold well. ATES reduces the net consumption of fossil energy for heating and cooling of buildings (Tomasetta et al., 2014). However, balancing the seasonal storage and extraction of thermal energy is essential to sustain long-term use of the subsurface for thermal aquifer storage.

Next to doublet systems, as presented in Figure 2, monowells are applied. Monowells have their warm and cold well screens installed in the same borehole. These screens must be separated vertically to prevent mutual interaction, which requires sufficient aquifer thickness.

2.2. ATES planning literature review

ATES wells are planned based on their thermal footprint, which is defined as the area of the circle defined by the well's so-called thermal radius. The thermal radius R_{th} is calculated by assuming a cylindrical volume of the stored water around the well (see Figure 3). The thermal radius of a well depends on the storage volume V, which is the volume of water that is injected during one storage cycle and half of the permitted capacity, well screen length, L, and the volumetric heat capacities of the water and the water saturated aquifer, c_w and, c_{aq}, and is calculated by:

$$R_{th} = \sqrt{\frac{c_w V}{c_{aq} \pi L}} \qquad (1).$$

Longer screens reduce the areal footprint because it reduces the well's thermal radius (Equation (1)). Note that the aquifer heat capacity depends on the porosity n following: $c_{aq} = n\, c_w + (1\text{-}n)c_{sand}$. Bloemendal and Hartog (2018) show that well screens are generally designed too short to meet the optimal geometric proportions to obtain the lowest heat losses. Such short screens result in unnecessary large thermal radii, which then causes the planning area to be full earlier, because the unused aquifer space below the short well screens cannot be utilized.

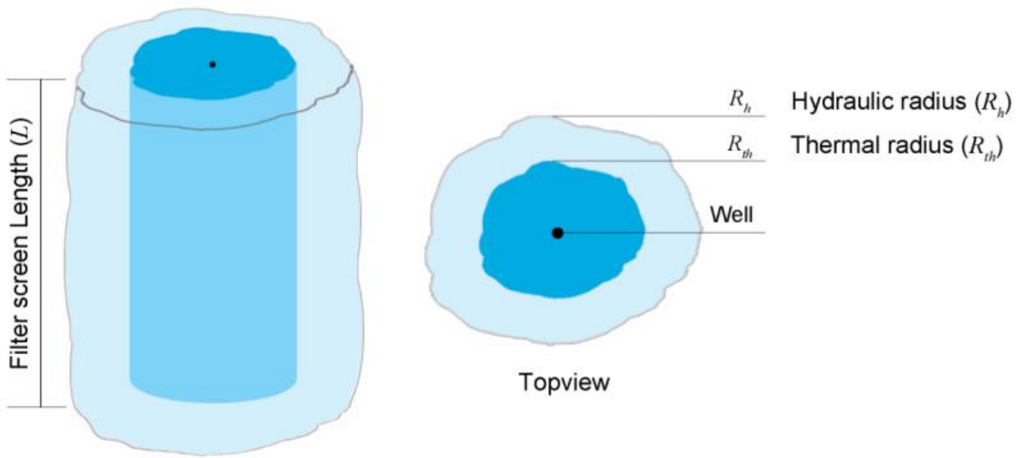

Figure 3. Schematic presentation of footprint and subsurface space use of thermal and hydrological cylinder. The thermal radius depends on the storage volume and the well screen length, which in turn depends on the available aquifer thickness. The heat in the injected water heats the sand particles in the aquifer, causing the thermal front to move slower compared to the front of the injected groundwater. The ratio between hydraulic and thermal radius is the square root of the thermal retardation (Bloemendal and Hartog, 2018).

Due to their forced infiltration and extraction of large volumes of groundwater, ATES systems dominate the temperature field in the aquifer around their wells. Thermal energy is lost at the boundary of the stored temperature volume, which is only noticed by the end of the wells' extraction period in the next season. Interaction between ATES wells at the boundary of their temperature fields may affect their recovery efficiency. In most countries the precautionary principle is followed (Haehnlein et al., 2010; Schultz van Haegen, 2013), due to which a spacious safety margin around the wells is obligatory so as to prevent mutual interaction. In ATES planning, the main challenge is to assess to what extent these interactions affect the combined energy savings of the future systems. The trade-off between individual well efficiency on the one hand and overall savings of GHG emissions on the other has been demonstrated for areas that are densely populated with ATES systems (Jaxa-Rozen et al., 2015; Li, 2014; Sommer et al., 2015). These studies indicate a large potential for improvement of aquifer space utilization by ATES systems and, hence, for the reduction of GHG emissions. Buildings and infrastructure in the shallow subsurface make it difficult to find suitable locations for ATES wells in dense urban settings, often leading to wells installed on sub-optimal locations. The existing struggle to facilitate an increasing number of ATES systems in the Netherlands has resulted in a coordinated approach towards their planning, aiming at reducing required mutual well distances and coordinating well locations, see

. The goal of these ATES plans is to maximize GHG-emission reductions by facilitating more ATES systems within the plan area as compared to when current standard rules are applied.

As an added complexity, a commonly accepted general assessment framework for subsurface space functions do not yet exist (Griffioen et al., 2014). Such a framework is, however, needed when finding optimal ATES planning strategies. Therefore, an assessment framework for aquifer space use by ATES systems is developed in this research. The theoretical approach of Sommer et al. (2015) indicating how ATES systems can best be organized in lanes is not sufficient for practical use since it strongly simplified the practical ATES conditions (varying ATES size (Bloemendal and Hartog, 2018) and uncertain/limited well placement opportunities at surface level). Bloemendal et al. (2014) proposed to apply ATES-systems with a model predictive control strategy to facilitate negotiation about use of subsurface space among ATES systems. This leads to self-organization but requires a radical change in both technical resources and legal framework. Also in other energy research similar solutions emerge for the future energy system, e.g. (Calvillo et al., 2016). Because of the many theoretical and practical questions to be answered, widespread implementation of this principle is not to be expected within the next decade. So additional to research on self-organization, this paper pursues assessing and improving implications of current design and governance practice, to the extent that it is essential for the ongoing, near-future adoptions of ATES systems. So rather than theoretical concepts, a “hands on” practical approach for ATES planning is needed.

3. Methods and materials

3.1. *Analysis through simulation*

Sommer et al. (2015) provided a theoretical basis for the organization of ATES wells, but did neither account for urban limitations of well placement nor for varying sizes of ATES systems. These conditions, however, limit the possibilities to follow optimal well patterns. The uncertainties and constraints show many similarities among areas with many ATES wells. This is an opportunity to evaluate how ATES planning design principles affect ATES system performance and overall GHG emissions. Therefore, the impact that development of ATES systems in dense urban settings has on their energy performance is best analyzed through a modeling approach that acknowledges three key aspects of this development: the complexity and dynamics of the spatial planning of areas;the operation of buildings and their ATES systems; and the analysis of subsurface space use and the energy efficiency of ATES systems. Uncertainties with respect to the use of subsurface space in the future, make it difficult to substantiate an ATES plan today, the upcoming integration of the electricity and heating systems even increase this uncertainty (e.g. (Alibabaei et al., 2017; Saffari et al., 2018)). However, scenario evaluation can be used to identify robust solutions under uncertainty (Bishop et al., 2007).

An agent-based model to simulate ATES adoption and ATES operation in dense settings was implemented using NetLogo (Wilensky, 1999). The involved groundwater dynamics are modeled using the MODFLOW / SEAWAT codes (Harbaugh et al., 2000; Langevin et al., 2008). Both models are widely applied, but have not been combined through a bi-directional coupling as in this study e.g. (Anderson et al., 2017; Hecht-Mendez et al., 2010; Reeves and Zellner, 2010; Sommer, 2015). MODFLOW/SEAWAT and NetLogo were linked through an object-oriented architecture written in Python. Python objects form the interface between the two models. Figure 4 illustrates the basic architecture and shows the data exchanges. The two coupled models run inside the Exploratory Modeling and Analysis (EMA) workbench package (Kwakkel, 2017; Kwakkel and Pruyt, 2013). EMA creates ensemble results for a set of scenario and policy combinations to allow evaluation of different parameter sets under uncertainty. Assessment criteria like energy consumption, GHG emissions, well efficiency and use of subsurface space were derived from the realized performance of the simulated ATES systems.

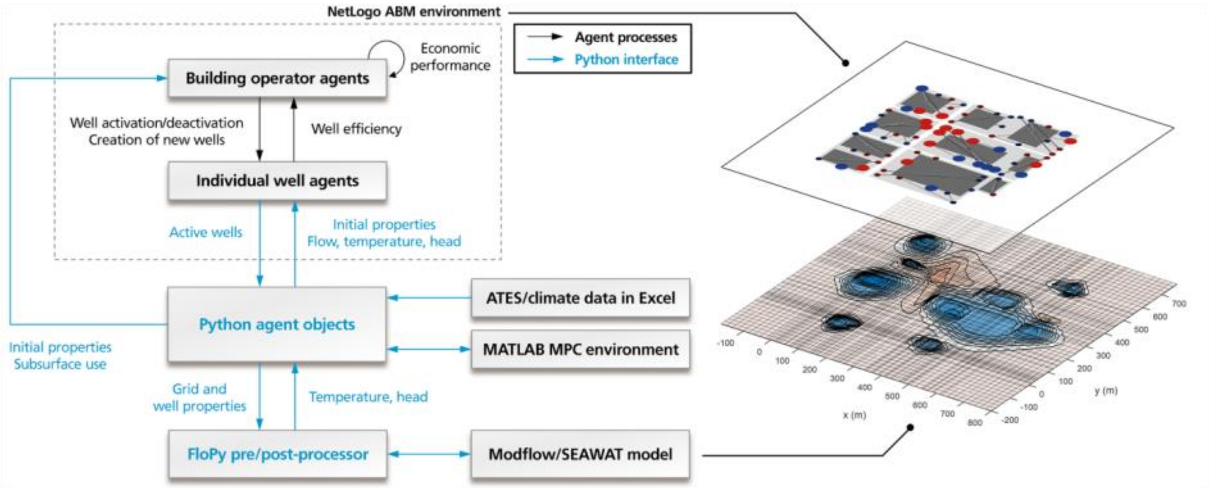

Figure 4. Coupled simulation architecture for agent-based exploratory modeling of ATES systems (Jaxa-Rozen et al., 2015)

Details of NetLogo;

NetLogo drives the simulations. It initializes ATES operators with their behavior (called agents) during startup. Each agent is characterized by its size and behavior representative for ATES systems currently installed in the Netherlands.

- The well size of each ATES system was randomly picked from a distribution describing the occurrence of ATES systems in the Netherlands contained in a dataset of the permitted capacity of over 430 ATES systems from 5 provinces, as was also used by Bloemendal and Hartog (2018).
- The known total heating and cooling demand of each ATES system was distributed over the year following a sine function to simulate basic seasonal ATES operation. Ideally, the actual operation dynamics among ATES systems would be simulated, but no data was available for this. To nonetheless simulate the effect of varying operational conditions, a random imbalance of up to 30% was added to the energy demand sine-profile of each agent.

The following placement procedure was implemented in NetLogo to represent the stochastic nature of ATES adoption dynamics, which vary from city to city:

- The systems to be simulated are constraint to an area of 1x1 km, equal to the average ATES plan area in the 24 plans of this benchmark (appendix A).
- During the simulation, less and less space remains available to place new wells, as a space around is required around each well to prevent mutual interaction.
- Each new ATES system randomly chooses a location for one of its wells in the still available area. The other well of this system is now placed as close as possible to the initial well, while respecting the

placement limitations. Each agent, i.e. ATES system, successively installs its wells using this procedure. The available space for placement declines with an increasing number of agents.

- Within the imposed spatial constraints, ATES systems continue to be added until the preset scenario threshold for maximum allocated subsurface fraction for ATES is reached, or when no more well locations can be found because the plan area is filled with ATES footprints.

Each scenario comprises 64 complete realizations; several test runs have shown that with 64 realizations per scenario the distribution of the results was sufficiently stable to confirm representative behavior suitable for analysis.

Details of MODFLOW/SEAWAT;

The MODFLOW/SEAWAT model is used to simulate subsurface flow with heat transport, from which well efficiencies are determined. This simulation environment takes into account heat exchange to adjacent confining layers and the surrounding aquifer, which can be at the ambient temperature or temperatures corresponding to injection by neighboring wells. The Dutch situation served as the basis for the set-up of the groundwater model; the choices made are listed and motivated below:

- Model layers: A confined 10 m thick clay layer was modeled at the top and bottom of the aquifer; the storage aquifer was modeled using 5 m thick layers, with the number of layers corresponding to the aquifer thickness in each scenario. Well-screen lengths were rounded to the nearest multiple of 5 m, as it is done in current ATES practice (Bloemendal and Hartog, 2018). Injection and extraction through the wells were distributed over the model layers penetrated by the well screen according to their transmissivity.
- Spatial discretization was chosen 5 x 5 m throughout the model; the resolution thus stays well within the minimum cell-size required by Sommer et al. (2014) to adequately model the temperature field around the wells. Time-varying input and output was generated on a monthly basis. Note that SEAWAT automatically takes smaller time steps as necessary to maintain accuracy. Monthly input and output is sufficient to take account for the seasonal operation pattern. The time horizon of each simulation was set to 15 years. Although this is shorter than the expected life span of ATES systems and surely of their buildings, it is sufficiently long to identify the effects of interaction between ATES systems over multiple storage cycles (Sommer et al., 2015).
- Model extent. To prevent boundary conditions from affecting the modeling results, the groundwater model extends 500 m beyond the mentioned boundary of the plan area; thus the size of the groundwater

model was 2x2 km. The initial and fixed boundary hydraulic heads were uniform, except for scenarios with groundwater flow, for which the initial and boundary heads were in accordance with the hydraulic gradient. Usually, in groundwater modeling, 500 m is a too small area to prevent hydraulic influence from the model boundary on the area of interest. Test simulations with larger boundaries distances, however, showed this effect to be negligible, mainly because each ATES system exactly balances inflow and outflow over the short distance between its wells.

