The hidden side of cities

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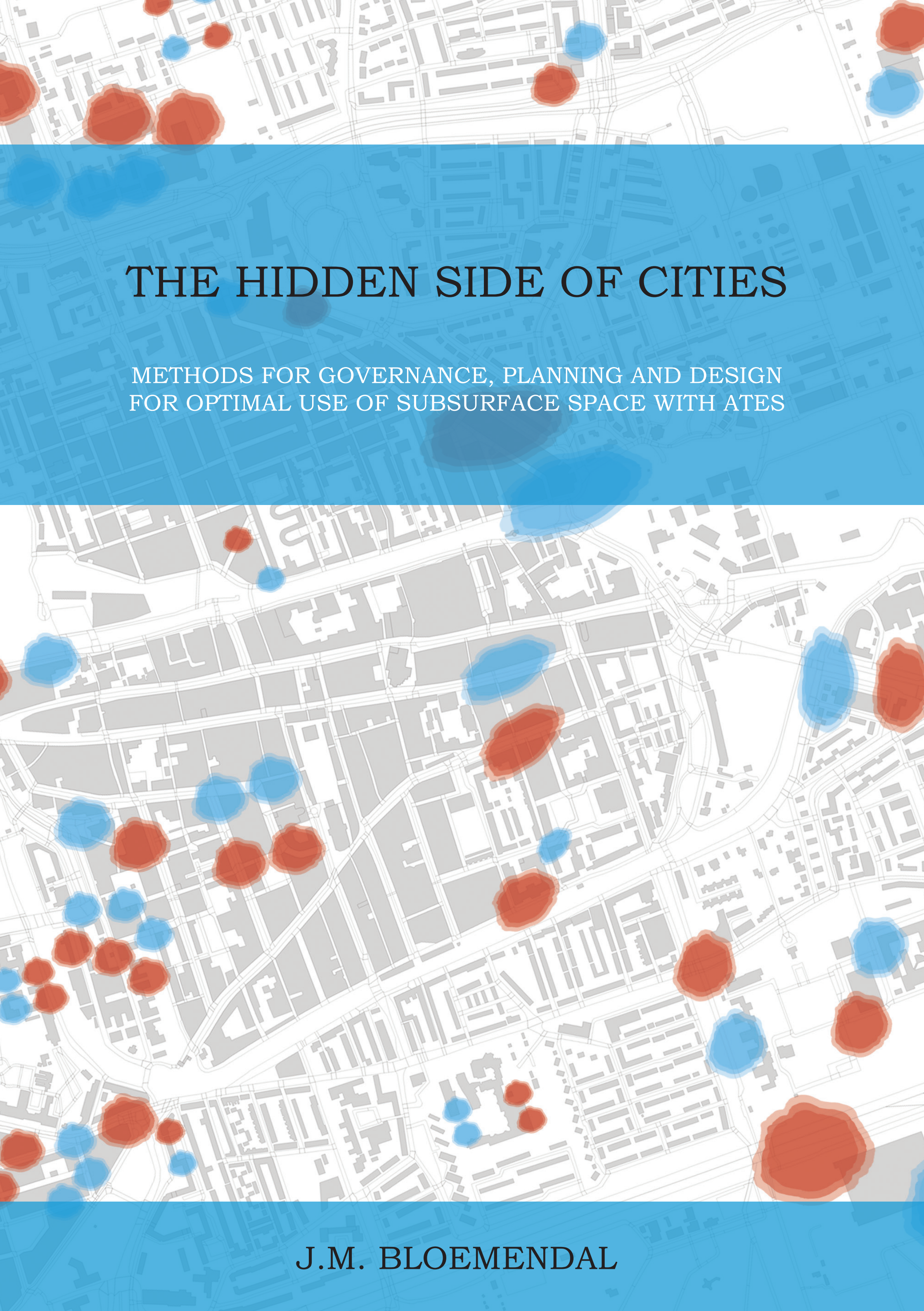

THE HIDDEN SIDE OF CITIES

METHODS FOR GOVERNANCE, PLANNING AND DESIGN FOR OPTIMAL USE OF SUBSURFACE SPACE WITH ATES

J.M. BLOEMENDAL

The hidden side of cities

Methods for governance, planning and design for optimal use of subsurface space with ATES

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Methods for governance, planning and design for optimal use of subsurface space with ATES

Proefschrift

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aan de Technische Universiteit Delft,
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voorzitter van het College voor Promoties,
in het openbaar te verdedigen op woensdag 16 mei 2018 om 15:00 uur

door

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geboren te Apeloorn, Nederland.

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Dr. N. Hartog heeft in belangrijke mate bijgedragen aan de totstandkoming van paragrafen 4.1-4.5 in hoofdstuk 4 van dit proefschrift.

Keywords: Aquifer Thermal Energy Storage; ATES planning, ATES design, ATES governance

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SUMMARY

MOTIVATION AND GOAL

BECAUSE the heating and cooling demand in the built environment is responsible for about 40% of the total energy consumption it is important to consider for minimizing the use of fossil fuels. Aquifer Thermal Energy Storage (ATES) systems provide sustainable space heating and cooling for buildings. In Dutch cities, around 25% of the buildings may rely on ATES for their space heating and cooling in the future. It is therefore important to explore how the subsurface can be utilized sustainably to its full potential for ATES.

ATES systems concentrate in urban areas where many buildings stand side by side on top of a suitable aquifer. In Dutch practice the spreading of warm and cold groundwater originating from the seasonal storage cycles varies between 20-150 m around each well and, therefore, often crosses the plots of adjacent building owners. Because interaction between wells reduces the thermal efficiency of these systems, overlapping warm and cold zones are to be prevented. In current practice ATES systems are over-dimensioned and kept at a large mutual distance[1] to prevent this interaction, which then results in artificially scarcity of subsurface space and under-utilization of ATES potential and its associated greenhouse gas (GHG) emission reduction. Therefore, both the design and organization of ATES need to be improved to safeguard optimal and sustainable use of the subsurface. This challenge then leads to the following main aim of this dissertation:

To identify design methods and organizational concepts that result in the most effective use of subsurface space by ATES systems in busy urban areas.

Because ATES adoption in The Netherlands is higher than elsewhere, it is also where the challenges discussed above occurred earliest. However, Given the international GHG emission reduction agreements, it is likely that such problems will also occur in other countries that are adopting ATES in (the near) future. So next to The Netherlands, also for governments and markets in such countries and cities it is important to know how to substantiate skills and legislation to facilitate optimal and effective use of the subsurface with ATES.

[1] Due to uncertainties inherent to future weather conditions, climate and use of the building, leading to uncertainties in their energy demand. Which causes its associated use of subsurface space to vary and hard to predict. At the same time, the spreading of warm and cold groundwater in the subsurface is invisible and both difficult and expensive to monitor.

Results and conclusions

The challenge is to accommodate the largest possible number of ATES systems, simultaneously optimized with respect to individual thermal recovery efficiency. As in many problems with common pool resources (CPR), there is a trade-of between individual and collective performance; accommodation of more ATES systems in an aquifer reduces the total GHG emission of all the buildings in that area, but may at the same time reduce the efficiency of individual systems. Both institutional arrangements and a technical framework to design, organize and operate ATES systems needs to be identified to allow for a responsible increase of the density of ATES systems.

To optimize the performance of ATES in a common aquifer under a city, both the location of ATES wells and the net storage requirement per unit of aquifer volume are key parameters in determining effective arrangements. In addition, the ATES wells should be designed a-priori to maximize recovery efficiency and minimize their claim on subsurface space, and to this end carefully consider local geohydrological conditions and operational aspects. Because modification of wells after installation is relatively costly and complex, both location and well design need to be taken into account.

- In chapter 2 a method to identify potential for ATES is developed and then used to identify where in the world potential for ATES exists. Geohydrological and climatic conditions are the two most important preconditions. Both characteristics are combined to identify ATES suitability worldwide, after which future “hot-spots” for ATES application were identified by relating ATES potential to urban development. This showed that in many North American, European and Asian urban area’s demand for ATES may exceed space available.

- Secondly, strategies to manage other CPR’s are evaluated in Chapter 3 for applicability on ATES systems. To improve the design, planning and operation of ATES systems, it is required to identify how they can use the subsurface optimally and sustainably, taking both individual and collective interests into account. ATES systems are planned and designed based on an expected but inherent uncertain energy demand. Governance should therefore, focus on the operation phase; with information and feedback from the actual subsurface status, a network of ATES systems can work towards an optimum for both the subsurface and buildings, instead of striving for a local optimum for individual buildings, as is current practice with autonomous operating ATES systems designed based on inherent uncertain expected energy demand.

- To facilitate increasing the number of ATES systems, well-design approaches which result in the highest efficiency and the most optimal use of subsurface space are identified in chapter 4. Insight is given in processes contributing to heat losses in the subsurface. Such a general framework for subsurface heat losses was lacking in literature and increasingly important when increasing the number of ATES well per unit of aquifer space. New methods are developed and relations identified to optimize recovery efficiency of ATES wells under varying conditions. It was found that thermal energy losses by dispersion can be neglected for practical ATES operating conditions. With the conduction losses dominant, thermal recovery efficiency correlates linearly with the area over volume ratio (A/V) of the heat stored in the subsurface. An analytical expression for the impact of ambient groundwater flow on recovery efficiency was derived and methods for limiting displacement losses due to ambient groundwater flow were identified. It is also identified that a salinity gradient as often present in coastal aquifers has negligible effects on ATES well efficiency, under the conditions present in The Netherlands.

- Finally in chapter 5 methods for spatial planning and operation of ATES systems are developed. Current practice uses the same inherent uncertain information for planning of ATES systems in busy areas. The choice of location for ATES wells depends on many factors like the space available at surface level, already existing ATES systems and geographical lay out of the plot of building owner, street plan and infrastructure in the subsurface. This makes the planning and design process ambiguous. The ATES-planning method used in practice is evaluated by assessing 24 plans, the benchmark revealed the required additional tools and steps for improving the method. 1) Thresholds of aquifer space use are determined beyond which planning is needed and below which self-organization can be used. 2) Design parameters for the ATES-plan are identified and 3) an assessment framework is defined to allow for objective comparison of different organization alternatives. The results give insight in how technical ATES-well design choices affect optimal use of subsurface space and in the trade-of between individual efficiency and overall emission reductions. The improved ATES-planning method now fosters planning and design rules ensuring optimal and sustainable use of subsurface space, i.e. maximizing energy saving by accommodating as much ATES systems as possible while maintaining individual well efficiency.

Discussion and outlook

The future for ATES is looking bright, goals for sustaining the energy system are higher on the (political) agenda then ever. Geothermal energy storage may contribute considerably to reducing greenhouse gas emissions, specially in cities in moderate climates. One of the important up-sides of ATES is that they are hidden in subsurface under the cities, you don't see or hear this type of sustainable energy. To retain the ability for seasonal energy storage in the near and far future, it is of importance that the use of the subsurface is sustainable and effective. With the environmental impact of ATES on groundwater quality negligible, ATES systems being relatively robust to mutual interaction, the concepts for design, planning and governance of ATES systems introduced in this dissertation are a solid basis for a strong increase of subsurface space utilization for ATES.

Because an ATES well is not easily/cheaply replaced while it has a large influence on the long term energy saving of its' associated building. The concepts and insights presented in this dissertation help to convince stakeholders to make a profound ATES well design and location choice. Compared to current practice, all strategies proposed in this dissertation come at a relatively little extra cost, but result in a much more robust network of ATES systems. With the expected operational life time of an ATES system and all the inherent uncertainties on subsurface space use during that time-span, this little extra cost will always pay out positive on the long run.

The work presented in this dissertation provides a valuable base to further improve the controls of ATES efficiency and governance in more complex conditions; e.g. in aquifers that are; stratified, highly irregular/anisotropic, under influence of tide, fissured, in bedrock. Or with more complex storage conditions; e.g. where both BTES and ATES systems occur or at higher temperatures where buoyancy flow will also contribute to heat losses.

Samenvatting

Aanleiding en Doel

Het energie gebruik van gebouwen draagt voor circa 40 % bij aan het totale energie verbruik. Bij het verduurzamen van het energiesysteem is het daarom belangrijk om duurzame technieken voor verwarmen en koelen te ontwikkelen en te implementeren. Bodemenergie (of Warmte koude opslag) is een techniek die gebouwen voorziet van duurzame verwarming en koeling. In Nederlandse steden kan het percentage gebouwen met een bodemenergiesysteem in de toekomst oplopen tot 25 %. Bij een dergelijk groot rol voor de bodem in de energievoorziening is het van belang om vast te stellen op welke manier de volledige potentie van de bodem op een duurzame manier kan worden benut.

Bodemenergie systemen concentreren zich in stedelijke gebieden waar veel gebouwen dichtbij elkaar staan. De verspreiding van warm en koud grondwater rondom de bronnen varieert in de Nederlandse praktijk tussen de 20 en 150 m en hangt af van de eigenschappen van de bodem en de energievraag van de betreffende gebouwen. De warmte komt door die verspreiding vaak onder het perceel van de nabij gelegen gebouwen. Onderlinge interactie tussen warme en koude bronnen vermindert het rendement, daarom moet het overlappen van warme en koude zones in de ondergrond worden voorkomen. Om deze negatieve onderlinge interactie te voorkomen worden bodemenergiesystemen in de huidige praktijk over gedimensioneerd en op grote afstand van elkaar gehouden[2], wat ervoor zorgt dat bodemenergiesystemen de ruimte in de bodem lang niet volledig benutten en daarmee potentiele energie besparing laten liggen. Daarom moeten zowel het ontwerp als beheer en organisatie van deze systemen worden verbeterd om zo optimaal en doelmatig gebruik van de bodem te garanderen. Deze uitdaging leidt tot het volgende doel van dit proefschrift:

Het vaststellen van ontwerp methoden en organisatie principes die leiden tot optimaal en doelmatig gebruik van de bodem door bodemenergie systemen in (drukke) stedelijke gebieden

De toepassing van bodemenergie opslag loopt in Nederland voor op de rest van de wereld, het is daarom ook niet verwonderlijk dat bovengenoemde problemen als eerste hier optreden. Maar gezien de wereldwijde verduurzaming van de energievoorziening is het te verwachten dat deze problemen ook in andere landen ontstaan. Naast Nederland is het daarom ook voor overheden en bedrijven van deze landen is het belangrijk om inzicht te hebben in welke regels en principes optimaal gebruik van de ondergrond met bodemenergie waarborgt.

[2] Onzekerheden inherent aan de weersomstandigheden, het klimaat en het gebruik van gebouwen zorgen ervoor dat de energievraag van een gebouw erg lastig is te voorspellen. Tegelijkertijd is het ook erg lastig en duur om de verspreiding van warm en koud grondwater in de bodem inzichtelijk te krijgen.

Resultaten

De uitdaging is om zoveel mogelijk bodemenergie systemen in de ondergrond te accommoderen en tegelijkertijd het individuele rendement van deze systemen zo hoog mogelijk te laten zijn. Zoals bij vele "common pool resources" (CPR) is er een trade-off tussen het belang van de individuele gebruiker en het collectief; meer bodemenergiesystemen toelaten verminderd de totale uitstoot van broeikasgassen in dat gebied; maar tegelijkertijd wordt het rendement van de individuele systemen daardoor mogelijk slechter. Dus in gebieden met veel vraag naar bodemenergie is een institutioneel en technische kader nodig op basis waarvan bodemenergiesystemen worden georganiseerd en aangelegd.

Zowel de locatie van de bronnen als de totale hoeveelheid warmte die in de gezamenlijke aquifer onder de stad moet worden opgeslagen zijn de belangrijkste aspecten bij het identificeren van geschikte oplossingen. Ook het ontwerp van de bronnen zou a-priori moeten streven naar minimaal ruimte beslag en optimaal terugwin-rendement, waarbij lokale geohydrologische omstandigheden en operationele aspecten cruciaal zijn om te beschouwen. Omdat het duur en complex is om bronnen in een later stadium aan te passen of verplaatsten zijn zowel de (onderlinge) locatie als het ontwerp van de bronnen een belangrijk onderdeel in dit proefschrift.

- In hoofdstuk 2 is inzichtelijk gemaakt waar in de wereld de omstandigheden voor bodemenergie geschikt zijn, nu en in de toekomst. De aanwezigheid van watervoerende zandlagen en geschikte klimatologische omstandigheden zijn de twee belangrijkste randvoorwaarden voor de toepassing van bodemenergie. Deze twee randvoorwaarden zijn gecombineerd om de wereldwijde potentie te kunnen vaststellen. Hiervoor is een methode ontwikkeld die het mogelijk maakt om voor sterk variërende omstandigheden de bodemenergie potentie vast te kunnen stellen. Met behulp van geografische gegevens over urbanisatie zijn de toekomstige "’hot-spots"’ voor bodemenergie vastgesteld. Hieruit bleek dat in veel Noord-Amerikaanse, Europese en Aziatische steden de vraag naar bodemenergie de aanwezige ruimte in de bodem kan overschrijden.

- Methoden om andere CPR’s te beheren/besturen zijn in hoofdstuk 3 geanalyseerd op hun bruikbaarheid voor bodemenergie. Om het ontwerp, de plaatsing en beheer van de bodemenergiesystemen te optimaliseren is het nodig om inzichtelijk te maken hoe bodemenergiesystemen de ondergrond duurzaam en doelmatig gebruiken, waarbij zowel het individuele rendement als collectieve belang in ogenschouw moeten worden genomen. Met informatie uitwisseling en feedback over de actuele status van de temperatuurverdeling in de ondergrond, kan een netwerk van bodemenergiesystemen zelfstandig toewerken naar optimaal gebruik van de bodem zowel voor het individuele gebouw als het collectief. De focus van governance kan daardoor verschuiven naar de operationele fase, zodat op basis van werkelijk gebruik de ruimte worden beheerd, in plaats van op basis van voorspeld gebruik met alle onzekerheden die daar bij horen.

- Om het vergroten van het aantal bodemenergiesystemen te faciliteren wordt in hoofdstuk 4 een ontwerpkader vastgesteld om te komen tot bronontwerp die leiden tot optimaal gebruik van de bodem en het hoogste rendement. Specifieke operationele condities zoals veranderende energievraag, totale opslag volume en energie balans worden daarbij ook beschouwd, wat in de huidige praktijk nog niet gebeurd. Ontwerpmethoden voor specifieke geohydrologische omstandigheden zoals hoge grondwaterstroming en variërende chloride concentratie ontbraken, en zijn in dit proefschrift geïntroduceerd. In dit hoofdstuk wordt data uit de Nederlandse praktijk gebruik om de ontwikkelde concepten te toetsen en illustreren. Uit dit hoofdstuk blijkt dat de dispersie verliezen kunnen worden verwaarloosd. Er is een analytisch verband afgeleid voor de invloed van achtergrond stroming en efficiëntie evenals methoden om verliezen daardoor te voorkomen. Het is ook aangetoond dat een dichtheid-gradiënt in het grondwater, zoals vaak aanwezig in aquifers in kust gebieden, geen significant effect heeft op bodemenergiesystemen in praktijk condities in Nederland.

- Tot slot is in hoofdstuk 5 inzichtelijk gemaakt welke ordenings-structuren leiden tot het meest optimale gebruik van de bodem. De keuze voor de bron locatie is van veel verschillende factoren afhankelijk; bestaande bronnen, vorm en grootte van betreffende perceel en gebouw, infrastructuur boven en onder de grond. Dit maakt de plaatsing van bodemenergie bronnen ondoorzichtig en lastig. De momenteel toegepaste "master-planning" methode is geëvalueerd door 24 van zulke plannen te analyseren, op basis waarvan de master plan methode is verbeterd. Zo zijn er ontwerp parameters voor bodemenergie plannen vastgesteld en is een indicatie gegeven voor grenswaarden voor wanneer het nodig is om een bodemenergieplan te maken. Ook is er een beoordelingskader vastgesteld waarmee verschillende ordeningsalternatieven objectief tegen elkaar kunnen worden afgewogen. De resultaten geven inzicht in hoe brontontwerp het gebruik van de bodem beïnvloedt en in de trade-of tussen individueel rendement en overall energie besparing. De verbeterde planningsmethode voorziet nu in duidelijke ontwerp regels en objectieve afwegingsmethoden om optimaal gebruik van de bodem te realiseren.

Discussie

De toekomst voor bodemenergie ziet er goed uit, energie besparingsdoelstellingen staan hoger dan ooit op de politieke en maatschappelijke agenda. Bodemenergie kan significant bijdragen aan de energiebesparingsdoelen, vooral in steden in gematigde klimaten. Een belangrijk voordeel van bodemenergie is dat je het niet ziet of hoort. Om deze vorm van energie besparing te kunnen blijven gebruiken, is het van belang om de bodem zo optimaal en effectief mogelijk te gebruiken voor deze techniek. De prestaties van bodemenergiesystemen zijn robuust voor enige verliezen in de ondergrond en het effect van deze systemen op de grondwater kwaliteit is verwaarloosbaar. De concepten die in dit proefschrift zijn gepresenteerd dienen daarmee als een solide basis waarop het gebruik van de bodem met bodemenergie systemen kan worden geïntensiveerd.

Omdat het aanpassen van bodemenergiebronnen relatief duur en complex is, heeft een eenmaal geïnstalleerde bron een grote invloed op de lange termijn energiebesparing van een gebouw. De concepten voor planning en ontwerp van bodemenergiebronnen die in dit proefschrift zijn geïntroduceerd helpen om betrokken partijen te overtuigen om slimme keuzes te maken met betrekking tot brontontwerp en locatie keuze. Vergeleken met de huidige praktijk, resulteren alle voorgestelde strategieën tot relatief beperkte extra installatie kosten, maar resulteren in een veel robuuster netwerk van bodemenergiesystemen. Met een verwachtte levensduur van bodemenergiesystemen van meerdere decennia en de onzekerheden over het benodigde gebruik van de bodem over die periode, wegen die kleine stijging in aanlegkosten op de lange termijn altijd op tegen de baten.

De resultaten van dit onderzoeken vormen ook een solide basis om het ontwerp en beheer van bodemenergiesystemen verder te verbeteren. Bijvoorbeeld in meer complexe omstandigheden zoals in: gestratificeerde, sterk heterogene/anisotrope en/of zandsteen aquifers, in aquifers onder invloed van getij, bij de toepassing van hoge temperatuur opslag en/of in gebieden waar zowel open als gesloten bodemenergie gezamenlijk worden toegepast.

Nomenclature

Chapter 2

F_{aq}	Scaling factor for aquifer characteristics [-]
F_{gw}	Scaling factor for groundwater characteristics [-]
P_j^{ext}	GW extraction as a % of total water consumption [%]
P_j^f	Extent of fissured aquifers [%]
P_j^i	Extent of intergranular aquifers [%]
P_{min}	Rainfall [mm]
P_j^{pf}	Extent of productive fissured aquifers [%]
P_j^{pi}	Extent of productive intergranular aquifers [%]
P^{p0}	Extent of zones without groundwater [%]
P^0	Extent of areas without aquifers [%]
R_j	Mean annual groundwater recharge [mm/y]
$S_j^\#$	Calculated ATES Suitability [-]
$s_\#^\#$	Relative suitability [-]
T_{avg}	Average Temperature [°C]
T_{max}	Maximum Temperature [°C]
$X_j^\#$	Standardization factor [-]

Chapter 3

R_{th}	Thermal radius [m]

Chapter 4

A	Surface area of the heat storage in the aquifer[-]
a_v	Vertical anisotropy factor [-]
α	Dispersivity [m]
c_w	Volumetric heat capacity of water; 4.2 x 10^6 [J/m^3/K]
c_{aq}	Volumetric heat capacity of saturated porous medium; 2.8 x 10^6 [J/m^3/K]
D	Distance between wells [m]
D_{eff}	Effective dispersion [m^2/d]
D_T	Thermal dispersion [m^2/d]
D_r	Distance ratio of w_c over 0.33 R_h [-]
Δh	Hydraulic head difference between wells [m]
$\Delta\bar{T}$	Average temperature difference between warm and cold well [°C]
ΔS	Salt gradient in groundwater with depth of aquifer [kg/m^3/m]
E	Energy [J]
η_{th}	Thermal efficiency [-]
G	Catalan's constant; 0.915 [-]
i	Groundwater head gradient [-]
k	Hydraulic conductivity [m/d]
$\kappa_{h/v}$	Aquifer permeability (horizontal/vertical) [m^2]
κ_{Taq}	Thermal conductivity of aquifer; 2.55 [W/m/K)]
L	Well screen length [m]
M	Mixed convection ratio [-]
μ	Dynamic fluid viscosity [g/m/d]
n	Porosity; 0.3 [-]
Q	Pumping rate /discharge of ATES wells [m^3/d]
q	Specific discharge [m/d]
ρ	Water density; 1,000 [kg/m^3]
R	Thermal retardation factor [-]
R_{th}	Thermal radius [m]
R_h	Hydraulic radius [m]
S	Salt concentration [kg/m^3]
σ	Standard deviation [-]
τ	Dimensionless time of travel parameter [-]
T	Temperature [°C]
$(\Delta)t$	Time (step) [d]
t_0	Characteristic tilting time [s]
u	Ambient groundwater flow velocity [m/y]
u_*	Velocity of the thermal front [m/y]
v	Flow velocity of the groundwater [m/d]
V	Yearly (permitted or actual) storage volume groundwater [m^3]
w_c	Width of free convection cell [m]
ω_0	The initial front rotation angular velocity [rad/s]

Chapter 5

A_{mp}	Surface area of master plan under consideration [m^2]
A_b	Surface area of buildings in master plan [m^2]
c_w	Volumetric heat capacity of water; 4.2 x 10^6 [$J/m^3/K$]
c_{aq}	Volumetric heat capacity of saturated porous medium; 2.8 x 10^6 [$J/m^3/K$]
COP_{hp}	Coefficient of Performance of the heat pump; 4 [-]
COP_c	Coefficient of Performance of the chiller; 3 [-]
COP_b	Coefficient of Performance of the boiler; 0.95 [-]
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 [$kg/m/s^2$]
$\Delta \bar{T}$	Average temperature difference between warm and cold well [°C]
$E_{h/c}$	Thermal Energy for heating/cooling [J]
E_e	Electrical Energy [J]
e_{fe}	Emission factor for electricity; 0.157 [1] [tCO_2/GJ]
e_{fg}	Emission factor for gas; 0.056 [2][tCO_2/GJ]
F_A	Allocated surface area fraction for ATES [m^2/m^2]
F_s	Allocated aquifer space fraction for ATES [m^3/m^3]
FSI	Floor space index [-]
GHG	Greenhouse gas emissions [tCO_2]
g	Gravitational acceleration; 9.81 [m/s^2]
L	Well screen length [m]
L_a	Aquifer thickness [m]
n	Porosity; 0.3 [-]
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	Pumping rate of ATES wells [m^3/d]
R_{th}	Thermal radius [m]
R_h	Hydraulic radius [m]
T	Temperature [°C]
$(\Delta)t$	Time (step) [month]
V	Yearly (permitted or actual) storage volume of groundwater [m^3/y]

CONTENTS

1

INTRODUCTION

It is not the strongest of the species that survive, nor the most intelligent, but the ones most responsive to change

Charles Darwin

A heat pump combined with Aquifer Thermal Energy Storage (ATES) has high potential in efficiently and sustainably providing thermal energy for space heating and cooling. This makes the subsurface, including its groundwater, of crucial importance for primary energy savings. However, in current practice the subsurface is not utilized to its full potential. This dissertation will first show where in the world ATES may be suitable for space heating and cooling. After that it provides new methods for design and organization of ATES systems to decrease the overall greenhouse gas emission from space heating and cooling in the built environment.

1.1. THE ROLE OF ATES IN THE ENERGY TRANSITION

To prevent climate change, treaties and agreements are made to reduce energy consumption and to promote sustainable energy for the remaining energy demand. On all organizational and societal levels, from countries down to local government and private parties, goals are set to reduce greenhouse gas (GHG) emissions, among which those bound in national and international agreements [3–5].

To meet these goals, it is important to consider the heating and cooling demand in the built environment, which responsible for as much as 40% of the total energy consumption [6–8]. Geothermal energy systems (Figure 1.1) may contribute significantly to fossil fuel use for heating. The systems indicated in Figure 1.1 are together expected to contribute 75% to the total heating and cooling demand in the built environment in the Netherlands in 2050 [9]. So each technology promises substantial contributions to reducing energy consumption; which is up to 25% for seasonal Aquifer Thermal Energy Storage (ATES) systems. It is therefore important to explore how ATES technology can be exploited to its full potential [10].

1.2. PRINCIPLE OF ATES TECHNOLOGY

The basic principle of ATES is its use of the subsurface to overcome the seasonal discrepancy between the availability and demand for thermal energy in the built environment. Buildings in moderate climates generally have a heat surplus in summer and a heat shortage in winter. Where groundwater is present in sandy layers (aquifers) of sufficient thickness and hydraulic conductivity, thermal energy can be stored in and extracted from the subsurface. An ATES system consists of one or more pairs of tube wells that infiltrate and simultaneously extract groundwater to store and extract heat. They do so by changing the groundwater temperature by means of a heat exchanger that is connected to the associated building (Figure 1.2).

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 1.2. 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. Balancing the seasonal storage and extraction of thermal energy is essential to sustain long-term use of the subsurface for thermal aquifer storage.

ATES reduces the net consumption of fossil energy for heating and cooling of buildings [11]. On average, application of ATES results in a reduction of 50% of primary energy consumption for heating and cooling of buildings, but to sustain subsurface energy stor-

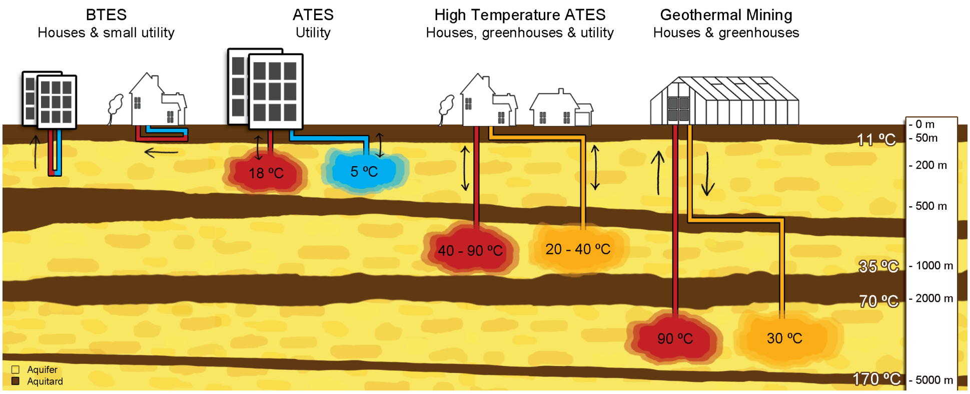

Figure 1.1: Different types of geothermal energy systems, as applied in The Netherlands

age, it is essential to balance seasonal storage and extraction of thermal energy. They are applied in buildings of any type, but larger office and utility buildings dominate in ATES use [12].