- Aquifer properties were taken as homogeneous; the effect of heterogeneity on ATES well efficiency has been studied by Caljé (2010), Sommer et al. (2013), Possemiers et al. (2015) and Xynogalou (2015), who concluded that only in specific conditions heterogeneity may have a considerable effect. Also buoyancy flow was ignored because at the relative small temperature differences between the wells and ambient groundwater as applied for ATES, buoyancy effects are negligible (Anderson, 2005; Bloemendal and Hartog, 2018; Doughty et al., 1982). Because hydraulic conductivity has negligible effects on thermal losses under homogeneous and no buoyancy flow (Bloemendal and Hartog, 2018), the horizontal hydraulic conductivity was set to a constant value of 40 m/d for aquifers and to 0.05 m/d for aquitards, both are common values for the Netherlands. A vertical anisotropy factor of 5 was used for both aquifers and aquitards. The other thermal and numerical parameters follow literature values and are given in Table 1.

Table 1, MODFLOW simulation parameters (Caljé, 2010; Hecht-Mendez et al., 2010; Langevin et al., 2008)

Parameter	value
Porosity	0.3 -
Longitudinal dispersion	1 m
Transversal dispersion	0.1 m
Bulk density	1890 kg/m^3
Bulk thermal diffusivity	0.16 m^2/day
Solid heat capacity	880 J/kg °C
Thermal conductivity of aquifer	2.55 W/m °C
Effective molecular diffusion	$1 \cdot 10^{-10}$ m^2/day
Thermal distribution coefficient	$1 \cdot 10^{-4}$ m^3/kg

3.2. Assessment framework

Scenario evaluation requires an assessment framework that allows for comparison of different simulation results. Commonly accepted general assessment frameworks for subsurface space functions do not exist (Griffioen et al., 2014). The analysis of the ATES planning method resulted in the identification of four parameters that determine the success of an ATES plan (Appendix II).

1. GHG emissions

To reduce GHG emissions associated with space heating and cooling to a maximum, all buildings in an area should have either an ATES system or another sustainable heating and cooling system (of course combined with minimizing demand). The key parameter to evaluate the reduction of GHG emissions is the total amount of GHG emitted by the buildings in an ATES plan area. These emissions should also include those of buildings not equipped with ATES, because only then the benefit of applying additional rules can be quantified. These emissions can be calculated when the future number of buildings in the plan area is known at planning time, together with their heating and cooling demands. Therefore, each scenario is simulated for the same number of buildings. When there is no place available to accommodate all ATES systems, the buildings that cannot place ATES wells are assumed to be equipped with conventional heating and cooling systems, and their associated emissions contribute to the emissions of the plan area of the scenario under consideration. Also, the feedback on the emissions, caused by mutual interaction between ATES systems has been included in the assessment parameter of GHG emissions.

2. Recovery Efficiency

Mutual heat interactions of the volumes stored by ATES wells have a negative effect on their energy efficiency. This effect is negative for wells of opposite type (warm vs. cold wells) and positive for wells of the same type (warm vs. warm and cold vs. cold wells). The more ATES system there are in an ATES plan area, the more likely such interactions are to occur. It is therefore clear, that subsurface use can only be intensified up to the threshold above which well efficiencies are reduced to the extent that individual ATES systems cannot no longer operate economically (Jaxa-Rozen et al., 2015).

3. Robustness of the ATES plans

Robustness is crucial for existing systems to adapt to changing building use and energy demand; use of buildings is likely to change during their lifetime and the same is true for their energy-demand profile. To prevent having to repetitively update the ATES plan, they should flexibly accommodate a range of possible future developments. The same flexibility is desired for the accommodation of new systems. As was indicated by Bloemendal and Hartog (2018), available space also allows for temporary energy imbalances because some winters are colder than others. Robustness may conflict with the goal for minimizing GHG emissions through ATES, i.e. conflict with the maximum utilization of subsurface space for ATES. On the one hand maximizing ATES adoption requires using as much subsurface space as possible, while on the other hand, accommodation of a wide range of ATES developments is easier when not the entire subsurface space is allocated. Therefore, the goal is to identify measures that reserve a maximum of subsurface space for this robustness but still accommodates as many ATES systems as possible. This can be analyzed by comparing the total space of the aquifer or subsurface that is allocated to ATES (3D) with the total surface area of the thermal radii (2D). ATES plans are more robust when the total surface area associated with the thermal well radii is lower for the same fraction of aquifer space that is allocated to ATES.

4. Cost for space heating and cooling

Rising costs as a result of planning may reduce ATES adoption / initiatives. Costs may increase or decline by changes in well efficiency or to comply with requirements that affect installation: 1) well screen length (drilling cost) and 2) distance between wells and their building (cost for horizontal piping). Changes in installation cost per ATES system as a consequence of the planning are difficult to determine because representative costs are not available. Therefore, the changes in installation costs are discussed qualitatively by the following two proxies: 1) well screen length, and 2) distance between the two wells of one ATES system. Exploitation costs are qualitatively discussed with well efficiency and GHG emission as proxies,

3.3. Calculation of the assessment parameters

Energy use and emissions of ATES systems

The energy balance of the heat pump is used to trace back the heating and cooling demand (E_h, E_c) of the associated buildings and the energy consumption by the heat pump. The total heating capacity for the building provided by the heat pump is described by two basic relations (Wu, 2009);

$$P_h = P_{ATES} + P_e \quad \text{and} \quad COP_{hp} = \frac{P_h}{P_e} \qquad (2),$$

where P_h [W] is the heating capacity deliverable to the building; P_{ATES} [W] the thermal heating power retrieved from the groundwater, P_e [W] the electrical power consumed by the heat pump and COP_{hp} coefficient of performance of the heat pump. Equation (2) shows that all electric power fed to the heat pump contributes to the heat output. When it is assumed that 100% of the heating and cooling demand of the building is delivered by the ATES system, the heating capacity and total heat energy ($E_{h,ATES}$) from the groundwater between times t and t_0 equals

$$E_{h,ATES}(t_0 \rightarrow t) = \int_{t_0}^{t} P_{ATES}\,dt = c_w \Delta\overline{T}_h \int_{t_0}^{t} Q\,dt = c_w V_h \Delta\overline{T}_h \qquad (3)$$

with

$$P_{ATES} = c_w Q(T_w - T_c) = c_w Q\Delta T \qquad (4).$$

The integration is done for the whole heating season ($t_0 \rightarrow t$). V_h [m^3] is the given seasonal volume of groundwater required for heating. ΔT [K] is the instantaneous temperature difference between the warm (T_w) and cold (T_c) well, $\Delta\overline{T}_h$ is the average temperature difference during heating season, Q [m^3/h] is the groundwater flow from the warm well to the cold well and c_w [J/m^3/K] is the volumetric heat capacity of the water. With V_h substituted in equations (2) and (4), equation (5) yields the heat E_h [J] delivered to the building over the heating season:

$$E_h = c_w V_h \Delta\overline{T}_h \frac{COP_{hp}}{COP_{hp} - 1} \qquad (5).$$

The cooling delivered to the building is calculated using the same equations, while distinguishing between free cooling and heat pump cooling[2]. An absolute temperature threshold of 9°C was set for the cold well above which no free cooling is assumed possible. When the extraction temperature of the cold well surpasses this threshold, the heat pump is used to meet the cooling demand and resulting heat is transferred to the warm well via the condenser of the heat pump. The total cooling delivered to the building then follows from:

$$E_c = c_w \Delta\overline{T}_{c,fc} V_{c,fc} + c_w \Delta\overline{T}_{c,hp} V_{c,hp} \frac{COP_{hp} - 1}{COP_{hp} - 2} \qquad (6),$$

in which $V_{c,fc}$ and $V_{c,hp}$ are the groundwater volumes required for free cooling and cooling by the heat pump and $\Delta T_{c,fc}$ and $\Delta T_{c,hp}$ are the average temperature differences between the warm and cold well for free cooling and cooling by the heat pump respectively. Note that the heat pump COP is 1 lower during cooling.

The total energy consumption of the ATES system (E_{ATES}) is completed by including the pump energy consumption. Substituting equations (2) into (5) and (6) yields:

$$E_{ATES} = \frac{E_h}{COP_{hp} - 1} + \frac{E_{c,hp}}{COP_{hp} - 2} + \frac{(V_h + V_{c,fc} + V_{c,hp}) \cdot \Delta p}{\eta_p} \qquad (7),$$

where Δp is the lifting pressure generated by the groundwater pump and η_p its nominal efficiency.

[2] Electricity consumed by the heat pump is the most important energy use for determining the efficiency of ATES. A change in well temperature during heating has a limited effect on energy use of the heat pump, and is taken account for by using a conservative COP_{hp} value. During cooling mode the temperature of the cold well determines whether the heat pump is used or not, which makes the cold well temperature a crucial parameter in the overall ATES efficiency.

The total GHG emission is retrieved by calculating the CO_2 emissions of the considered ATES systems:

$$GHG_{ATES} = \sum_{i=1}^{n} E_{ATES,i} e_{fe} \qquad (8),$$

where e_{fe} is the emission factor for electricity and E_{ATES} is the electricity consumption of the ATES system and n the number of active ATES wells.

Conventional boiler and chiller energy use and their GHG emissions

Buildings without ATES are assumed to have a conventional boiler and compression chiller. The COP_b of the boiler and the COP_c of the cooling machine are used for comparison with conventional climate installations. GHG emissions are calculated using emissions factors for natural gas (for heating) and electricity from the Dutch grid (for cooling). The energy consumption for these buildings then equals:

$$E_{boiler} = \frac{E_h}{COP_b} \quad \text{and} \quad E_{chiller} = \frac{E_c}{COP_c} \qquad (9).$$

Their GHG emissions equal

$$GHG_{conv} = \sum_{j=1}^{m} \left(E_{boiler,j} e_{fg} + E_{chiller,j} e_{fe} \right) \qquad (10),$$

in which e_{fg} and e_{fg} are the emissions factors for gas and electricity, and m the number of active conventional systems.

Efficiency of ATES wells

The energy efficiency (η) of a well over the simulation period is calculated in monthly steps by dividing the extracted amount of thermal energy by the infiltrated amount of thermal energy:

$$\eta_i \left(t_0 \rightarrow t \right) = \frac{E_{out,i}}{E_{in,i}} = \frac{\int_{t_0}^{t} \Delta T_{out,i} Q_{out,i} dt}{\int_{t_0}^{t} \Delta T_{in,i} Q_{in,i} dt} = \frac{\Delta \overline{T}_{out,i} V_{out,i}}{\Delta \overline{T}_{in,i} V_{in,i}} \qquad (11).$$

The thermal efficiency taken over all the wells in the model (η_{tot}) is the average of the individual efficiencies determined from Equation (11) weighted by the individual total storage volume of the wells ($V_i = V_{h,i} + V_{c,fc,i} + V_{c,hp,i}$)

$$\eta_{tot} = \frac{\sum_{i=1}^{n} \eta_i \, V_i}{\sum_{i=1}^{n} V_i} \qquad (12).$$

Spatial parameters

Because the extent of the ATES plan areas and its subsurface conditions differ between the various busy ATES areas in the benchmark shown in appendix A, the following characteristics are defined to allow comparison between plans:

- The fraction F_s of subsurface/aquifer space allocated to ATES. The allocated fraction of subsurface space quantifies the density of the ATES setting and allows comparison between different areas. It is the yearly stored volume of groundwater taken over all (n) ATES wells and divided by the available aquifer space in the plan area:

  $$F_s = \frac{\sum_{i=1}^{n} V_i}{L_a A_{Ap}} \qquad (13).$$

  With A_{Ap} the ATES plan area [m^2] and L_a the aquifer thickness [m].

- The surface area fraction F_A allocated to ATES is the sum of the circular areas resulting from applying the thermal radii to all ATES wells and divided by the ATES plan area. The lower this number is, the more space is available for new systems and the less interaction occurs. The allocated fraction of surface area then is:

  $$F_A = \frac{\sum_{i=1}^{n} \pi R_{th,i}^{\ 2}}{A_{Ap}} = \frac{c_w}{c_{aq}} \frac{\sum_{i=1}^{n} \frac{V_i}{L_i}}{A_{Ap}} \qquad (14)$$

4. Simulation results

4.1. ATES plan design variables and scenarios

Prior to making an ATES plan, parameters must be identified that can actually be used to organize the ATES wells and optimize the use of the available subsurface space. Li (2014) was the first to identify such parameters; her set of parameters is extended here and discussed in appendix II, and summarized in Table 2. This table shows that only few of the parameters that can be adapted during operation of an ATES system; most design parameters can only be controlled before installation. To limit regulatory pressure on both authorities and ATES owners, the planning preferably constrains as few design parameters as possible.

Table 2. Design parameters ATES systems/ATES plans

Design parameter	Depends on	Changeability	Suitable for planning?
Energy demand / storage volume in aquifer	Building properties	By building owner during design/installation	No; higher level legislation should limit energy use of buildings
	Building function	By building user/operator during use	No; building owners should autonomously decide on use. However, local regulations may designate areas for only housing or industry etc.
	Type of installation	By building owner during design/installation and retrofit	Indirectly, through type of well, also depending on building regulation. Preferably autonomous decision of building owner
	Management of installation	By building user/operator during use	Yes, Maximum storage volume, flow and/ or temperatures may be used. Although only max. storage volume is an effective variable to prevent negative interaction with neighboring systems.
	Weather	Not	No
	Energy balance	Keeping an energy balance between warm and cold well may require extra energy use and/or extra subsurface space.	Yes, Can be used to limit continuous growth of wells, but in busy areas it is more efficient to combine warm and cold wells of buildings with a matching energy demand profile.
	Size of Storage volume	By building owners at installation.	Yes, when beneficial stimulating small buildings to make a collective system may be possible.
Well design	Type of well	By building owner during design/installation	Yes, preferably autonomous decision of building owner, but can be used in very busy areas
	Filter screen length	By building owner during design/installation	Yes, Effective way to ensure that entire aquifer thickness is utilized, may be unbeneficial for small systems in thick aquifers.
	Number of wells	By building owner during design/installation	No, Has a large effect on installation cost, so it's preferred not to dictate this. Number of well is however influenced indirectly via distance rules, filter screen length and storage volume
	Well temperature	By building owner during design/installation and use	No, Can be used to increase energy density of the used subsurface space, but may have significant effects on type of installation and effective GHG emission reductions, so only to be applied in very busy areas and in consultation with concerned building owners.
Well location	Spatial rules for wells	By local authority during design/installation	Yes, Can be used for spatial planning of wells., self-placement, patches, lanes or well locations can be used
	Distance between wells	By building owner and local authority during design/installation	Yes, Expressed as a function of expected thermal radius (R_{th}). Depending on the expected subsurface space usage smaller distance policies may be applied, there is a trade of with flexibility and efficiency for existing systems though.

With the design parameters of the ATES plan of Table 2, the efficiency of ATES planning for wells in busy areas can be quantified. This is done by systematically evaluating how the control of these parameters affects the performance of the systems within an ATES plan area. Both individual systems and the overall efficiency of the plan area are evaluated using the simulation framework introduced in section 2 by running the following scenarios:

A. Reference policy: applying the standard regulations; no policy for well placement is enforced, i.e. self-placement is applied (Bloemendal et al., 2014; Caljé, 2010)), no prescriptions for well type and well design, obligatory minimum mutual distance of $3R_{th}$ and no groundwater flow. In this basic scenario the agent-based model tries to maximize the allocated subsurface fraction. To identify the effect that a lower allocated aquifer fraction has on individual well efficiencies, also scenarios were run in which this fraction was maximized. The applied values are in Appendix C; this fraction varied between 3 and 37%, equal to the range in the ATES plan benchmark (Appendix A).

B. The effect of policies with respect to the required distance between ATES wells. Each policy is translated into a multiplication factor for the thermal radius. For the same well types (D_{same}) these factors are 1, 1.5, 2; for opposite well types ($D_{opposite}$) the factors are: 1.5, 2, 2.5, 3. All combinations are analyzed, except those for which the distance between opposite well types is smaller than that for wells of the same type.

C. The effect of aquifer thickness combined with requirements with respect to type (monowell/doublet) and design, i.e. screen length of the ATES wells. Aquifer thickness is varied over the benchmark range by choosing three distinct values of 30, 60 and 90m. This is combined with four alternative well design approaches: 1) current design practice, in which screen length depends on well capacity, 2) the design rule following Doughty et al. (1982) who optimized the ratio L/R_{th}, which was reformulated to $L=V^{1/3}$ by Bloemendal and Hartog (2018), 3) in which all wells are fully penetrating, and 4) well type is either free (small systems can apply a monowell) or all systems are required to apply doublets.

D. The effect of spatial planning of ATES wells in lanes as compared to the self-placement. Lane placement is analyzed by varying the number of parallel lanes within the plan area. See Appendix C for details. The basic approach was to start with 2 lanes and increase the number of lanes up to 10, keeping the width of the lanes equal to their distance. Ten was the maximum possible number of lanes to fit in the 1 x 1 km area. Variations on width and spacing were applied to the 4, 6 and 8 lane scenarios, see Appendix C.

E. The effect of variations in well operation. A random yearly imbalance of up to 30% was independently applied to the heat or cooling demand of each ATES system. This means that each ATES system obtains a constant yearly surplus of either heat or coldness, randomly chosen between -30 and 30% (with a truncated normal distribution with mean 0 and sigma equal to 15%). This follows the results of an analysis of ATES systems performance in practice (Willemsen, 2016).

F. The effect of ambient groundwater flow. An ambient groundwater flow of either 10 and 25 m/y was applied, which covers common values like were identified in the benchmark (appendix A) and in Bloemendal and Hartog (2018).

G. The effect of only allowing large (collective) systems. The minimum size of ATES systems was set to 250.000 m^3/y. This explores the effect of small systems hooking-up to a neighboring (large) system thus integrating small buildings into a collective system.

Appendix C presents the detailed descriptions of the different policies that are evaluated.

4.2. Results

Self-placement scenarios

The first set of simulations analyzes self-placement, but with different distance requirements. The results together with those of the reference scenario are given in Figure 5. It gives the efficiencies and GHG savings for the different allocated aquifer space fractions. Figure 5 consists of 12 subplots that represent distance policies: each column gives the minimum distance for wells of the opposite type; each row the minimum distance of wells of the same type. Each marker in Figure 5 is the average of the 64 realizations. The allocated aquifer fraction is indicated by the shading of the markers. The error bars indicate the inter quartile range (IQR) within the 64 realizations computed for each policy.

Figure 5 shows that, regardless of the distance policy, a larger fraction of allocated aquifer space (F_s), results in strongly reduced GHG emissions, with a mild decrease of individual efficiency. There is potential for extra GHG savings, because when comparing the subplots, the top rows and left hand column give the highest GHG savings combined with the highest allocated aquifer fraction (darkest markers). This was also found by (Jaxa-Rozen et al., 2016; Sommer et al., 2015). Maximum utilization of subsurface space for ATES systems is achieved when the mutual well distance is reduced to $1R_{th}$ for wells of the same type (top row) in combination with and $2.5R_{th}$ for wells of opposite types (3rd column), while keeping individual well efficiency above 80% as was the case in the reference scenario.

The reference scenarios (lower right sub-plot in Figure 5) show a relatively large spread of the efficiencies for low fractions of allocated subsurface space. This caused by the variation in clustering that emerges from the self-placement of the wells by the agent-based model. At low densities, clustering varies between simulations due to stochastic choice of buildings and their well locations; at high allocated aquifer fractions, warm and cold wells are always clustered as warm and cold volumes in the subsurface are then joined, which reduces thermal losses.

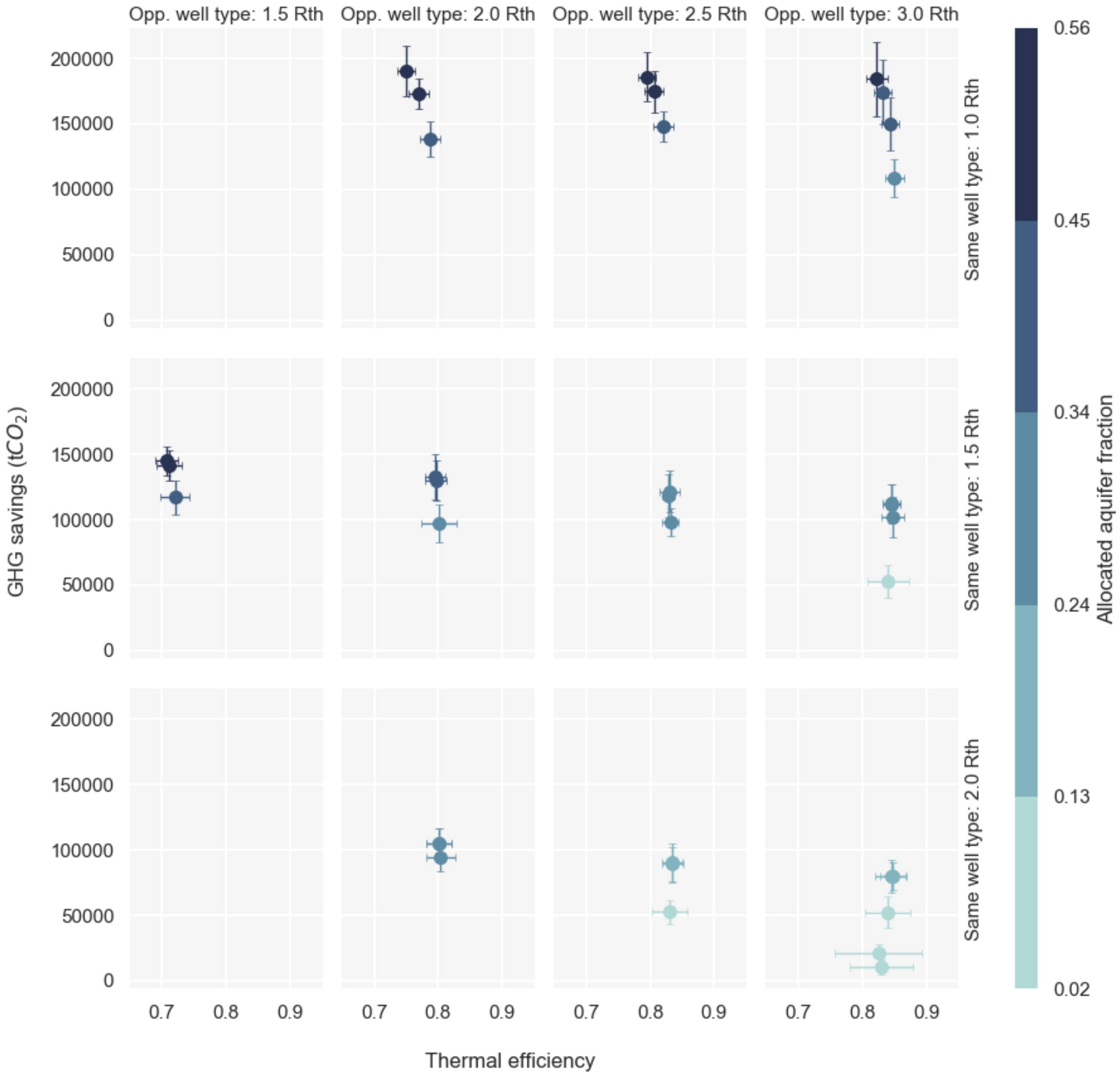

Figure 5. The average of all model realizations for the self-placement scenarios, grouped by same and opposite type of well distance policy. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

Well design scenarios

Figure 6 shows the simulation results for the scenarios in which well screen length and well type (mono vs. doublet) were varied. Again, each marker represents the average of 64 realizations. Like Figure 5, the results are divided over 12 subplots. Each column fixes the aquifer thickness, together spanning the range encountered in the benchmarked plans. Each row fixes a well strategy. Only in the first row monowells are allowed together with doublets. Rows 1 and 2 both have default screen length, which is the screen length determined by the desired well capacity derived from the data used by Bloemendal and Hartog (2018); i.e. an average of 0.2 m of screen length for each thousand m^3 of yearly storage volume, randomly varying between 0.04 and 0.4

m/1,000m^3. Row 3 shows the results with only doublets when their length is determined according to the Doughty (1982) rule ($L=V^{1/3}$). Row 4 shows the results with only doublets that have wells whose screens fully penetrate the aquifer.

It should be noted that all well design scenarios were constrained to a minimum distance of $3R_{th}$ between wells of opposite type and $2R_{th}$ between wells of the same type. These distances exceed those of some of the scenarios shown in Figure 5 and, as a consequence, somewhat lower maximum GHG savings are now obtained. Nevertheless, these results indicate that longer screens are beneficial. A minimal screen length is required to allow pumping at the required capacity. Fully penetrating screens seem optimal. Fully penetrating screens are currently only applied in thin aquifers, but for thick aquifers, say thicker than about 30 m, prescribing fully penetrating screens would be highly beneficial to overall GHG savings; in aquifers of 60 m thickness, fully penetrating screens would double the allocated aquifer space compared to current practice. Not only is this large effect due to utilizing currently unused space deeper in the aquifer, but also to longer screens resulting in smaller thermal radii, making it easier to place extra wells within given placement constraints.

Prescribing the type of well, also helps raise both efficiency and total GHG savings. Monowells require a minimum vertical spacing between their screens, limiting use of the full aquifer thickness as aquifer space in between the monowell screens is not used. Furthermore, the distance between a monowell and a doublet well always equals that required between two wells of opposite type, which is larger than that between two wells of the same type. Therefore, with monowells allowed, it is more difficult to reduce the claim on subsurface space than with only doublets.

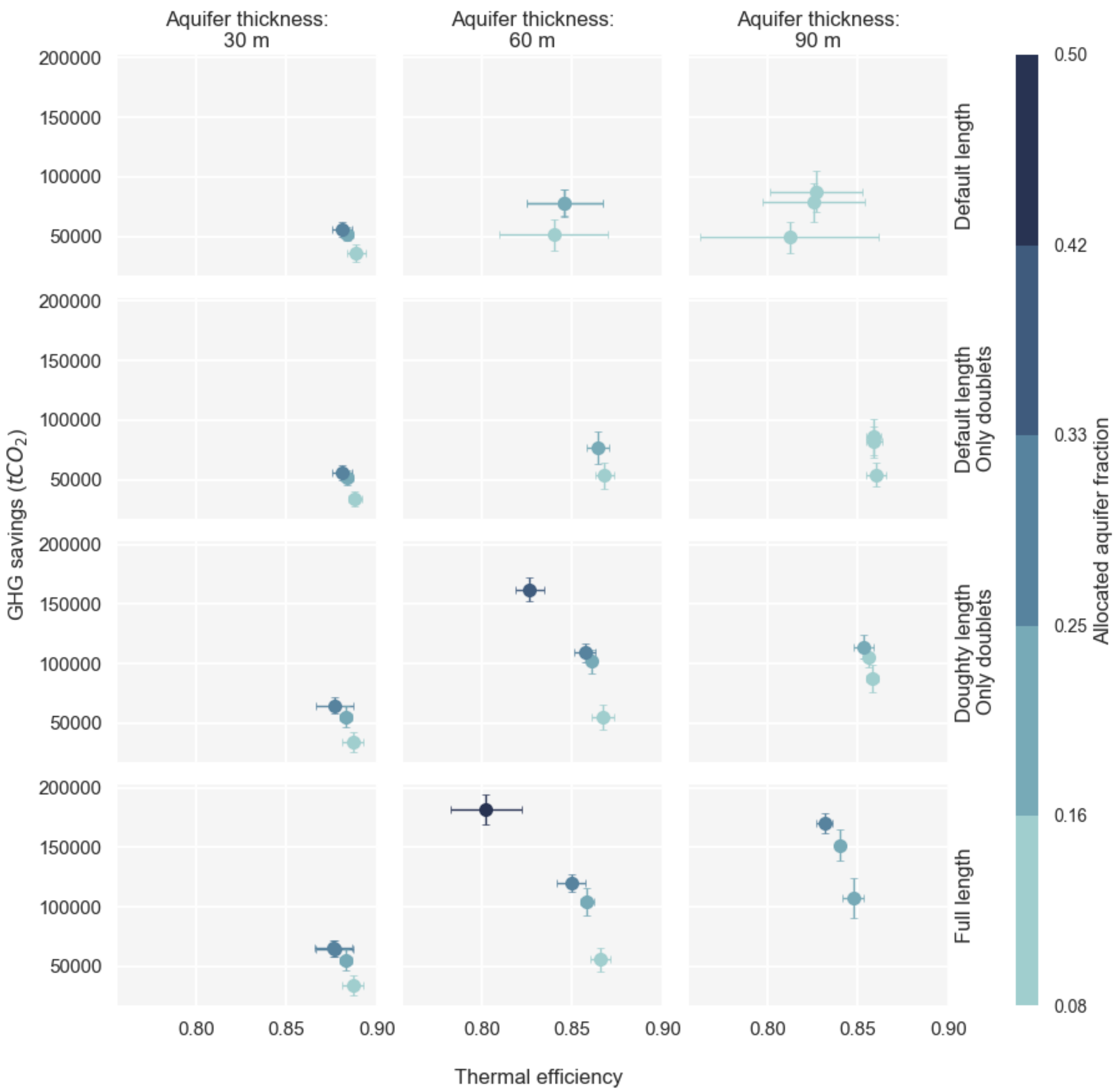

Figure 6. The average result of all model realizations for the scenarios where well design is varied, grouped by aquifer thickness and well design parameters. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

Lane placement scenarios

In these scenarios, warm and cold wells were placed in separate, parallel lanes. Each marker in Figure 7 shows the average result of the 64 realizations computed for each of 36 lane placement scenarios. Again, GHG savings are on the vertical axis and well efficiency is on the horizontal, with the shading of the markers indicating the allocated aquifer fraction. The dashed lines indicate the lane configuration.