Different types of ATES wells exist; the most common types are 1) doublets where the warm and cold well are separated horizontally and 2) monowells where the warm and cold well screens are placed above each other in a single borehole. Monowells are mostly applied for smaller energy demands, i.e. smaller buildings, but the vertical screen arrangement requires a thick aquifer to allow for enough space between the screens to prevent short-circuit flow.

Another familiar geothermal energy storage system for small buildings is the closed-loop borehole heat exchanger. These systems consist of a number of closed tubes that contain a transport medium, which is water, sometimes with an additive to improve its thermal properties. By pumping the medium around, thermal energy is extracted from or stored in the subsurface using only thermal conduction. This limits the subsurface extent of their thermal influence. Therefore this research focuses on open ATES systems as they are most commonly installed in large buildings and, therefore, demand explicit use of a large part the subsurface space below urban areas like especially city centers.

The ambient groundwater temperature in The Netherlands is around 10-12°C. Both experience and research show that this type of groundwater use, where temperature remains within a few degrees from the ambient groundwater temperature, has negligible effects on the chemistry and microbiological activity of the groundwater [13].

1.3. DEVELOPMENT OF ATES TECHNOLOGY

Although ATES is applied worldwide, its adoption is still underdeveloped in many parts of the world. Practical experience with the development of ATES systems has been gained

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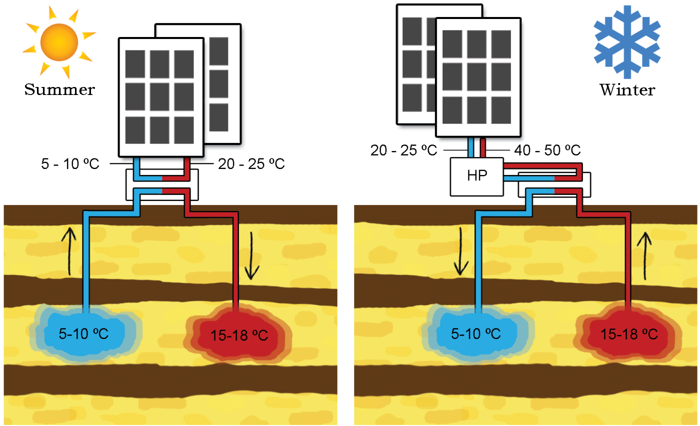

Figure 1.2: Working principle of an Aquifer Thermal Energy Storage system. In The Netherlands Aquifer thickness ranges from 10 to 160 m

in several European countries, North America and Asia [14–18]. The number of ATES systems in The Netherlands is rapidly growing as a consequence of the desire to reduce energy consumption; and it is expected to grow rapidly.

The Netherlands saw a rapid growth of the number of ATES systems over the past decade, often in conjunction with (re)development of urban areas. On top of favorable climatic and subsurface conditions in the country, this "boom" was triggered by the introduction of progressively stricter energy efficiency requirements for buildings, reflected in the so-called Energy Performance Coefficient (EPC). In the EPC calculation method, applying an ATES system in a building helps to meet the required EPC standard [19]. Figure 1.3 shows that the EPC-value correlates negatively with the percentage of new buildings equipped with an ATES system. Despite the significant decrease in building activities with the economic crisis since 2007/2008, this resulted in only a slightly smaller growth rate in the number of ATES systems, as well as in the percentage of new buildings equipped with ATES. Accelerated growth is expected in The Netherlands with the nationally agreed energy efficiency requirement for 2020 (EPC=0) and with the elaboration of the 2013 agreement [4] that targets at around 8.000 operational ATES systems in 2023, from 2.000 operational systems in 2015 [20–22]. So Aquifer Thermal Energy Storage (ATES) systems already contribute to reducing energy consumption by providing sustainable space heating and cooling for buildings through seasonal storage of heat in aquifers.

1.4. GOAL: UTILIZE FULL POTENTIAL FOR ATES

ATES systems concentrate and cumulate in urban areas where many large buildings like offices and commercial areas stand side by side on top of a suitable aquifer. The spread-

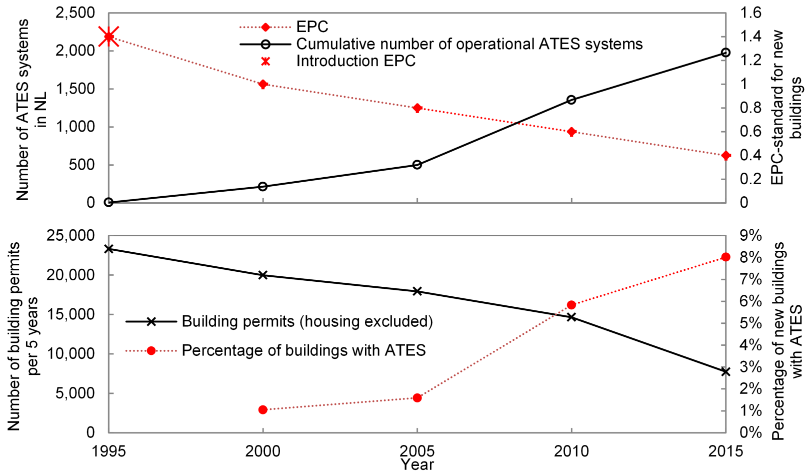

Figure 1.3: Top: number of ATES systems in the Netherlands related to EPC-standard for houses, the EPC value reflects the expected energy use of a building, EPC = 0 means that a building has no net energy use. Bottom: number of ATES systems relative to new buildings build.[19, 21, 23].

ing of warm and cold groundwater originating from the their storage cycles depends on aquifer properties, ambient groundwater flow and energy demand of the associated buildings. This spreading varies between 20-150 m around each well in Dutch practice and, therefore, often crosses the plots of adjacent building owners. Because interaction between wells reduces the thermal efficiency of these systems, overlapping warm and cold zones are to be prevented.

Uncertainties inherent to future weather conditions, to climate and use of the building, lead to uncertainties in their energy demand and causes its associated use of subsurface space to vary and hard to predict. At the same time, the spreading of warm and cold groundwater in the subsurface is invisible and difficult and expensive to monitor. In current practice, to deal with the uncertainties ATES systems are over-dimensioned [22] and kept at a large mutual distance [24] to prevent negative interaction between them. Also, little attention is paid to operational aspects such as variation in energy demand between and over the years, which results in both suboptimal use of the subsurface and in reduced thermal efficiency. These different aspects causes under-utilization of potential GHG savings with ATES systems. Therefore, both the design and organization of ATES need to be improved to safeguard optimal and adequate use of the subsurface. This challenge then leads to the following main aim of this dissertation:

Identify design methods and organizational concepts that result in the most effective and sustainable use of subsurface space by ATES systems in busy urban areas.

The focus is on urban areas because that is where the scarcity of space is largest, but the solutions proposed will also be applicable in areas that are not yet or less densely built and used for ATES.

1.5. APPROACH FOR OPTIMAL USE OF SUBSURFACE SPACE

Because ATES adoption in The Netherlands is higher than elsewhere, it is also where the challenges discussed above occurred earliest. But it is likely that they will also occur in other countries that are adopting ATES. For governments and markets in such countries and cities it is important to know how to substantiate skills and legislation to facilitate optimal and effective use of the subsurface with ATES.

To maximize reduction of the emission of greenhouse gases by ATES, it's crucial to identify on the optimal claim on the subsurface that individual systems need. The challenge is to allow accommodation of the largest possible number of ATES systems, simultaneously optimized with respect to thermal recovery efficiency. As in many problems with common pool resource (CPR), there is a trade-off between individual and collective performance [25]; accommodation of more ATES systems in an aquifer reduces the total GHG emission of all the buildings in that area, but at the same time it reduces the efficiency of individual systems [26]. Both institutional arrangements and a technical framework to design, organize and operate ATES systems need to be identified where the density of ATES systems needs to be increased.

To optimize the performance of ATES in a common aquifer under a city, both the location of ATES wells and the net energy storage per unit of aquifer volume are key aspects in determining effective arrangements. In addition, the ATES wells should be designed a-priori to maximize recovery efficiency and minimize demand of subsurface space, and to this end carefully consider local hydrogeological conditions and operational aspects. Because modification of wells after installation is relatively costly and complex, both location and well design need to be taken into account.

1.6. RESEARCH STEPS AND OUTLINE

In order to meet the aim of this dissertation, the key aspects pointed out in Figure 1.4 are addressed. Chapter 2 is a general study to identify the significance of the problem by showing where in the world scarcity of space for ATES may occur. The following 3 chapters constitute the 3 main pillars under the aim of the dissertation because they focus on finding solutions: first by identifying regulatory and organizational frameworks, then by optimizing individual performance of ATES systems and, finally, by optimization of performance of the regional aquifer.

Chapter 2: Is this a local or global challenge?
This chapter identifies where current and future preconditions for application of ATES occur. Geohydrological and climatic conditions are the two most important of these preconditions and both characteristics are combined to identify ATES suitability worldwide. A method to identify ATES potential for widely varying geohydrological and climatic conditions did not exist and is developed, after which future "hot-spots" for ATES application were identified, in relation to urbanization data.

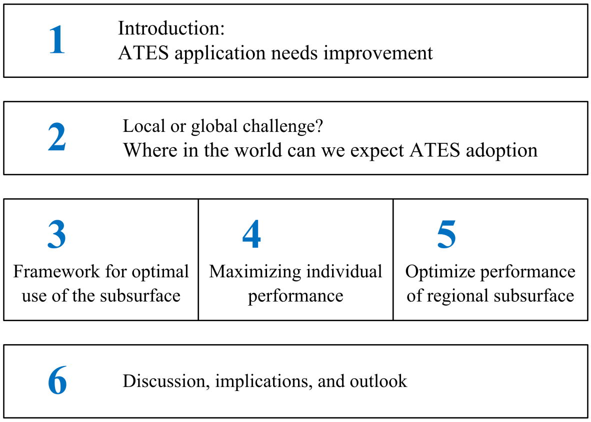

Figure 1.4: Graphical outline of this dissertation.

Chapter 3: Framework for optimal use of the subsurface
To improve the design, planning and operation of ATES systems, it is required to identify how ATES systems can use the subsurface optimally and sustainably, taking both individual and collective interests into account. Strategies to manage other CPRs may also be useful to optimize the overall performance of ATES systems. For example, with detailed information and feedback from the actual subsurface status, a network of ATES systems can work towards an optimum for both the subsurface and buildings, instead of striving for a local optimum for individual buildings.

Chapter 4: Maximizing individual performance
In addition to increasing the number of ATES systems, it is required to identify which well-design approaches result in the highest efficiency and the most optimal use of subsurface space. Specific operational aspects for ATES systems (e.g. varying energy demand over years, required energy balance) are introduced in the design phase, which is lacking in current practice. Also, the tools to take account for energy losses in specific geohydrological conditions were missing in current practice, like salinity variations within the aquifer and the impact of high ambient groundwater flow velocity. In this chapter data from practice is used and analyzed to explain and illustrate the developed methods.

Chapter 5: Optimize performance of regional aquifer
Replacement of wells is costly and complex, therefore it is necessary to identify what spatial planning and operation methods result in the most optimal utilization of subsurface space for ATES systems, given the uncertainty in development in adoption of ATES. The choice of location for ATES wells depends on many factors like the space available at surface level, already existing ATES systems and geographical lay out of the plot of building owner, street plan and infrastructure in the subsurface. This makes the design process ambiguous. The currently used ATES planning method is evaluated by assessing 24 of

them, and improved by changing and adding tools and steps to the method.

Chapter 6: Discussion, implications and outlook
This chapter discusses the relations and inter-dependencies between the solutions that were developed in the 3 different chapters. This discussion concludes with an outline of implications and an outlook on further research and application of ATES technology.

2

World potential for ATES

Every BIG helps

David MacKay

The two most important preconditions for the applicability of ATES are favorable climatic conditions and the availability of a suitable aquifer.This chapter shows how these two preconditions can be combined to identify where in the world ATES potential is present, or will become present as a consequence of climate change. Countries and regions are identified where regulation and stimulation measures may increase application of ATES technologies and thus help reduce CO_2 emissions. Two types of data determine ATES suitability, and their combination with a 3^{rd} identifies potential hot-spots in the world: 1) geo-hydrological conditions, 2) current and projected climate classification and 3) urbanization. A method is developed to combine the data into an ATES-suitability score as explained in this chapter. On the one hand the results confirm the suitability for ATES where it is already applied and on the other they identify places where the technology is or will become suitable. At the end of the 20^{th} century about 15% of urban population lived in areas with high potential for ATES. However, this number will decrease to about 5% during the 21^{st} century as a consequence of expected climate change. Around 50% of urban population lives in areas of medium ATES suitability, a percentage that will remain constant. Demand for ATES is likely to exceed available subsurface space in a significant part of the urban areas.

This chapter is published in Science of the total environment journal **538**, 621 (2015) [27]. The introduction has been modified to fit within the storyline of this thesis and to prevent repetition, also some headings were shortened.

2.1. Introduction

2.1.1. Local or global challenge?

Lack of knowledge regarding potential and (future) applicability of ATES is one of the main barriers for its application in several European countries [28–30]. Based on sustainable energy targets discussed in chapter 1 and the socio-economic developments such as economic growth and high energy prices it is expected that in the future more buildings can and will rely on ATES for their heating and cooling demand, but only when local conditions are known to be suitable. A worldwide overview showing where ATES technology is likely to be, or becomes successfully applicable, will therefore foster the technology.

Such an overview would also help governments to substantiate their legal framework and to stimulate ATES application to meet their energy saving goals. As briefly discussed in chapter 1, it is important for governments to prepare for the potential growth of ATES systems and adapt legislation and groundwater-management practice if needed. A key aspect to such preparation is identification of areas that indicate the suitability for ATES and show potential hot-spots for ATES systems.

In this chapter the significance and applicability of the problems and solutions discussed in this thesis are identified, by establishing an ATES suitability map for the world.

2.1.2. Problem statement

Lack of insight in potential, poorly substantiated legislation and/or socio-economic factors are among the main reasons why ATES is not adopted in many countries [28]. These barriers have to be razed to allow ATES to contribute significantly to CO_2 emission reduction. A worldwide overview showing where ATES technology is likely to be, or becomes successfully applicable, may foster the technology. Such an overview would help governments to substantiate their regulation and to stimulate ATES application to meet their energy saving goals.

2.1.3. Approach

Climatic conditions and the availability of a suitable aquifer are the two most important conditions for the applicability of ATES. Geo-referenced climate and geo-hydrological conditions are combined to identify areas with suitability for ATES. ATES suitability maps are combined with projections of population in urban areas to identify ATES hot-spots. Different sources of geographically referenced properties and conditions are combined and evaluated to identify the suitability for any building in a specific area. This method is similar with multi criteria decision analysis (MCDA) as it is often applied in spatial planning [31, 32], however, in our case the evaluation purpose is not decision making. Methods used for MCDA available in literature are, therefore, only partly applicable. Nevertheless, 5 of the 8 steps that were introduced by Ferretti [33] were applied in this study.

I Data acquisition. Four sources of data were selected to be combined into a world map of ATES suitability: 1&2) occurrence and properties of aquifers and groundwater [34, 35], 3) climate classification [36] and 4) urbanization data [37, 38].

II Problem structuring. The available datasets were not composed with the purpose to identify ATES suitability, their characteristics had to be converted to ATES suitability. The attributes of the data sets were evaluated and their mutual suitability was determined based on the requirements for ATES systems. In section 2.2 this done for the geo-hydrological conditions and in section 2.3 for the climatic conditions.

III Comparison. This step consists in the identification of the ATES suitability for each geo-referenced unit relative to others. Each database entry is given an ATES suitability score relative to the other entries of that same property, based on the mutual suitability which was defined in step II.

IV Standardization & Validation. The obtained relative suitability scores are standardized to a uniform scale to enable combining and comparing different intermediate maps. In the standardization step an extra step was introduced, namely the validation of the suitability score. This is done by applying scale factors, that can be altered to obtain the required result (detailed explanation in section 2.2). Because a frame of reference or assessment framework was not available, the validation of the obtained results was an important aspect of this research. We define ATES suitability from low to high on a 1 to 10 scale. This allows for enough level of detail and provides as clear differentiation between high, medium and low-suitable areas as well.

V Processing. The determined suitability scores are processed with a Geographical-Information-System (GIS) into a map displaying the ATES-suitability's.

The schematic overview in Figure 2.1 shows how steps I and V relate in this research. Steps II, III and IV are located in the grey blocks; a detailed scheme for those steps is given in the corresponding sections of this paper. Different data sets were used, forcing to carry out some of the steps explained above multiple times on different datasets.

Section 2.2 and 2.3 discuss the method and results to translate geo-hydrological and climatic data respectively into ATES suitability. The results are then combined and discussed in relation to urbanization data to identify the hot-spots in section 2.4. A discussion and conclusion follow in section 2.5.

2.2. GEOHYDROLOGICAL ATES SUITABILITY

2.2.1. METHOD

DETAILED information is required to determine geo-hydrological suitability for ATES application. General available geo-hydrological data lacks the required level of detail. Nevertheless, aquifer suitability for ATES can be estimated worldwide by assessing available worldwide aquifer characteristics and groundwater data as explained in section 2.1.3. Figure 2.2 shows the steps required to obtain the geo-hydrological ATES suitability scores. Steps III and IV that are specific for determination of the geo-hydrological suitability are described below.

III) Comparison; Assessment of mutual suitability. It is not possible to derive ATES suitability directly from these data, because the data regarding the subsurface originate

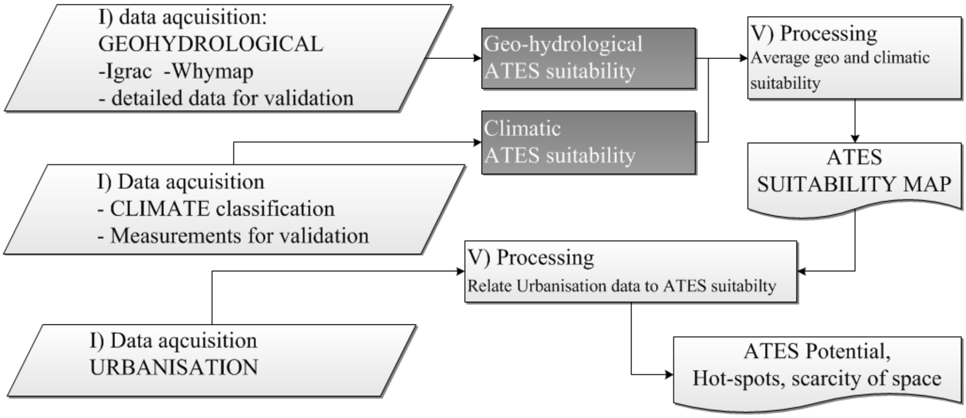

Figure 2.1: Schematic overview of approach to determine ATES suitability

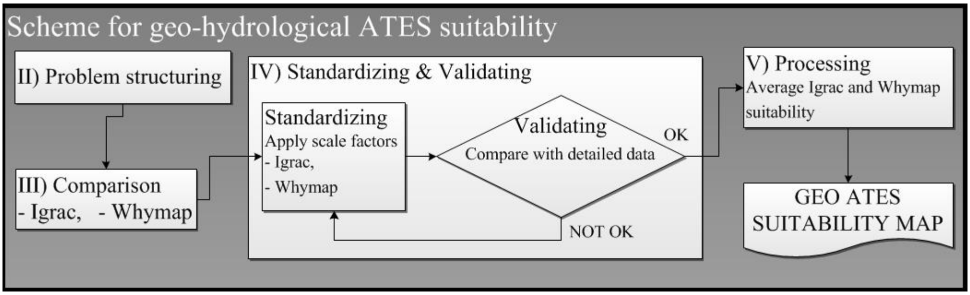

Figure 2.2: Approach to determine Geo-hydrological ATES suitability

from different databases that have many different attributes [34, 35]. However, the relative ATES suitability of locations is based on geo-hydrological properties in the available data sets.

IV) Standardizing and Scaling. Applying a scale factor for each characteristic allows combining the different characteristics into an ATES suitability value. The analysis results in a calculation scheme similar to a multi-criteria analysis. A first estimate of the scaling factors was determined by the author's expert judgment.

IV) Validating. The so-obtained worldwide ATES suitability scores were then validated using already available detailed ATES suitability maps [29], known adoption rates [28–30] and detailed subsurface characterization maps for Europe [39]. The scaling factors were manually altered to make the obtained suitability scores match the expected suitability score based on the local detailed information and characterization.

2.2.2. ANALYSIS OF IMPORTANT GEOHYDROLOGICAL CONDITIONS

This section elaborates step II as presented in section 2.1.3 and Figure 2.1: Problem structuring. Identifying the places with suitable aquifers for the application of ATES systems requires definition of aquifer properties that facilitate application of such systems.

ATES can be applied in aquifers with sufficient capacity, so tube wells can be installed and operated [24]. The specific geo-hydrologic properties on which efficient operation and design of ATES systems depends is explained in the following bullets.

- Water quality. Groundwater quality conditions determine the life expectancy of ATES wells and their required maintenance. Groundwater from different depths of the aquifer is mixed in extraction wells and then re-injected in injections well, and vice versa in the next season. When the chemical composition of the groundwater varies over the depth of the aquifer, mixing of these different water qualities may result in chemical reactions that affect well performance by forming chemical precipitations, leading to clogging of filter screens. As an example mixing of reduced iron-rich water with oxygenated water, leads to clogging by iron-ferric-hydroxides (iron flocs) in the receiving well screen [40]. ATES systems in polluted groundwater also tend to be vulnerable to clogging as well as to corrosion, especially when operating in brackish groundwater [41]. Shallow aquifers below urban areas often carry such water-quality differences and contaminations; these types of aquifers are less suitable for ATES. Aquifers less than 50 m deep are considered shallow in our framework.

- Fresh vs. saline water. ATES can be applied in both fresh and saline aquifers, but saline water requires salinity-resistant equipment to prevent corrosion. Therefore, ATES, is cheaper and less sensitive to maintenance in fresh aquifers. Suitable aquifers with fresh water below urban areas will often be intensively exploited, thus offering little potential for use of ATES that may interfere with extractions of groundwater. With many urban areas developing near coasts, the local groundwater may be brackish or saline, with little or no use to domestic users or agriculture. This offers an opportunity to apply ATES. In coastal aquifers, the transition from fresh to saline groundwater resides generally in relatively shallow aquifers. It is often not allowed to influence this interface to prevent salinization, see for instance [42]. Salinity generally increases with depth. Extracting from and infiltrating water in a salinity-stratified aquifer results in buoyancy-flow that is driven by density differences; this effect decreases the thermal efficiency of the ATES wells [43]. Freshwater aquifers are preferable but groundwater from such aquifers is also used, for drinking water production or irrigation so that ATES often has to compete with limiting its applicability.

- Ambient groundwater flow. Even though groundwater displacement is generally not fast in most cases, less than say 25 m/year, the associated advection of the thermal energy stored in it may cause loss of efficiency of ATES systems, which generally have a thermal radius within the aquifer in the range from 25 to 100 m [21]. The efficiency of larger ATES systems is less affected by ambient groundwater flow than that of small systems, but still losses due to groundwater advection may be substantial. In any case, aquifers with higher groundwater flow rates are less suited to store thermal energy.

- Composition of the aquifer. Any layering, heterogeneity, fissures, fractures and faults negatively affect thermal efficiency of ATES systems. High hydraulic conduc-

2

tivities often imply larger advection rates and associated advection losses, while heterogeneity implies zones with higher and lower velocities causing lateral loss of heat by heat exchange with confining layers and less pervious structures having different temperatures due to slow exchange, thus adding to heat dispersion [44]. Vertical anisotropy, however, is a benefit for ATES systems since it limits vertical flow losses. Fissures, fractures and faults are likely to cause preferential flow paths with extreme lateral loss of thermal energy through exchange with the aquifer blocks in between the fractures, in which the flow rate may be orders of magnitude less than in the fractures. In aquifers with faults or fractures, it is difficult to control where the stored water flows and with that the thermal energy. As a consequence of geologic processes, aquifers and their enclosing layers may have been tilted. In tilted aquifers with nearby outcrops/recharge zones, groundwater flow is often high and water-quality conditions are likely to vary. These aspects makes complex hydrological structures less suitable for ATES application.

- Depth of Aquifer. Aquifer depth below ground surface is of little importance from the perspective of energy efficiency, but it affects well drilling and installation cost. While larger depths may imply salinity issues, shallower depths tend to encounter water-quality issues as was outlined above. The optimal depth is often a trade-off between installation costs (the shallower the better), expected problems with water quality (the deeper the better) and efficiency (the more uniform the composition and groundwater quality the better).

2.2.3. SUBSURFACE CHARACTERISTICS TRANSLATED TO ATES SUITABILITY

This section elaborates step III and IV as presented in section 2.1.3 and Figure 2.1: comparison, standardizing & validating. UNESCO and BGR [35] constructed the WHYMAP transboundary aquifer maps with associated data that include two types of characteristics useful to derive ATES suitability from; 1) the composition of the aquifers and 2) the amount of recharge. IGRAC on the other hand, made an overview on a country by country basis for many different subsurface and groundwater characteristics [34] utilizing over 450 different sources to compose its maps and database. The data comprises four main types of characteristics: 1) extent per aquifer type for each country as a percentage of the country's surface area, 2) occurrence of highly productive aquifers per country as a percentage of the country's surface area, 3) mean annual recharge, and 4) groundwater abstraction as a percentage of the country's water consumption. In the following, the relative suitability for ATES is defined for these characteristics.

OCCURRENCE AND TYPE OF AQUIFER. By definition, aquifers contain groundwater, making aquifer occurrence an important characteristic for ATES suitability. The scaling factor that is used for this characteristic is called F_{aq}. Within this characteristic, distinction is made between:

- Major groundwater basins such as sand aquifers, gravel aquifers and inter-granular aquifers. These generally are vast with a constant-in-time water quality and a high hydraulic conductivity. Areas with major groundwater basins are the most suitable, even if some of them might have too low a hydraulic conductivity for ATES application.

- Local and shallow aquifers are also generally suitable for ATES application because the local scale and impact of ATES systems does not require an extensive aquifer. Shallow aquifers may, however, pose problems due to water-quality issues that cause clogging of the wells as shallow urban aquifers are often contaminated. Because of these considerations the shallow and local aquifers were ranked to be of medium suitability.

- ATES suitability in so-called complex hydrological structures such as tilted aquifers, karstified aquifers, fissured and fractured rock aquifers, always strongly depends on local conditions. Since ATES is a local-scale technology, there may be zones within complex structures that are suitable for ATES application. Mostly, however, ATES systems will not be easily applicable or even possible in such complex formations, because of which such formations are ranked to be of lowest suitability.

GROUNDWATER. Information about groundwater may also indicate about ATES suitability, especially when no other information is available. A second scaling factor is applied to deal with characteristics, denoted F_{gw}. Within the groundwater properties distinction is made between:

- Groundwater recharge, the yearly percolation into local aquifers. In some locations recharge is the only information in the databases that can be linked to groundwater availability. Despite the fact that recharge is a poor indicator for groundwater availability, it is used in characterizing ATES suitability; the more there is the higher is the probability that ATES can be applied.

- Production from aquifers. This characteristic is more important for ATES applicability than is groundwater recharge, because it provides actual information on how much water can be produced from the considered aquifer. So the more water produced from aquifers, the more suitable it is considered for ATES. There are two remarks, however: 1) areas with saline groundwater will thus end-up low in the ranking because these are not contained in the groundwater data while still suitable for ATES systems, and 2) in fresh water aquifers, ATES has to compete with irrigation, industrial and drinking water production, which constraints ATES application.

With this analysis, the different characteristics available in the WHYMAP and IGRAC databases allows ranking of ATES suitability on a worldwide scale according to step III and IV of the method described in section 2.1.3 and 2.2.1. For these datasets, the ATES suitability is established by using a calculation scheme, explained next. The calculation method applies the scaling factors F_{aq} and F_{gw}. The same scaling factors are applied in the analysis of both datasets because the relative importance of different data types cannot depend on the source of the data with the same trustworthiness.

Both datasets were validated individually with respect to the actual ATES suitability based on detailed aquifer and groundwater information from 5 selected countries in Europe. The thus obtained ATES suitability scores from these countries were used to optimize the scaling factors F_{aq} and F_{gw}, such that the obtained suitability scores match the expected suitability based on detailed local information as closely as possible.

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Table 2.1: Relative ATES suitability of WHYMAP characteristics

Relative suitability of aquifer characteristics ($s_{aq,j}$)		Relative suitability of groundwater recharge ($s_{gw,j}$)		Calculated ATES suitability (S_j)
Major groundwater basin	3	< 2 mm/y	0	7.2
Major groundwater basin	3	2 - <20 mm/y	1	7.9
Major groundwater basin	3	20 - <100 mm/y	2	8.6
Major groundwater basin	3	100 - <300 mm/y	3	9.3
Major groundwater basin	3	>= 300 mm/y	4	10
Complex hydrogeological structure	1	< 20 mm/y	1	1.0
Complex hydrogeological structure	1	20 - <100 mm/y	2	1.7
Complex hydrogeological structure	1	100 - <300 mm/y	3	2.4
Complex hydrogeological structure	1	>= 300 mm/y	4	3.1
Local and shallow aquifers	2	< 100 mm/y	2	5.2
Local and shallow aquifers	2	>= 100 mm/y	3	5.8
Scaling factor (F_{aq})	5	Scaling factor (F_{gw})	1	

Despite the limited number of characteristics it was chosen to use these data because the WHYMAP database is a complete set that covers the whole world and has a detailed spatial reference that matches geo-hydrological units. The calculation of the ATES suitability scores for the WHYMAP data (S_j) is described in Equation 2.1, the subscript "j" refers to the parameters location, X_j represents the standardization factor. The other symbols are explained in Table 2.1, which contains the WHYMAP data characteristics. Columns 1 and 2 show the aquifer characteristics with their relative importance based on the analysis described in section 2.2.1 and above, these columns result from the comparison operation. Columns 3 and 4 show the relative importance of the groundwater recharge based on the analysis described in section 2.2.1 and above. Column 5 contains the ATES suitability normalized between 1 and 10. It was obtained by first multiplying the scores in column 2 and 4 with the scale factor in the corresponding column of the bottom row, adding them and normalizing (with X_j) afterwards.

$$S_j^{whymap} = X_{aq}^{whymap} \cdot F_{aq} \cdot s_{aq}^{whymap} + X_{gw}^{whymap} \cdot F_{gw} \cdot s_{gw}^{whymap} \tag{2.1}$$

Table 2.2 contains the IGRAC data for 5 selected countries in Europe on which the validation was based. The IGRAC dataset characteristics and their spatial reference differ very much from the WHYMAP data. Firstly, the IGRAC database contains many more and more detailed characteristics, and secondly, the spatial reference is based on countries instead of geo-hydrological units. Unfortunately, many characteristics are only available for a few countries and, therefore, had to be excluded from this analysis. The remaining characteristics used for the analysis, are presented in table 2.2, but even these were not complete for all countries. For the countries with missing data with respect to the used characteristics, the ATES suitability was based on only the remaining available characteristics. Equations (2.2), (2.3) and (2.4) show how the IGRAC ATES suitability score is calculated, again X represent the standardization factor, the other symbols are

Table 2.2: Relative ATES suitability of used IGRAC characteristics
P^i = Extent of intergranular aquifers, P^f =Extent of fissured aquifers, P^0 =Extent of areas without aquifers, P^{pi} =Extent of productive intergranular aquifers, P^{pf} =Extent of productive fissured aquifers, P^{p0} =Extent of zones without groundwater, R_j =Mean annual groundwater recharge (mm/y), P^{ext} =GW extraction as a % of total water consumption

	Relative suitability of aquifer characteristics						Relative suitability of groundwater characteristics		ATES Suitability (S_j)
Relative suitability ($s_{\#}$)	2	1	0	2	1	0	1	3	
Country	P^i	P^f	P^0	P^{pi}	P^{pf}	P^{p0}	R_j	P^{ext}	
Belgium	29	33	38	18	16	35	29	4	3.5
Germany	41	33	24	26	18	16	128	4	4.0
Netherlands	99	1	0	61	1	0	108	1	10
Spain	20	15	65	8	11	17	59	5	2.2
United Kingdom	10	28	62	4	10	48	40	1	1.3
Scaling Factor	$F_{aq} = 5$						$F_{gw} = 1$		

explained in the following and indicated in table 2.2.