The first observation is that GHG savings with lanes in Figure 7 easily exceed the values achieved with self-placement in Figure 5. The highest efficiency combined with the highest GHG savings are obtained with only 2 lanes. This is because in that case the warm and cold wells each form a large joined volume, which is a maximum distance apart, both reducing thermal losses. The opposite with 10 lanes is also true. Therefore, well efficiencies vary more strongly and decline when lanes are narrower and have smaller spacing, as Figure 7 also shows. A practical optimum, maintaining an efficiency of 80% would correspond to lanes with a mutual distance in the range of 100 -150m, which then reduces the costs for pipe connections. This optimal lane distance is about twice the average thermal radius of ATES systems in the Netherlands (Bloemendal and Hartog, 2018).

It follows that also the width of the lanes is important, as smaller widths limitthe positive effect of clustering wells of same type. Narrow lanes hinder finding well locations, which limits the attainable allocated aquifer fraction. Figure 7 also illustrates this lane-width effect.

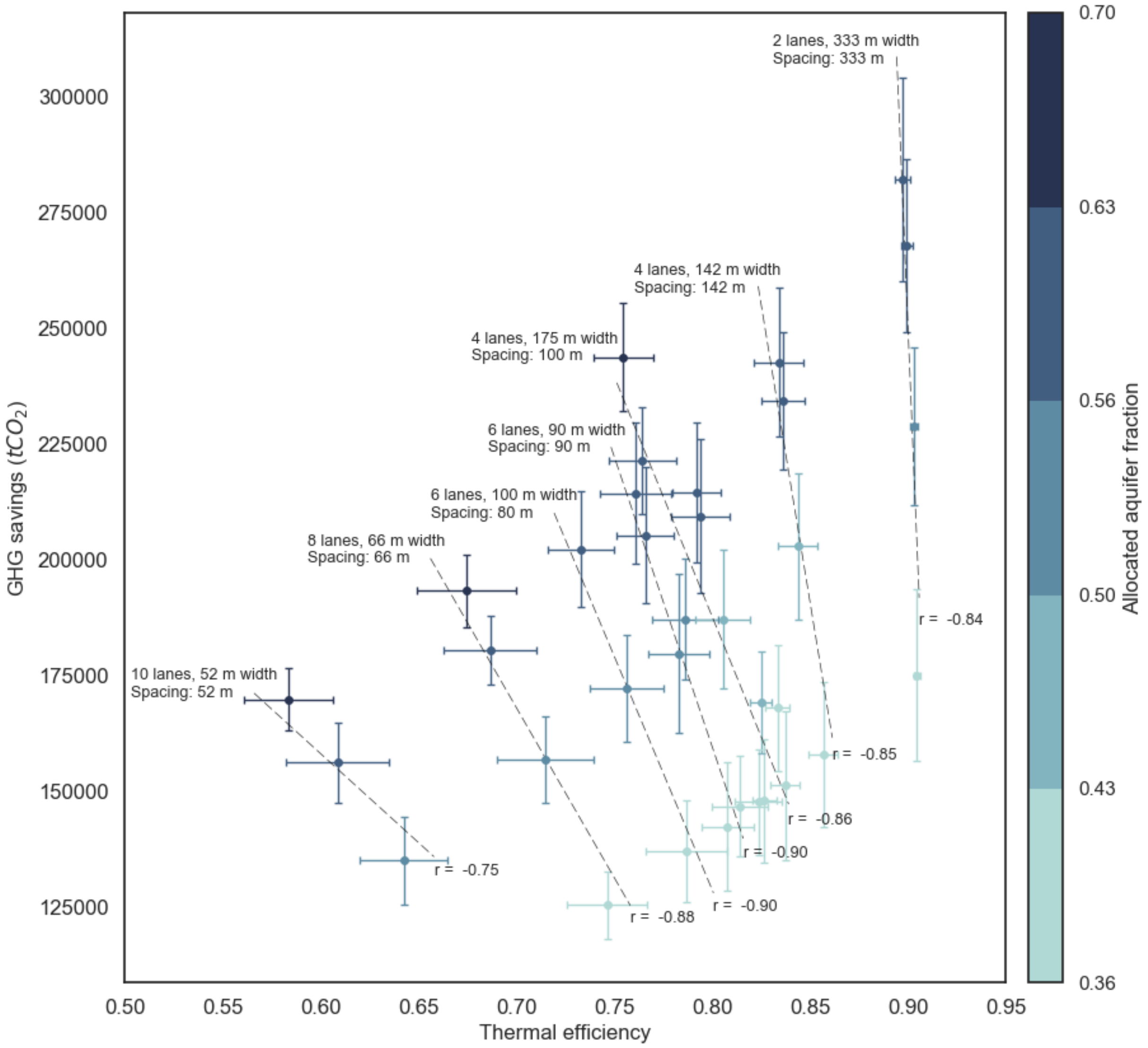

Figure 7. The average of all model realizations for the lane placement scenarios where wells are placed in lanes with given distance and width (details in appendix III). The linear trend lines indicate the correlation between thermal efficiency and GHG savings for each simulated

lane width and spacing condition. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

Ambient groundwater flow

Figure 8 shows the effect of groundwater flow velocity on four particular scenarios discussed earlier. Each of the four scenarios was simulated for three values of the true groundwater velocity, i.e. 0, 10 and 25 m/y. The impact of ambient groundwater flow on well efficiency and aquifer use was tested for two ATES layouts, self-placement and lane placement shown in the left and right subplots in Figure 8, respectively. The results of the zero groundwater velocity for the self-organized scenarios can be found in Figure 5 in the corresponding column and row for the opposite and the same type distances, and the corresponding value of the allocated aquifer fraction indicated below Figure 8. The results of the lane scenarios for zero groundwater flow can be found in Figure 7 for corresponding lane spacing and allocated aquifer fraction.

It is noted that groundwater velocity limited to 25 m/y has almost no effect on ATES efficiency when lanes of sufficient spacing and width are used. Even in the situation of self-placement is the impact of groundwater flow on ATES efficiency limited to a few percent (maximum 5%).

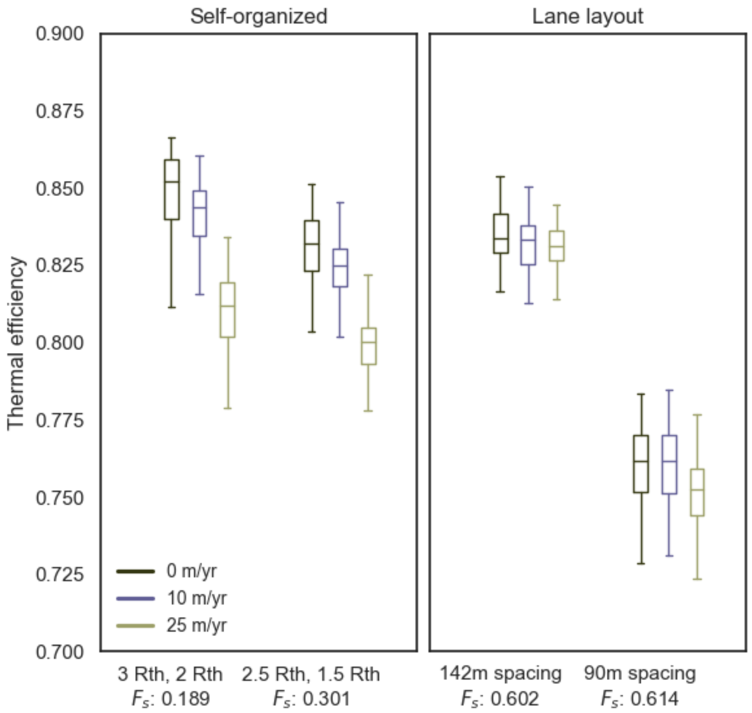

Figure 8. Boxplot for thermal efficiency in a set of representative policies, across three scenarios for ambient groundwater flow. Lane width and spacing were the same. Each box-plot represents the efficiency results of 64 realizations for each scenario.

Storage volume constraints 1: thermal energy imbalance

Currently the permitting authorities require a periodic energy balance, i.e. moments when the injected thermal energy balances the extracted thermal energy may not be further apart than 5 years. This requirement constrains operation of building systems and through this their GHG emissions. Therefore, allowing a structural imbalance fosters effective use of aquifer space and reduces GHG emissions. The effect of allowing such an imbalance is difficult to capture in simulations because thermal energy imbalance varies considerably between years and buildings. Since a detailed simulation of the building heating and cooling system itself is outside the scope of this paper, the impact of the thermal energy imbalance was evaluated for well efficiency and not for the GHG-emissions. The imbalance was implemented as a structural yearly surplus or shortage of heat, constant for each ATES system but for each building randomly chosen from the normal distribution between -30 and 30% compared to the yearly storage volume.

Thermal energy imbalances change the effective thermal radius, which can result in unforeseen interactions between neighboring wells. But as Table 3 shows, an imbalance between -30 and 30% only has a small negative effect on average areal and seasonal performance of the simulated ATES systems: none of the scenarios shows a significant efficiency difference. This implies that flexibility on thermal balance constraints may be allowed in high-density ATES areas as long as the plan area as a whole does not have a structural net imbalance. With this limitation in mind, dropping the thermal energy balance requirement may help reduce GHG emissions compared to the situation in which ATES systems are forced to balance their wells by additional energy consumption. Clearly, when the plan area as a whole has structural surplus of either heat or coldness, long term use of the aquifer for ATES is not possible.

Table 3: Mean thermal efficiency for a set of representative policies, under a nominal scenario with imposed thermal balance, and a random imbalance scenario with 30% imbalance towards warm and cold wells.

	Nominal	**Random imbalance**
3 Rth / 2 Rth (mean F_s: 0.189)	0.840	0.838
2.5 Rth / 1.5 Rth (mean F_s: 0.301)	0.831	0.827
4 lanes, 142m spacing & width (mean F_s: 0.602)	0.844	0.843
6 lanes, 90m spacing & width (mean F_s: 0.614)	0.761	0.758

Storage volume constraints 2: Collective systems

The difference in this scenario with respect to previous ones is the requirement that ATES systems have a minimum size of 250,000 m^3/y. Figure 9 shows the results for different policies with collective systems, indicated with a number referring to the legend. Each marker is connected by a dashed line to the result of that same policy without the collective system constraint. Each marker is the result of 64 realizations with its IQR; higher values of the final allocated aquifer use fraction are, again, indicated with darker shading.

The figure shows that prescribing a large minimum size results in higher GHG emission reductions but in lower thermal efficiencies. This is true for all scenarios except for scenarios 1 with groundwater flow; as larger thermal radii make ATES systems less sensitive for groundwater flow as was also shown by Bloemendal and Hartog (2018). Collective (i.e. larger) systems lead to a higher allocated aquifer space fraction as indicated by darker markers in Figure 9. This results in a higher reduction of GHG emissions. However, a higher allocated aquifer space fraction also leads to more interaction between wells of the opposite type. This reduces the average thermal energy efficiency of the systems. It is noted that for the scenarios with lanes, the efficiency decrease is much stronger than the other scenarios. This is because larger systems require a larger lane spacing to prevent interaction between wells of opposite type.

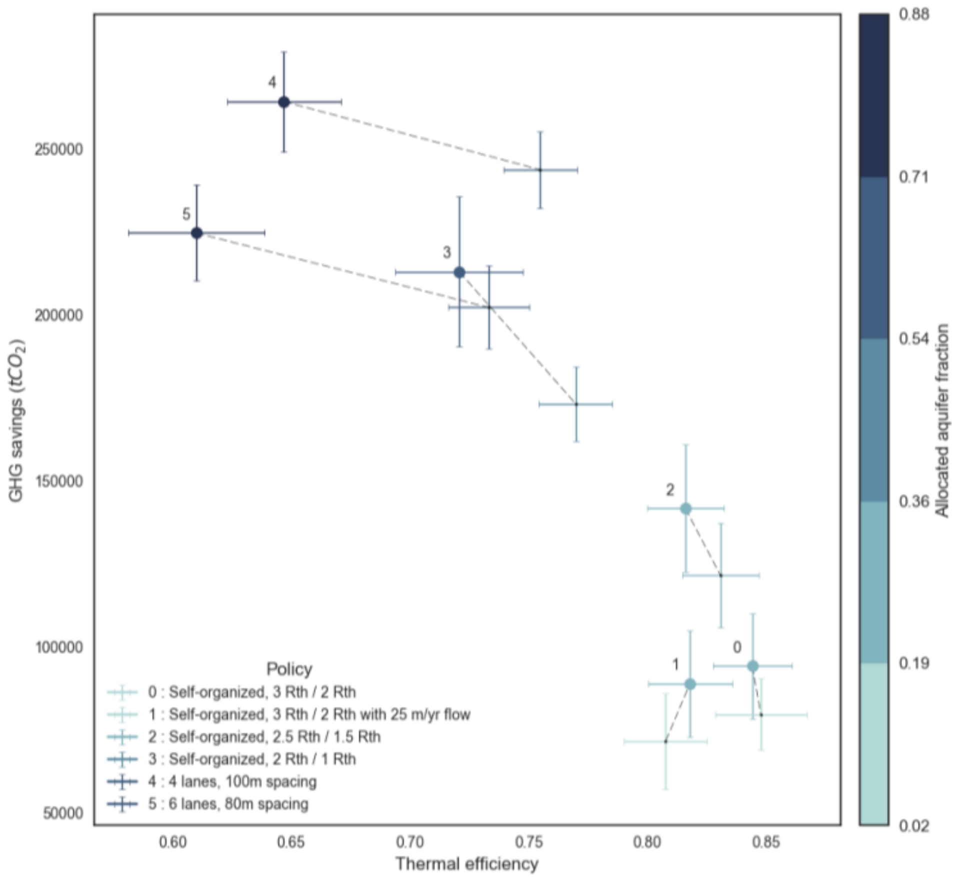

Figure 9. The average of all model realizations for the scenarios with collective ATES system, compared to policies with normal sized ATES systems. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

Cost considerations

The costs of drilling and installing wells and piped connections comprise a considerable part of the initial investment of ATES systems. The effect that the chosen planning rules has on these costs is discussed next (for analysis see Appendix D).

- The mutual distance between wells was varied across the different scenarios discussed above. Compared to the reference policy determined by a required distance between wells of same and opposite type of $2R_{th}$ and $3R_{th}$, that with required distances of $1R_{th}$, and $2.5R_{th}$ results in an average 15% decrease of the distance between the wells of the same system. Placing wells closer together obviously also reduces connection costs.
- In the lane placement scenarios, also the mutual distance between wells of the same system changes. Compared to the reference scenario, the average distance between the wells of the ATES systems increases by a factor 2 and 5 for the 100 m and 333 m lane spacing scenarios respectively.
- None of the scenarios that varied well type and screen length show a considerable influence on their average distance. Larger screen lengths reduce their thermal radii and with them also their mutual distance, although only a little. This compensates for the obvious increase in drilling costs of longer screens. In some cases, it is beneficial to drill deeper to save on horizontal piping, as the latter can be very expensive in densely built urban areas.

4.3. Synthesis and Discussion

Thresholds for ATES planning

The simulation results suggest that at allocated subsurface fractions for ATES below 25% planning rules neither affect well efficiency nor overall GHG savings. The lower right subplot in Figure 5 shows this, because the scenarios following the current rules/practice reach a maximum allocated subsurface fraction of only 24%.

The other subplots in Figure 5 and Figure 6 show that well distance and design constraints achieve ultimate allocated subsurface fractions a little over 50%. This suggests that with the general rules prevailing, self-placement can still facilitate optimal use of subsurface space up to 50%, and in thin aquifers to a little below 40%.

Figure 7 and Figure 8 show that only lane placement combined with a coordinated approach to minimize well size (Figure 9) can make the simulated scenarios reach allocated subsurface fractions beyond 50%.

These values: < 25%, 25-50% and >50% suggest that 25% and 50% can be regarded as thresholds. However, two aspects have a large influence on the identified thresholds for ATES planning, which may result in situations in which the here identified thresholds are either too strict or too loose.

1. Well placement.

   The agent-based exploratory modelling in this study mimicked the behavior of well placement conditions in dense urban settings in which it is difficult to find suitable spots for drilling ATES wells. Despite this extensive modelling effort, it is advised to apply the identified thresholds conservatively, and let the application in practice confirm their validity with more certainty.
2. Actual volume stored in the aquifer by the ATES wells. The model always fully utilizes the permitted storage volume for each ATES system in the plan area. Practice is, however, quite different, where less than 50% of permitted capacity is actually used (Graaf et al., 2016; Willemsen, 2016). But optimization of ATES in busy settings requires all allocated space to be actually used. This can be achieved by A) a thorough assessment of the technical substantiation of the requested storage volume in permit applications and B) by implementing a " use it or lose it" policy, which "frees" unused allocated aquifer space for new ATES requests (Bloemendal et al., 2017). Of course, variations between years in the use of the allocated aquifer space should be taken into account (Bloemendal and Hartog, 2018). Also under standard rules would such a "use it or lose it" permitting strategy be effective to prevent crossing the density thresholds beyond which areal planning of ATES systems is necessary.

Planning rules for spatial lay-out of ATES wells

Lane well placement comes at a cost because the distance between wells often more than doubles, raising connection costs. At low allocated subsurface fractions, lane placement is counterproductive because it prevents clustering of wells of the same type, which results in lower well efficiencies and GHG reductions. Lane placement should be favored where ambient groundwater velocities are considerably beyond 25 m/y, regardless of the required allocated subsurface space. This value of 25 m/y corresponds with the threshold for individual ATES wells as identified by Bloemendal and Hartog (2018).

Monowells and small doublets vs collective ATES system

Small ATES systems tend to only use the upper part of the aquifer. This saves drilling costs but at the same time limits access of new systems because the lower part of the aquifer remains unused. Therefore, ATES in dense settings on top of a thick aquifer, e.g. Amsterdam where the aquifer is 180 m thick, benefits most from enforcing the utilization of the full aquifer thickness. Fully penetrating wells may be too expensive and inefficient for small ATES systems in a thick aquifer, which is why they then prefer monowells. But the vertical screen separation required for monowells is not optimal from the perspective of maximum utilization of the available aquifer. In fact, monowells require a horizontal distance to neighboring systems as well as the vertical distance between the two screens. This reduces their storage capacity relative to doublet wells. Monowells are nevertheless cost-effective for small buildings. Banning them from busy areas may prove counterproductive for the ATES adoption given their large potential for medium to small utility buildings of which many exist (Agterberg, 2016). Therefore, it is advised to only exclude monowells in the busiest areas (e.g. > 50% allocated subsurface space).

Additional research may identify how groups of small buildings can work together using a collective doublet system, or if a subarea within an ATES plan can be dedicated to monowells. Many aquifers are intersected by local clay layers that eliminate the otherwise required vertical screen separation of monowells. Under such aquifer conditions, monowells are far less inefficient with aquifer space compared to when vertical separation of valuable aquifer space is needed. So, under such circumstances monowells should not be excluded.

The limited effect that collective systems have on GHG emissions, and the negative effect that they have on individual well efficiency, makes collective systems difficult to implement. On top of this, the organizational arrangements and the operational control required for collective systems are complex compared to individual systems.

Heterogeneity of the aquifer

Sommer et al. (2013) indicate that aquifer heterogeneity reduces ATES efficiency when distances between wells are short and groundwater velocities are high. Simulations with layered conductivity profiles obtained for real Dutch aquifers studied by Xynogalou (2015) show an average efficiency decrease of about 5% for ATES systems in aquifers with medium and large heterogeneity. Some of the scenarios were carried out with layered aquifers as used by Xynogalou (2015); well efficiency dropped with little over 5% in the $1R_{th}$ / $2.5R_{th}$ distance policy. In general, heterogeneity has a limited effect on overall efficiency, but of course, specific settings, like aquifers with gravel layers, may require specific rules for well design/placement in the ATES plan.

Other subsurface functions

The method to organize subsurface space discussed in this research solely focused on ATES. In practice, however, also other functions may be present in the aquifers designated for ATES, e.g. storage of other energy carriers (Guo et al., 2017; Rapantova et al., 2016), fresh water storage and recovery (Zuurbier et al., 2013a) or de presence of contamination (Sommer, 2015; Zuurbier et al., 2013b). In the case of such coinciding use of the subsurface an integrated plan should be made to enable optimal and sustainable use of the subsurface for all, or at least as much as possible, the intended functions e.g. (Procesi et al., 2013).

5. ATES planning method for use in practice

5.1. ATES planning goals and considerations

The goal of ATES plans is to ensure maximum utilization of the available aquifer space by organizing the vertical and spatial distribution of the ATES wells, thus allowing accommodation of future developments in the plan area. This approach allows ATES users to, for instance, combine their wells with those of their neighbors and to apply a smaller distance between their warm and cold wells. ATES plans result in specific rules, which are likely to vary between ATES plans, and, therefore, results in fragmentation of legislation, which will hinder ATES development. Therefore, it is best to avoid the need for ATES plans by implementing proper national rules, i.e. fully penetrating screens and the $1R_{th}$ / $2.5R_{th}$ distance policy.

If an ATES plan is needed, scenario evaluation should be applied to establish the best planning rules. The assessment framework developed in this study, can be used to evaluate combinations of energy use and well design/locations that result in the most optimal plan, given the uncertainties in future developments. This approach was tested in practice (Bloemendal et al., 2016) and resulted in a clear insight on the effect that various planning rules have on installation cost, individual efficiency, robustness and allocated subsurface space and on their interactions. This was then used by the stakeholders to choose the best planning rules (Table 4).

Table 4. Result of the scenario evaluation for one of the energy demand scenarios of the Lelystad airport ATES plan report. The top scenario is the reference, the shadings indicate the relative benefit compared to the other scenarios. Local authorities and area developer together agreed to apply the bold indicated rules. No spatial lay outs were evaluated because the allocated subsurface fraction in the plan area is 0.1 m^3/m^3. Due to the large aquifer thickness ~100m relatively basic well design rules help to utilize subsurface space for ATES effectively. Also the large aquifer thickness in combination with the limited allocated subsurface fraction make that monowells are very beneficial to reduce allocated surface area.

Well type	**screen length**	**Energy balance**	**D_opposite**	**Cost** % change	**Individual efficiency** %	**Allocated surface area** m2/m2	**GHG emissions** Ton CO2/m2
Free	Normal practice, based on max. required flow rate	Balance	3 x Rth	0%	77%	0.64	1.54
			2,5 x Rth	2%	74%	0.64	1.54
			2 x Rth	1%	69%	0.64	1.54
			1,5 x Rth	1%	63%	0.64	1.55
		Flexible	3 x Rth	4%	77%	0.51	3.23
			2,5 x Rth	4%	74%	0.51	3.23
			2 x Rth	3%	69%	0.51	3.24
			1,5 x Rth	3%	63%	0.51	3.25
	Longer screens, using Doughty et al. (1982) based on storage volume	Balance	3 x Rth	20%	83%	0.15	5.55
			2,5 x Rth	20%	80%	0.15	5.56
			2 x Rth	19%	75%	0.15	5.56
			1,5 x Rth	19%	69%	0.15	5.57
		Flexible	3 x Rth	22%	83%	0.11	12.29
			2,5 x Rth	**21%**	**80%**	**0.11**	**12.30**
			2 x Rth	21%	75%	0.11	12.30
			1,5 x Rth	21%	69%	0.11	12.31
Monowell	Longer screens, using Doughty et al. (1982) based on storage volume	Balance	3 x Rth	*n.a*	83%	0.12	14.59
			2,5 x Rth	*n.a.*	80%	0.12	14.59
			2 x Rth	*n.a.*	75%	0.12	14.59
			1,5 x Rth	*n.a.*	69%	0.12	14.59
Doublet		Flexible	3 x Rth	*n.a.*	83%	0.24	7.30
			2,5 x Rth	*n.a.*	80%	0.24	7.30
			2 x Rth	*n.a.*	75%	0.24	7.30
			1,5 x Rth	*n.a.*	69%	0.24	7.30

5.2. ATES planning steps

The steps of the developed ATES planning method to be presented next, follow from on the identified requirements, see introduction and Appendix B. The developed tools, i.e. the allocated aquifer fraction thresholds, distance and well-design rules, energy balance, collective systems and lane placement strategies, form the core of the method.

STEP 1 Introduction and approach: a) introduce and describe the ATES plan area and identify the involved (future) stakeholders, b) define the approach, methods and parameters to be used in the ATES plan and c) identify any constraints and/or conditions that stakeholders may set with respect to the ATES plan.

Result of step 1: Project plan.

STEP 2 Orientation: a) identify the local geohydrological conditions and b) a min-max range on expected use of aquifer space for ATES, taking into account the uncertainty of developments and energy demand variations. c) Based on the confrontation between available space and required space, decide whether or not to use ATES planning, a decision based on the thresholds for allocated subsurface space that were identified in this study.

Result of step 2: Information needed for the ATES plan, or support that ATES plan is not needed.

STEP 3 Planning of ATES wells: a) Identify which design variables specific to the plan area can be adjusted to achieve optimal use of the available subsurface space. b) Develop scenarios for future energy demand and different layouts of the ATES wells. c) Assess these scenarios and identify which rules are optimal for the plan area.

Result of step 3: Identification of the preferred planning rules for the plan area.

STEP 4 ATES plan implementation and governance: a) Anchor the final ATES plan in legislation. b) Identify which party will be responsible for the implementation of the ATES plan and its maintenance.

6. Conclusions

This study evaluates ATES planning methods and characteristics from practice. Analysis of existing ATES plans and the methods currently in use showed that ATES plans lack steps that are essential to unambiguously define a strategy leading to maximum overall reduction of GHG-emissions of the ATES systems within the ATES plan area. With the results of this work optimal use of subsurface space can now be achieved in practice because exploratory modeling and analysis identified the missing tools in the framework for ATES planning:

A. Effective parameters for planning that help prevent the need for ATES planning: 1) fully penetrating well screens and 2) distances between wells of opposite and same type of $2.5R_{th}$ and $1R_{th}$ respectively.

B. Thresholds to tell when ATES planning is needed. The simulated allocated aquifer space fractions varied from 2% to 75% , which allowed to identify a stepwise approach for planning. Self-placement scenarios don't need ATES planning rules for allocated aquifer fractions below 25% within the current practice and regulatory framework. At allocated aquifer fractions for ATES ranging from 25% to 50%, rules for well design and well spacing foster self-placement. Beyond 50% allocated aquifer space fraction, the highest GHG emission reductions are obtained with a prescribed spatial arrangement of the warm and the cold wells in separate lanes.

C. Effective placement and operation methods for lane placement in the busiest areas. Both the width and the spacing of the lanes must be twice the average thermal radius of the ATES systems in the area. Arrangements on collective systems and an area-wide energy balance increase effective use of aquifer space for ATES even more.