Table 2.2, columns 2, 3, 4 and 5, 6, 7 contain the extent of the countries' surface area with a certain aquifer property as a percentage of the counties surface area. The numbers should add up to 100%, but some don't, as was explained earlier. The numbers in these columns below row 3 are the areal percentage within each country (P), which are weighted by multiplying them with the relative aquifer suitability shown in row 2 ($s_{\#}$) and the corresponding scale factor given in the bottom row, similar to the calculation scheme in table 2.1. Columns 8 and 9 refer to groundwater properties, with column 8 recharge rate, which was truncated at a maximum of 300 mm/y to prevent outliers, and column 9 holds the groundwater abstraction relative to total water consumption. Both the recharge rate and the abstraction percentages were normalized between 1 and 10 before multiplying them with the suitability factors in row 2 and the scale factor in the bottom row and summing the column results. Finally, the three sets of columns were combined by multiplying the normalized scores with the corresponding scaling factors in the bottom row, and then taking the sum, of which the results are shown in the right-most column of table 2.2.

$$S_j^{igrac} = F_{aq} \cdot s_{aq,j}^{igrac} + F_{gw} \cdot s_{gw,j}^{irgac} \tag{2.2}$$

$$s_{aq,j}^{igrac} = X_{aq}^{igrac} \left(P_j^i \cdot s_j^i + P_j^f \cdot s_j^f + P_j^{pi} \cdot s_j^{pi} + P_j^{pf} \cdot s_j^{pf} \right) \tag{2.3}$$

$$s_{gw,j}^{igrac} = X^{rech} \cdot s_j^{rech} \cdot R_j + X^{ext} \cdot s_j^{ext} \cdot R_j^{ext} \tag{2.4}$$

2

Validation procedure
The ATES suitability calculation is based on 1) database properties, 2) the relative suitability of characteristics and 3) the scaling factor. The database properties cannot be altered and the relative suitability simply follows from the problem structuring step (II) in section 2.2.2 and is, therefore, also fixed. The only manipulated parameters in the validation procedure are the two scaling factors. Allowing more than 2 scaling factors would give more opportunity for optimization during the validation and may result in a more representative and more detailed suitability map. This approach would make the validation process more complex and more difficult to explain and understand, while the data did not warrant a more sophisticated analysis and calibration. In addition, no frame of reference is available to allow quantification of the validation. Therefore, it was chosen to rely mainly on the datasets and the relative suitability's defined in the analysis in section 2.2.1 and above, and limit our optimization to only 2 scaling factors to allow for corrections on the found suitability's.

Existing general ATES suitability maps and adoption rates [28–30] were used to validate the IGRAC ATES suitability scores. As a consequence of the diversity in the attributes and geographical reference in the validation data, it was not possible to identify a single expected suitability score to base the validation on. Therefore, the validation was carried out at a 3-scale basis as follows: for each of the selected countries/areas it was defined whether the ATES suitability is good, medium or poor. Subsequently, during validation, the obtained scores where fit within the corresponding bandwidth of suitability score: poor = 1-3, medium = 4-6, good = 7-10. The detailed European aquifer characterization maps [39] were used to validate our scoring based on the WHYMAP data. Without going into detail about the characteristics of the reference map, the validation data and corresponding results in the form of a suitability map are given in Figure 2.4 as an example of how the validation was carried out. For the validation of the IGRAC data, local information about ATES adoption and application research [28–30] were used to define if the ATES suitability of the selected countries is good, medium or poor. The validation step taught us that the conditions regarding aquifer characteristics rather than groundwater characteristics dominate the determination of ATES suitability.

2.2.4. Result & discussion of geohydrological ATES-suitability

This section elaborates step V as presented in section 2.1.3 and Figure 2.1: Processing. After the validation, the obtained ATES suitability scores from both data sets are combined by averaging them in a GIS-environment $S_{GEO} = (S_{whymap} + S_{igrac})/2$. The suitability map resulting from the exercises explained in this section is given in Figure 2.5.

The surface area with high suitability is limited to about 5%, in most places the subsurface conditions are medium suitable (65%) for application of ATES. This is due to the difference between the results of the two data sets. The IGRAC data tend to give lower results than the WHYMAP data, the average score differs 3 points. In 40% of the areas, the difference is smaller than 3 suitability points. However, in 75% of the cases the results from the data sets agree on if a suitability score is higher or lower than their average score or the suitability score differs less than 3 points. The differences in the remaining 25% of the areas can be explained by considering two aspects:

- IRGAC lumped aquifer characteristics to country-averaged values, while WHYMAP

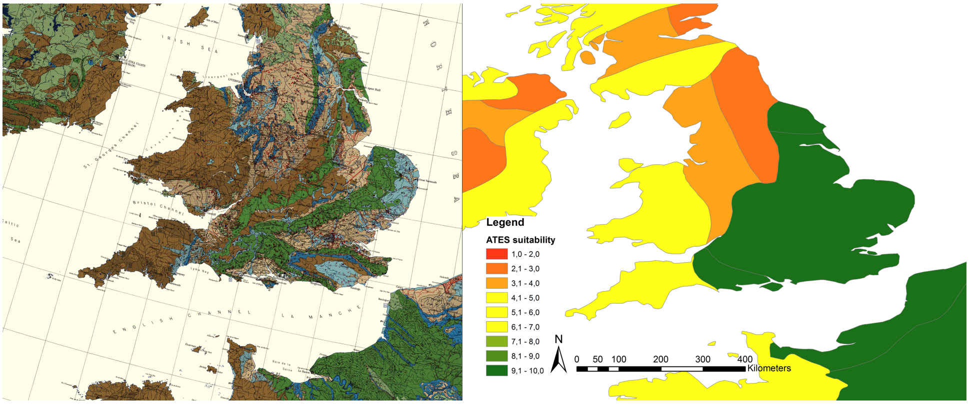

Figure 2.3: Detailed characterization map [39] and the WHYMAP suitability score map of South-West Britain

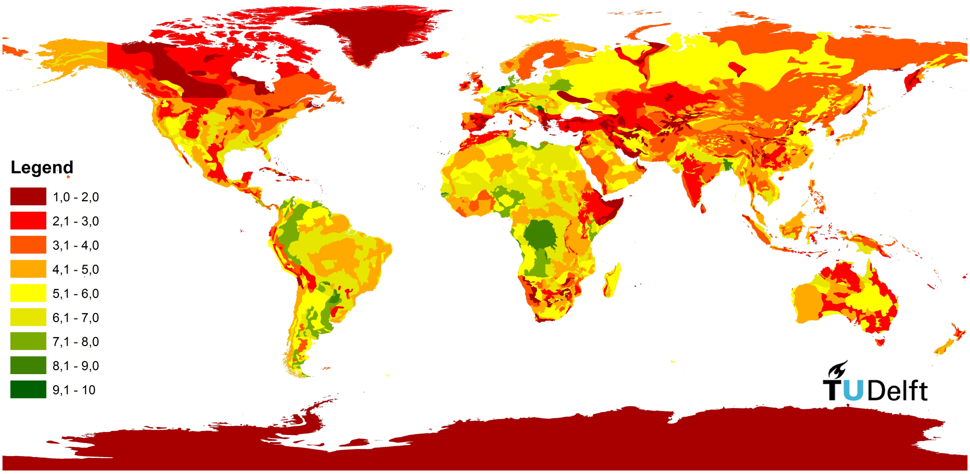

Figure 2.4: ATES suitability based on WHYMAP & IGRAC data

lumped its data by geological formation. For large countries, this biases the result, as can be seen at the border between the USA and Canada. Also, the results show that large countries like USA, Russia, Brazil, Argentina and Australia, tend to have many areas of medium suitability. While IGRAC data were useful for smaller countries, these country lumped data are not accurate enough to deduce ATES suitability for bigger ones. This leads to the recommendation towards IRGAC to rather collect data per state, province, county or district in bigger countries.

- The IGRAC database requires data collection and validation for each country, which is lacking in many less developed countries [45], resulting in incomplete data sets. It is very likely that many African countries are in the medium range of suitability due to this effect.

Groundwater quality is an important aspect for ATES systems. Since only limited groundwater quality information is present in the available datasets, groundwater quality could only be considered implicitly by considering shallow aquifers to be less suitable. This implies that deviations from the presented maps are possible due to groundwater-quality issues when using the ATES suitability map in practice.

The ATES suitability map was constructed from different data sources. Where the different sources agree on their ATES suitability, it is reasonable to assume that the map gives a correct representation of ATES potential. Areas scoring in the middle range between 4 and 7, is in many cases the result of averaging higher and lower suitability values where the scored WHYMAP and IGRAC data sources did not match. Further development of this map should, therefore, focus on these areas. Given that the validation is only based on detailed maps from Europe and data of the WHYMAP and IGRAC are not congruent, a likely follow- up is to explore how an extra scaling factor that distinguishes between the relative contribution of each dataset, would improve the results with in combination with an extra validation with detailed information about ATES applicability from other continents.

2.3. Climatic ATES suitability

2.3.1. Method

To identify where the climate is suitable for ATES the relevant climatic conditions are identified first. Climate control in buildings and their resulting demand for thermal energy storage depends, among others, on climate. To translate general climate data to ATES suitability was done in 5 steps, of which II to V are schematically shown in Figure 2.6. Steps III and IV are described as follows:

III) Assign an ATES suitability score to each climate class. The 31 Koeppen climate classes [36, 46, 47] were divided in ATES suitability classes based on individual climate-class characteristics such as average temperature levels and yearly variation in temperature [47, 48] taking into account properties and use of buildings.

IV) Validation. Actual climate data of locations were used to validate our climate-based suitability classification obtained in step I.

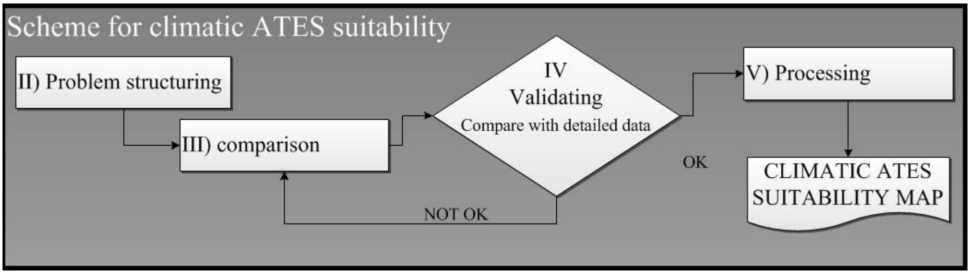

Figure 2.5: Schematic overview of approach to determine climatic ATES suitability

2.3.2. ANALYSIS OF IMPORTANT CLIMATIC CHARACTERISTICS

This section elaborates step II as presented in section 2.1.3 and Figure 2.1: Problem structuring. For optimal efficiency and to sustain an ATES system about as much thermal energy has to be stored and extracted on average. Balancing seasonal heat extraction and storage prevents ongoing growth of either of the warm or cold zone in the subsurface, which would ultimately negatively affect the extraction temperature of the other well of the system, or neighboring wells [24, 49, 50]. Therefore, suitability for ATES depends on the energy demand of the connected building, that itself depends on climate conditions. The balance between cooling demand in summer and for space heating demand in winter however, also depends on building properties and building use, like orientation, insulation and internal heat load as caused by computers, occupancy and lighting. Therefore, climate, properties of buildings and use of buildings must be considered jointly to determine whether buildings in a region may benefit from application of ATES. It is practically impossible to incorporate building properties in an ATES suitability map as that would result in a wide range of different conditions and thresholds for suitability. To allow defining suitability of ATES for a given region solely on climate data, the following simplifications and assumptions were made:

- It is relatively expensive and inefficient to install an ATES system in an (existing) poorly insulated building, Therefore ATES is mainly installed in buildings that obey high insulation standards [49, 51, 52]. Aebischer et al. [51] show that the demand for cooling grows strongly, while that for heating decreases only little. High-quality insulation of buildings combined with the internal heat load causes cooling demand to become more dominant in the energy balance of modern buildings. This results in the fact that in climates with a longer and colder winter period, more buildings may have a balance in heating and cooling demand, and thus can successfully apply ATES, contrary to buildings in climates where summers are longer and warmer and, therefore, the cooling demand will dominate the energy balance.

- Every building has redundancy in its heating and cooling facilities to deal with imbalances and disturbances in energy demand and supply. An imbalance in heating and cooling demand larger than the ATES system can handle must be overcome with an additional regeneration facility, for instance by withdrawal of thermal energy from surface water or discharging surplus thermal energy into surface water, or by road heat exchangers or by exchanging heat with outside air.

2

- The temperature threshold between heating and cooling demand is around 18°C with a bandwidth of 5°C and a temperature difference of at least 5°C between the warmest and coldest month.

- The description of the ATES suitability of climate classes is based on the required balance between yearly heating and cooling demand to be supplied by the subsurface. The size of the associated buildings was not taken into account.

2.3.3. CLIMATIC CONDITIONS TRANSLATED TO ATES SUITABILITY

This section elaborates steps II and IV as presented in section 2.1.3 and Figure 2.1: comparing and validating. The assumptions adopted in the previous section allow us to translate climatic properties to ATES suitability. The climate classifications of Koeppen-Geiger were divided into 5 ATES suitability classes as shown in table 2.3.

A Mainly cooling demand. This is the least favorable situation because it is then not possible to store the required cooling energy by lack of a sufficiently cold season.

B Prevailing cooling demand. In this temperature range, ATES might be applicable [53], but most of the buildings will have difficulties to store the required cooling capacity during the colder period.

C Heating and cooling demand. In the regions with distinctive warm and cold seasons, heating and cooling demand will more or less balance, creating the most favorable conditions for ATES.

D Prevailing heating demand. Based on the fact that insulation of buildings will improve and the fact that internal heat loads in buildings will grow, these regions may become more suitable for ATES systems; this is a consequence of the rising temperature under climate change, since the average heating and cooling demand will better balance in the future [54, 55]. Therefore, suitability is better than type B, with prevailing cooling demand.

E Mainly heating demand. In this climate, it is not possible to store the required heat by lack of sufficiently warm summers; because of the same reason with climate types D and B, suitability was scored a little better than type A climate.

Based on these general properties, the ATES suitability scores defined above were associated with each climate class. The climatic descriptions and attributed ATES suitability's are given in table 2.4. The ATES suitability classes resulting from the validation in step IV are also given in table 2.4; for the validation step, the temperature intervals given in table 2.3 were used. Only for the 'BWk' and 'Dfb' climate classes deviated the suitability scores considerably from the validation data. The other classes match well; the results generally confirm the suitability scores that were chosen to properly take into account climatic data for this classification.

Table 2.3: Temperature thresholds for energy balance and ATES suitability

	T_{avg} [C]	Energy balance	Suitability for ATES	Score (S_{Clim})
A	> 25	Mainly cooling demand, no heating demand	hardly	1
B	$20 < T_{avg} < 25$	Prevailing cooling demand, small heating demand	specific buildings	4
C	$15 < T_{avg} < 20$	Heating and cooling demand (more or less) balance	most buildings	10
D	$10 < T_{avg} < 15$	Prevailing heating demand, small cooling demand	specific buildings	6
E	< 10	Mainly heating demand, no cooling demand	hardly	2

2.3.4. RESULTS & DISCUSSION FOR CLIMATIC ATES SUITABILITY

This section elaborates step V as presented in section 2.1.3 and Figure 2.1: Processing. Rubel and Kottek [46] used several socio-economic scenarios to make projections for the Koeppen-Geiger climate classification towards the end of the 21^{st} century. In this paper, two different scenarios were used to classify ATES suitability: the classification based on observations of climate characteristics between 1976 and 2000 (figure 2.6), and the climatic-projection for the period 2051-2075 (figure 2.7) from Rubel and Kottek [46].

Figure 2.7 shows that the area with climate conditions suitable for ATES is limited and mainly concentrated in the Eurasian and North American continent. The light-blue areas indicate where ATES can be used for buildings with a relatively low cooling or high heating demand, as the pink areas do for a relatively high cooling and high heating demand. Figure 2.7 shows that in the second half of the 21^{st} century, the suitable regions for ATES shift to the North and shrink. Only in southern Chili and Argentina the climatic conditions for ATES improve.

The classification in this chapter was based on general information on climate properties and was checked with observation data of a limited number climate classes. It might strengthen the reliability of the proposed ATES climate classification when more observed field data were used to validate the classification standard. Despite the limited scope of the validation, the obtained map indicates which regions may be suitable for applying ATES technology that also match regions with known ATES application.

The ratio between heating and cooling demand was generalized for buildings. In any climatic region, cases with an unexpected energy demand may occur.

In the climate classification of Koeppen-Geiger [36], the size of the geographical unit appointed to a certain climate varies from the size of half a continent such as North-Western Europe and Siberia, to that of one grid-cell of 0.5° x 0.5°. As a result, in some coastal and mountainous areas, climate classes vary a lot over a short range, while in practice ATES applicability does not differ much over a 0.5° distance. This ambiguity supports the approach of lumping the 31 original climate classes into 5 ATES suitability classes and the distinction that was made between areas with mainly cooling and mainly heating demand. So climate types B and D are likely to be more suitable when they are located close to type C climates, and less suitable when they are close to climate types A

2

Table 2.4: Climate classification linked to ATES suitability

Code	Description	Validation (S_{Clim})	Suitability (S_{Clim})
Group A: Tropical/megathermal climates			
Af	Equat. rainforest, fully humid; P > 60 mm/month	1	1
Am	Equat. monsoon climate	1	1
As	Equat. savannah with dry sum. P_{min} < 60 mm in sum.	-	1
Aw	Equat. savannah with dry wint. P_{min} < 60 mm in wint.	2	1
Group B: Dry (arid and semi-arid climates			
BWk	Cold Desert, T_{avg} <18°C	4.3	10
BWh	Warm Desert, T_{avg} >18°C	2.3	4
BSk	Cold Savanna, T_{avg} <18°C	5.3	6
BSh	Warm Savanna, T_{avg} >18°C	5	4
Group C: Temperate/mesothermal climates			
Cfa	Warm sea-climate, T_{avg} hottest month >22°C	5.2	4
Cfb	Moderate sea-climate, T_{avg} hottest month <22°C	6	10
Cfc	Cold sea-climate, max 4 months/year T_{avg} >10°C	-	6
Csa	Warm med.climate, T_{avg} hottest month >22°C	6.0	4
Csb	Moderate med.-climate, T_{avg} hottest month <22°C	6	10
Csc	Cold med.-climate, max 4 months/year T_{avg} >10°C	-	6
Cwa	Warm China-climate, T_{avg} hottest moth >22°C	-	4
Cwb	Moderate China-climate, T_{avg} hottest moth <22°C	-	10
Cwc	Cold China-climate, max 4 months/year T_{avg} >10°C	-	6
Group D: Continental/microthermal climates			
Dfa	Warm cont. climate, T_{avg} hottest month >22°C	4	4
Dfb	Moderate cont. climate, T_{avg} hottest month <22°C	5	10
Dfc	Cool cont. climate, max 4 months/year have an T_{avg}>10°C	-	6
Dfd	Cold subartic cont. climate, T_{avg} Coldest month <-38°C	-	2
Dsa	Warm med. cont. climate, T_{avg} hottest month >22°C	-	4
Dsb	Moderate med. cont. climate, T_{avg} hottest month <22°C	-	10
Dsc	Cool cont. climate, max 4 months/year T_{avg} >10°C	-	6
Dsd	Cold subartic cont. climate, T_{avg} Coldest month <-38°C	-	2
Dwa	Warm cont. climate, T_{avg} hottest month >22°C	-	4
Dwb	Mod. cont. climate, T_{avg} hottest month <22°C	-	10
Dwc	Cool subartic cont. climate, max 4 months/year T_{avg} >10°C	3,3	6
Dwd	Cold subartic cont. climate, T_{avg} Coldest month <-38°C	-	2
Group E: Polar and alpine climates			
EF	Tundra climate 0 °C < T_{max} < +10 °C	2	2
ET	Frost climate T_{max} < 0	2	2

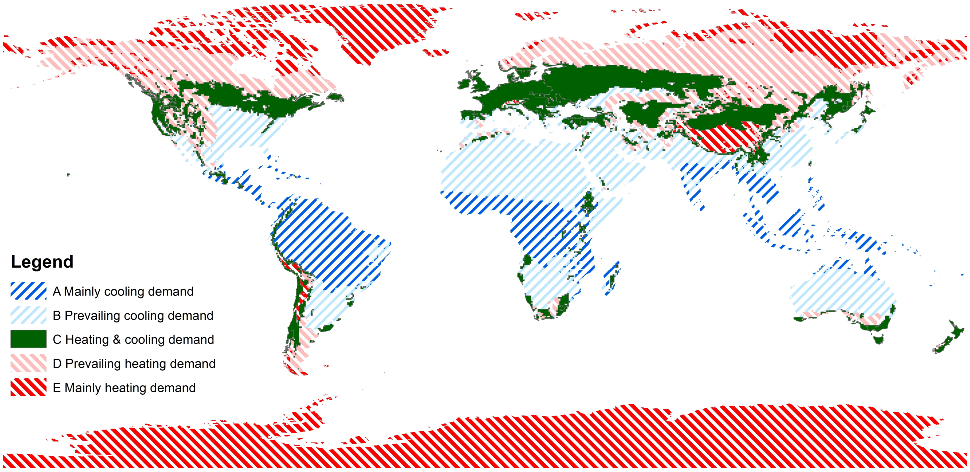

Figure 2.6: Dominating demand for space heating and cooling, observation 1976-2000

or E.

A way to improve the results, is to distinguish between different types of buildings and energy demand profiles that depend on climatic conditions. However, this would make the validation process more laborious and more difficult to understand and explain. Therefore, it was chosen not to follow that path in this paper, but it may be a route to follow in further detailing this map.

It is still uncertain to what extent the projected climate classification will be effective in reality. So the results of this study should be updated periodically, with recent climate data and new projections.

2.4. RESULTS: POTENTIAL FOR ATES

2.4.1. THE WORLD ATES SUITABILITY MAP

To obtain our ATES suitability map, the obtained geo-hydrological and climatic suitability scores were combined in a GIS environment. Because ATES suitability is considered to be equally dependent on climatic and on geo-hydrologic conditions, the suitability scores are averaged in this operation ($S_{ATES} = (S_{GEO}+S_{Clim})/2$). Only when either the geo-hydrological or the climatic suitability score was low (i.e. less than 3), this score is considered to be decisive for the applicability. For instance, a building with a perfect energy balance will not adopt ATES in an area unsuitable to make groundwater wells. So when a suitability score is lower than 3 in either map, it will be weighted 3 times in the averaging, preventing the final map to contain many areas of middle-range suitability that in practice have no suitability at all. Figure 2.8 shows the ATES suitability based on 1967-2000 climate observations; the ATES suitability for the climate projection of 2051-2075 is shown in Figure 2.9. As can be seen, there will be very suitable areas in Europe, Asia and North-America, but also in other continents several smaller isolated areas will

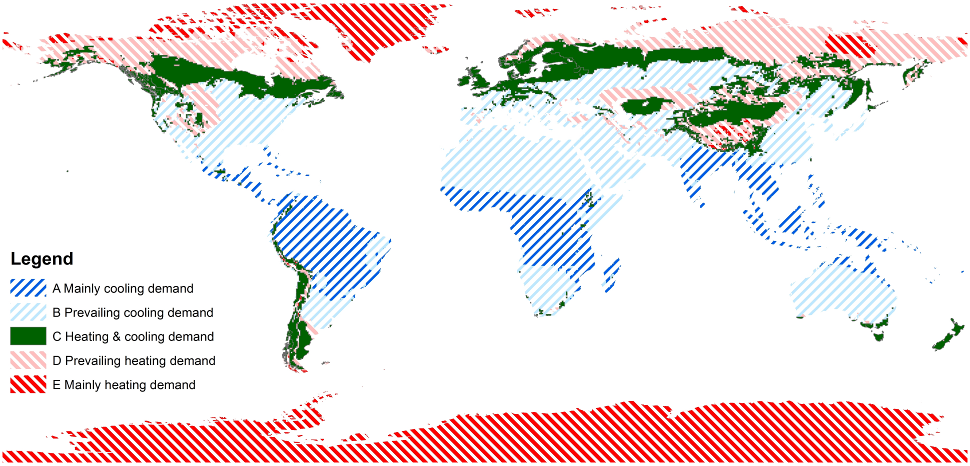

Figure 2.7: Dominating demand for space heating and cooling, projection 2051-2075

Table 2.5: Potential for ATES as a percentage of urban population

ATES potential	Poor			Medium			Good		
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
1976-2000	0%	13%	18%	9%	23%	21%	10%	5%	0%
	31%			54%			15%		
2051-2075	0%	22%	25%	7%	29%	14%	2%	1%	0%
	47%			50%			3%		

be suitable for the applying of ATES systems.

2.4.2. USING URBAN POPULATION DATA TO IDENTIFY ATES HOT-SPOTS

The urbanization data used consists of historic population numbers and the population projections for 588 urbanized areas spread over the world [37, 38]. The percentages of urban population living in areas of different ATES potential are given in table 2.5. The data used does not include all urban areas in the world, however the percentages derived from the maps are representative indicators for the world urban population. At the end of the 20^{th} century, 15% of the world's urban population lives areas with a high suitability for ATES application. This percentage will drop to about 3% in 2051-2075 as a result of climate change. As a consequence of urbanization, the total number of people living in high potential areas will decrease by 50% with respect to the situation in 2000.

The urban population living in the medium ATES suitability range will be constant, around 50%; the climatic zones shift for these areas, the total fraction of the urban population however, remains more or less constant. Because of increasing urbanization, the number of people living in medium ATES suitability areas will increase by 140%. For these people, ATES applicability depends on local climate, geo-hydrological and build-

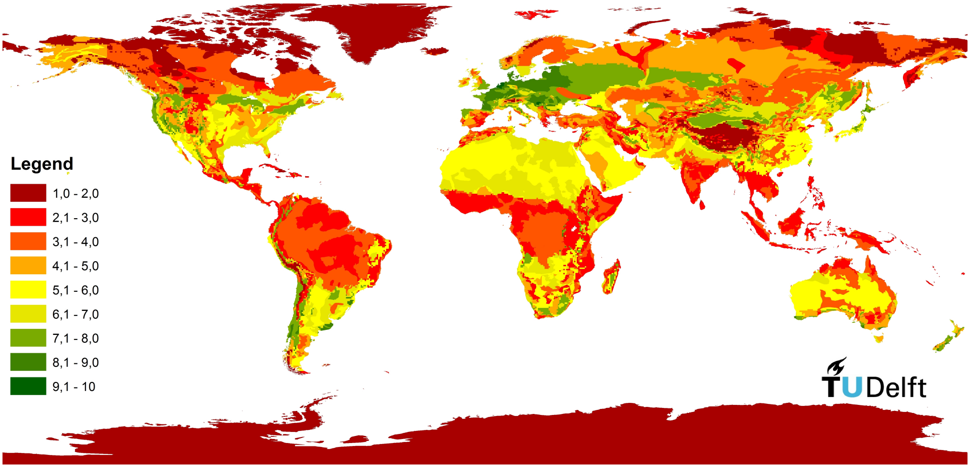

Figure 2.8: ATES suitability 1976-2000

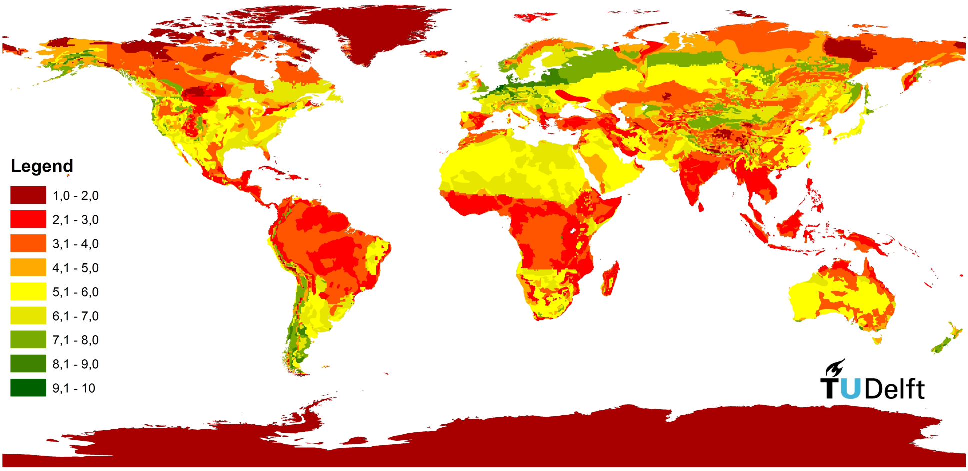

Figure 2.9: ATES suitability 2051-2075

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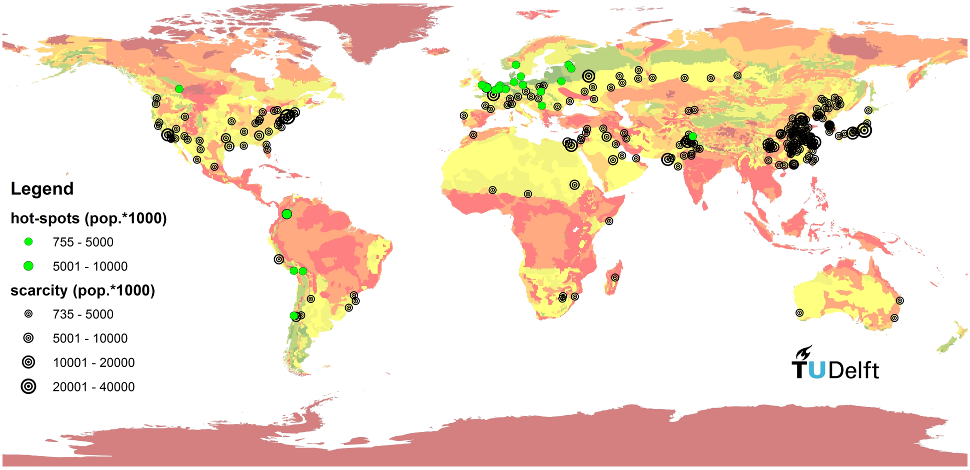


Figure 2.10: Urban areas with ATES hot-spot & possible scarcity of space (2051-2075)

ing conditions.

About 30%, and later 50% of the population living in urban areas does not have the opportunity to efficiently apply ATES.

Where climate conditions are favorable and geo-hydrological conditions are medium to good, mutual interference between adjacent ATES systems is likely to occur because demand for ATES is most likely to exceed availability of subsurface space in these areas, which results in scarcity of subsurface space for accommodation and further development of ATES [49]. Therefore, it was analyzed where climate conditions are best (scores 6 and 10), and geological conditions are medium and good (scores in the range 4-10). This analysis showed that in the second half of the 21st century 44% of the urban population will live in areas where scarcity of space in the subsurface may become an issue. As can be seen in Figure 2.10, most cities where lack of subsurface space is likely to occur lie in North America, Europe and mainly Asia.

2.5. CONCLUSIONS AND DISCUSSION

THE ATES suitability maps constructed and presented in this paper, were composed of freely available information and datasets. The actual suitability for the application of ATES systems in practice may deviate from results in presented maps due to differences with local subsurface conditions or deviating energy demand of buildings. The method used to establish the potential maps was proposed in this paper and was validated using local and detailed information from regions where ATES is already applied. Application of the method gave the insight in; where ATES should be applicable, but where it is not yet applied, like in Russia and in parts of Asia and in southern South America. It also showed that ATES will become applicable in other parts of northern North America and Russia during the second half of the 21^{st} century. The combination with urbanization data showed which part of the urban world population lives in areas with a suitable aquifer and climate and where demand for ATES may exceed available subsurface space. In these areas, legislation may need substantiation to allow for sustainable and optimal use of the subsurface for ATES.

In some cases, the suitability derived from the two geo-hydrological data sets did not agree as was discussed in section 2.2.4. This is partly caused by differences in the scales of spatial reference and limited availability of some data subsets. Improvement of the geo-hydrological ATES suitability maps should best focus on detailing larger countries and the collecting more data from developing countries. Nevertheless, it was shown that for 75% of the validated areas the results were in agreement, indicating that after validation the defined geo-hydrological suitability is a good representation of the expected suitability for ATES that was based on detailed information of a number of selected countries.

The climatic suitability was determined in a straightforwardly by lumping all types of buildings, building use and insulation standards to a single energy-demand pattern albeit with a large bandwidth. Considering the fact that the climatic dataset has a relative large (50%) influence on the final suitability score, a more sophisticated approach would be justified. For instance, A) validating the seasonal patterns and average temperature values of the climate-class descriptions with more data from different climate classes and B) evaluate how the ATES suitability of different types of buildings and/or insulation standards differ. Despite the limitations underlying the determination of climatic ATES suitability, this simple but well substantiated approach was shown to give the required insight in ATES suitability and allows concluding what to expect for in most regions.

3

OPTIMAL AND SUSTAINABLE USE OF THE SUBSURFACE FOR ATES

If you want to go fast go alone, if you want to go far go together

African proverb

This chapter seeks solutions for the institutional hindrances to the diffusion and adoption of ATES. The use of aquifers by individual ATES systems can be optimized to maximize their efficiency on the one hand, and to optimize the performance of the regional subsurface for energy storage on the other. The application of ATES in an aquifer has similar properties as other common resource pool problems. Only with detailed information and feedback about the actual subsurface status, a network of ATES systems can work to towards an optimum for both the subsurface and buildings, instead of striving for a local optimum for individual buildings. Future governance of the subsurface may include the self-organization or self-governance. For that the ATES systems need a complementary framework; interpretation of interaction, feedback, and adaptable dynamic control are the key elements to come to optimal and sustainable use of the subsurface.

This chapter is published in Energy Policy journal **66**, 104 (2014) [49].The introduction has been modified to fit within the storyline of this thesis and to prevent repetition, also some headings were shortened.

3.1. Introduction

3.1.1. Framework for optimal use of the subsurface

The framework for optimal use of the subsurface is the first of the 3 main pillars of this thesis and addressed in this chapter. Since (local) governments are responsible for the optimal and sustainable utilization of aquifers, specific properties and behavior of ATES systems are analyzed from a governance perspective. ATES systems use the subsurface to minimize GHG-emissions and reduce cost for space heating and cooling. To identify a framework in which ATES systems maximize GHG-emission reductions while preventing a tragedy of the commons [56], it is first required to evaluate the working principles and define what use of the subsurface is optimal and sustainable in the case of ATES. Based on these characteristics and definitions, current legislation and possible alternative frameworks are evaluated.

3.1.2. Legislation for ATES

Legislation for shallow geothermal energy storage systems, including, ATES and Borehole Thermal Energy Storage , varies between countries [28–30, 51, 57]. Specific legislation was developed in countries where ATES is applied or it was altered to properly govern and/or stimulate the technology [58]. Dedicated legislation is either lacking or poorly substantiated in countries with little application of ATES [57], even though its technical potential may be or will become high. This might result in suboptimal and unsustainable use of the subsurface for ATES or even prohibit application of the technology.

3.1.3. ATES growth is not systematically

From historical developments is concluded that a new energy technology would take fifty to hundred years to reach its full potential [59]. According to Grubler [59] going too big too early will cause the new technology to fail. Up-scaling will be successful if it is: A) substantial, B) relatively rapid and C) systematic. While the growth of ATES systems in the Netherlands is substantial and rapid, it is not systematic because: 1) many different types of ATES systems are applied, 2) legislation and (spatial) planning are not uniform and 3) combination or exclusion with other subsurface functions is legally ambiguous.

To come to successful development of ATES technology its application needs attention. Because the subsurface needs to be available for the application of ATES, not only now but also over 50, 100 and many more years. The up-scaling of ATES technology is prospective, but to make ATES a success and to keep the subsurface available for future use, this must be done in a more systematic way. The combined issues of scarcity of space and longevity of impact call for the coordination the installation and operation of ATES systems at a scale beyond individual units/buildings.

3.1.4. Scarcity of subsurface space for ATES

Currently more and more buildings (will) rely on ATES to meet energy saving goals set by European energy saving requirements [3], and many more will in the future [60]. This causes pressure on subsurface space in urban areas, where building density is highest. For instance in the city centre of Utrecht, one of the largest cities in the Netherlands has a high concentration of multipurpose buildings in an area of roughly 600 m radius and an aquifer thickness of 20 m. The thermal energy from the subsurface in the issued and requested ATES permits comprises around 60 GWh_{th} for both heating and cooling. The thermal energy storage capacity of 1 m^3 subsurface space is about 3 kWh if the temperature difference between warm and cold ATES wells is 4°C. This results in the use of about 20 million m^3 of subsurface space, while total volume of the aquifer under the centre is 23 million m^3. This implies that the demand may exceed supply soon.

The energy demand of buildings is hard to predict and is also likely to vary during the lifetime of a building. To have enough redundancy for unknown variations in climate and future use of the building owners apply for a larger permit than is necessary in an average year. This results in oversized claims on subsurface space. Monitoring data [61, 62] and the capacity of issued permits [21, 62] show that on average only about 60% of the permit capacity is used.

3.1.5. LONGEVITY OF IMPACT

ATES systems are generally designed to work during the lifetime of the building (30-50 yrs).Thermal energy is left behind in the subsurface when buildings are replaced or get another function. It takes hundreds to thousand years for the temperature of volumes of warm and cold of groundwater left behind to disperse and diffuse due to heat conduction and groundwater flow, as was simulated for a number of characteristic ATES systems in the Netherlands according to Hecht-Mendez et al. [63]. The legacy of abandoned ATES systems remains much longer in the subsurface than the lifetime of a building. The societal and economic process causing the sequence of using and replacing buildings will continue for many years.

Subsequently, to ensure sustainable use of the subsurface, future ATES systems must be able to benefit from the energy stored in the subsurface, or at least not be hampered by it. This is not possible under current governance because it is not monitored or calculated what happens with the stored energy in the subsurface, as will be further elaborated in section 3.2.

3.1.6. PROBLEM STATEMENT

To come to successful development of ATES technology its application needs attention. Because the subsurface needs to be available for the application of ATES, not only now but also in fifty, hundred and many more years. The up-scaling of ATES technology is prospective, but to make ATES a success and to keep the subsurface available for future use, this must be done in a more systematic way.

The combined issues of scarcity of space and longevity of impact call for the coordination the installation and operation of ATES systems at a scale beyond individual units/buildings. In The Netherlands as in many other European and North American countries coordination currently takes place through government issuing permits on a ‘first come, first served’ basis. In addition, the longevity issue is given precedence by using a precautionary principle which leads to division of the subsurface or spatial planning of the subsurface resulting in issuing of permits for an unlimited period based on an uncertain and oversized energy demand.

3.1.7. IN THIS CHAPTER

In section 3.2 it is first described what optimal and sustainable use of the subsurface would look like in relation to ATES systems. With simulations their impact on the subsurface in shown. Section 3.3 describes the current way of dealing with these impacts in The Netherlands and consider self-organization and self-governance to improve the adoption and operation of ATES. Such new forms of governance require different information systems; section 3.4 describes an information system needed to meet these challenges, followed by a discussion and conclusions in section 3.5.

3.2. OPTIMAL AND SUSTAINABLE USE OF THE SUBSURFACE

BECAUSE ATES systems reduce the use of primary energy, they are sustainable energy systems. The way ATES systems use the subsurface and the groundwater therein is not automatically also sustainable. Additionally, because of the a priori subdivisions in permits, optimal use is also not guaranteed under current practice. Optimal and sustainable use of the subsurface for ATES is that as much energy as possible will be stored en recovered at as less expenses as possible, during the entire time in which there is demand for thermal energy storage and recovery in the subsurface.

3.2.1. SUSTAINABLE USE OF THE SUBSURFACE WITH ATES

To sustainably apply ATES groundwater must not be depleted, fortunately ATES systems simultaneously extract and infiltrate groundwater so there is virtually no net extraction. The socio-economic changes in a city impose that location and energy demand of systems will change over time. Additionally it should be known where the groundwater is warm or cold, to allow new systems to use available thermal energy and/or space, or at least to prevent them from being hampered by already stored energy it should be known where the groundwater is warm or cold. Although a lot of operational data is continuously gathered at each ATES systems, none is utilized to calculate or verify temperature distribution inside the aquifer. Summarizing: sustainability is essentially longevity of impact with regards to continued use of the subsurface for the purpose of thermal energy storage, as well as for possible other uses in an unpredictable future. One issue is a potential more or less random distribution of temperature due to abandoned systems, changing use of systems and natural groundwater flow, that would seriously affect continued and future use. Another might be potential impacts on functioning of the subsurface due to chemical changes and salt redistribution in the subsurface.

The stored energy cannot be retrieved completely. This is caused by imbalance in demand and supply, ambient groundwater flow both natural and caused by adjacent systems, heat conduction to adjacent layers, preferential flow paths caused by heterogeneity of the aquifer, and finally, dispersion and diffusion. In a city with numerous ATES systems simultaneously active, one cannot easily determine the distribution of warm and cold zones after many years of operation as is illustrated by our simulations for the city centre of Utrecht. MODFLOW [64] and MT3DMS [65] were used to do the simulations, both are widely used programs for fluid flow and transport processes in porous media [63]. In these simulations the data of existing and planned ATES systems was used

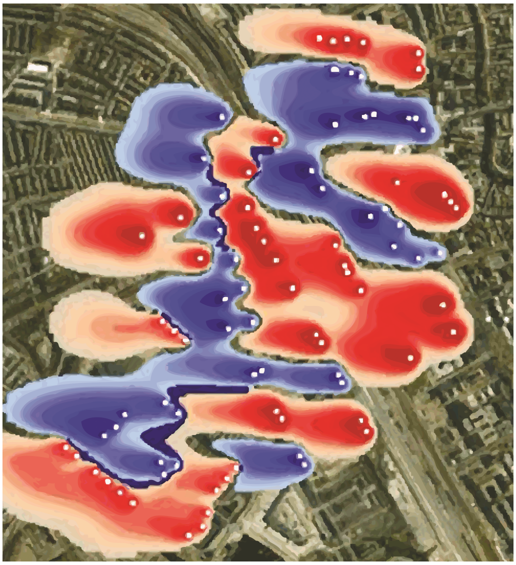


Figure 3.1: illustration of the temperature distribution in the subsurface after 70 years of simulation of the ATES systems in Utrecht

which were incorporated in the groundwater model. The results in Figure 3.1 show that after 75 years, large areas in the subsurface have become either relatively warm or cold while there are no well installed. Also with much mutual thermal interference between warm and cold wells occurs.

To sustainably exploit an ATES system, disproportional large cold or warm zones which can hardly be recovered or restored and will influence other and future systems must be avoided. For that the seasonal energy storage and recovery must more or less balance. Unfortunately, No building has a perfectly balanced heating and cooling demand. The perfect energy balance for individual ATES systems, required in the current permit, goes at the cost of extra energy use. But as long as the heating and cooling demand storage in a certain area is more or less equal this is not likely to become a problem. The perfect energy balance required in the current permit goes at the cost of extra energy use. Knowing the actual temperature distribution around the wells allows to deal with this constraint in such a way that thermal surpluses or shortages can be interchanged in the subsurface which results in saving more energy.saving energy, otherwise required meeting rigid rules for energy balance.

The challenge is to keep track on what actually happens with the stored warm and cold groundwater inside the aquifers. Extensive temperature logging in the subsurface and/or simulation of actual extraction and infiltration data are necessary to get this insight.

3.2.2. Optimal use of the subsurface with ATES

Because of the changing configuration of ATES systems and the varying energy demand it is not possible to define the optimal use of an aquifer in advance, because it is not known what the demand in the future will be. To approach optimal use it is required that use of the aquifer can be adapted to current demand and availability. Maximum Optimal use of the subsurface requires that 100% of the available space is used in such a way that it can meet its full potential with respect to the demand for (ATES or other desired functions[1]). Optimal use of the subsurface for ATES requires that as much energy as possible is stored per m^3 and that 100% of the thermal energy stored in the groundwater also is used again when there is a demand for that thermal energy., sooner or later. Both requirements are not met under current practice.

The prevailing Dutch guidelines [24] for ATES system design require 3 times the so-called thermal radius as distance between individual ATES wells. The thermal radius (R_{th}) is the radius of thermal influence based on the analytical solution for heat transport in porous media. In an aquifer with no ambient flow this distance can theoretically can be reduced to 1,4 times the thermal radius, as can be seen in Figure 3.2 where the variation of thermal radius of a warm and cold well over a year are presented. The minimum distance between the wells should the sum of the two. Because of variations in weather conditions and actual use of the building the amount of groundwater/energy applied for in permits and used to calculate the thermal radius is much larger than eventually needed [21, 61, 62, 66]. This is putting safety upon safety and results in larger predicted thermal radii and thus larger distances between wells, wasting subsurface space as the permitted capacity is never put to use.

There are different kinds of systems which can store and retrieve thermal energy from the subsurface. Doublets, i.e. warm and cold well screens at the same elevation in the aquifer and monowells, i.e. warm and cold well screens placed above each other are only some of the so called open systems applied while they actually pump groundwater. So-called closed[2] systems consist of tubes installed in the subsurface that circulate a fluid, often glycol, to exchange heat with the subsurface. Two doublets next to each other could make a communal warm or cold well, or both. Different type of systems next to each other requires larger well distances to prevent negative mutual influence.

Existing systems do not perform optimally [66]. The average actual temperature difference between warm and cold well is generally 4°K whereas at least 8°K was used in their design and even bigger differences should be possible. Consequently, theoretical savings [24], with that CO_2-emission reduction goals are not met and too much groundwater is used. Thermal energy imbalances are likely to grow under current practice due to increasing cooling demand caused by climate change and changing design and use of buildings [54, 67]. Favorable performance of the ATES systems requires that for each building the energy supplied to, and withdrawn from the subsurface contributes to the overall performance of both the ATES system and the building system. This means that in the entire chain of heating and cooling not only the current energy demand in the

[1] Most other functions in the subsurface are located relatively shallow. The deeper aquifers used for ATES are sometimes only used for drinking water supply, those areas are excluded for ATES.

[2] Closed systems generally have a lot of boreholes, since there was no legal framework for these systems until 7-1-2013 it most of the time not known where these systems are installed.

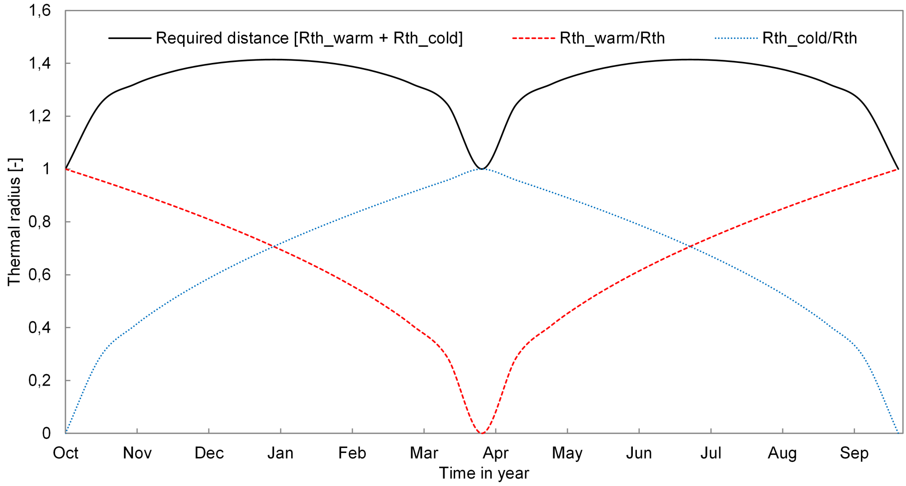


Figure 3.2: Thermal radii and minimum required well distance over a year

building is prevailing in control actions; also the injection temperature of the groundwater must be controlled properly.

To obtain optimal use of the subsurface the performance/efficiency of ATES systems has to improve, wells must be placed closer to each other while within a certain area the same type of systems should be applied (systematic application). The latter can be achieved by agreement between users or by permitting. Smaller distances between wells and systems are possible when there is insight in the actual distribution of heat and cold in the subsurface. Performance of ATES systems will be improved with control strategies based on actual data on both the subsurface and the building system[3].

3.2.3. SYNTHESIS

To facilitate the application of ATES in the near and far future and To make ATES a long-term success, it is necessary that the subsurface is used in an optimal and sustainable way. The requirements are: A) agreement about type of ATES in certain areas, B) insight in actual subsurface temperature distribution C) effective operational control. The required information for proper ATES governance becomes available when the wells are drilled and the systems are operated. A control system which controls the use of the subsurface is proposed to ensure optimal and sustainable use of the ground(water) under cities, dynamic control is proposed, based on the actual dynamic ATES induced temperature distribution in the aquifer. Instead of a priori fixed rules and subsurface subdivisions, dynamic control is proposed, which means that the subsurface use for individual ATES systems changes during operation based on the actual situation in the subsurface.

[3]Because of the moderate temperature differences in the groundwater, each ATES system is connected to a series of machines which make sure the water has the right temperature to actually deliver the desired cooling or heating. This series of machines is referred to as the building system The options for configuration and number of machines are endless but in the end their functioning determines the temperature of the re-injected groundwater; the energy source for next season.

Only then it is possible to optimally fit new systems, to use available space between systems and to prevent mutual influence now and in the far future.

3.3. Analysis

3.3.1. Permits and ATES plans

The permit system introduced to govern ATES systems in the Netherlands has the objective to prevent possible environmental impacts and mutual interference. Permits are given on a “first come first served” basis to any party that applies for one. Permits and are based on requested size, type and their expected environmental impact. Approved permits grant owners the right of use of a prescribed yearly amount of groundwater to store thermal energy. Similar rules differ little from country to country are also in force in Belgium, France, UK, US [68, 69], they all use the precautionary principle and give users permission to use the subsurface based on a priori assumptions/design parameters. In ATES plans regulators foster spatial planning of ATES systems; they design and apply the a priori, static rules to subdivide subsurface space in areas where many ATES systems are (expected to come).

Current practice of requesting oversized permits, restrict the application of new ATES systems, while in practice there is still unused space available; this constitutes a self-created problem of scarcity of space. Obviously, issued (oversized) permits in aquifers are in analogy with Hardin’s statement: “Every new enclosure in the common resource involves infringement of other users’ liberty” [56].

Despite the international similarities in legislation, even in a small country like the Netherlands the rules for applying ATES vary in different parts of the country. Sometimes rules are even completely opposite. Different laws and authorities apply for planning, realization, operation and maintenance. These factors prohibit systematic application of the technology. However, legislation is about to change in the Netherlands [58]; from July 2013 onwards closed systems that hitherto did not require any permit will have to apply for one. Small systems, both open and closed, require a simple permit, they only have to notify the local authority. In areas densely populated with ATES systems, ATES planning is enforced in an attempt to improve incorporating new systems and their long-term efficiency. ATES plans allow adapting of well locations to better fit future users, often cold or warm wells for different buildings and users are combined, sometimes even with direct mutual exchange of energy surpluses. Unfortunately, ATES plans are, like is the case with single-user permits, based on the same varying and uncertain energy demand. So subsurface space is still allocated based on uncertain data and oversized expected influence.

Both, permits and ATES plans are an effort to prevent a tragedy of the commons [56]. Because it is not possible to look into the subsurface, large-enough permits are needed to prevent mutual interaction. Buildings are constructed, changed and replaced, therefore the use of the subsurface will change. It is impossible to predict the future in a permit or ATES plan. Fixing use of the subsurface as is current practice, exclude parties from stepping in later and imposes inefficient and unsustainable use of the subsurface. Arranging everything on beforehand raises barriers for development, as already happens in cities like Utrecht. In many other cities existing oversized permits also frustrate new initiatives.

ATES plans tend to be very difficult to change after it has finally been approved, which hinders unforeseen changes in developments later on.

3.3.2. THE REQUIRED GOVERNANCE FOR ATES

In this section the characteristics and/or conditions, governance should meet, in order to ensure optimal and sustainable use of the subsurface with ATES are identified. Governance concerns the way through which public and private actors coordinate their activities around collective problems [70]. Traditionally, the government is considered to be the prime mover in organizing solutions for collective problems through the development of formal plans and systems of rules. With the application of ATES, government acts as the controlling agent, while private actors (firms companies and citizens) are the subjects within a hierarchical system of command and control.

3

The position of governmental agencies has changed considerably since the mid 1980's. Experience has shown that plan-based rule systems are suboptimal, while entailing considerable costs for maintaining monitoring and sanctioning capabilities. In addition, the government model of governance relies on the ability to make adequate plans to handle collective problems. The increasing complexity of ecological and social systems forces governments to face the limits to what planning can achieve in the societal context. [71]

The term governance signifies that there are alternatives to governments to take charge of collective issues. It acknowledges that in many cases, private actors are able to coordinate through self-organization, for example through the market mechanism. In all, four types of governance can be distinguished [70]. For the purpose of this paper, the following two are relevant in addition to the option of government:

1. Self-governance: actors develop a set of rules and ways to enforce those rules among themselves. This type places higher demands on the connections between actors, both in terms of information exchange (which is about monitoring behavior, communicating changes in rules and administrating sanctions), and the level of mutual trust. Typically, self-governance emerges in social systems where repeated interaction among a bounded set of individuals takes place.

2. Self organization: actors coordinate their activities through decentralized exchange of information. A crucial boundary condition that needs to be fulfilled concerns the way in which information is summarized and made available to all actors involved. In a market, this is achieved through the price mechanism, which summarizes relevant information about quality of products and availability of supply.

In other fields of research around common pool resources (CPR's), self-organization is applied to prevent a tragedy of the commons [25, 56]. They show that in current society, self-organization is the core of successful governance processes. Control over, and steering of processes occurring in the system should be effectuated by all actors and process systems. Translated to ATES systems this means that all systems need to have insight in what is actually happening in the subsurface during operation of ATES systems. This complies with what is required for optimal and sustainable use of the subsurface at the end of section 3.2. Additionally, self organizing or governing ATES systems requires that the ATES systems have control options to use the information of the current subsurface status to optimal use of primary energy and groundwater (i.e. subsurface space). With the insight in the subsurface and with control options during operation, incentives to impose temperance when needed can be constructed to prevent exhaustion which has been prevented with current legislation.

Both self-organization and self-governance describe the option of decentralized co-ordination of actors dealing with a collective issue like the adoption of ATES systems that make use of the same aquifer. The definition highlights the information challenge and social conditions that need to be met in order to make them feasible alternatives to current government-based approaches. From this, two questions emerge:

3

a Is it possible to develop information systems and organizational arrangements that make self-organization/self-governance possible?

b Are the efforts to organize self-governance or self-organization proportional to the expected advantages compared to current governance strategy?

In the next section the first question is answered.

3.4. Self-organization and self-governance for ATES

ATES systems need a complementary adaptive institutional framework; a set of "rules which evolve during the game". As was elaborated in section 2, optimal and sustainable use of the subsurface requires; A) agreement on the type of ATES system, B) insight in the warm and cold groundwater distribution in the subsurface during operation and C) the ability to steer/act on that information in order to improve performance at system level. Only then is it possible to optimally fit new systems, use available space between systems and prevent mutual influence, based on actual use of the subsurface. From the requirements needed, elaborated in section 3.2, insight in actual temperature distribution in the subsurface (B) and the ability to steer/act on that information (C) are the most difficult to obtain so the focus is on those.

3.4.1. Communication

Self-organization and self-governance are concepts used in many different fields of research such as biology, informatics, physics, chemistry public administration and sociology, but an undisputed definition is hard to find. Intuitively, it implies that within a system an organization or structure appears without no explicit control or constraints from outside the system. The organization results from internal mechanism and interactions between the system's components [72]. But what is organization? The work of Ashby [73] is used to get a grip on the concept. According to Ashby the core of organization is conditionality . He shows that conditionality is directly related to communication, what of course is plausible, because you can only organize elements or systems when they directly or indirectly communicate with each other.

Based on the properties of ATES systems in cities and the governance principles elaborated above it is very likely that the operational control of ATES systems can be adapted in such a way that they can communicate and organize themselves. Facilitating direct or (indirect) communication between many different systems would result in the development of a network of ATES systems instead of operating systems operating independently next to each other. One of the most important constraints for communication [74] is to synchronize the (different) physical and decision making systems timescales. With synchronized systems one can impose self-organization or self-governance for which governance can provide boundary conditions [74]. In both cases a network of dependent but (partially) autonomous actors will emerge. The level of autonomy depends on how well the rules of the game can be defined under present conditions.

From the above it is concluded that the basis of self-organization and self governance of ATES systems is knowledge and information exchange, as was also concluded by [73]. "One only knows if the impact of an activity in the common resource is positive or negative when you know the total system in which your act appears" [73]. This resonates with Ostrom [25], who showed that when all users have insight in their impact, processes and status of the CPR, optimal use of a resource system is best organized. The great challenge facing us is how to invent the corrective feedbacks that are needed to induce self-organization or self-governance. This requires that system actors must have the ability to act on the acquired information.

Only with corrective feedbacks the operation of the fast and slow systems will become synchronized, thus enabling system anticipation [74]. Currently anticipation in control is not needed because the distances between ATES systems are large enough to prevent mutual interference. When ATES systems are placed more closely together, anticipation is only done based on the expected influence, based on a priori and uncertain data.

To enable short feedbacks and to better identify and manage the groundwater resources, access to information about the characteristics (flow, temperature, biological and chemical conditions) of the groundwater is needed. Currently, ATES systems are individual systems that do not communicate with each other, while physically influencing each other in many ways. Connecting a set of ATES systems into a communicating network would allow extensive information exchange most of which comprise operational data that is already measured and available at the level of individual operational systems. In the heart of this communication network a management or control system can be used to employ control on the ATES systems connected to the network.

3.4.2. CORRECTIVE FEEDBACKS

Although it does not enable optimal and sustainable use of the subsurface, the a priori permit system is an effective way to prevent a tragedy of the commons. It makes use of existing institutional framework (legal rules, administrative bodies responsible for monitoring and sanctioning) and requires no additional technology. Its main drawback, as was argued above, is that it focuses on the longevity of impact dimension and helps to create, rather than relieves, scarcity. Leaving the permit system, as was recently propagated by Hähnlein et al. [75] for a flexible dynamic and operational system of self-governance or self-organization might seem to bring us to risking a tragedy of the commons. With self-governance and self-organization it is important to introduce incentives for temperance use in times of scarcity. A major question is what set of rules is required for adequate self-organization and self-governance. The properties of rules enabling optimal adaptive control are discussed in the following and summarized in Figure Table 3.1.