D. An assessment framework to evaluate possible planning strategies. The following assessment parameters were identified: total GHG-emission reduction, cost for installation, recovery efficiency and robustness.

It is concluded that the improvements of governance, design and planning practices presented in this study can be easily used and implemented in practice in the Netherlands because they fit within the Dutch regulatory framework. Although in many countries ATES adoption is not as high as in the Netherlands, the specific problem discussed in this study is also likely to occur on other cities around the world. Countries at the early stage of ATES adoption can take advantage of this research and the experience in the Netherlands by planning and applying ATES according to the methods presented in this study, and thus ensuring maximum GHG savings with ATES from the early start.

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Appendix A – Benchmark 24 ATES plans

A.1. The analyzed ATES plans

Subsurface planning is not limited to ATES (Epting et al., 2017; Parriaux et al., 2004; Willems et al., 2017), but in recent years, tens of ATES plans were made in The Netherlands. All 24 publicly available Dutch ATES plans were used for the analysis in this paper. They are listed below:

- Amersfoort (5); Randenbroek Zuid, Hogeweg, De Wieken – Vinkenhoef, Vathorst, De Laak 3
- Amstelveen; Stadshart
- Amsterdam (7); Buiksloterham, Dam, Minervahaven/houthaven, Parooldriehoek, Science park, Slotervaart, Kop van Zuidas
- Apeldoorn; Kanaal zone
- Breda; Stationskwartier
- Delft; University campus
- Gouda; Goudse poort
- Hoofddorp; Beukenhorst
- Lelystad; Lelystad Airport Businesspark
- Rotterdam; City Centre
- Utrecht (2); City centre, Uithof
- Zwolle (2); Voorsterpoort, A28

A.2. ATES plan metrics

For each plan an area is demarcated in which the existing and expected future buildings with ATES will be taken into account for the ATES planning, see Figure A.1Figure A.1.

The following statistics were obtained from these ATES plans: 1) number of buildings, 2) total plan area (A_{Ap}), 3) total floor space area, of the buildings (A_b) 4) total thermal energy to be obtained from the subsurface for heating and for cooling (E) derived from permitted storage volumes and expected temperature difference between wells, 5) aquifer thickness, 6) ambient groundwater flow velocity and its direction, 7) type of planning. Generic information was gathered as well, like a) the consultancy that made the plan, b) the dominating building type (housing, utility or mixed).

Because the extent of the plan area and its subsurface conditions differ between plans, the following characteristics were defined to make comparison of plans possible:

- Floor Space Index (*FSI*). The *FSI*, is the total floor space of the buildings divided by the ATES plan area ($FSI = A_b/A_{Ap}$). The *FSI* quantifies the urban setting.
- The allocated fraction of subsurface space (F_s) for ATES.

  Allocated fraction of available aquifer space is used to quantify the density of the ATES setting between different areas. It is defined as the ratio of the yearly stored volume of groundwater of all ATES systems over the available aquifer space (plan area time aquifer thickness) in the plan area.
- The allocated fraction of surface area (F_A) to ATES is the sum of the thermal radii of all ATES wells divided by the ATES plan area.

The actual well design, diameter, screen length etc., is never given in the ATES plans, so that aquifer thickness was used as a proxy of the screen length. This is a valid assumption in relatively thin aquifers (<30m thickness) where wells are usually fully penetrating (Bloemendal and Hartog, 2018). In thick aquifers, where well screens are generally partially penetrating, this assumption may underestimate the thermal radius and, therefore, the ATES footprint.

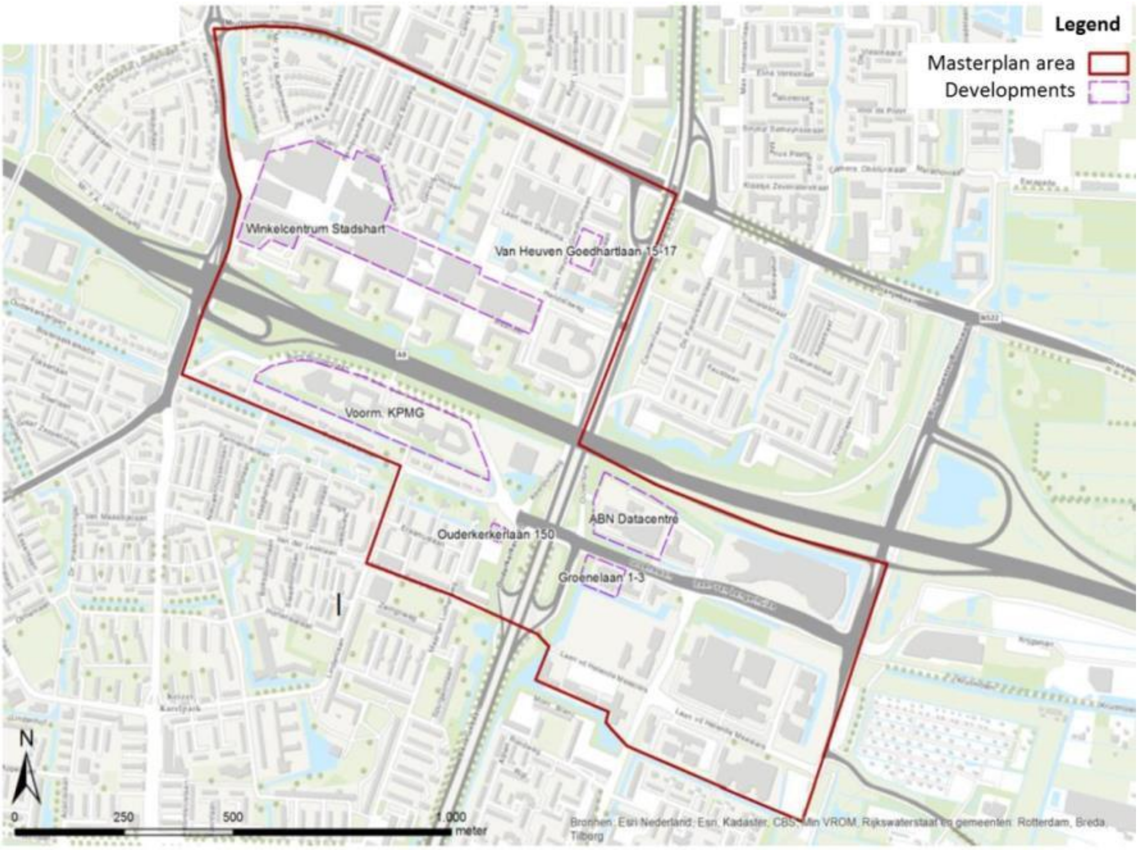

Figure A.1. Example of ATES plan area demarcation. (Figure 4 from ATES plan Amstelveen)

A.3. Benchmark results

Table A.1 presents the metrics introduced in section A.2 of the 24 available ATES plan areas analyzed for this study. These plans were made by five different consultancies, but 17 of the 24 plans stem from only one. Four ATES plans are within the city of Amersfoort and deal only with housing. The other 20 plans have either utility buildings or a combination with housing as their subject. Despite the limited variability in building functions and plan-makers, the 24 ATES plan areas have widely varying characteristics.

Table A.1. Summary of ATES plan characteristics (perc = percentile, stdev=standard variation)

	0.1 perc	average	0.9 perc	stdev	unit
Surface area of buildings	95,000	86,000	815,000	520,000	[m^2]
Surface area of ATES plan (A_{Ap})	144,000	925,000	2,324,000	960,000	[m^2]
Total thermal energy storage (E)	25,000	133,000	298,000	110,000	[GJ/y]
Aquifer thickness (t_a)	25	65	100	30	[m]
Groundwater flow	5	10	12	10	[m/y]
Floor space index (FSI)	0.2	0.8	1.5	0.71	[-]
Allocated fraction subsurface space(F_S)	0.03	0.21	0.37	0.14	[$m^3/m^3/y$]
Allocated fraction surface area (F_A)	0.07	0.33	0.54	0.21	[m^2/m^2]

The summarized floor surface of the buildings, the ATES plan area, the associated total energy storage, the aquifer thickness and groundwater velocity vary strongly among the ATES plans, reflecting variations in local conditions. All plans consider urban areas with high demand for ATES systems, their subsurface space and surface area allocated to ATES are, therefore, expected to be high in all ATES plans with limited variation. Some of the plans state that a subsurface claim over 50% is used as a threshold above which an ATES plan is necessary; however, the data show that only 5 of the 24 plan cases exceed this percentage.

Most plans (54%) organize their wells in warm and cold lanes that are oriented either in the direction of the groundwater flow, or match the street layout when groundwater flow is low. 25% of the plans use search areas for placement of warm and cold wells, while 13% of the plans directly indicate future well locations. The remaining 13% only prescribe general rules for the distance between wells. The corresponding average allocated fraction of subsurface area values are: 28%, 43%, 44% and 12% respectively. Although the differences and number of plans are small, this indicates that the busier an area is, the more strict/explicit the formulated rules for spatial planning of wells are.

The Pearson correlation coefficient ($r_{x,y} = \mathrm{cov}(x, y)/\sigma_x\sigma_y$) is suitable to quantify to what extent ATES plan characteristics are related and to identify if the proposed allocated aquifer space and surface area for ATES are suitable metrics to compare ATES plans and identify thresholds for planning rules. Due to the limited number of ATES plans in the dataset, the correlations identified are not statistically relevant, but may point towards reasons why the allocated subsurface space and surface area differ among ATES plans. Table A.2Table shows the Pearson correlation coefficients of different ATES plan area characteristics.

Table A.2. Pearson correlation coefficient for different ATES plan characteristics.
(>0.8/<-0.8 = strong correlation, green fill; >0.5/<-0.5=moderate, no fill; >0.2/<-0.2=weak, red fill)

ATES plan metric	A_b	A_{Ap}	E	t_a	*FSI*	S_s	S_A
Building s. area (Ab)	1.0						
Surface area of ATES plan area (A_{Ap})	0.52	1.0					
Total thermal energy storage (E)	0.88	0.64	1.0				
Aquifer thickness (t_a)	0.21	0.14	0.23	1.0			
Floor space index (*FSI*)	0.18	-0.41	0.12	0.29	1.0		
Allocated aquifer space fraction (F_s)	-0.12	-0.45	0.00	-0.46	0.49	1.0	
Allocated surface area fraction (F_A)	-0.08	-0.55	-0.10	-0.30	0.61	0.80	1.0

Aquifer thickness varies between ATES plans; thick aquifers result in lower allocated fraction of subsurface space and vice versa. This is mildly reflected in the moderate negative correlations between aquifer thickness and both allocated aquifer space and surface area. The difference between the correlation of both the allocated fraction of surface area and the allocated fraction of subsurface space with the aquifer thickness (-0.30 & -0.46), indicates that the plans in this data set do not take full advantage of the available aquifer thickness, which was also found by Bloemendal and Hartog (2018).

Both the allocated fraction of surface area and the allocated fraction of subsurface space show a moderate (to weak) negative correlation with the aquifer thickness (-0.30 & -0.46). This indicates that the size of the ATES plan area influences the value of the allocated fraction of surface area a lot. The allocated surface area and subsurface space fraction have a negative correlation (-0.55 & -0.45) with the total surface area of the ATES plans area, indicating that ATES plan areas have been chosen too large. This then result in a lower allocated surface area fraction when a large area around the most densely built area is included in the ATES plan as well as when large areas of infrastructure are included. This was observed almost all ATES plans, e.g. Figure A.1Figure A.1.

Conclusions

The allocated aquifer space fraction for ATES is only a good measure for comparing ATES plans and identifying thresholds when there is no ambiguous inclusion of areas in the plan with few or no ATES systems. When well screens are fully penetrating, both allocated surface area and subsurface space fraction show the same result. Together, the allocated subsurface fraction and surface area fraction are a good indicator on how efficiently subsurface space is used.

Appendix B – Current ATES planning method

B.1. Analysis of ATES planning steps

To allow for a higher density of ATES systems than can be achieved with the current legal framework, a special planning framework is currently applied in The Netherlands (Arcadis et al., 2011; Schultz van Haegen, 2013), which allows stepping off from the standard rules and policies that target individual systems in favor of a more organized lay-out of wells in areas under high demand (Schultz van Haegen, 2013). There currently exists only one formal ATES planning method in the Netherlands, the guidelines by Arcadis (2011). The four steps in these guidelines are shortly summarized, followed by an analysis using the findings in benchmark on the available ATES plans in Appendix A.

STEP 1 Orientation;

Description from the Arcadis ATES planning guidelines: In this step the local geohydrological conditions and the energy demand of the present and planned buildings are quantified. The results determine whether an ATES plan is required or not.

Analysis: All 24 ATES plans contain an orientation step, which was generally divided over two sections of the plan: one focusing the geohydrology and one focusing the energy demand of the buildings (to be) developed. No clear threshold was found upon which it was decided when a ATES plan is required or not. Because a rationale was nowhere clearly indicated in the plans, the decision to organize ATES systems with an ATES plan appears to follow from expert judgment of the involved engineers and/or local authorities. Only in one plan it was concluded that planning was not necessary, but rules to organize layout of ATES wells were still made for the plan area. Most ATES plans only sparingly indicated or referred to data or parameter values on which their calculations were based. This made it often difficult to reconstruct and compare results.

Recommendations: Define (well-founded) thresholds above which planning of ATES systems is required, and explicitly end the orientation phase by checking these thresholds before deciding to proceed making an ATES plan. Communicate used data and assumptions explicitly, preferably by a standard regarding data and characteristics.

STEP 2 Project plan;

Description from the Arcadis ATES planning guidelines: Once it is decided to produce an ATES plan, a so-called “project plan” is drawn up to involve all relevant stakeholders, i.e. provincial and municipal authorities and building and plot owners in the specified area, in the process of making the ATES plan. Agreements are then made regarding communication, costs and organization of the process of establishing the ATES plan.

Analysis: There was no “project plan” in any of the ATES plans. Agreements on who will carry the cost for the ATES plan was something (probably) decided prior to the study and, therefore, not mentioned in any of the ATES plan reports. Local municipality commissioned the ATES plan in most cases. Instead of organizational agreements, one third of the ATES plans outline their approach.