3

Table 3.1: Properties of different types of governance

	Permits and ATES plans	Self-governance	Self-organization
Information base	Uncertainty	Building up of use data and its impact	Evolving model based on connected ATES systems
Principles	Ask as much as you can get, Precautionary principle	Collective responsibility for CPR	Optimizing performance at the collective level
Role of owners	Build and use according to own needs	Defining rules and monitoring them	Absent: consume services from ATES (in combination with other heat/cold sources)
Who makes rules	Government	Users	Market
Incentive for temperance	None, Only within issued permit	Social control, live up to own rules	Cost; markte value of heat/cold
Technology / system	None	Central model, fed with data from previous period, make new arrangements after certain period (for example: yearly)	Central model, fed with realtime data, give current state of aquifer back to users, simple geohydrologic model in every building control system. Capitalize value of thermal energy in subsurface.
Information required	Approximation of energy use	Periodic overview of of used subsurface space	Real time water and temperature flows in and out of the subsurface, from every system
Longevity of impact, Sustainable use?	Moderate	Good	Good
Scarcety of space, Optimal use?	No	Good	Close to optimal
Realistic/feasible form?	Yes	Complex arrangements, but possible within current state of technology	Development of new technology needed

With self-governance the users of ATES systems in the same aquifer jointly decide on rules and agree upon a strategy how to deal with monitoring and sanctioning, as well as compensation, both during business as usual and during scarcity. Rules about periodic feedback, evaluation and re-agreement of the use and control strategy allow for adaptability of this regime. In a periodical evaluation the users themselves control the use of the subsurface and make arrangement for compensation. When competition in the subsurface arises, the compensation mechanism and arrangements must ensure that the tragedy of the commons will not occur because using a disproportional quantity of subsurface energy will make one break rules you he made and agreed upon himself.

For self-organizing ATES systems, an autonomous network of participating autonomous ATES systems is required. Central in this network is control or management layer. Based on the actual use of the subsurface. The control strategy can be based on the value of thermal energy in place and can be recalculated periodically based on current energy prices. During a hot day in fall the groundwater in the cold wells will be more valuable than in the beginning of summer because there is less available. This mechanism imposes temperance in the use of the subsurface space without strict permit boundaries. For this up-to-date information about and interpretation of status in the aquifer is required. Use and compensation takes place through a market mechanism. Like with self-government, periodic evaluation is necessary to see if the prices set indeed lead to optimal use of the subsurface. Individual building control systems must be able to adapt and react to the price mechanisms that are in place for the entire area. In addition to striving for maximization of individual economic goals, there must be provable guarantees that the constraints of the system operation (e.g., heat pumps, stored energy) and other long-term objectives (such as sustainability of the underground aquifers) are maintained. The desired high level of performance can only be achieved with a model-based control method that is on one hand easy to maintain and updated, and on the other hand delivers capabilities that are difficult and expensive to realize with classical control approaches (like monitoring, as was discussed earlier). Thus the particular requirements for efficient and economically sound operation, the enforcement of critical operation constraints for long-term sustainability and the adaptability/flexibility required to operate in a price-driven distributed environment demand the development of a novel control methodology.

In 2009 Ostrom [76] presented 10 variables which were found to be key parameters in the feasibility of self-organization or self-governance in a managing a social-ecological systems. Except one (knowledge of resource) all of these variables are positive for applying self-organization or self-governance for ATES systems. 1) The size is not too big and not too small; 2) System dynamics are predictable; 3) Production from resource is high; 4) The number of users is manageable; 5) Users have the same ethical norms/standards; 6)There will be one or more trustworthy leading parties in an area; 7) The resource sustainability is of high importance for all parties in the area; 8) The resource reacts slowly to incentives and disturbances, and finally; 9) The productivity of the system reduces when no organization is applied.

In addition to Ostrom [76], Boons and Gerrits [77] argue that systems that have the ability to self-configuration, self-optimization and self-healing are self-organizing and/or self-governing systems. The configuration of ATES systems is already self-organizing/self-governing. In 2010 Caljé [43] used a modeling approach to show that with simple constrains and information about the location of the existing wells of all ATES systems, randomly appearing ATES systems in Amsterdam configure themselves in an optimal way, such that warm and cold well are clustered. For each different randomly generated scenario of ATES system an optimal configuration was created, one example is given in (figure 3.3). What is needed as well; is that during operation the use of the subsurface, the individual performance of systems is optimized in an autonomous way (self-optimization) and systems after an extra-ordinary hot summer are able to restore the desired amount of thermal energy in the subsurface (self-healing). With that, a pattern of interactions in which operation changes will emerge because of external influences, mutual changes and consequent optimization pressures. For self-healing and self-optimization, like was found with Ostroms [76] argument, information about the status of the resource is needed.

In self-governance, self-healing and self-optimization happens periodically with evaluation and rearrangement of control strategies. For self-organization this requires development of new technology. In the following is elaborated how this can be done.

The challenge is how to dissect and harness complexity [76], instead of eliminating them from the system, like is done with permits. This can be done by making sure that users have insight in about the temperature distribution (next section) and they can autonomously alter their control strategy to that (subsequent section).

3.4.3. KEEPING TRACK OF HEAT IN THE SUBSURFACE

The actual thermal distribution in the subsurface can only be obtained during operation of the systems. This can be done by monitoring and/or by modeling. Monitoring would require a dense and expensive monitoring network. The large number of boreholes of the wells in a network provides the required knowledge of the properties of the subsurface. These are unique circumstances to feed a groundwater model, verify its performance with monitoring data and get information about actual distribution of warm and cold groundwater. So modeling is the most promising option to pursue.

An approach which intelligently uses available information in an "online and on time" framework or a periodic simulation is a promising step in maturation of the ATES

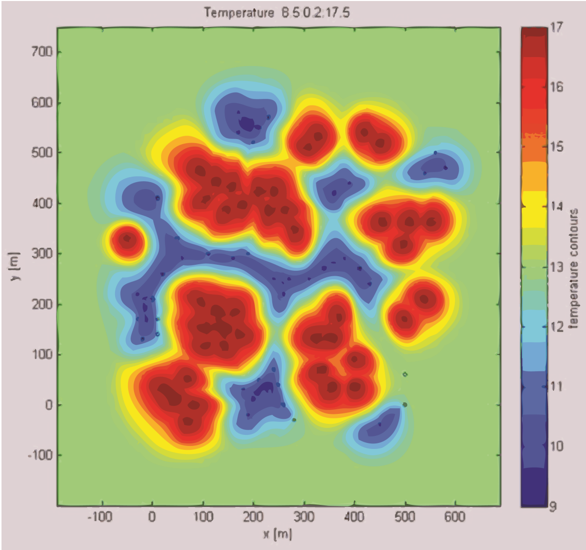


Figure 3.3: Self-configuring ATES systems [43]

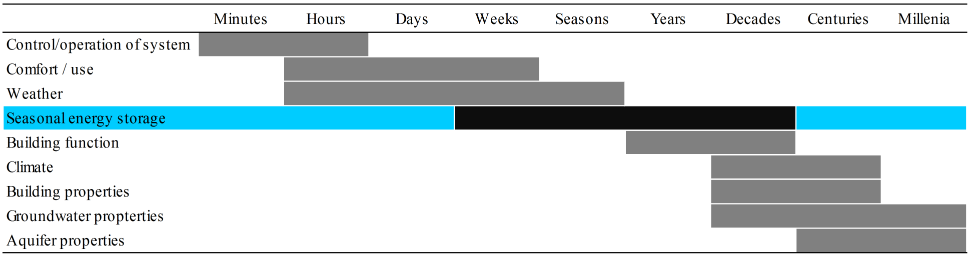
technique. It is most probably the only way to handle continuous advective and conductive thermal energy flow propelled by the numerous interacting individual ATES systems. They respond in accordance with local subsurface conditions, individual demand as well as fluctuating weather and climate. A regional groundwater flow and transport model can track all stored thermal energy and function as a base model for distributed model predictive control. However, most data required to calibrate it to the required level of precision, will only become available with the installation and during operation of the ATES systems. Therefore self-learning and self-expanding regional groundwater models are required. In their automatic calibration procedures, these models continuously and systematically incorporate additional static geo-information together with the continuous stream of dynamic groundwater flow and temperature data.

3.4.4. OPTIMIZE CONTROL WITH AGENT BASED MODELING

Ostroms' results indicate that next to the regional groundwater model, the individual ATES systems require their own local model to locally optimize their performance using their measured operational data and the feedback that incorporates the dynamic behavior of neighbors. These local models must be utilized with optimal control strategies for the benefit of both local users and the system over well-defined scales of time. Since ATES systems have modularity (the delivery of heat and cold is done with different components) there are opportunities for the system to adapt operation as a reaction on feedback about the system status.

Combining the concept of multi agent systems in the way it is already used in building climate control [78] and with aquifer management strategies [74, 79], it can be used not only to optimize energy flow and storage above, but also below ground surface. Af-

Table 3.2: Time scales of ATES systems processes



ter combination, these control systems can be embedded in an agent based model of dynamic, regional ATES development that will challenge the performance of ATES systems. This is challenging because with the extra information the systems need to decide for an overall control strategy making sure that; current desired heating or cooling is provided, primary energy use is minimized, optimal control of thermal energy in wells (long term functioning of wells) and current and future cost for thermal energy is minimized.

The model needs to operate on wide ranging time scales. The entire process of climate control in buildings is focused on short-term control. Optimally exploiting an ATES system requires that the short term control strategy sufficiently takes into account the impact on the long term for the slower reacting components. Table 3.2 shows the time scales in which the governing processes in climate control with ATES systems vary. As you can see the scales vary from minutes to decades and even millennia, this is often an important issue in resource management [76] (but not one of the 10 main variables that determine the feasibility of self-organization or self-governance). The Table also clearly shows that it is because of the ATES system that these “fast” and “slow” processes are suddenly connected, while with conventional climate techniques one only had to deal with the fast components and an “inexhaustible” source of energy (electricity and gas). In systems with such big differences in time scales it is of crucial importance to have the right feedbacks for optimization and control in the long term.

The agent based model control layer will include investment and operational decision making of individual ATES systems owners/operators, interacting with each other both through the status of the aquifer, the institutional framework and regional market conditions for thermal and electrical energy.

3.4.5. CHALLENGING APPROACH

The proposed approach is scientifically challenging for three main reasons: Firstly, it deliberately examines the potential of self-organization or self-governance of a complex socio-technical system with many characteristics of a ‘common pool’ resource, as a possible ‘third way’ besides ‘the market’ or ‘hierarchy’, as traditional solutions for coordination of such infrastructural systems. This requires a multidisciplinary analysis of relevant variables and their relationships, both at the level of the actors, as well as on that of the system. Secondly, it employs Ostroms institutional analysis and development (IAD) framework on a system that cannot be fully characterized as a natural resource, but that

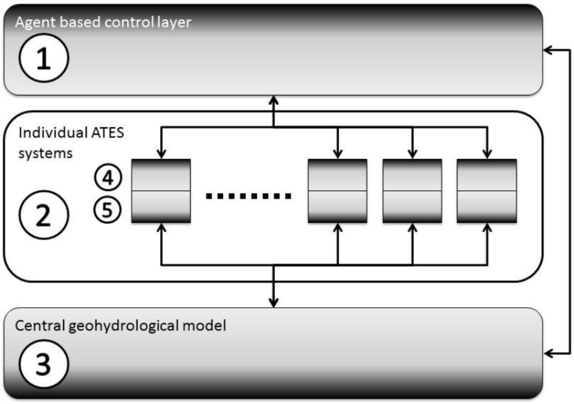


Figure 3.4: Schematic framework of self-organizational for ATES systems

involves important attributes of such a system in combination with elements of a humanly constructed infrastructure. Currently, this is one of the main challenges to this framework for understanding and designing appropriate institutions for the governance of complex systems [80]. Thirdly, it attempts to investigate the impact of technology development in direct interactive association with the design of a set of rules of organization and/or governance; coherent with the requirements of the wider 'environment', the characteristics of the several actors involved and the attributes of the physical/technical system.

Physically, the proposed approach should be combined in a three layered control structure as is depicted in Figure 3.4. Central are the individual energy users with an ATES system (2) with their own control system (4) like are already build today. Together with a simple geohydrological model (5) these systems must be able to operate individually. Currently individual control systems already have geohydrological intelligence (priva, liftmonitoring) so this is already possible and is only necessary to improve. The individual control systems are fed by an agent based control layer (1), the local groundwater models (5) are fed by a central groundwater model (3).

To feed the central groundwater model (3), the ATES systems automatically send temperature data, pumping data, head data etc. to a central server on which the groundwater model runs. With the actual data as input, the model calculates the use of the subsurface by simulating the combined operations of the individual ATES systems, the results of which is downloaded by the individual ATES systems and the agent based control layer. The agent based control layer can also send different scenarios for future use to the central groundwater model, to reduce uncertainty and to enable model predictive control. Running a geohydrological model at the scale of a city with many ATES systems is common practice in the Netherlands, for instance like was done by the authors or Caljé [43] in previous sections. The challenge is to get the model automatically improving/calibrating, running and stopping.

In the agent based control layer (1) each ATES system has an agent (the real estate owner or building operator) which responds the actions the ATES systems would take under certain circumstances. Together with model predictive control the agent based control layer should create time varying constraints for te individual ATES systems based on actual subsurface status and expected use. Agent based control systems been successfully implemented in combination with ATES systems [78, 79]. These agent based models have yet not been integrated with a distributed model predictive control system, so that is one of the main challenges following from this approach.

From the analysis above it has become clear that it is possible to develop information systems and organizational arrangements that make self-organization/self-governance possible based on the combination and connection of existing technology and ongoing development in the climate control of buildings it is possible to develop information systems and organizational arrangements that make self-organization/self-governance possible.

3.4.6. EXPECTED ADVANTAGES OF SELF-ORGANIZATION OR SELF-GOVERNANCE

Further research must quantify the benefits of the proposed approach. But based on the inefficient use of the subsurface in current practice the potential advantage will might be around more than double the amount of thermal energy storage in the subsurface, only based on the gained possibility to use the space which is not used under current practice as was explained about reducing well distance from 3 times the thermal radius to less, in section 3.2.

Advantages caused by improved performance are yet also hard to quantify. but Because of better control ATES systems will have better efficiency. Looking beyond the lifetime of a building or ATES system and in the long run new and replacing buildings/systems will have a jump start because well design and allocation is optimized in accordance to actual subsurface temperatures.

The organizational advantages are numerous; short and simple permit procedures, no rigid rules, everything is arranged in a market model or self made rules, and still leaving each system with its own operational strategy. In the central model the governing authority has direct insight in avoided primary energy consumption.

3.5. CONCLUSIONS

3.5.1. GOVERNANCE FOR ATES SYSTEMS

IN urban areas the subsurface is used to create a comfortable living and working climate. For the heating and cooling in our homes and offices we rely on the subsurface, everything we do has direct or indirect impact on the subsurface and this impact will only grow. The subsurface is part of a physical system that is part of a collective resource. Because of the high intensity use, the subsurface has become a complex system in which simple cause-effect relations no longer apply. Many of the processes in this system have different spatial and time scales. This makes it difficult to agree on control, optimal use of space and sustainable application. Actors involved have different problem perceptions, different and similar interests, system boundaries and opportunities for solutions. Also decision making systems, socio economical developments and politics have another time frame than the physical processes and the patterns of usage.

It is recognized that it is a challenge for governments to prevent a tragedy of the commons, while encouraging the application of ATES technology. But, with the current effort, the subsurface is not put to its maximum beneficial use and is only available to a limited amount of users. The optimal use of the subsurface is not ensured under current practice. With rising energy prices and the increasing need to provide sustainable heating and cooling, this is a missed opportunity. And more importantly, the sustainable use of the subsurface is not guaranteed. Governance of changing processes should therefore also be flexible and dynamic, meaning that rules which should evolve during the game. These flexible dynamic rules are necessary to govern the direct and indirect interaction between the systems involved. The rules of the game must incorporate licensing, planning, system development, operation and the financial-economic aspects on the one hand, and the emerging ATES system(s), with their particular physical and technical attributes and performance on the other.

3.5.2. CONCLUSIONS AND FURTHER RESEARCH

The subsurface is a common resource pool of great value, which should be used and exploited only with care.We showed that the current governance of the subsurface is sub-optimal and endangers sustainable use. Only fully taking into account the subsurface in a dynamic and operational control of ATES systems with self-organization or self-governance will guarantee this buffer function to subsist. Governance should be facilitated with self-organizing or self-governing ATES systems. In this paper the required conditions and facilities to enable self-organizing or self-governing ATES systems are given. Based on literature and experience in comparable fields it is concluded that interpretation of interaction, feedback and adaptable and dynamic control are the key elements to come to optimal and sustainable use of the subsurface. In modern times this should result in autonomous control. This research showed that the subsurface can and should be used more optimally and sustainably with self-organizing or self-governing ATES systems. Also a perspective was presented on how this technically can be realized. The scientific challenges resulting from the analysis in this paper are both challenging and numerous:

1. The required dynamic physical and mathematical properties, behavior, scale and self-learning strategies of the area-wide and local “on-chip” groundwater models and their cooperation and interaction.

2. The required information to be collected from new-system installations and operational data to make optimal local and area-wide performance possible. Systematic and automatic incorporation of this information in the underlying geo-base and area-wide and local updating of the model/ATES-controller parameters and state.

3. The determination of an appropriate time and spatially distributed control architecture that achieves a desired level of trade-off between sub-optimality and modular, robust operation.

4. The handling of the feedback received through the ATES systemcontrol layer by to the individual building, without compromising their comfort standards. The

uncertainties in energy demand, due to weather conditions and losses of stored energy in the aquifer, make this control task even more daunting.

5. The multidisciplinary analysis of relevant variables and their relationships, at the level of the individual system as well as that of the area, in order to find the potential for self-organization of a complex socio-technical system with the characteristics of a CPR.

6. Understanding and designing appropriate institutions for the governance of complex systems, as is one of the main challenges of Ostroms' framework of institutional analysis and development [80].

7. The investigation of the impact of technology development in direct interactive association with the design of rules for governance which are coherent with the requirements of the wider environment.

8. The integration of deterministic models based on differential equations (aquifer and control systems) with agent-based models for investment and operational decision making.

9. The incorporation of widely varying time scales ranging from minutes to decades.

10. The combination of a number of transition frameworks such as multi-level perspective, strategic niche management and technological innovation systems.

11. The translation of an integrated framework into design, monitoring and evaluation of pilot projects.

4

THE IMPACT OF STORAGE CONDITIONS ON RECOVERY EFFICIENCY OF ATES WELLS

Design is not just what it looks like and feels like. Design is how it works

Steve Jobs

The thermal recovery efficiency is one of the main parameters that determines the energy savings of such systems. In this chapter it is shown how efficiency can be optimized by controlling the losses that occur across the boundaries of the stored volume by conduction and dispersion and due to the displacement of stored volumes by ambient groundwater flow. Such a general framework for subsurface heat losses was lacking in literature and increasingly important when increasing the number of ATES wells per unit of aquifer space. New methods were developed and relations identified to optimize recovery efficiency of ATES wells under varying conditions. It was found that thermal energy losses by dispersion can be neglected for practical ATES operating conditions. With the conduction losses dominant, thermal recovery efficiency correlates linearly with the area over volume ratio (A/V) *of the heat stored in the subsurface. An analytical expression for the impact of ambient groundwater flow on recovery efficiency was derived and methods for limiting displacement losses due to ambient groundwater flow were identified. It was also found that a salinity gradient as often present in coastal aquifers has negligible effects on ATES well efficiency under practical working conditions.*

Section 4.1 to 4.5 is published in Geothermics journal **71C**, 306-319 (2018) [81]. The introduction has been modified to prevent repetition and to fit within the storyline of this thesis.

4.1. Introduction

For an optimal energy performance of an ATES system, the thermal energy recovery efficiency needs to be as high as possible. Under these conditions, the electricity required for groundwater pumping and heat pump (Figure 1.2) is minimized.

Previous studies have shown that the thermal recovery efficiency of ATES systems are negatively affected by thermal energy losses from the stored volume by conduction, diffusion and dispersion [50, 82]. While for high temperature (>45°C) ATES systems, the negative impact of the buoyancy of the stored hot water on thermal recovery efficiency typically needs to be considered [83, 84], this can be neglected for low temperature ATES systems [41, 82]. However, as these low temperature ATES systems are typically targeting relatively shallow aquifers, the impact of stored volume displacement by ambient groundwater flow requires consideration. Although the impact of ambient groundwater flow on injected and recovered water volumes has been studied [85, 86], the impact of ambient groundwater flow on thermal recovery efficiency in ATES systems, has thus far not been explored.

4

Moreover, it is unclear how the combined impact of these processes (dispersion, conduction and advection) affects the thermal recovery efficiency of ATES systems under practical conditions and how the efficiency can be optimized. Therefore, the aim of this study was to use analytical methods to elucidate the impact of ambient groundwater flow and conduction and dispersion on the thermal recovery efficiency of ATES systems and to use numerical methods to assess how the combined heat loss by multiple processes can be minimized. As a practical framework for the conditions investigated, the wide range of ATES system characteristics and geohydrological conditions in the Netherlands was used. The resulting insights are meant to provide a useful basis to enable the optimization of the thermal recovery efficiency of ATES systems and to further their optimal development for sustainable heating and cooling of buildings world-wide.

4.2. Materials and methods

4.2.1. Theory of losses and storage of heat in the subsurface

Definition of thermal recovery efficiency for ATES systems

The thermal energy stored in an ATES system can have a positive and negative temperature difference between the infiltrated water and the surrounding ambient groundwater, for either heating or cooling purposes (Figure 1.2). In this study the thermal energy stored is referred to as heat or thermal energy; however, all the results discussed equally apply to storage of cold water used for cooling. As in other ATES studies [44, 82], the recovery efficiency (η_{th}) of an ATES well is defined as the amount of injected thermal energy that is recovered after the injected volume has been extracted. For this ratio between extracted and infiltrated thermal energy (E_{out}/E_{in}), the total infiltrated and extracted thermal energy is calculated as the cumulated product of the infiltrated and extracted volume with the difference of infiltration and extraction temperatures ($\Delta T = T_{in} - T_{out}$) for a given time horizon (which is usually one or multiple storage cycles), as described by:

$$\eta_{th}(t_0 \to t) = \frac{E_{out}}{E_{in}} = \frac{\int_{t_0}^{t} \Delta T_{out} Q_{out} dt}{\int_{t_0}^{t} \Delta T_{in} Q_{in} dt} = \frac{\Delta T_{out} V_{out}}{\Delta T_{in} V_{in}} \tag{4.1}$$

with, Q being the well discharge during time step t and $\Delta\bar{T}$ the weighted average temperature difference between extraction and injection. Injected thermal energy that is lost beyond the volume to be extracted, is considered lost as it will not be recovered. To allow unambiguous comparison of the results the simulations in this study are carried out with constant yearly storage and extraction volumes ($V_{in} = V_{out}$).

LOSS OF HEAT DUE TO DISPLACEMENT BY AMBIENT GROUNDWATER

Significant ambient groundwater flow is known to occur at ATES sites [87–89], which leads to displacement of the injected volumes [85, 90]. This may lead to significant reduction in the thermal energy recovery efficiency of ATES systems as ambient groundwater flow (u) contributes to thermal losses by displacing the injected water during storage. The heat transport velocity (u_*) is retarded with respect to ambient groundwater flow due to heat storage in the aquifer solids [63, 82]. The thermal retardation (R) depends on porosity (n) and the ratio between volumetric heat capacities of water (c_w) and aquifer (c_{aq}, with $c_{aq} = nc_w + (1-n)c_s$ and c_s the solids volumetric heat capacity), following:

$$u_* = \frac{1}{R} u = \frac{nc_w}{c_{aq}} u \approx 0.5u \tag{4.2}$$

Resulting in a heat transport velocity at approximately 50% of the groundwater flow velocity (u). Under conditions of ambient groundwater flow, thermal energy stored in an aquifer will thus be displaced and can only be partly [85] recovered.

LOSS OF HEAT BY DISPERSION AND CONDUCTION

Mechanical dispersion and heat conduction spread the heat over the boundary of the cold and warm water bodies around the ATES wells. As a consequence of the seasonal operation schedule, diffusion losses are negligible [91, 92]. Both other processes are described by the effective thermal dispersion (D_{eff}) which illustrates the relative contribution of both processes to the losses, following:

$$D_{eff} = \frac{\kappa_{Taq}}{n\rho c_w} + \alpha \frac{q}{n} \approx 0.1 + \alpha \frac{q}{n} \tag{4.3}$$

where, the first term represents the conduction, which depends on the volumetric heat capacity (c_w) of water and the thermal conductivity (κ_{Taq}) and porosity (n) of the aquifer material which are considered to remain constant at about 0.15 [m^2/d] in a sandy aquifer with porosity of 0.3. The rate at which conduction occurs can be determined by the increasing standard deviation: $\sigma = \sqrt{2D_T t}$, with D_T, the effective thermal dispersion (the left hand term of Equation (4.3) and t the storage time. For half a year storage period the rate at which heat moves through conduction is about 7 m.

The second term of Equation (4.3) represents the mechanical dispersion, which depends on the dispersivity (α) of the subsurface, porosity and the flow velocity of the water (v), which is the sum of the force convection due to the infiltration and extraction of the well, as well as the ambient groundwater flow (u). For ATES wells that fully penetrate an aquifer confined by aquitards, the dispersion to cap and bottom of the thermal cylinder (Figure 4.1) is negligible due to the lack of flow [43, 82]. With regularly applied values of 0.5 to 5 for the dispersivity [93], the dispersion is in the same order of magnitude as the conduction at flow velocities of 0.01 to 0.1 m/d.

Since losses due to mechanical dispersion and conduction occur at the boundary of the stored body of thermal energy, the thermal recovery efficiency therefore depends on the geometric shape of the thermal volume in the aquifer [82]. Following Doughty, the infiltrated volume is simplified as a cylinder with a hydraulic radius (R_h) defined as:

$$R_h = \sqrt{\frac{V_{in}}{n\pi L}} \tag{4.4}$$

and for which the thermal radius (R_{th}) is defined as:

$$R_{th} = \sqrt{\frac{c_w V_{in}}{c_{aq}\pi L}} = \sqrt{\frac{n c_w}{c_{aq}}} R_h = \sqrt{\frac{1}{R}} R_h \approx 0.66 R_h \tag{4.5}$$

The size of the thermal cylinder thus depends on the storage volume (V), screen length (L, for a fully screened aquifer), porosity (n) and water and aquifer heat capacity (Figure 4.1). This equation is approximate because heterogeneities and partially penetration of the screens are ignored. Doughty et al. [82] introduced a dimensionless ratio of screen length and the thermal radius (L/R_{th}) as a parameter to describe thermal recovery efficiency of ATES systems for a particular stored thermal volume. They found that the ATES recovery efficiency has a flat optimum between a value of 1 and 4 for this ratio.

Losses due to interaction between ATES systems are not taken into account in this chapter. Also interaction between the warm and cold well of the same system is not taken into account as this is prevented by the permitting requirement to ensure sufficient separation distance (three times the thermal radius).

4.2.2. NUMERICAL MODELING OF ATES

As losses due to conduction, dispersion and displacement occur simultaneously, MODFLOW [64] simulations is used to evaluate their combined effect on recovery efficiency.

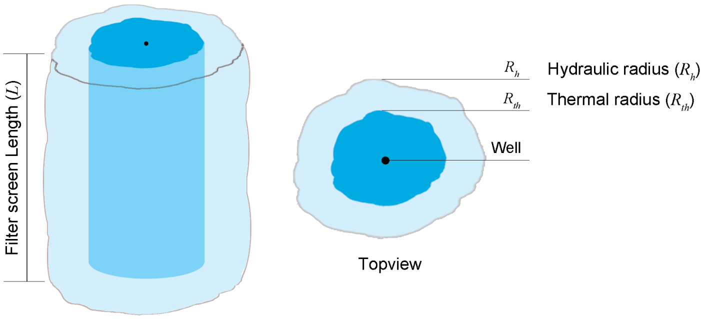


Figure 4.1: Simplified presentation of the resulting subsurface thermal and hydrological storage cylinder for an ATES system for homogeneous aquifer conditions.

For the simulation of ambient groundwater flow and heat transport under various ATES conditions, a geohydrological MODFLOW model [64] coupled to the transport code MT3DMS [63, 65]. These model codes use finite differences methods to solve the groundwater and (heat) transport equations. This allows for simulation of infiltration and extraction of groundwater in and from groundwater wells and groundwater temperature distribution, as was done in previous ATES studies e.g. [13, 43, 94, 95]. In the different modeling scenarios the storage volume is varied between 12,000 and 300,000 m^3 with flow rates proportionally ranging from 8 to 200 m^3/hour, screen lengths between 10-105 m and ambient groundwater flow velocities between 0 and 50 m/y following the characteristics from Dutch practice as will be introduced in the next section. Density differences are neglected as this is considered a valid assumption [43] for the considered ATES systems that operate within a limited temperature range (<25°C). The parameter values of the model are given in Table 4.1, the following discretization was used:

- Model layers; the storage aquifer is confined by two 10 m thick clay layers. The storage aquifer is divided in 3 layers, a 5 m thick upper and lower layer, the middle layers' thickness is changed according to the required screen length of the modeled scenario.
- The spatial discretization used in horizontal direction is 5 x 5 m at well location, gradually increasing to 100 x 100 m at the borders of the model. A sufficiently large model domain size of 6x6 km was used to prevent boundary conditions affecting (<1%) simulation results. The gradually increasing cell size with distance from the wells results the cell size of 15 m at 200 m of the well. This discretization is well within the minimum level of detail to model the temperature field around ATES wells as was identified by Sommer [96].
- A temporal discretization of one week is used, which is sufficiently small to take account for the seasonal operation pattern and resulting in a courant number smaller than 0.5 within the area around the wells where the process we care about occur. The simulation has a horizon of 10 years, sufficiently long to achieve stabilized yearly recovery efficiencies.

Table 4.1: MODFLOW simulation parameter values [43, 63]

Parameter	Value
Horizontal conductivity aquifers	25 m/d
Horizontal conductivity aquitards	0.05 m/d
Anisotropy	5
Longitudinal dispersion	1 m
Transversal dispersion	0,1 m
Bulk density	1890 kg/m^3
Bulk thermal diffusivity	0.160 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	$2 \cdot 10^{-4}$ m^3/kg

The PCG2 package is used for solving the groundwater flow, and the MOC for the advection package simulating the heat with a courant number of 1. To set the desired ambient groundwater flow velocity for the different scenarios simulated, the constant hydraulic head boundaries were used to set the required hydraulic gradient. In the aquifer an ATES doublet is placed with a well distance of five times the maximum thermal radius of the wells to avoid mutual interaction between the warm and cold storage volumes. In scenarios with groundwater flow, the ATES wells are oriented perpendicular to the flow direction.

The energy demand profile of ATES systems varies due to variations in weather conditions and building use which is of importance for the actual value of the thermal efficiency. For 12 varying scenarios the efficiencies are determined for both a weather dependent and the regular energy demand profile, showing that the efficiencies of the corresponding conditions differ. However, they show the same relation according to the changes in conditions; the Pearson correlation coefficient of the two simulation result collections is 0.97. Based on this evaluation all simulations are done with one basic energy demand profile, to allow for comparison with the analytical solutions also the constant storage volume energy demand pattern will be used; heat injection, storage, extraction and again storage during 13 weeks each as is commonly done in other ATES research (e.g.[41, 96]).