Recommendation: Start the ATES plan describing the criteria, key factors and their values upon which the decision is made whether or not to establish an ATES plan, followed by describing the methods used for planning of the wells. Organizational agreements better be arranged in separate documents/contracts, where it is recommended to make a clear indication in release of budgets for 1) the orientation phase and decision to make the ATES plan or not and 2) the actual making of the ATES plan.

STEP 3: Planning of ATES wells;

Description from the Arcadis ATES planning guidelines: The actual planning of future wells is based on the existing distribution of ATES wells in the ATES plan area and on expected demand and on the aquifer characteristics.

Analysis: The Arcadis guidelines identify different layouts for ATES wells in a general fashion. Spatial lay-outs in the 24 ATES plans result from this description, but none of the plans gave a rationale for its choice. Neither did they give an overview of design variables, which also lack in the Arcadis (2011) guidelines. Most of the 24 plans use only well location as a design variable; some also use well type. However, many other ATES systems characteristics (e.g. energy balance, storage volume, well screen length) affect ATES use of the subsurface but were not considered for manipulation while planning. As a result of this, the identification of the chosen spatial planning of the ATES wells is indistinctly substantiated in 23 of the 24 ATES plans. Only the plan for Lelystad airport evaluated alternative lay-out patterns.

Many studies argue that the actual building energy use and, therefore, subsurface space use by any ATES system will likely vary strongly during the life time of a building (Bloemendal and Hartog, 2018; Bloemendal et al., 2014; Jaxa-Rozen et al., 2015; Li, 2014; Sommer, 2015). However, all ATES plans organize the subsurface based on the snapshot of the existing and planned developments at the time of the planning. These preconditions will often change considerably during execution of the ATES plan, which will render the plan suboptimal over time. A robust ATES plan must take these uncertainties into account, for instance by assessing scenarios developed for different planning schemes.

Little over half of the ATES plans evaluated the environmental effects of the ATES systems by also providing figures for GHG emission reduction for comparison with conventional space heating and cooling. However, the added environmental value of an ATES plan is only shown by comparing the GHG emissions for the plan area with and without the ATES plan installed. This comparison then justifies additional rules following from the ATES plan for ATES systems in busy urban areas. Only one the plan for Lelystad airport made a statement on its benefit over normal regulation.

Recommendation: The current planning method is still incomplete; it should be made explicit to allow well-founded decisions. Start with clearly identifying which parameters/characteristics can be manipulated during the planning procedure. Then use scenario analysis regarding future energy use of buildings, and different types of lay-outs. These results should be compared ATES plan with the situation without ATES planning. To be able to comparing different ATES planning scenario's an assessment framework to judge the actual functioning of ATES plan also needs to be developed.

STEP 4. Incorporate the ATES plan-rules in law/regulation;

Description from the Arcadis ATES planning guidelines: Because the lay-out and design rules of the ATES systems through an ATES plan deviates from regular/prevailing regulation. Therefore, the local ATES plan needs to be included in local policy or regulation to make it legally binding for the area of interest.

Analysis: Anchoring ATES planning in legislation was recommended in two-third of the ATES plans. These plans also considered the best way to achieve this. Recently, a national legal framework was set-up to facilitate specific rules like ATES plans for busy settings. This framework enables straight forward securing of ATES plan rules in law in The Netherlands (Schultz van Haegen, 2013). Still, anchoring in legislation is considered an important step to enforce the plan, also given that this step may not be well facilitated in other countries.

Recommendation: This step must not be overlooked. Although ATES planning is currently well facilitated by Dutch law, it may not be the case in other countries; as such it requires more international attention.

B.2. Required improvements for ATES planning

Several points for improvement were identified for ATES planning:

- Justify the necessity of planning,
- Only include areas that require planning (so no infrastructure or areas with low energy demand).
- Substantiate the planning layout that was applied by:
  - Evaluating different alternative ways to organize the ATES wells
  - Compare the added value of ATES planning with the situation of no planning of ATES systems
  - Evaluate how the uncertainties in expected subsurface space use affect ATES plan performance.

These improvements can only be implemented in practice when the following required tools are identified;

- Thresholds of subsurface space use beyond which planning is needed.
- Design variables that can be used to plan the ATES wells (discussed in II.3).
- An assessment framework to compare alternative ATES plans (discussed in II.4).

B.3. Design parameters

Energy demand

It is not desirable that users of ATES systems are limited in the amount of energy that they are allowed to store and extract from the subsurface because of limitations in available subsurface. Laws and regulations on energy performance for buildings and quality standard for contractors lead to minimizing energy demand of buildings and making ATES systems highly efficient (Ministry-of-Internal-affairs, 2012; Schultz van Haegen, 2013). Additional measures would not help much to further limit energy use and expedient use of subsurface space and will only be seen as an aggravation of the regulatory load (Graaf et al., 2016). To keep the use of subsurface space within bounds, a maximum storage volume can be applied like it is already the case in the current Dutch legal framework. This can, however, only be used effectively when storage volume is not over-claimed as is generally done in current practice (Willemsen, 2016). Bloemendal & Hartog (2016) proposed a method to prevent such over-claiming, but still guarantee sufficient mutual distance to prevent negative interaction between wells. To prevent continuous heating or cooling of the aquifer it is required to extract as much heat from the subsurface as was stored in it. Buildings, however, hardly ever require balanced energy storage, which results in additional energy consumption and inefficient subsurface space use. When more ATES wells are installed within a limited area, the chances are that imbalances at the level of individual buildings compensate each other. It is, therefore, interesting to explore how relaxation of the individual energy-balance requirement to an “area overall” balance helps to improve subsurface space use and reduce overall GHG emission. With respect to size of wells; larger wells are more efficient, but may also be harder to allocate in already densely populated areas. It is not yet clear whether promotion of collective systems is positive or not, but of course a local authority may set a minimum size of at an energy storage system.

Conclusion: Promote energy-efficient buildings, if not yet in place, make regulation to enforce this. Evaluate how constraints in well design may limit over-claiming of subsurface space. Allow systems with combined wells to exchange energy to meet overall energy balance, and evaluate how size of systems may affect performance and planning and adoption rates.

Well design

Well design has to consider various parameters;

A. The usable energy content of the water pumped between the wells is set by the applied temperature difference between them. With higher temperatures, less subsurface space is required to store a given amount of thermal energy. From the perspective of optimal use of the subsurface the design temperature is an effective parameter to control. From an energy efficiency perspective it may however be counterproductive. ATES systems use direct cooling from the cold well during summer, as a consequence of that the infiltration temperature in the warm well depends on the required cooling demand. Thus infiltration temperature in the warm well may deviate considerably during the warmest days, compared to moderate or little cooling demand. Despite the limited temperature difference between the wells during such so-called partially load situation, the system does supply sustainable cooling. Artificially increasing the groundwater temperature in such cases would increase primary energy use, and thus also increase of GHG emissions.

   Conclusion: At the current state of technology a minimum temperature difference between well may be a counterproductive ATES planning rule. In really busy areas it can and should be used, but has to communicated to the building installation designers in a very early stage to allow for suitable initial design.

B. The type of well (e.g. monowell, doublet) is chosen in consideration/consistence with the climate installation in the building. Influencing the type of well through ATES planning thus requires conditions for types of wells to be known to building owners. The effectiveness of influencing the type of well type strongly depends on aquifer thickness and building sizes in the area under consideration.

In the busiest situation doublets would be preferable because they use the available subsurface space most optimally by penetrating the full aquifer thickness. Depending on conditions, it may however be legitimate to use other types of wells, for small buildings requiring a doublet may kill the business case and therefore prevent adoption of ATES.

Conclusion; first evaluate how well type constraints/requirements affect subsurface space use and availability, is it really needed to constrain that? If so try to arrange if it is possible to arrange collective wells for the smaller buildings.

C. In Dutch practice, filter screen lengths are made as short as possible within the required flow rate, which results in higher losses due to ATES systems mutually influencing each other and underutilization of aquifers; the lower parts of the aquifers remain unutilized (Bloemendal and Hartog, 2018; Doughty et al., 1982; NVOE, 2006). Rules for requiring minimal filter screen lengths may reduce ATES footprint where aquifers are thick (Hoogmoet, 2016). Minimum filter screen lengths could be set dependent on expected storage volume using the rule proposed by Bloemendal & Hartog (2018). To get maximum effect of this rule; when two wells of the same type are combined the combined storage volume of those wells has to be used as a basis for filter screen length determination

Conclusion: evaluate how requirements for filter screen length affect subsurface space use, individual performance and additional costs for individual systems. This measure has less impact then well type, but may still have considerable influence on installation cost on one and efficiency on the other hand.

Well location

Any given layout of ATES wells that is based on an expected fixed future situation restricts the possible use of the available subsurface space when development deviates from that future (Li, 2014). Several studies showed that ATES wells organize themselves when each additional system chooses its own well location for its own benefit (Bloemendal et al., 2014; Caljé, 2010). Fixed regulations for minimum and maximum distances between wells facilitate control over the spatial claims by the involved ATES systems. Small well distances reduce flexibility for individual systems to deal with changing energy demand and also reduce efficiency of individual systems. Below a certain efficiency ATES operators will shut down their system (Jaxa-Rozen et al., 2016; Jaxa-Rozen et al., 2015). On the other hand placing wells closer together increases GHG savings for the considered area because more ATES capacity can be utilized in a given area. This trade-off needs to be discussed and decided on in the ATES plan. In areas with a high ambient groundwater flow, roughly over 25 m/year, the planning of the wells should take account advection losses into account (Bloemendal and Hartog, 2016).

Conclusion: Evaluate to what extent spatial planning rules for layout of ATES wells affect the future use of the available subsurface space, the individual performance and total GHG emissions of ATES systems in a certain area, with and without considerable groundwater flow.

B.4. Assessment framework

Commonly accepted assessment frameworks for subsurface space functions does not exist (Griffioen et al., 2014). Due to the trade-off between individual performance and overall GHG emissions, assessment parameters and performance of an ATES plan depends on the stakeholder. Future building owners are not known at the time the ATES plan is made. This makes substantiation of the choices that underlying the ATES plan a prerequisite to ensure acceptability by future stakeholders who want to install.

Common interest / Governments: For government there are two important aspects. 1) Ensuring the availability of the subsurface for future use. 2) Utilizing the full potential of the subsurface to limit GHG emissions. Apart from the local disturbance of the aquifer by the well construction and small temperature changes in confining layers, the environmental effects of ATES are negligible (Bonte, 2013). From this perspective, ATES is regarded an effective way for governments to achieve GHG-emission reduction. Because of the trade-off between total GHG emission reduction and energy efficiency (Bloemendal et al., 2014; Jaxa-Rozen et al., 2015; Sommer, 2015) ATES systems in busy areas in should be planned such that as many buildings as possible have access to ATES while maintaining recovery efficiency of individual wells.

Individual ATES owners: Key interests for individual owners are 1) cost efficient well construction, 2) guarantee for sufficient space and flexibility to store the required amount of thermal energy and 3) minimal energy losses in the subsurface.

Possible assessment criteria described in (Li, 2014) are: 1) Thermal efficiency of wells. 2) The size of the thermal influence zone. 3) The installation and operation costs. 4) The increased GHG reduction compared to the situation without the ATES plan. 5) Flexibility for existing systems and to add new ATES systems. 6) Mutual thermal interaction. Most of these criteria are difficult or even not possible to quantify at the time of writing of the ATES plan. Moreover, most of these criteria are interrelated, which introduces the risk of double assessment of some of them. In a workshop[3] with local authorities and real-estate developers from an ATES plan (Lelystad

[3] Workshop for establishment of a ATES plan for to be developed business area next to Lelystad Airport, dated 1-21-2016. Participants were representatives of the developer of the business area, Lelystad airport, municipality of Lelystad, Province of Flevoland, KWR, TUDelft.

airport (Bloemendal et al., 2016)) site, it was concluded that four of the identified criteria are suitable to assess different planning options in an ATES planning process:

- GHG emissions
- Recovery Efficiency
- Robustness of the ATES plans
- Installation costs

Appendix C – Description of simulated scenarios

This appendix introduces the details of the scenarios applied in the simulations.

A. Reference scenario.

Area properties: The average size of ATES plan areas following from Table is used; 1 km x 1 km. Also the average aquifer thickness of the 24 ATES plans is used in the reference case; 60m. Ambient groundwater flow is zero.

Specific energy storage: The allocated aquifer space fraction varies between 0.07 to 0.54 $m^3/m^3/y$ in the 24 available ATES plans. As it is the goal to explore to what extend the use of the subsurface can be increased, the number of ATES systems is stepwise increased to identify at which allocated aquifer space fraction the total GHG savings and individual well efficiencies change considerably. NetLogo creates random sizes of ATES systems for all buildings, until no more wells can be placed or the maximum allocated aquifer space fraction is reached. The remaining buildings get their energy requirements to be fulfilled by a conventional heating and cooling system. This way comparison between different specific energy storage densities is made possible, given that all buildings within a specific area require both heating and cooling.

Infiltration temperature: The temperature difference between the warm and the cold wells determines the subsurface space required for the allocated aquifer space fraction under consideration. Because data from practice shows the average temperature difference to be around 4°C (Willemsen, 2016), this value is used.

Well placement: Wells are placed at random location but with respect to the $3R_{th}$ distance policy to opposite ($D_{opposite} = 3$) and $2R_{th}$ policy for same type of wells ($D_{same} = 2$) as this is the current policy in areas without ATES plans. Wells of the same system are placed as close as possible to each other while also respecting the $3R_{th}$ distance policy. No buildings or building plots are defined, the random positioning of the first well represents the uncertainty which is also present in practice; as well locations in urban areas depend stronger on conditions on surface level rather than subsurface (Boerefijn et al., 2010).

Well design and well type: Wells get a filter screen length based on their storage volume, a relation between storage volume and filter screen length is derived from field data of ATES systems (Bloemendal and Hartog, 2018). This data showed a range in which the filter screen length lie, NetLogo determines the filter screen length within this range. When the filter screen length is larger than aquifer thickness, the filter screen length is set to the aquifer thickness.

NetLogo allows to apply a monowell if the spacing between the two filter screens is the same length as the filter screen length, as regularly applied in practice (Xynogalou, 2015).

B. Evaluation of distance policy;

Well placement: Each of the combinations of the values for distance policies indicated below are evaluated, only the ones where opposite type of wells are allowed closer together than same type of wells are not. Same well types (D_{same}): 1, 1.5, 2; and opposite well types ($D_{opposite}$): 1.5, 2, 2.5, 3

C. Well design

Well design and well type: Three alternative well design approaches were evaluated. 1) current practice 2) the design rule identified by Doughty et al. (1982) and Bloemendal and Hartog (2018); $L=V^{1/3}$, and 3) all wells are fully penetrating. The first two scenarios are evaluated for the situation where monowells are allowed as well as for the case where every system is a doublet. In the fully penetrating case, all wells are always doublets.

Area properties: the effect of putting constraints / requirements on wells design, may differ depending on aquifer thickness. Therefore the simulations in this scenario will be evaluated for three aquifer thicknesses: 30, 60 and 90 following the range presented in Appendix A.

D. Evaluation of different lay-out;

Well placement: Sommer et al. (2015) evaluated different spatial lay-outs for ATES spatial planning and concluded that the lane lay out allows for the largest density of ATES systems. Therefore, warm and cold lanes are used to organize warm and cold wells. Lane width and spacing based on average thermal radius of systems. The opposite distance rule ($R_{th} \cdot D_{opposite}$) is no longer active and the same type well distance rule is set to 0.5 (D_{same} = 0.5), to allow for enough space available to place wells within in the lanes. Also monowell are no longer allowed in this scenario, because they cannot be placed in any of the lanes. It is not yet known how lane properties affect performance, therefore, a range of possible lane lay-outs (number, width and spacing) are evaluated, starting at the basic 1 warm, 1 cold lane, up to the maximum possible number within the 1x1 km simulation area; 5 warm, 5 cold lanes.

- 1 warm, 1 cold lane; equally distributed, lane spacing and width = 333m
- 2 warm, 2 cold lanes; equally distributed, lane spacing and width = 142m (more or less similar with the minimal spacing of 150m (150/138), which is therefore not considered)); spacing 100m & width 175m

- 3 warm, 3 cold lanes; equally distributed (90m); spacing 150m & width 42m; spacing 100m & width 83m
- 4 warm, 4 cold lanes; equally distributed (66m); spacing 125m & width 15m; spacing 100m & width 37m
- 5 warm, 5 cold lanes; equally distributed (52m); spacing 100m & width 10m;

E. Energy balance

Well design and well type: A random imbalance is given to the energy demand of the buildings for both the default and fully penetrating well design.

Well placement: both random placement (D_{same} /$D_{opposite}$; 1.5/2.5 & 2/3) as well as lane placement scenarios are evaluated (4 and 6 lanes with equally distributed spacing and width.)

F. Groundwater flow;

Area properties: Ambient groundwater flow of 10 and 25 m/y is applied

Well design and well type: A random imbalance is given to the energy demand of the buildings for both the default and fully penetrating well design.

Well placement: both random placement (D_{same} /$D_{opposite}$; 1.5/2.5 & 2/3) as well as lane placement scenarios are evaluated (4 and 6 lanes with equally distributed spacing and width.)

G. Collective systems;

Energy storage: because the distribution of ATES system sizes from practice consists of many relatively small systems, it is also evaluated how ATES planning would help when such systems use one large combined warm and cold well.

Several test runs were carried out to assess the influence of the uncertainties; the threshold above which the results show a constant normal distribution is 64. So each of the scenarios described above is simulated 64times under uncertainty, with a total of about 140 scenarios this results in roughly 9,000 realizations. The required minimal discretization, long time horizon and 64 required realizations per policy required a substantial effort from our computational resources which was an important driver to carefully consider the effect of model properties on accuracy as well as run time. In this set-up the simulations took over 2 weeks of net-runtime on a 96 core cluster.

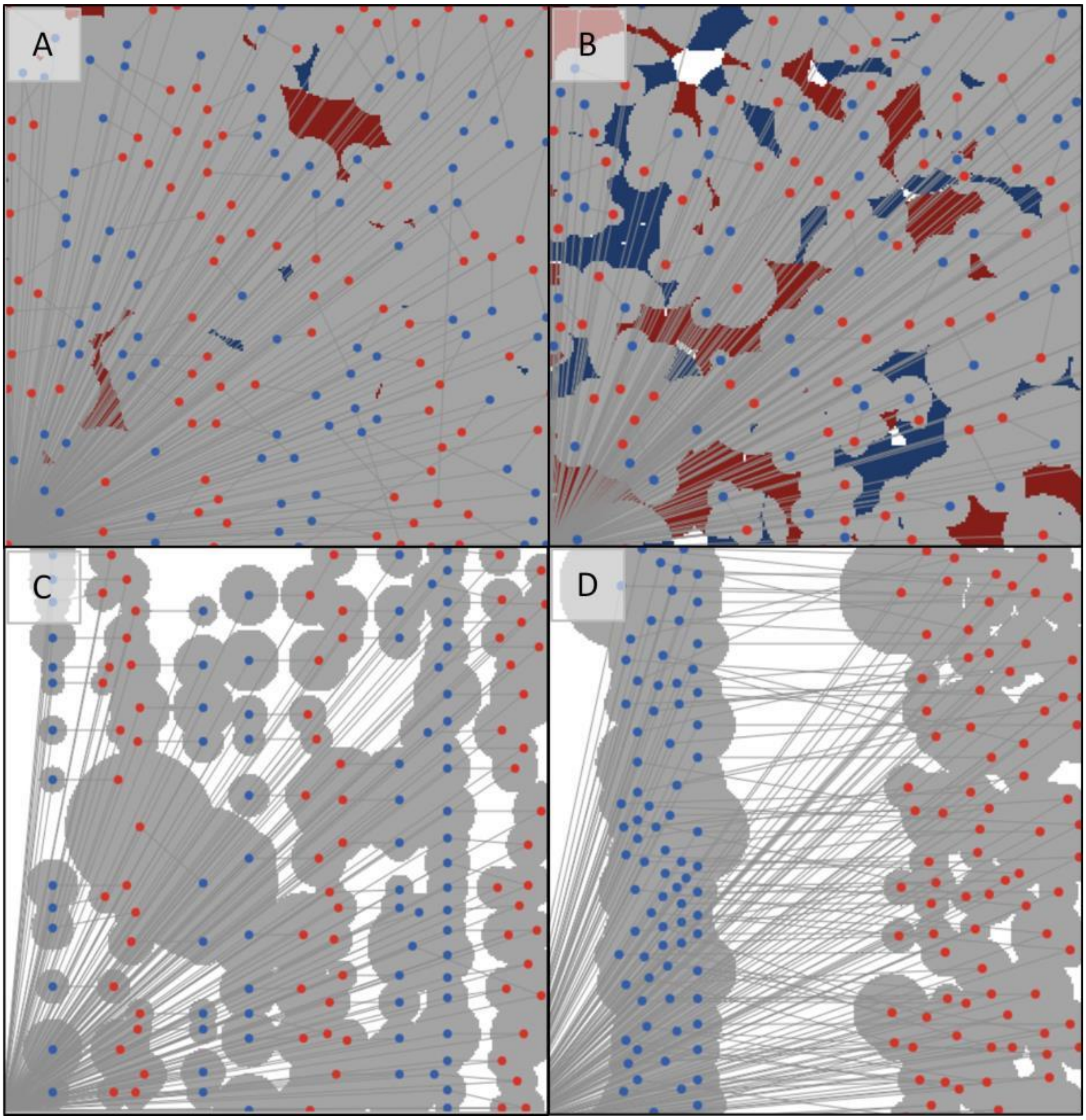

Figure C.1. Well placement by the agent-based model for 0.5 [m^3/m^3] allocated subsurface fraction for ATES. Red/blue markers = warm/cold wells. White space = search area for new well, grey area= allocated space, blue/red area = search area for new warm/cold wells. A= current practice, screen length based on required discharge, well placement 1,5 and 3 times R_{th}. B= fully penetrating, well placement 1.5 and 3 times R_{th}. C= 6 lanes at 90m spacing and width. D = 2 lanes at 333 m spacing and width.

Appendix D – Well distances and screen lengths in A, B, C, D scenarios

The graphs below present a kernel density estimate for the distribution of well distances (expressed in relation to the thermal radius, and in meters) and filter screen lengths, across all realizations of a set of representative scenarios for the A, B, C and D groups.

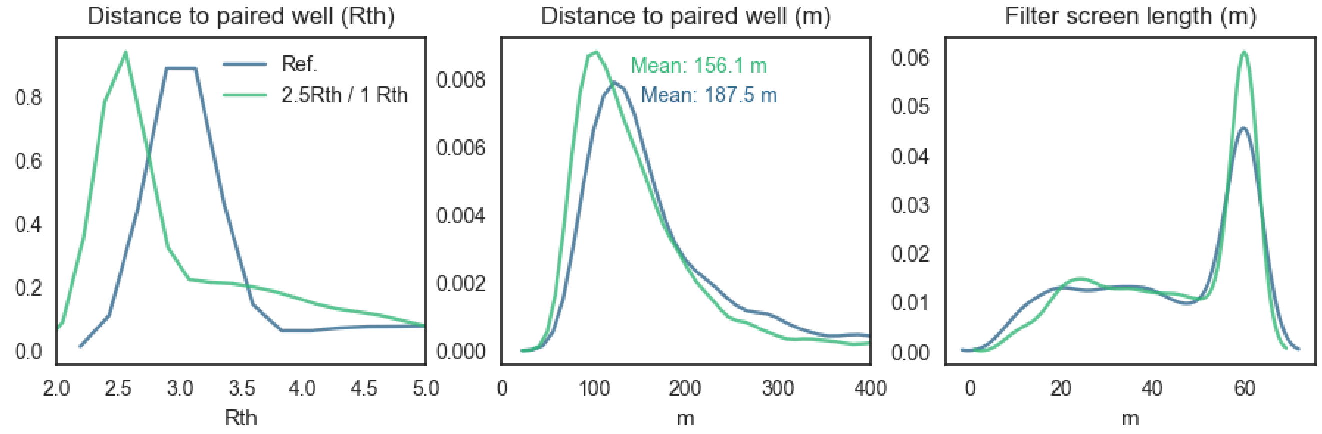

Figure D.1: Distribution of well distances and screen lengths for A and B scenarios

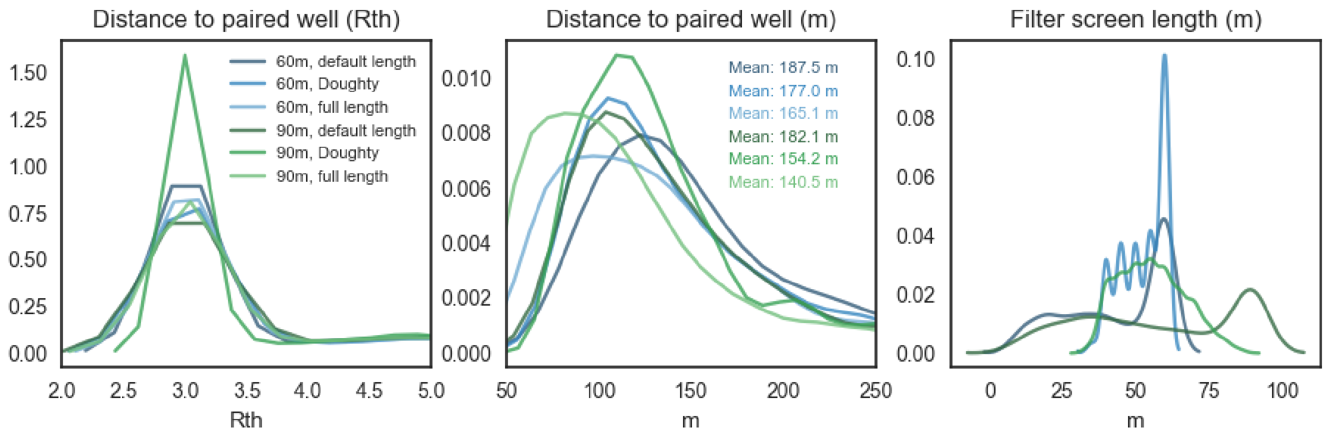

Figure D.2: Distribution of well distances and screen lengths for C scenarios

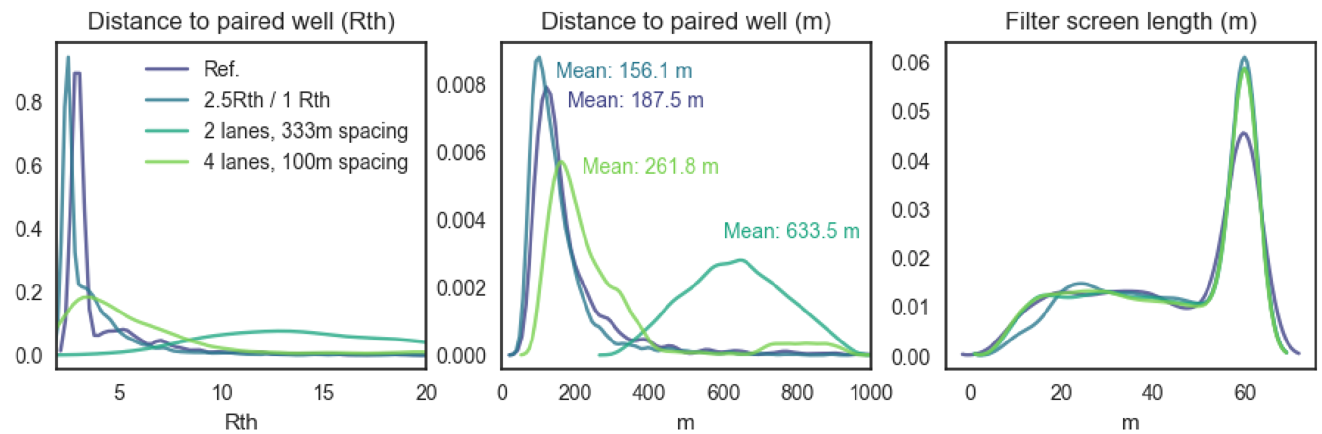

Figure D.3: Distribution of well distances and screen lengths for A, B, D scenarios