4.2.3. CHARACTERISTICS AND CONDITIONS OF ATES SYSTEMS IN THE DATA

CHARACTERISTICS OF ATES SYSTEMS

Data on the location, permitted yearly storage volume, pump capacity and screen length of 331 ATES systems in The Netherlands (15 % of total number of systems) were obtained from provincial databases that keep combined records for ATES characteristics of interest for this research (Provinces of Gelderland, Noord-Brabant, Noord-Holland, Utrecht and Drenthe, Figure 4.2).

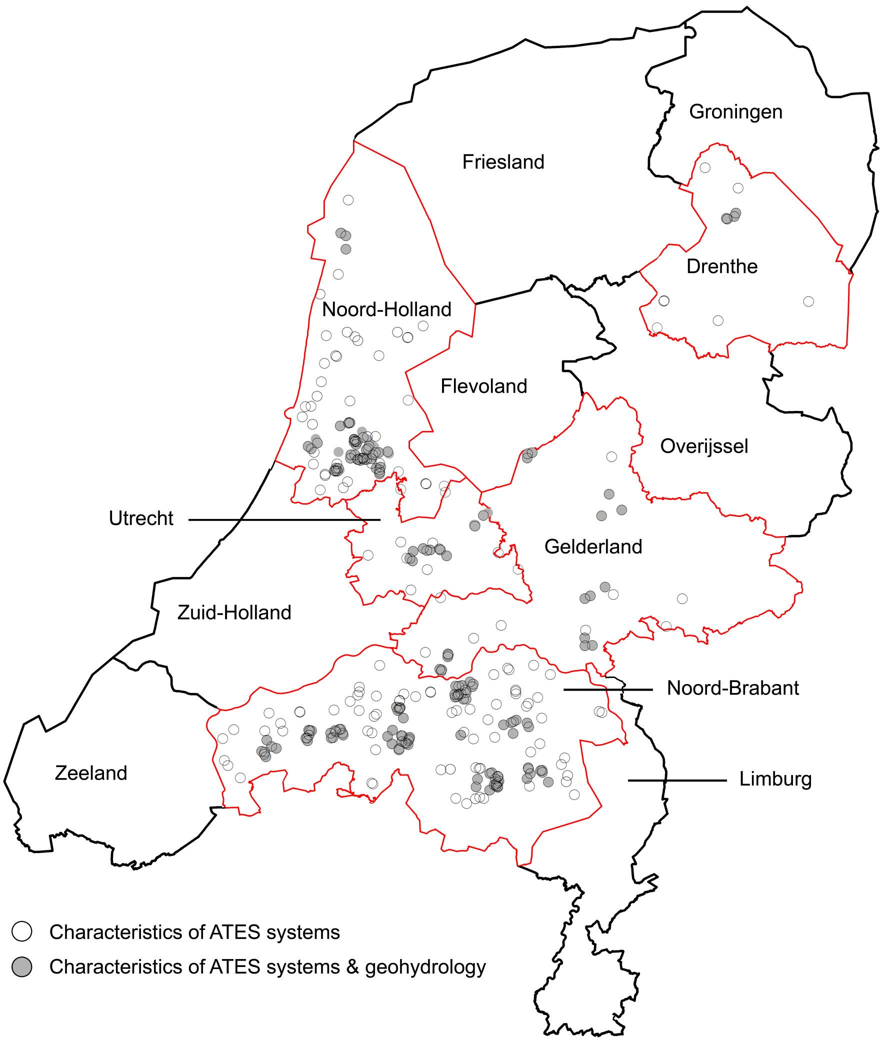


Figure 4.2: Locations of selected ATES systems from 5 provincial databases. Open circles indicate locations for which ATES characteristics were available. Filled circles indicate locations for which also the local geohydrological conditions were available.

Table 4.2: ATES system characteristics in provincial datasets selected for this study

	Number of ATES systems	Permitted capacity (V) $[m^3/y]$			Installed screen length (L) $[m]$		
		0.25 perc.	Average	0.75 perc.	0.25 perc.	Average	0.75 perc.
Initial data	434	90,000	539,000	674,000	20	37	45
selected data	331	80,000	244,000	320,000	20	32	40

GEOHYDROLOGICAL CONDITIONS AT ATES SYSTEMS

For a geographically representative subset of 204 ATES systems (Figure 4.2) it was possible to extract available aquifer thickness and derive estimates on the ambient groundwater flow, as this additional data are not available in the provincial databases. These estimates are based on hydraulic conductivity and head gradients derived from the Dutch geologic databases [97] for the coordinates of these ATES systems. The groundwater head gradient is read from equipotential maps [97] while the hydraulic conductivity and aquifer thickness is obtained from local soil profiles in the REGIS II [97, 98] subsurface model of the Netherlands and literature values for hydraulic conductivity [92, 99] corresponding to the soil profiles from the bore logs. The data are abstracted and processed for the aquifer regionally targeted for ATES systems, therefore, ATES systems with wells installed in other aquifers are excluded from the local analysis. Legal boundaries are also taken into account, in Noord-Brabant for instance it is not allowed to install ATES systems deeper than 80 m below surface level, so any aquifer available below 80 m is disregarded for the systems in this province. For all locations a porosity value of 30 % is assumed, a value common for Dutch sandy aquifers [24, 27, 100].

4.3. RESULTS

4.3.1. ATES SYSTEMS PROPERTIES IN THE NETHERLANDS

PERMITTED CAPACITY AND FILTER SCREEN LENGTH

The permitted capacity of the ATES systems ranges up to 5.000.000 m^3/year but most (70%) are smaller than 500.000 m^3/year (Figure 4.3, Table 4.2). The observed differences in ATES system characteristics for the different provinces were limited and therefore not presented separately.

To be able to evaluate the resulting geometry of the storage volume in evaluating dispersion and conduction losses it is assumed that the thermal energy is stored in a single cylindrical volume. Most ATES systems in the Netherlands are single doublet systems or multiple doublet systems with clustered warm and cold wells. However, particularly for some larger systems, warm and cold wells are not clustered, due to for example spatial planning or geohydrological and/or geotechnical reasons [27]. Unfortunately the provincial data did not include the number or type of well pairs. Therefore the data was filtered for the systems for which a multiple number of well pairs or other deviating aspects could be confirmed. Those systems mostly belong to the largest 10 % of the systems, or belong to outliers in the data distribution of screen length over stored volume, and were therefore excluded. For the largest systems, multiple doublets were confirmed

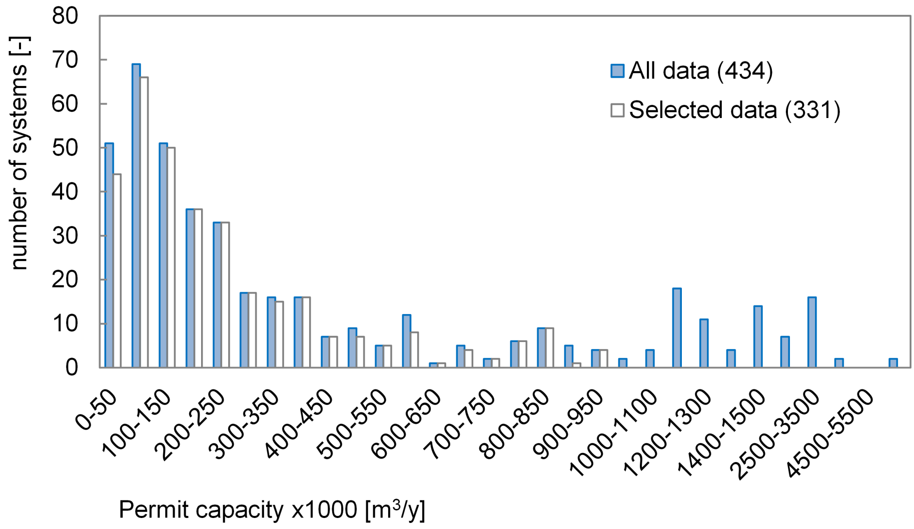


Figure 4.3: Frequency distribution of dataset according to permitted yearly storage volume of groundwater. Distribution of well design metrics of selected data is shown separately.

for several systems (e.g. C, D, F,G, H, I). In addition, some errors were found in the data of the provincial databases, inconsistent, incomplete entries (e.g. E) with errors (e.g. impossible short or long screen lengths), such as monowell systems with only one very long screen which should be divided in two screens (A and B in Figure 4.4). As a result of this validation of the dataset, 331 systems were selected for further evaluation (Figure 4.4). The data used for analysis represents about 15 % of the approximately 2,000 systems operational in the Netherlands [22].

GEOHYDROLOGICAL CONDITIONS

Table 4.3 shows the overall geohydrological characteristics at the location of 204 ATES systems. Both hydraulic conductivity and ambient groundwater flow velocity show a wide range.

Table 4.3: Ranges in geohydrological characteristics of the 204 ATES systems under consideration, for which geohydrological conditions could be retrieved.

Available aquifer thickness range	Hydraulic conductivity Range	Groundwater flow range
[m]	*[m/d]*	*[m/y]*
30-180	5-45	3-100

4.3.2. ANALYTICAL EVALUATION OF ATES THERMAL RECOVERY

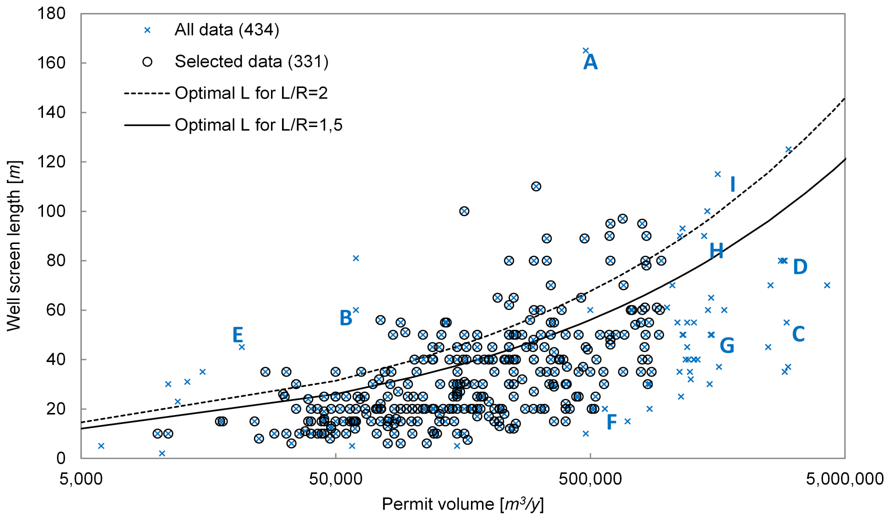


Figure 4.4: Dataset characteristics; outliers are excluded from the dataset. A, B=monowells with only top of upper and bottom of lower filter in the data, C=University Campus 6 doublets, D=Office with 3 doublets, E=Office building with only extracted volume of one year available in data, unrealistically small for size of building, F=office with 4 doublets, G=Hospital with 4 doublets, H=conference center with 2 monowells, I=Office with 3 doublets

LOSS OF THERMAL ENERGY DUE TO DISPERSION AND CONDUCTION

Both conduction and dispersion losses occur at the boundary of the stored thermal cylinder. Following Equation (4.3); near the well, where flow velocity of the infiltrated water (v) is high, dispersion dominates the conduction term, while further from the well, the effects of dispersion decreases. Equation (4.3) and the values for the dispersion and aquifer properties in Table 4.1 are now used to identify the distance from the well at which the dominating process contributing to loss, changes from dispersion to conduction , Figure 4.5. The pump capacity data of the ATES systems together with the storage volume and screen length are used to plot the thermal radii of the systems with respect to their maximum specific discharge, showing that even assuming a relatively high dispersivity of 5 m, beyond 10 % of permitted storage volume infiltration, conduction is dominating in the dispersivity equation, indicating that at full storage capacity conduction losses will be dominating.

When the infiltration continues, the movement of the thermal front is dominated by the advective heat transport of the injection. The (high) dispersion losses that occur at the high flow velocities close to the well are ”overtaken” when infiltration of heat continues, resulting in sharp heat interface as the infiltration volume increases. This sharp interface remains sharp during infiltration because the heat injected by the well travels faster than the standard deviation for the conduction ($\sigma = \sqrt{2D_T t}$). During storage and extraction the interface will become less sharp due to respectively conduction and the opposite effect of these mechanisms. The heat that thus stays behind causes that effi-

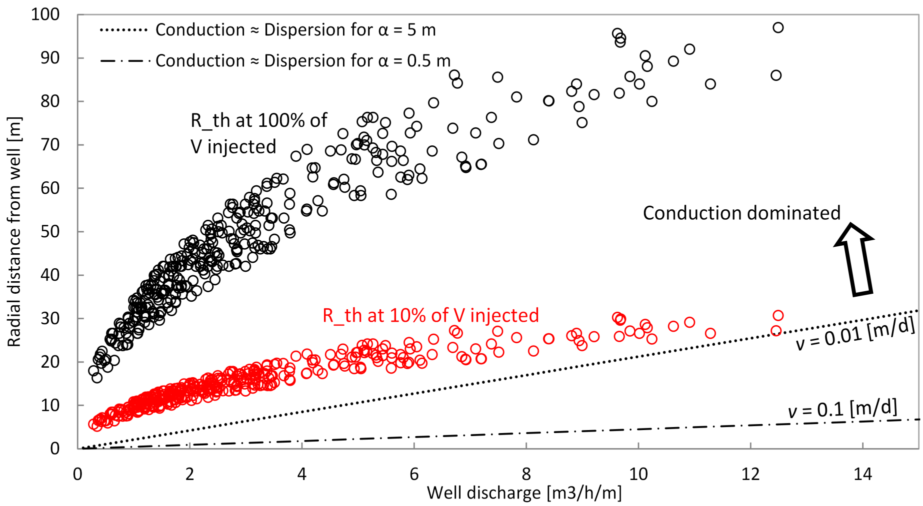


Figure 4.5: Lines: the relation between specific well discharge and radial distance at which the radial flow velocities where conduction and dispersion are equal (Eq. 4.3) for the outer-bounds of the range of thermal dispersivity regularly applied in literature. Open circles the thermal front of the ATES systems in the data at different storage capacities related to their specific well discharge.

ciency improves and stabilizes over multiple storage cycles. From which it is concluded that losses can be minimized by minimizing the total surface area of the circumference and the cap and bottom of the thermal cylinder (A) of the stored heat volume (V) in the aquifer. This can be done by identifying an appropriate screen length according to the required storage volume and local conditions, in order to minimize the surface area – volume ratio;

$$\frac{A}{V} = \frac{2\pi R_{th}^2 + 2\pi R_{th} L}{\pi R_{th}^2 L} = \frac{2}{L} + \frac{2}{R_{th}} \tag{4.6}$$

For any given storage volume an optimal screen length exists at which conduction and dispersion losses are minimal at the screen length - thermal radius ratio (L/R_{th}) is 2, when the diameter of the cylindrical storage volume is equal to its screen length. From Figure 4.6 can be seen that for larger storage volumes the A/V-ratio is smaller, and less sensitive at larger screen lengths, exhibiting a relatively flat minimum compared to small storage volumes. Although the absolute losses increase with increasing storage volume, the relative losses are smaller.

To identify the optimal filter screen length the derivative for surface area is equated to zero, which results in an expression for optimal filter screen length as a function of required storage volume;

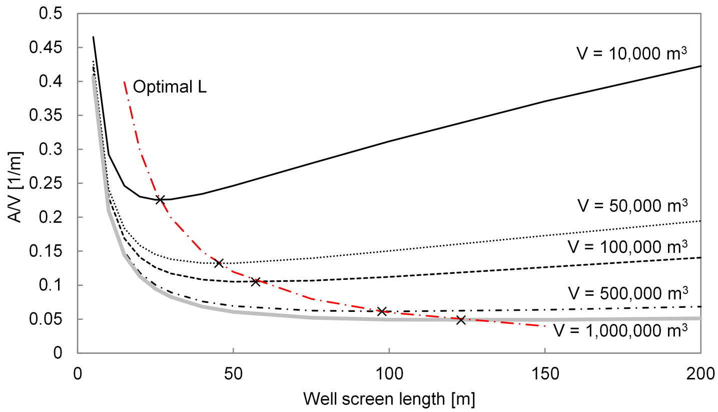


Figure 4.6: The A/V values for different storage volumes and well screen lengths

$$A = \frac{2c_w V}{c_{aq} L} + 2\pi\sqrt{\frac{c_w V}{\pi c_{aq} L}} L \rightarrow A' = \frac{-2\pi c_w V}{c_{aq} L^2} + \pi\sqrt{\frac{c_w V}{\pi c_{aq}}}\frac{1}{\sqrt{L}} \rightarrow L \approx 1.23\sqrt[3]{V} \tag{4.7}$$

Consequently, relatively small storage volumes experience higher losses due to dispersion losses. Because there is no or little flow to and from the confining layers of an ATES well, conduction losses along the interface with the confining soil layers may differ from the ones around the circumference. Therefore Doughty et al.[82] distinguished between the two in their research to optimize well design, to account for the reduced conduction losses to confining layers after several storage cycles. Their Simulation showed that efficiency increases with the first number of storage cycles and found that the optimal ratio between screen length and thermal radius (L/R_{th}) has a flat optimum around 1.5 when taking into account different thermodynamic properties of aquifers and aquitards. Substituting the expression for the thermal radius (R_{th}, Equation (4.5)) in the optimal relation of L/R_{th}=1,5 gives the optimal screen length (L) as a function of storage volume (V);

$$L = \sqrt[3]{\frac{2.25 c_w V}{c_{aq}\pi}} \approx 1.02\sqrt[3]{V} \tag{4.8}$$

This shows that the solution for the screen length results in the same third root of the storage volume, only with a smaller constant 1.02 [-] instead of 1.23 [-] as was derived from the optimal A/V-ratio solution, Equation 4.7 & 4.8. This is the case because over multiple cycles, the conduction losses to “cap & bottom” decrease; losses from earlier cycles dampen the losses during following cycles.

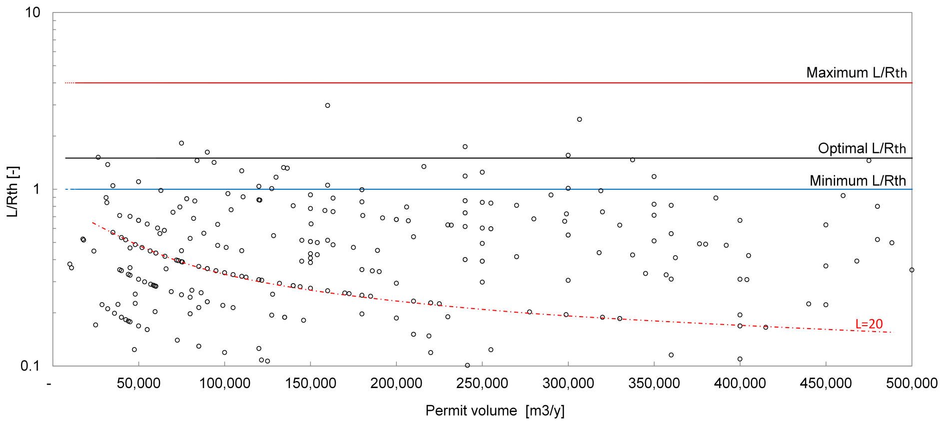


Figure 4.7: L/R_{th}-value relative to storage volume of ATES systems in practice, combined with minimum ($L/R_{th} = 1$), maximum ($L/R_{th} = 4$) and optimal ($L/R_{th} = 1,5$) L/R_{th} for conduction and dispersion losses

From the lines for L/R_{th} is 1.5 it can be seen that on average, screen lengths are designed far from optimal with respect to minimizing conduction losses. Doughty et al. [82] however, found a flat optimum for L/R_{th}-value, thus it may also be acceptable when the L/R_{th}-value is between 1 and 4, based on the moment of deflection of the L/R_{th}-curve constructed by Doughty et al. [82]. However most systems have L/R_{th}-values lower than 1, indicating that screen lengths used in Dutch practice are relatively short (Figure 4.7). Analysis shows that 56 % of the ATES systems with an L/R_{th}<1 have insufficient aquifer thickness available for longer screens.

THE EFFECT OF AMBIENT GROUNDWATER FLOW ON RECOVERY EFFICIENCY

For the analysis of the impact of ambient groundwater flow on the recovery efficiency, it is assumed that a cylindrical shape of the injected volume is maintained during displacement. Ceric and Haitjema [86] determined that this assumption is valid for conditions where their dimensionless time of travel parameter τ, [86] is smaller than one;

$$\tau = \frac{2\pi(ki)^2 L t_{sp}}{nQ} = \frac{2\pi u^2 L t_{sp}}{Q} \tag{4.9}$$

The groundwater head gradient (i), hydraulic conductivity (k), screen length (L) and pumping rate (Q) of the ATES systems in the data are used to determine the time of travel parameter for each system. The only unknown is the length of storage period (tsp). With an average storage period of 183 days (half a year) only one of calculated τ values for the 204 ATES systems was larger than one; a very small system in high ambient groundwater flow velocity. On top of meeting the requirement of Ceric and Haitjema, the thermal

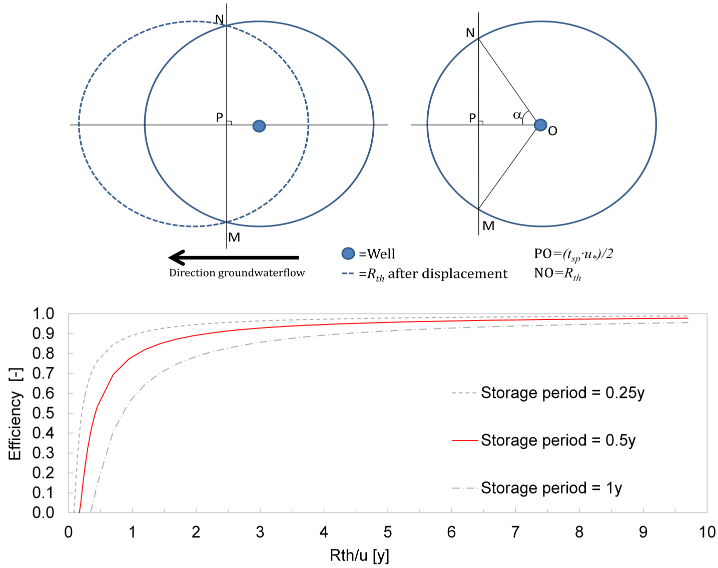


Figure 4.8: Top: schematic overview of calculating the overlapping surface area (A) of 2 identical thermal cylinders. Bottom: the derived analytical relation between losses and the thermal radius - groundwater flow velocity ratio.

retardation also causes the heat to flow at half the speed of water, which then makes the assumption of preservation of a cylindrical shape during displacement an acceptable simplification. These conditions allow the definition of the recovery efficiency as a function of the overlapping part of the cylinders, with and without the displacement induced by ambient groundwater flow. Assuming that the ambient groundwater flow is horizontal, the surface area of the thermal footprints before and after displacement with the groundwater flow represents this efficiency, Figure 4.8 (top).

Goniometric rules are used to express the overlapping surface area ($A_{overlap}$) of the thermal footprint as a function of groundwater flow velocity and thermal radius, as follows:

$$A_{overlap} = 2{R_{th}}^2 a\cos\left(\frac{t_{sp}u_*}{2R_{th}}\right) - t_{sp}u_*\sqrt{R_{th}^2 - \frac{1}{4}(t_{sp}u_*)^2} \tag{4.10}$$

in which the velocity of the thermal front ($t_{sp} \cdot u_*$) is 2 times PO in Figure 4.8 (top). Substituting the relation between efficiency (η_{th}), thermal footprint ($A_{footprint}$) and overlapping area:

$$A_{overlap} = \eta_{th} A_{footprint} \rightarrow A_{overlap} = \eta_{th}\pi R_{th}^2 \tag{4.11}$$

results in a relation between efficiency, flow velocity and the thermal radius;

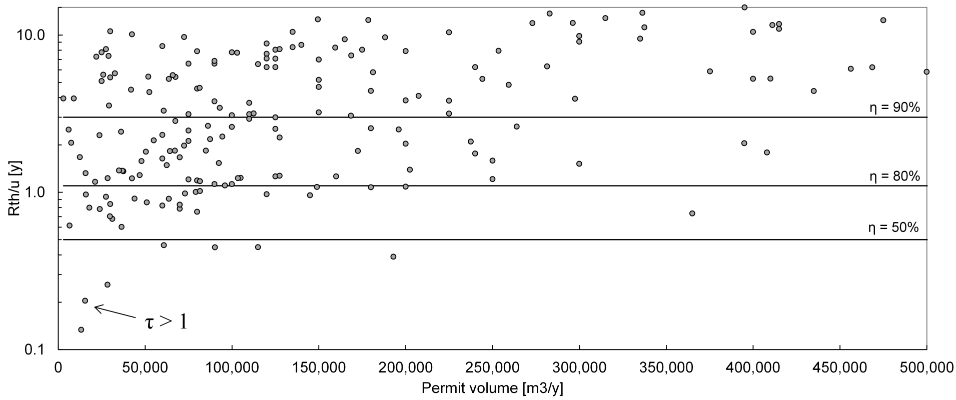


Figure 4.9: R_{th}/u-values for ATES systems in the data set with thresholds for different thermal recovery efficiencies

$$\eta_{th} = \frac{2}{\pi} a\cos\left(\frac{t_{sp}u_*}{2R_{th}}\right) - \frac{t_{sp}u_*}{\pi R_{th}^2}\sqrt{R_{th}{}^2 - \frac{1}{4}(t_{sp}u_*)^2} \tag{4.12}$$

For every ATES system with $\tau < 1$ the efficiency can be obtained with this relation. When $R_{th} > u$, the $t_{sp}u_*$ -term under the square root contributes less than 1 % to the obtained efficiency. Under these conditions, both right and left term of Equation 4.12 depend on the ratio between the traveled distance and the thermal radius. So for any constant combination of u_* over R_{th}, the efficiency is the same, which allows to identify the efficiency as a function of the R_{th}/u-ratio for different storage periods, Figure 4.8 (bottom). This can be used to identify minimum desired thermal radius (i.e. maximum desired screen length for a given storage volume) at a location with a given groundwater flow velocity to meet a minimal efficiency.

The derived relation is now used to assess the well design data with respect to the local ambient groundwater flow velocity, hydraulic conductivity and thickness of the aquifer. For each of the ATES systems in the dataset the R_{th}/u–value was determined, the relation given in Figure 4.8 (bottom) is used to indicate lines of expected thermal efficiency only taking into account losses due to displacement caused by ambient groundwater flow, Figure 4.9.

Figure 4.9 shows that about 20 % of the systems have an expected efficiency lower than 80 % (R_{th}/u<1.1). For the ATES systems with an expected efficiency lower than 80 % (Table 4.4) the average storage volume is relatively small and the average flow velocity relatively high at 36 m/y. Although minimizing screen length reduces heat losses due to displacement, minimizing for conduction and dispersion losses require an optimal screen length for a particular storage volume.

Table 4.4: Results of analysis of filter screen length with respect to groundwater flow velocity

	average u	average V	average R_{th}
	[m/y]	[m^3/y]	[m]
η >80 %	6	263,000	46
η < 80 %	33	100,000	32

4

CONCLUSION ANALYTICAL ANALYSIS

In optimizing the storage geometry of ATES systems the applied length should be carefully considered. However, in both Figure 4.4 and Figure 4.7 it can be seen that many ATES systems with varying storage volumes have identical screen lengths, at various multiplications of 5 m. This likely relates to the fact that screen sections are supplied in 5 m sections, which can, but are not adjusted to a specifically required length. The wide range of storage volume per single screen length (e.g. 40,000 – 420,000 m^3 for L=20 m, Figure 4.7) thus indicates that the screen length design indicated in the permit application are generally not based on an evaluation of storage volume and local geohydrological conditions, Dutch design standards only consider the clogging potential for ATES well design [24]. Particularly for smaller ATES systems, the sensitivity of recovery efficiency for screen length selection is high, as these are most vulnerable for significant losses as a consequence of ambient groundwater flow and dispersion and conduction (Figure 4.6 and Figure 4.8.

4.3.3. NUMERICAL EVALUATION OF ENERGY LOSSES

To assess the combined effect of conduction, dispersion and displacement losses, the results of the performed numerical MODFLOW simulations are discussed and compared with the straightforward and simple analytical solutions presented in the previous section. The wide range of ATES conditions for which the numerical simulations were performed resulted in recovery efficiencies between 10 and 70 %.(Figure 4.10).

CONTRIBUTION OF DISPLACEMENT LOSSES

The lowest efficiencies are associated with the scenarios with high ambient groundwater flow (>50 m/year), together with relatively small thermal radius, which results in a small thermal radius over ambient groundwater flow (R_{th}/u-ratio < 1 y). For both the numerical and the analytical solution for the impact of ambient groundwater flow on recovery efficiency is very sensitive for low Rth/u-values. However, at higher R_{th}/u–values (> 1 y) the efficiency becomes less dependent of Rth/u, as dispersion and conduction losses are dominant under such conditions. In all cases the analytical solution overestimates the efficiency compared to numerical results, because the analytical solution does not take account for conduction and dispersion losses. To estimate the efficiency for the numerical simulations that would result under the impact of displacement only, the obtained efficiencies under no flow conditions are used as a reference (following (N_u) for u= 5 m/y; $N_5 = (1 - \eta_0) + \eta_5$). These numerically derived estimates show a good resemblance

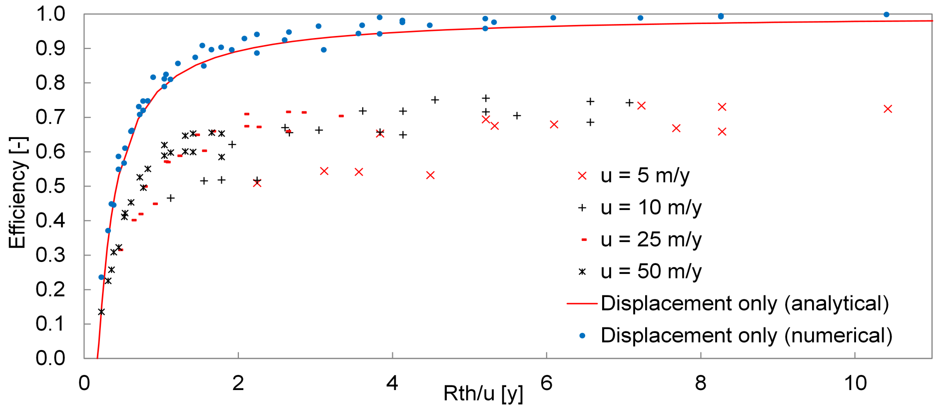


Figure 4.10: Relation between efficiency and thermal radius over groundwater flow velocity (R_{th}/u) for numerical simulation results and analytical solution (Eq.4.12) for 0.5 y storage period.

with the analytical relation. This confirms that the analytical approach is valid to determine displacement losses separately.

CONTRIBUTION OF CONDUCTION AND DISPERSION LOSSES

Simulated efficiencies for the scenarios without ambient groundwater flow were highest, up to 75 %, and highly correlated with the surface area over volume ratio A/V (Figure 4.11), in contrast with the simulations with the highest ambient groundwater flow (50 m/y). Also the A/V ratios calculated for earlier simulation studies and experiments without ambient groundwater flow [43, 82, 83] strongly correlate with the observed efficiencies in these studies. Like in this study, the results from Lopik et al. (2016) and Doughty et al. [82] consist of a series systematic changing boundary conditions which allows for verification of the relations found in Figure 4.11. Results of both Lopik et al. and Doughty et al. [82] show a linear relation with similar slope between the surface area over volume ratio (A/V) and efficiency in the absence of ambient groundwater flow. The excellent correlation efficiency with the A/V ratio for each study with no ambient groundwater flow, indicates that under similar condition the efficiency of ATES systems for a particular aquifer system and operational mode can be interpolated based on A/V. Although similar, the efficiencies at a particular A/V-ratio deviate for these different modeling studies and are likely to be caused by small differences in parameters and model set-up. E.g.; both Doughty et al. [82] and Lopik et al. [83] used an axisymmetric model and a finer vertical spatial discretization compared to this study, resulting in differences in numerical dispersion. Also, Doughty et al. [82] uses no dispersion, which explains why their simulations show the highest efficiency. Lopik et al. [83] uses shorter and less storage cycles as well as a slightly smaller dispersion coefficients compared to this study. From these (small) differences can be seen that at simulations with higher dispersion, the A/V – efficiency relation becomes steeper, small systems which have a larger A/V-ratio then suffer relatively more, confirming the earlier observation from Fig-

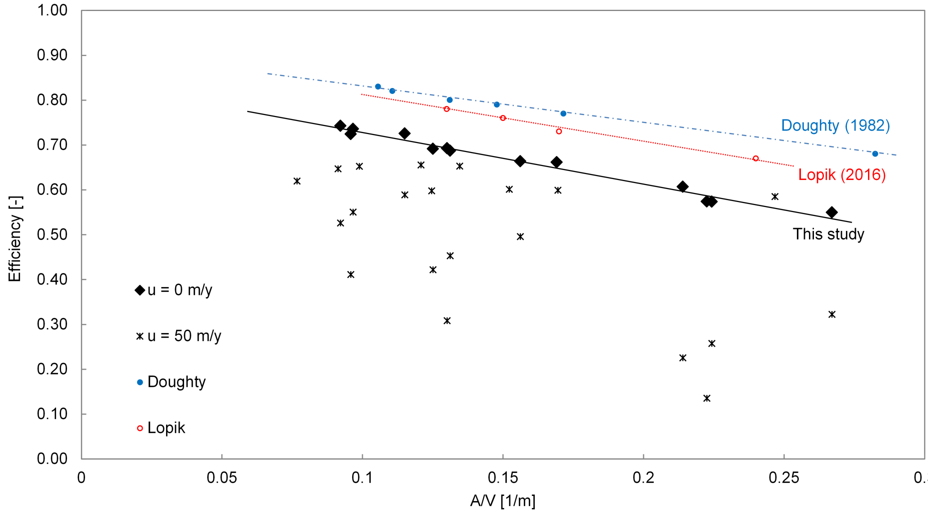


Figure 4.11: Simulated efficiencies relative to geometric property (A/V) from this and other studies at $u = 0$ m/y and for u =5 0 m/y from the simulations done in this study. The Pearson correlation between A/V and efficiency is -0,99 for $u = 0$ m/y. and -0,58 for $u = 50$ m/y. From the Lopik et al. [83] study, only the data was used from the simulations that excluded buoyancy flow.

ure 4.5 that at larger storage volumes conduction losses dominate.

COMBINED DISPLACEMENT AND CONDUCTION & DISPERSION LOSSES

As found by Doughty et al. [82] the optimum for L/R_{th}-ratio for a particular ATES storage volume is around 1.5 in the absence of ambient groundwater flow. However this optimal ratio shifts to lower values with increasing ambient groundwater flow velocity (Figure 4.12). The optima remains flat for higher groundwater flow velocity, only for the smallest system (12,000 m^3) at the highest ambient groundwater flow (50 m/y) tested, this is not the case within the simulated conditions.

To identify the optimal L/R_{th} at different rates of groundwater flow velocity, the L/R_{th} value of the simulation series of each storage volume and groundwater flow velocity with the highest efficiency was selected from the different L/R_{th} scenarios simulated. To take into account the flat optima also the L/R_{th} values with less than 5 % deviation in efficiency were selected. For each of the simulated ambient groundwater flow velocity, the average and the standard deviation of the optimal L/R_{th} values were calculated and plotted in Figure 4.13. This empirical relation shows how the well design for ATES wells can be optimized taking account conduction, dispersion and displacement losses. It also shows that at higher ambient groundwater flow, well design is more critical, since the allowed deviation of the optimal solution becomes smaller. Despite the limited number of simulations (120), the number and spreading of different conditions is sufficient to use this relation in design practice.

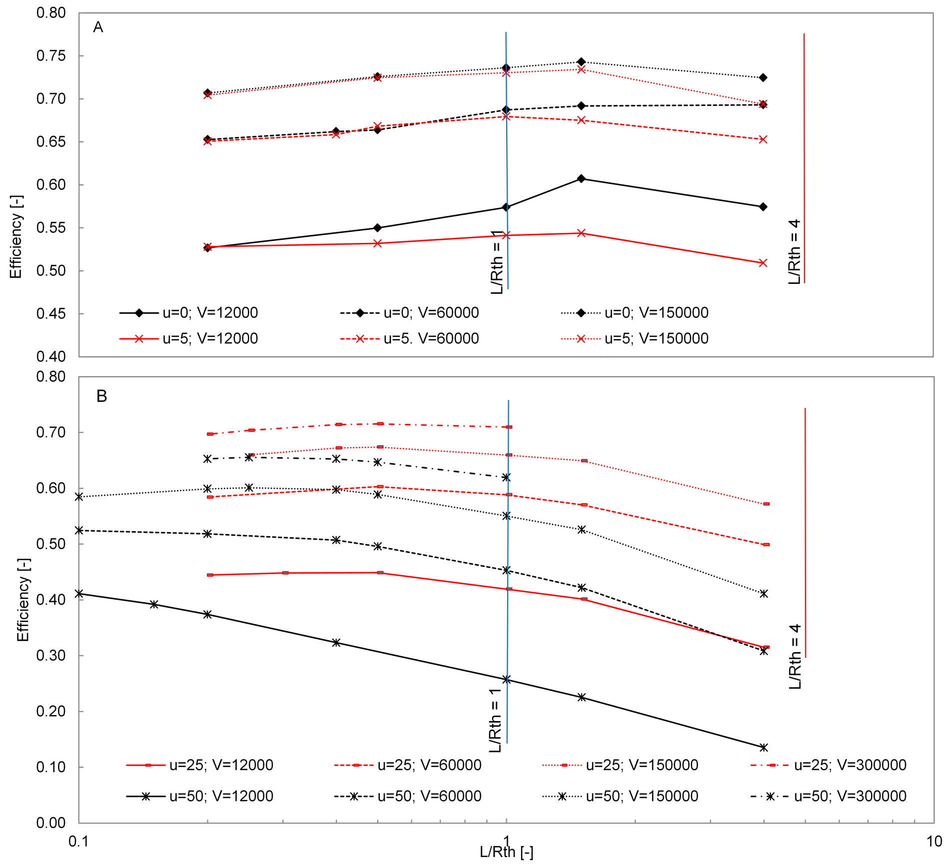


Figure 4.12: Simulated efficiencies for different groundwater flows (u) and Filter screen length over thermal Radius (L/R_{th}) of various storage volumes. A: is at no/low ambient groundwater flow (Doughty applies). B: is at high ambient groundwater flow.

4.4. DISCUSSION

SIZE AND VARIATION IN SEASONAL STORAGE VOLUME

As shown in this research storage volume is an important parameter affecting recovery efficiency. In assessing this efficiency it has been assumed that the infiltrated and extracted volume is equal for each cycle. However, in practice the infiltration and extraction volume from wells are typically not equal due to variations in heating and cooling demand. This can have a significant influence on the perceived recovery efficiency per cycle. Monitoring data indicates energy imbalances varying between -22 % and + 15 % [22]. Because in general ATES systems have to meet energy balance for a certain period, in The Netherlands 3-5 years depending on provincial legislation, a representative

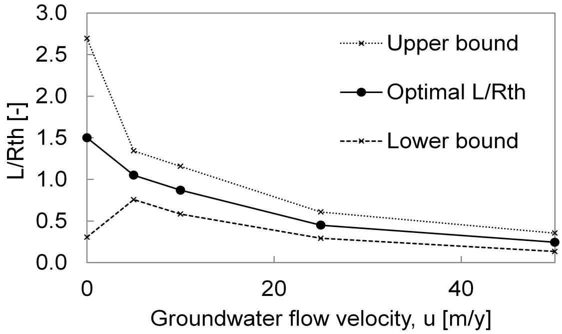


Figure 4.13: Optimal L/R_{th} for different groundwater flows derived from simulation results

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storage volume can be used to assess conduction and displacement losses. Because the absolute losses increase with increasing storage volumes, it is more beneficial to optimize for maximum storage volume. This is also reflected in Equation 4.7 where can be seen that the A/V-value has a flat optimum at larger storage volumes (Figure 4.6, and also in the relation identified by Doughty et al. [82] and shown in Figure 4.12. Therefore, the permitted capacity data of the ATES wells in The Netherlands were used to compare theoretical well design approaches with field data, Figure 4.7. However, in practice ATES systems deviate from their permit capacity to store heat because ATES operators request a larger permit capacity to allow for flexibility during operation; e.g. building energy demand may be higher than expected, possible future growth, change of building function and seasonal fluctuations. This influences the shape and thus the losses of the heat storage. Operational data of ATES systems from different databases have been used in regional and national studies and evaluations [12, 22, 101] all showing that ATES systems yearly actually only use 40-60 % of their initially requested and permitted capacity. The ranges of systems sizes presented in this study, e.g. Figure 4.3 and Figure 4.4, are therefore much smaller in practice.

Also variations in seasons affect the total storage volume in the ATES wells. In this study the common assumption was made, that the average yearly volume is infiltrated and extracted during the winter and summer, with a storage period in between, resulting in a block-scheme like infiltration, storage and extraction pattern. However, heating and cooling demand typically does not balance perfectly during a year and seasonal variations may cause temporal imbalances, resulting in a sometimes smaller and sometimes larger heat storage compared to the yearly average storage. For example, heat may remain in warm wells during a couple of warm winters until a colder winter depletes the warm well. The effect of this aspect is illustrated by the presentation of the cumulative volume stored in a well relative to the average value for multiple years, Figure 4.14. This pattern is derived from the storage volume variation based on the monitored and projected outside air temperature (2010-2020) of the weather station of De Bilt in The Netherlands [102]. The energy demand pattern is determined by deriving the energy demand for each day by scaling the yearly average energy demand to the deviation of the daily temperature from the average outside air temperature of the evaluation period. As

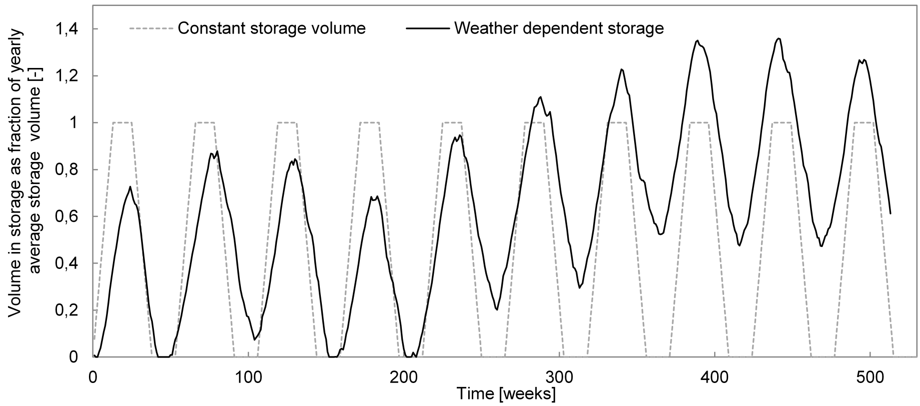


Figure 4.14: Volume in storage of well for different energy demand patterns

a result of this seasonal variations imbalances occur over the years, resulting in varying stored volume in the wells. From Figure 4.14 can be seen that the maximum storage capacity occurring in practice is around 150 % of the average yearly storage volume. This exercise was done for different climatic datasets (monitored as wells as projections), all giving the same outcome, that the maximum storage in the well is about 150 % of the average yearly storage.

The fact that well design can be best determined for maximum storage volume, then leads to the conclusion that 150 % of the expected yearly average storage volume, which in turn is about 75 % of the permitted capacity (50 % of permitted capacity is used in practice) must be used as a basis for well design. Correcting the data of the permitted volumes for these two aspects results in the ATES systems plotted in Figure 4.7 and Figure 4.9 to respectively move up- and downwards.

ADDITIONAL WELL DESIGN CRITERIA IN PRACTICE

The well design criteria required to assess and optimize the thermal recovery efficiency were considered in this study. However, in practice additional aspects such as capacity, prevention of well clogging, available aquifer thickness, mutual interaction and drilling and installation costs all play a role in determining the well design. In practice the determination of screen length is mainly based on the maximum desired pumping rate [24]. Together with minimizing drilling costs this is a driver for screen lengths that are too short to achieve optimal thermal efficiency, which is clearly reflected in Figure 4.7. In the Netherlands, a clear guideline or method available to take account for losses as a result of ambient groundwater flow in well design is currently lacking [24], which is reflected in Figure 4.9. The effect of a partially penetrating well on the distribution and A/V-ratio of heat is both not discussed in this study and not taken into account in current practice. However, given the identified significant effect of the A/V-ratio on efficiency, the efficiency of a partially penetrating well may deviate significantly from a fully penetrating well with the same storage volume and screen length. For partially penetrating wells the aquifer anisotropy is also an important parameter to consider.

In this study is shown that suboptimal well design may have a large influence on well efficiency, but can also be limited relatively easily. As shown in Figure 4.6 and Figure 4.12, the dependency for both A/V and L/R_{th} with efficiency has a flat optimum beyond some threshold, which then allows dealing with local aquifer thickness conditions and uncertainties in storage volume now this threshold is known.

THE IMPACT OF AMBIENT GROUNDWATER FLOW ON THE EFFICIENCY OF ATES SYSTEMS

High ambient groundwater flow affects the recovery efficiency of ATES systems significantly. The missing framework to assess stored heat losses due to groundwater flow was introduced in this paper. Also the orientation of ATES wells with respect to the ambient flow direction needs to be taken into account. Warm and cold wells need to be oriented perpendicular to the flow direction. For individual systems this framework helps to improve well efficiency, a drawback of the presented framework is, however, the resulting large thermal radii and suboptimal use of aquifer thickness. In areas with many ATES systems close together this may lead to scarcity of subsurface space for ATES. In such busy areas with high ambient groundwater flow, planning strategies should work towards placement of same type of wells in the direction of the groundwater flow, where then only the most upstream wells will suffer from losses due to groundwater flow, for which compensation arrangements may be made. Multi doublet systems on the other hand may better use the strategy to place well of the same type in the direction of the flow and infiltrate relatively more heat in the upstream and extract more from the downstream well to compensate for the ambient groundwater flow losses, as was used by Groot [88] and discussed in more detail in section 4.6.

THE EFFECT OF AQUIFER CONDITIONS

The shape of the stored heat was assumed to have a cylindrical shape in this evaluation of well design. However, in a heterogeneous aquifer the storage volume does not have the shape of a 'perfect' cylinder, resulting in a varying thermal radius over the depth of the screen. As a consequence of heterogeneity the A/V-ratio in practice is higher compared to the expected value for a homogeneous aquifer. Although they both use a single ATES configuration, Sommer and Caljé [43, 96] show that the net effect of heterogeneity on efficiency is limited over multiple storage cycles and its influence is much smaller compared to the effect of A/V and ambient groundwater flow on the efficiency. Only when gravel layers are present such heterogeneity may affect efficiency significantly, and should therefore best be blinded [43]. Next to variations in hydraulic conductivity, also variations in salinity may affect the shape of the storage volume due to buoyancy flow due to density differences. Such aspects will affect the efficiency dependencies derived for the homogeneous and isotropic conditions evaluated in this study. Also the efficiency dependency for application of ATES in more challenging geohydrological environments will require further study.

A particular example is the increasing salinity of groundwater with depth, which will be disturbed by ATES operation and cause buoyancy flow due to the density differences

Table 4.5: Efficiency change at different conditions of split filter screens

thin impermeable layer(s) in storage aquifer							multiple aquifers	
1 of 2m	1 of 4m	1 of 8m	2 of 2m	2 of 4m	3 of 2m	3 of 4m	2	3
0.0%	-0.4%	-0.9%	-0.3%	-0.4%	-0.7%	-1.9%	-7.6%	-12.7%

between ambient and stored water, originating from the mixing of water of different depths in the ATES well, which is discussed in more detail in section 4.7.

SPLIT WELL SCREENS

In groundwater well constructions peat and clay layers cannot be screened to prevent well clogging. In practice it is therefore often not possible to install the required / optimal filter screen length as a single screen, because aquifers are of limited thickness or intersected by thin peaty and clayy depositions. These conditions have effect on the heat losses in the aquifer. Equation 4.6 can be altered to also represent such conditions and derive an optimal relation, this will however result in an ambiguous and complex relation because the distribution of the storage volume in the different screened formations depends on the transmissivities of the associated layers, which will also result in varying thermal radii around the different filter screen sections. Several exploratory simulations were carried out to get an indication on how such conditions affect recovery efficiency, Table 4.5.

- The average doublet system with a storage volume 200.000m^3 per year in a well of 45m ($L/R_{th} = 1$) with a single screen was used as a reference case.
- Applying one or more relatively thin clayy layers hardly affects the efficiency
- Separating the filter screen in 2 or 3 section separated by 20 m thick clay layers.

These exploratory simulations show that thin impermeable layers in an aquifer have limited effect on the efficiency, because overall A/V-ratio hardly changes under such conditions. While at using multiple aquifers separated by thick impermeable layers significantly affects efficiency in such conditions.

COMBINED WELLS AND MUTUAL INTERACTION

This study focuses on optimizing the recovery efficiency of a single ATES systems and individual wells, ATES systems however cumulate in urban areas [28, 49] and regularly share subsurface space to store or extract heat. As a consequence, additional considerations need to be taken into account, which might lead to deviations from the design consideration presented in this research. For example, planning of subsurface space occurs based on the thermal footprint (Figure 4.1) of an ATES well projected at surface level [103, 104], which then promotes the use of longer screens. From the flat optima shown in Figure 4.12 it can be seen that the individual well efficiency may not have to suffer much from such additional consideration. This will allow larger number of ATES systems to be accommodated in such areas and with that the overall CO_2 emission reduce

[26]. Also, large ATES systems often have multiple warm and cold wells which are placed together and function as one single storage in the subsurface. The length of the screens of such combined wells should therefore also be determined based on the fact that they function as one storage volume in the subsurface, disregarding this aspect gives a sub-optimal A/V and amplifies the effect of having a larger footprint, in areas where this must be prevented. From this is concluded that combining wells, also requires a well design for the individual wells based on storage capacity of both wells together. However, in such busy aquifers best would be to promote the use of the full aquifer thickness for wells and use a full 3D planning strategy.

4.5. CONCLUSION

In this study an evaluation of ATES characteristics from practice together with analytical and numerical simulations were used to develop the missing framework for ATES well design to achieve optimal recovery efficiency. This work includes the losses due to heat displacement with ambient groundwater flow. The results show that two main processes control thermal recovery efficiencies of ATES systems. These are due to the thermal energy losses that occur 1) across the boundaries of the stored volume by mainly conduction and dispersion only at smaller storage volumes and 2) due to the displacement of stored volumes by ambient groundwater flow.

For the latter process, an analytical expression was deduced that suitably describes thermal recovery efficiency as a function of the ratio of the thermal radius over ambient groundwater flow velocity (R_{th}/u). For the conditions tested, at $R_{th}/u < 1$ the displacement losses were dominant and thus would require minimization of the well screen length or maximize the volume stored. Obviously, practical aspects, such as required minimum well capacity or the availability of suitable aquifers, may prevent the use of optimal screen lengths as is illustrated for a large part (15 %) of the evaluated Dutch ATES systems that indicate an a efficiency of less than 50 %, due to ambient groundwater flow (Figure 4.9).

With respect to the dispersion and conduction losses it was shown that conduction is dominating and for the numerical simulation results of this and previous studies, thermal recovery efficiency linearly increases with decreasing surface area over volume ratios of the stored volume (A/V) for a particular set of operational and geohydrological conditions. With respect to the losses due to conduction and dispersion, the optimal screen length has a flat optimum, which allows to also take account for other considerations in well design like neighboring systems and partially penetrating effects.

For the optimization of thermal recovery efficiency with respect to both main processes, the optimal value for the ratio of well screen length over thermal radius (L/R_{th}) decreases with increasing ambient groundwater flow velocities as well as its sensitivity for efficiency. With the insights on the controls on thermal recovery efficiency derived in this study, the assessment of suitable storage volumes, as well as the selection of suitable aquifer sections and well screen lengths, can be supported to maximize the thermal recovery of future seasonal ATES systems in sandy aquifers world-wide.

WELL DESIGN AND OPERATION STRATEGIES FOR ATES IN HIGH AMBIENT GROUNDWATER FLOW

The details are not the details. They make the design

Charles Eames

In areas with high ambient groundwater flow velocity (> 25 m/y) thermal energy losses by displacement of groundwater may be prevented by application of multiple doublets. In such configurations two or more warm and two or more cold wells are aligned in the direction of the ambient groundwater flow. By controlling the infiltration and extraction rates of the upstream and downstream wells, the advection by ambient groundwater flow can be compensated by storing thermal energy through the upstream well, while re-extracting it from the downstream well.
This study uses analytical and numerical tools and a case study to analyze the relevant processes, and provides guidelines for well placement and an operation strategy for ATES wells in aquifers with considerable groundwater flow. The size of the thermal radius relative to ambient groundwater flow velocity is an important metric for the choice of the screen length of the wells, as was shown in section 4.3. With multiple wells to counteract groundwater flow, this ratio affects the pumping scheme of these wells. The optimal distance between them is around 0.4 times the distance traveled by the groundwater in one year. A larger distance negatively affects the efficiency during the first years of operation; especially with smaller groundwater flow velocities the distance between the wells should be kept as small as possible.

Section 4.6 is under review for publication in a peer review journal, revisions have been submitted. The introduction and method section has been modified to prevent repetition and to fit within the storyline of this thesis.

4.6. ATES SYSTEMS IN HIGH AMBIENT GROUNDWATER FLOW

4.6.1. INTRODUCTION

PROBLEM STATEMENT

IN aquifers with a high ambient groundwater flow velocity (u), losses of thermal energy caused by groundwater advection can be limited by choosing a shorter screen length, as was shown in section 4.3. However, in many cases this strategy is neither possible nor desirable, because short screens limit the capacity of the wells and increase their thermal radius, which precludes optimal use of subsurface space, as discussed in section 4.4. In practice under high ambient groundwater flow conditions the so-called recirculation systems (Figure 4.15) is often applied. Compared to the normal ATES systems, these systems have a smaller temperature difference between the warm and cold well, a lower efficiency and a large downstream thermal plume, which may affect other ATES systems or groundwater uses.

In the previous section was shown that at groundwater flow velocities of >25 m/y, heat losses due to the groundwater displacement become considerable, relative to the conduction losses. In areas with a high ambient groundwater flow velocity, these displacement losses can be prevented by installing multiple doublets, where at least two wells of the same type are aligned in the direction of the ambient groundwater flow. By injecting the yearly storage volume (V) in the upstream well and extracting it from the downstream well in the next season, the ambient groundwater flow is counteracted, resulting in a higher recovery efficiency. This principle schematically represented in Figure 4.16.

The optimal design and operation strategy of such an ATES system depends on several conditions;

- The actual ambient groundwater flow velocity and direction.
  Field estimates of groundwater flow velocity and its direction always come with an uncertainty, because limited groundwater head measurement locations are available. The same is true for aquifer samples to identify the spatial variation of horizontal anisotropy and hydraulic conductivity. Reducing the uncertainty of the flow velocity, its direction and its range is expensive.
  NB. In this study, variations in groundwater flow velocity and direction are not considered. In the Dutch aquifers used for ATES such variations rarely occur.

- The possibility to place wells at a required distance and in line with the groundwater flow.
  In urban areas, well placement is often limited by buildings and by infrastructure in the shallow subsurface, which may lead to wells at suboptimal locations (e.g. not precisely in line with the groundwater flow and/or at larger or smaller mutual distance than optimal).

- The possibility to control the wells for counteracting the groundwater flow.
  The basic scheme for counteracting the groundwater flow depicted in Figure 4.16 is to install two warm and two cold wells, in order to infiltrate in the upstream well

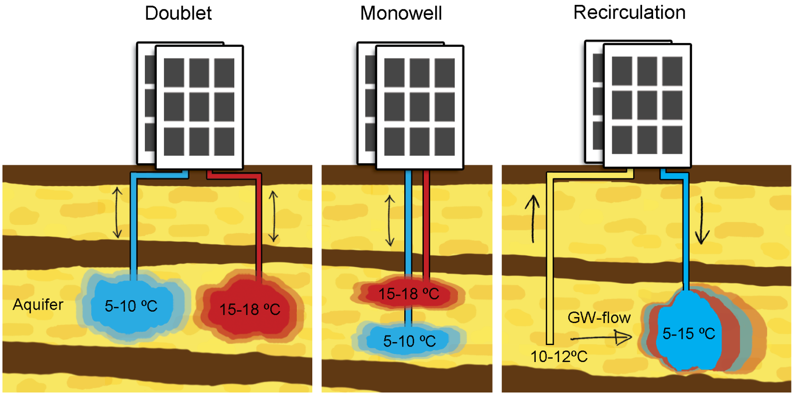


Figure 4.15: Schematic representation of ATES doublet, Monowell and Recirculation wells. Recirculation systems always use the same wells for extraction and infiltration; water is extracted from the upstream well and injected into the downstream well (sometimes also referred to as "pump and dump" systems), the arrow represents the ambient groundwater flow direction.

during one season and extract from the downstream well in the next. However, for ATES systems with multiple warm and cold wells, the full pumping capacity of both warm and cold wells is required during the warmest and coldest days of the year to provide peak heating and cooling capacity to the building. Under such conditions when heating or cooling demand exceeds the capacity of one well, both warm and cold wells are needed to supply energy (so that all wells are involved, for either pumping or injection), regardless of any desired groundwater flow counter-action.

Goal and Approach

The goal of this chapter is to identify under which conditions individual ATES systems can counteract ambient groundwater flow by using multiple wells of the same type aligned with the flow direction. The approach to meet this goal is to first identify the dominating variables and control possibilities, which is done in section 4.6.2 by describing the analytical relations, working conditions and numerical simulation tools. During extraction and infiltration at high groundwater flow velocity, the flow lines from and to the wells cannot be treated as radial, as would be valid for ATES systems in aquifers with low flow velocity (section 4.3). The processes and the dependency of the energy efficiency on dominant parameters are described, as well as the controls that help optimize design and operational strategy. Secondly, results of the basic and detailed conditions specific for ATES systems in practice are analyzed in section 4.6.3 by numerical simulations, to assess the required control under more realistic conditions encountered in practice. This is done with a general simulation following the working conditions identified in section 4.6.2, as well as for a case study.

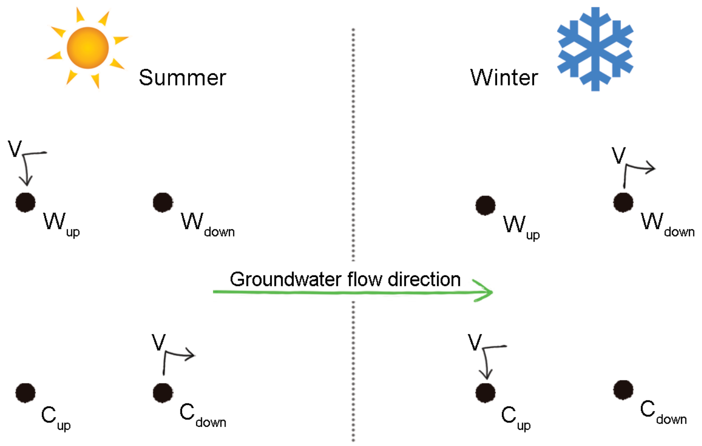


Figure 4.16: Schematic representation of warm and cold wells lay out and basic pumping scheme for counteracting the ambient groundwater flow

4.6.2. METHODS & MATERIALS

WORKING CONDITIONS

The range of working conditions that are analyzed in this section are derived from the characteristics of existing ATES systems in the Netherlands presented in section 4.2. The average groundwater flow velocities of interest in the Dutch aquifers range from 25 to 200 m/y. Distances between ATES wells of the opposite type range from several meters to building plot sizes, regularly around 50 to 150 m, so well distances of the same type can be in the same range or even smaller. ATES system storage volumes (V) range from 50,000 m^3/y to 500,000 m^3/y for doublet systems, with well screen lengths (L) between 5-150 m.

LOSS OF HEAT DUE TO DISPLACEMENT BY AMBIENT GROUNDWATER FLOW

Significant ambient groundwater flow is known to occur at ATES sites [87–89], which leads to displacement of the injected volumes [85, 90]. This may considerably reduce the thermal energy recovery efficiency of ATES systems as ambient groundwater flow (u) contributes to thermal losses by displacing the injected water during storage. The heat transport velocity (u_*) is retarded with respect to ambient groundwater flow [63, 82] due to heat storage in the aquifer solids. The thermal retardation (R) depends on porosity (n) and the ratio between volumetric heat capacities of water (c_w) and aquifer (c_{aq}, with $c_{aq} = nc_w + (1-n)c_s$ and c_s the solids volumetric heat capacity). Resulting in a heat transport velocity at approximately 50% of the groundwater flow velocity (u). these processes are more extensively introduced in section 4.2.

RETRIEVING HEAT FROM THE DOWNSTREAM WELL

The heat transport follows the same rules as water transport, only at a lower rate due to thermal retardation. Disregarding conduction, dispersion and diffusion then allows the use of water particle tracking to assess the distance at which wells should be placed to capture all heat in the downstream well that was infiltrated by the upstream well.

The approach to counteract the effect of ambient groundwater flow (u) on heat displacement in the subsurface with multiple wells also used for ATES systems by Groot [88]. This work focused on a system with two wells aligned along the groundwater flow in which the upstream well injects a volume of water that is recovered by the downstream well after a possible intermediate storage period in which no pumping takes place. It follows from Figure 4.16 that the distance D between the upstream and downstream well should equal the distance by which the heat is displaced by the groundwater, during the time[1] between infiltration of the first warm/cold water, and extraction of the last. At this distance, any particle that leaves the injection well under an angle with the ambient flow will be captured at the downstream well at an intermediate time. Hence, for the analysis of the ideal placement of the two wells, it suffices to consider only the flow along the straight line through the two wells, which are aligned with the ambient groundwater flow. The specific discharge q_x [m/d] by a well with flow Q [m^3/d] (injection positive) in an aquifer of thickness L [m], with a uniform ambient flow with ambient groundwater flow $q = un$ [m/d] along a line through the well parallel to the ambient flow, can be expressed as:

$$q_x = \frac{Q}{2\pi L x} + q_0 \tag{4.13}$$

During the storage period Q=0, the water moves entirely with the ambient flow, while during infiltration and extraction the combined effect of the wells and ambient flow influences the flow of the water and heat. During injection water particles cannot move beyond the upstream stagnation point (x_s, where $q_x = 0$)[2] of the injection well; during extraction water particles beyond the downstream stagnation point of the extraction well cannot be retrieved. Therefore, the specific discharge can be rewritten as:

$$\frac{u_x}{u_0} = 1 - \frac{x_s}{x} \tag{4.14}$$

or, equivalently

[1] This period is a year under theoretical operational conditions, where storage volume is completely extracted and the pumping pattern has a symmetrical shape for infiltration and extraction.

[2] The stagnation point is a point of no flow. For a well in an aquifer with groundwater flow, the stagnation point for extraction is downstream of the well at a distance of $Q/(2\pi q_0 L)$. Water particles downstream of this point can never be extracted by the well

$$\frac{dx}{dt} = \left(\frac{x - x_s}{x}\right) u_0 \tag{4.15}$$

With $u = dx/dt$, the obtained ordinary differential equation can be integrated and solved with initial location x_0 at $t = 0$, to find the position of x as a function of time;

$$x - x_0 + x_s ln\left(\frac{x - x_s}{x_0 + x_s}\right) = u_0 t \tag{4.16}$$

The solution is only valid when the argument of the logarithm is positive, i.e. x and x_0 are both on the same side of the stagnation point x_s. The optimal distance between the well depends on the stagnation point, which in turn depends on the well discharge and screen length. For a given yearly storage volume, V [m^3/y] and discharge Q [m^3/h], the required distance between the infiltrating and extracting well depends also on the time it takes the well to inject and extract this volume and, of course, on the length of the storage period. An added complexity is that ATES wells only operate at maximum capacity Q during the coldest and warmest days, which is a limited time. During low to moderate energy demand, the wells do not pump at full capacity, which shifts the position of the two stagnation points closer to the wells. To fix the locations of the stagnation points it is assumed that ATES wells operate at a constant capacity, like is often done in ATES simulation [44, 87]. This approach allows to iteratively identify the optimal distance D between the upstream infiltrating and downstream extraction well. The iteration is done with the Newton-Raphson method [105](Appendix 4.6-A).

The velocity of a water particle traveled to/from any well (i) can be expressed by:

$$\begin{pmatrix}\dot{x}\\ \dot{y}\end{pmatrix} = \frac{Q}{2\pi nL\big((x - x_i)^2 + (y - y_i)^2\big)}\begin{pmatrix}x - x_i\\ y - y_i\end{pmatrix} + \begin{pmatrix}u_x\\ u_y\end{pmatrix} \tag{4.17}$$

With $x - x_i$ the distance along the x-axis from the upstream well and $y - y_i$ along the y-axis, Q is the flow (injection positive, extraction negative), $u_{x/y}$ the ambient groundwater velocity in the x and y direction, n porosity, and L aquifer thickness. This expression can be solved by numerical integration, allowing tracking of water particles which are respectively infiltrated and extracted by an upstream and a downstream well, with known ambient groundwater flow velocity and direction. The numerical solution is found by implementing the Euler method for temporal discretization using 4-order Runge-Kutta [106].

Table 4.6: The required distance between upstream and downstream well identified with applying Newton-Raphson on Equation 4.16, for 50 and 100 m/y ambient groundwater flow.

		u = 50 m/y				**u = 100 m/y**					storage period / total period
		injection	storage	extraction	total	injection	storage	extraction	total		
A	Period (t)	1	180	1	182	1	180	1	182	*[d]*	**0.99**
	Distance	0	25	0	25	0	50	0	50	*[m]*	
	D/(u*t)	0	1	0	**0.99**	0	1	0	**0.99**	*[-]*	
B	Period (t)	90	180	90	360	90	180	90	360	*[d]*	**0.50**
	Distance	8.4	25.0	8.4	41.7	16.7	50.0	16.7	83.3	*[m]*	
	D/(u*t)	0.67	1	0.67	**0.83**	0.67	1	0.67	**0.83**	*[-]*	
C	Period (t)	120	120	120	360	120	120	120	360	*[d]*	**0.33**
	Distance	11.1	16.7	11.1	38.8	22.0	33.3	22.0	77.4	*[m]*	
	D/(u*t)	0.66	1	0.66	**0.78**	0.66	1	0.66	**0.77**	*[-]*	
D	Period (t)	180	0	180	360	180	0	180	360	*[d]*	**0.00**
	Distance	17.0	0.0	17.0	33.9	33.4	0.0	33.4	66.7	*[m]*	
	D/(u*t)	0.68	-	0.68	**0.68**	0.67	-	0.67	**0.67**	*[-]*	

NUMERICAL MODEL AND ASSESSMENT FRAMEWORK

Next to analytical evaluation, the combined effect of hydrodynamic dispersion, conduction and advection losses requires numerical simulations that simultaneously solve the groundwater flow and transport equations. The numerical simulations apply the assessment framework and model as was used in section 4.3. The simulation results are assessed relative to those for a single well. The simulations are carried out for the warm wells only, assumed to also be representative for cold wells. This is valid when there is no thermal interaction between warm and cold wells and the differences in both density and viscosity has negligible effect on the behavior of the stored heat in the aquifer. The validity was shown in section 4.2.

4.6.3. RESULTS

DISTANCE BETWEEN THE WELLS

ANALYTICAL / PARTICLE TRACKING RESULTS

This analysis was carried out for several different groundwater flow velocities and pumping schemes, with the results given in Table 4.6. The results in Table 4.6 distinguish between the displacement during infiltration, storage and extraction.

The first and the last pumping schemes in Table 4.6 (A & D) are beyond the situations in which ATES systems operate. During the night and in weekends, climate systems of buildings are often idle; during spring and autumn, energy demand may be so small that ATES systems are not running all the time. The ratio between storage and infiltration/extraction depends on the building and its operation, as well as on climatic conditions. ATES systems typically have a limited operation at nighttime, when buildings are not used. During daytime, ATES systems may also often be inactive when energy demand is small, as buffer tanks prevent the ATES wells from alternating and pumping at low capacity. It is therefore safe to assume that the storage time is between one half to one third of a year (B-C scenarios in Table 4.6).

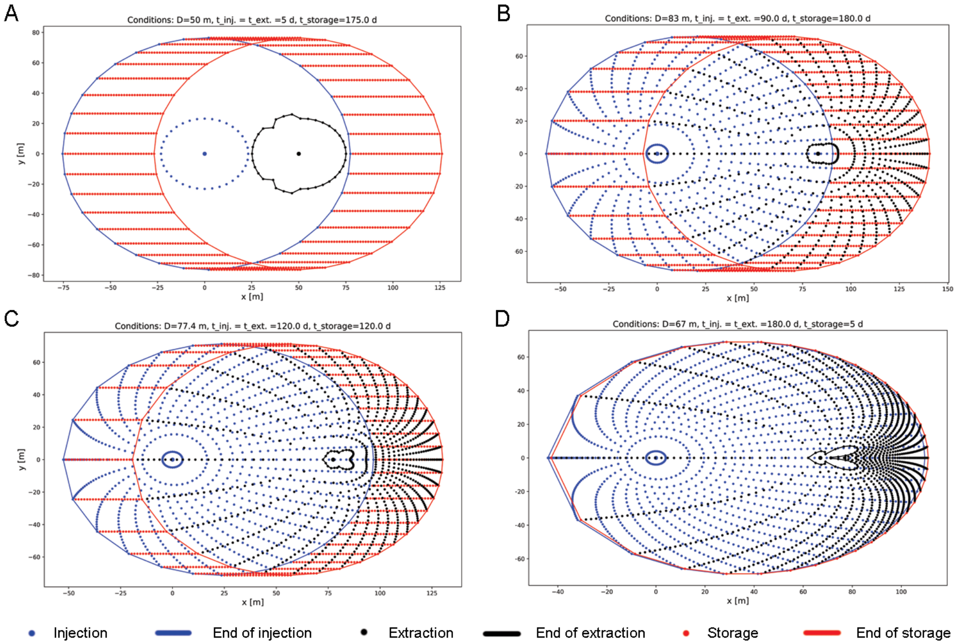


Figure 4.17: Results from numerical integration of Equation 4.17 for the conditions indicated in Table 4.6. Groundwater flow direction is to the right and velocity is 100 m/y.

The results in Table 4.6 show that during pumping the required distance between the wells to counteract the groundwater flow is invariably about 2/3 of the expected groundwater flow during the pumping period (underlined values in Table 4.6). The groundwater is also moved when the ATES system is inactive, which then suggests that the ratio between storage and pumping time determines the required distance between the wells. The well distance between the upstream infiltrating and downstream extracting wells should be around 80% of the yearly groundwater flow following the results for the B and C scenarios (bold) in Table 4.6. Corrected for the thermal retardation of 2 (Equation 4.2), this becomes around 40% of u. Figure 4.17 shows that all water particles are captured by the downstream well for the four scenarios indicated in Table 4.6.

The explanation for this constant 2/3, is that the average distance that all the particles travel in the direction of the groundwater flow is always 2/3 of the groundwater flow during the infiltration/extraction period. For example the B case in Figure 4.17: the upstream distance of the particle on the x-axis is -57.4m, the downstream distance 90.7m, so the average distance is 16.6m, the infiltration time is 90 days, so the ambient groundwater displacement 24.6m → 16.6/24.6=0.67. For example the D case in Figure 4.17: upstream distance is -44m, the downstream distance 110m, so the average distance is 33m, the infiltration time is 180 days, so the ambient groundwater displacement 49.3 m → 33/49.5=0.67.

The explanation and implications of these results are schematically depicted in Fig-

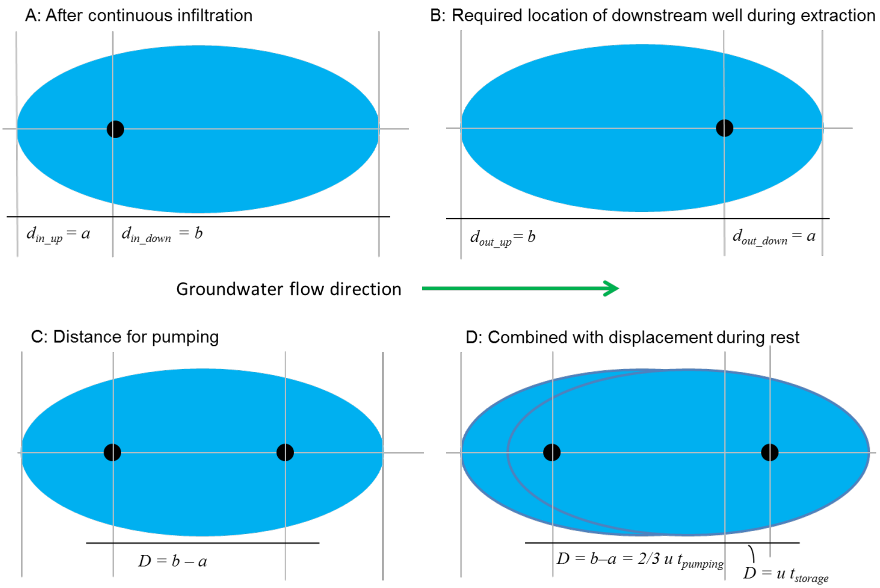


Figure 4.18: Schematic representation of required distance between upstream and downstream well for continuous infiltration followed by continuous extraction and same infiltration and extraction volumes ($V_{in} = V_{out}$)

ure 4.18. The pattern of flow lines of the upstream infiltration well during injection are mirrored for the extraction well during extraction. The stored thermal energy is also displaced when the ATES system is inactive (e.g. during nighttime). This then results in a required distance of:

$$D = \frac{b - a + ut_{storage}}{R} = \frac{u}{R}\left(\frac{2}{3}t_{pumping} + t_{storage}\right) \tag{4.18}$$

With a and b corresponding to the distances indicated in Figure 4.18, and $t_{storage}$ the time during which the ATES system is not operating. An important note is that this distance does not depend on the thermal radius, which is usually used as a metric to identify the opposite well type distance for ATES wells [24, 44, 104]. This is caused by the fact that the upstream and downstream distances (a and b) do not depend on storage/extraction volume and screen length, but on groundwater flow velocity and pumping time.

Basic simulations for counteracting the groundwater flow

The optimal strategy for the optimal distance between the upstream and downstream well under different ambient groundwater velocities is to place them at a mutual distance of around 40% of yearly groundwater flow (0.4 ut with t=1 year) in the direction of groundwater flow. However, due to existing infrastructure, such optimal placement is

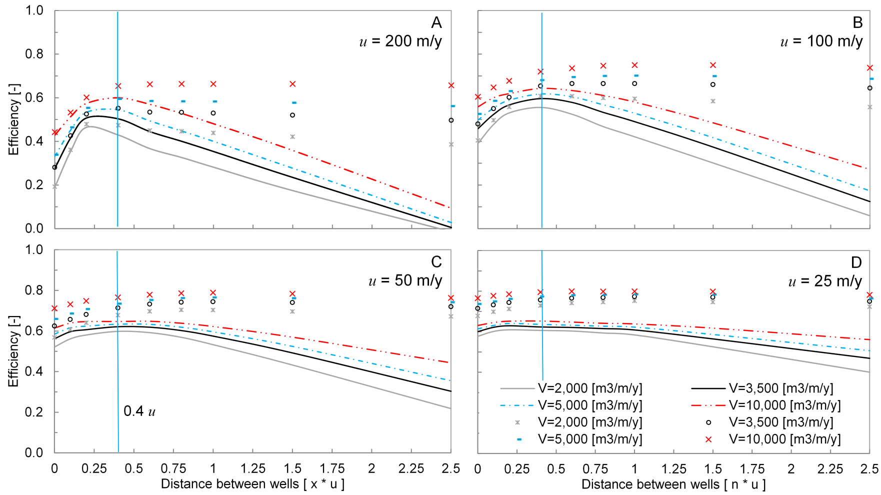


Figure 4.19: Numerically simulated efficiencies as a function of the distance between up and downstream wells for different specific storage volumes under a given groundwater velocity The lines are the 10-year average efficiencies, the markers show the thermal efficiencies during the last year of the 10-year simulation period. The efficiency is calculated using Equation 4.1

often difficult to achieve in most (dense) urban settings. In this section, numerical simulations are used to assess the effects of well distances which are either smaller or larger than optimal under ambient flow conditions.

Figure 4.19 shows the thermal well efficiency as a function of well distance (as a multiplier of the yearly groundwater velocity u), averaged over a 10-year simulation period (lines) and as achieved during the last simulated year (markers). The simulations were done for a range of specific-storage volumes[3] and a range of ambient groundwater flow velocities encountered in practice in section 4.3. As with to normal/single well storage, both the largest storage volumes and smallest groundwater flow velocity result in the highest efficiency. Efficiency is also less sensitive with the largest storage volumes and at the lowest groundwater velocity, compared to small ATES systems in aquifers with high groundwater flow velocity.

The calculated efficiencies confirm that the distance between the wells needs to be around the 0.4 u identified in previous subsection. Counteracting the groundwater flow also works when wells are placed at larger mutual distance as can be seen by the high and constant last year efficiency at $D > 0.4u$ (markers). But this has a negative effect on the total efficiency, as during the first year(s) of operation the heat does not yet reach the downstream well; this is reflected in the decrease of overall efficiency at larger mutual distance of the wells. This is illustrated in Figure 4.20 which shows the temperature for the downstream well during a 20-year simulation period for different well distances

[3]To allow for easy comparison between ATES systems sizes, the specific storage volume is used, which is defined as the storage volume per meter well screen (V/L). For the Dutch situation the specific storage volume varies between 2,000 to 10,000 m^3/m/y.

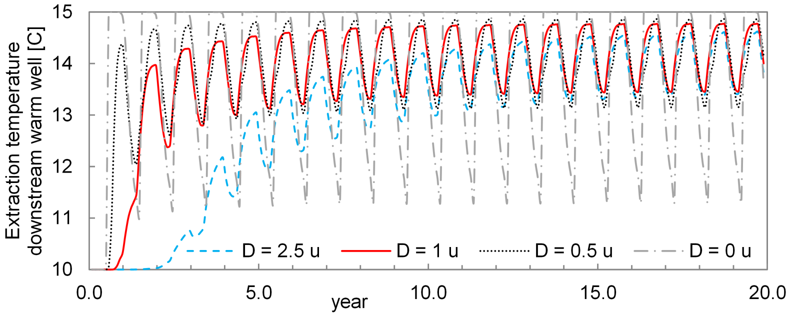


Figure 4.20: Extraction temperatures of the downstream well for different well distances. u=100m/y, constant injection temperature of 15°C, sinusoidal injection-extraction of volume of 250,000 m^3 in an aquifer of $L = 40$m with thermal retardation of 2

(note that $u = 100$ m/y), where the reference refers to the case with a single well (distance is zero).

Using a downstream well is always efficient in situations with high ambient groundwater flow. For larger distances, e.g. 2.5 u in Figure 4.20, it takes about 10 years to reach the highest efficiency. The efficiency can be derived from the extraction temperature of the downstream well always being lower than the 15°C injected.

However, the last year efficiencies (markers) show a flat optimum at $D > 0.4u$ in Figure 4.19, which indicates that efficiency hardly decreases when well distance increases. Only in the Figure 4.19-D subplot is a small decrease visible. The limited magnitude of these losses is partly caused by the model set-up for these basic simulations. The simulation of specific-storage volumes (V per meter screen length) allowed using thin model layers (which saved computational resources), but in turn results in relative larger losses to confining layers. Simulations with conditions closer to practice show a steeper decline in last year efficiency, which is to be expected due to the increased area over which conduction losses occur in the aquifer (i.e. across the circumference area).

The groundwater flow causes the stored heat in the aquifer to have a stretched shape, which in turn results in an increasing total area over which losses occur. The A/V-ratio can, therefore, be used as an indicator for the increase in losses with increasing well distance[4]. The A/V-ratio increases linearly with increasing well distance, the simulation results indicate that the optimal well distance has a relatively flat optimum for $D > 0.2u$ but it is best to try to stay as close to the recommended 0.4 u as possible.

[4] A/V-ratio is a metric for the expected conduction losses, see section 4.3.2 for detailed explanation. The yearly storage volume must be applied here, and not the total volume that is actually stored over multiple cycles in the aquifer (both are the same for the cylindrical case in section 4.3.2). Applying the volume of the stretched cylinder for V results in a smaller and constant A/Vratio of $1/R_{th} + 2/L$ at increasing well distance, instead of the $2/R_{th} + 2/L$ for cylindrical shaped storage volume (Equation 4.6).

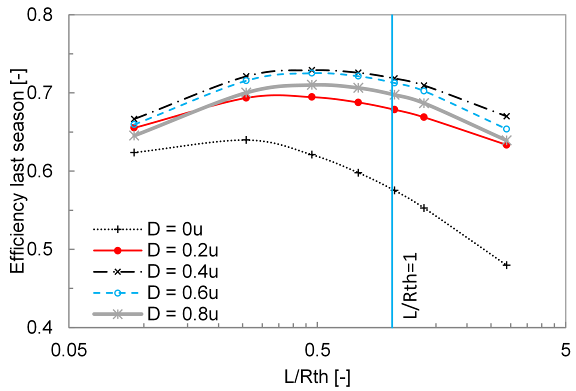


Figure 4.21: Recovery efficiency as a function of geometric properties of the storage volumes at different mutual well distances for 100 m/y groundwater and a yearly storage volume of 250,000 m^3/y. Only the screen length of the well is changed within the different simulation distance scenario's

WELL SCREEN LENGTH

The results in Figure 4.19 were obtained for a range of specific storage volume of ATES systems. In practice, aquifer thickness and storage volume, which both affect the thermal radius, will vary from place to place. Therefore, it is important to obtain insight in how mutual distance, thermal radius and screen length affect the heat losses. Bloemendal and Hartog [81] and Doughty et al. [82] used the geometric ATES well property, L/R_{th} (i.e. screen length over thermal radius), to assess conduction losses of ATES wells, section 4.3. Figure 4.21 shows the results of the last year's efficiencies for scenarios as a function of L/R_{th}. The differences in last year's efficiency among the distance scenarios are small at least for $D > 0.2u$. In addition, although heat losses increase with well distance, their magnitude ramains relatively small as was already noticed in Figure 4.19 .

Figure 4.21 shows that changing the wells' screen length has a large influence on the efficiency. Figure 4.21 shows that in the reference case ($D = 0$) the L/R_{th}-ratio has its optimum around 0.1, confirming that with single-well operation in high ambient groundwater flow, the thermal radius needs to be large [81]. The results for ($D > 0.2u$) show that to counteract ambient groundwater flow, the screen lengths need to be smaller compared to the 1 to 4 L/R_{th} bandwidth identified by Doughty et al. [82]. The required well distance has a flat optimum around 0.5 L/R_{th}. This is similar to the values found in Figure 4.13 for higher groundwater velocities with single wells.

PUMPING SCHEME OF THE UPSTREAM AND THE DOWNSTREAM WELL

This subsection discusses how the pumping schedule affects the overall efficiency. The basic scheme for counteracting the groundwater flow analyzed in previous sections is to only infiltrate in the upstream well and only extract from the downstream well. However, as discussed in the introduction, ATES systems with multiple wells have to use both wells during the coldest and warmest day to provide heating and cooling to the building.

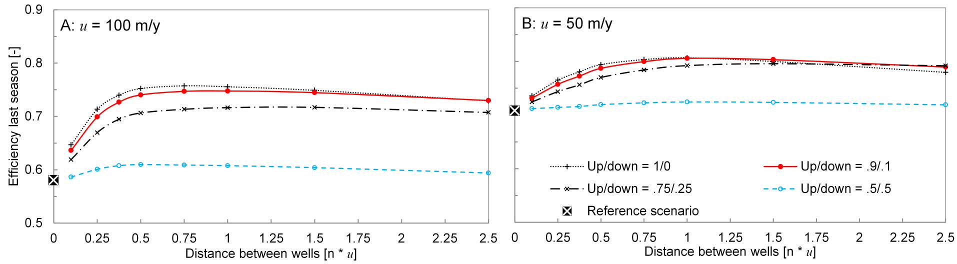


Figure 4.22: Simulation results showing last year efficiency over 20y simulation period for different groundwater velocities, distances between wells and pumping strategies for a yearly storage volume of 250,000 m^3/y.

To allow for flexibility during operation, different pumping schemes for upstream and downstream wells are analyzed next to identify how such schemes may affect optimal well distance and/or screen length.

Predefined pumping schemes

Four different pumping schemes were evaluated;

- The "1/0" scheme in which total storage volume is infiltrated upstream and extracted downstream
- The "0.9/0.1" scheme in which the second well is only used to cover peaks, so that 90% of the storage volume is infiltrated upstream and extracted downstream
- An intermediate scheme (0.75/0.25) in which the second well is used more frequently. In this scheme 75% of the volume is infiltrated upstream and extracted downstream
- The usual operation mode for a two-doublet ATES system in a non-flowing aquifer, which stores and extracts 50% of the storage volume in each well

For ambient groundwater velocities of 50 and 100 m/y Figure 4.22 shows the recovery efficiency achieved in the last year of the 10-year simulation period for different distances and pumping schedules. This shows that the pumping scheme is more important with higher ambient groundwater velocity. At a small mutual distance between the two warm wells, it is best to stay close to the 1/0 pumping scheme defined above, but the efficiencies for a pumping regime of 0.9/0.1 or 0.75/0.25 are almost the same. At $D > 0.4u$ (and $R_{th} < D$), the heat infiltrated in the upstream well does not reach the downstream well within one storage cycle. Figure 4.23 shows that some (25% of V) infiltration in the downstream wells helps improve the downstream well's efficiency during the first years of operation, resulting in higher extraction temperatures.

Automatic control of pumping scheme

During operation in practice, the downstream well is also needed for injection and the upstream well for extraction of heat During operation in practice, the downstream well is also needed for injection and the upstream well for extraction of heat, in order to

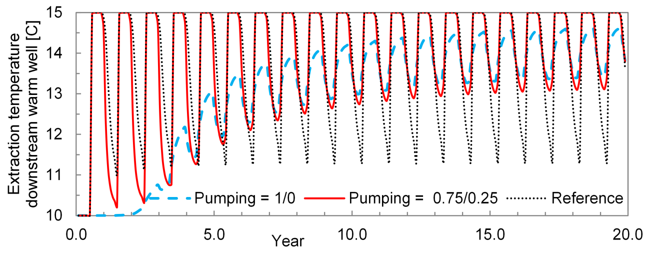


Figure 4.23: Extraction temperatures of the downstream well for different pumping schemes, u= 100m/y, D=250m (2.5u).

cover maximum demands. Because the pumping scheme has an impact on recovery efficiency, it is evaluated in more detail. However, identifying the optimal pumping strategy is complex: the number of possible pumping strategies is practically infinite, and under practical working conditions the required pumping capacity cannot be predicted, as it follows the building's energy demand – which in turn depends on highly uncertain factors such as weather conditions and the use of the building. As a result of differences in heating and cooling demand, the pumping scheme may commonly be asymmetrical.
The objective for identifying the optimal pumping scheme is to avoid the "escape" of heat away from the downstream well. Therefore, in the MODFLOW model, a temperature monitoring point downstream of the downstream well is used to automatically control the pumping scheme. The 0.5/0.5 pumping schedule is applied to the wells as a basic pumping scheme, which is then altered by the controlling temperature measured at the monitoring point at run-time. When the temperature in the monitoring point increases above a given threshold, pumping at the next time step is set to either a higher percentage of infiltration in the upstream well, or to a higher percentage of extraction in the downstream well, depending on whether the wells are in heating or cooling mode. The downstream distance of this monitoring point from the downstream well should not be farther than the downstream stagnation point. It must also be within the maximum thermal radius of the downstream well to provide rapid feedback.
Simulations were done with this control scheme for varying storage volumes (125,000; 250,000 and 500,000 m^3/y) and varying groundwater flow velocities (50; 75; 100; 150 and 200 m/y)). The optimized pumping schemes obtained from these simulations are presented in Figure 4.24; they show that schedules vary from 0.7/0.3 to 0.9/0.1. The temperature threshold or trigger temperature of the temperature monitoring point had virtually no effect on the obtained pumping schemes. The following observations and conclusion appear from the results in Figure 4.24;

- The larger the ambient groundwater flow velocity is, the closer the pumping scheme needs to be to the 1/0 scheme. This is logical, as the efficiency is more sensitive to the groundwater flow at higher velocity values.
- The larger the storage volumes/thermal radii, the closer the pumping scheme needs to be to the 1/0 scheme. This is counter-intuitive, as efficiency is generally less sen-

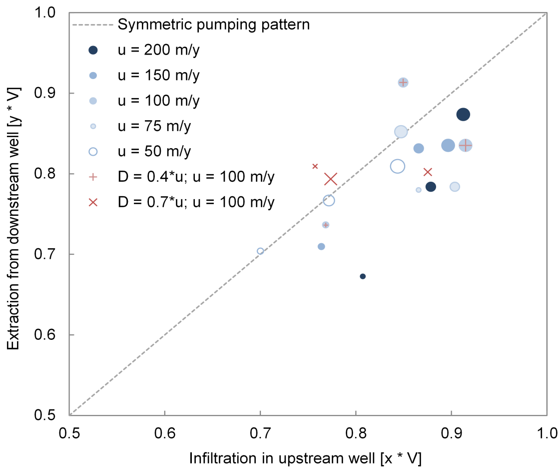


Figure 4.24: Multiplication factors (x, y) for the total amount of water that is infiltrated in the upstream and extracted from the downstream well, as was found by controlling the pumping schemes with a temperature monitoring point downstream of the downstream well for varying conditions. Size of indicator represents storage volume (125,000; 250,000 and 500,000 m^3/y), $D = 0.4u$, $L = 50m$.

sitive to disturbances at larger storage volumes. This is caused by the fact that at larger storage volumes, the temperature threshold in the monitoring point is exceeded earlier. This indicates that the location of the monitoring point should, therefore, consider the expected/required amount of time the ATES system needs to run on both wells.

- In all situations, the pattern between infiltration and extraction is more or less symmetric, with a light preference to more infiltration upstream. This can be explained by the fact that during infiltration, the temperature threshold will be reached sooner in the monitoring point.

This type of automatic control works well because the groundwater flow responds virtually instantaneously to the control signal, which prevents oscillations.

CASE STUDY OF AN ATES SYSTEM IN AN INCLINED AQUIFER

A case study is used to illustrate how the separately discussed aspects come together in practice. The city of Apeldoorn, in the east of The Netherlands, is situated on inclined[5] aquifers with large head gradients, in combination with high permeable (k_h = 30 m/d) sandy aquifers. The groundwater flow velocity in the local aquifer used for ATES in

[5] Please note that the effect of groundwater flow on ATES wells in horizontal and inclined aquifers can be treated similarly. In inclined aquifers the actual change in depth of the aquifer will be very limited in most cases. The depth of the two well screens may differ considerably only at very steep inclinations or large well distances, which then causes a slightly longer flow path between the wells, compared to their mutual distance at surface level.

Apeldoorn is about 35 m/y. At a site with multiple office buildings, a joint ATES system with two doublets and a total seasonal storage capacity of 425,000 m^3 is situated in this aquifer. The wells have a screen length of 40 m and a capacity of 175 m^3/hr each; the mutual distance between the wells is 200 and 150 m for the warm and cold wells respectively (5.7 *u* and 4.3 *u*), and both sets are aligned in the (expected) direction of the groundwater flow [88]. To prevent thermal interaction between the warm and cold wells, the sets of warm and cold wells are separated over 200 m perpendicularly to the groundwater flow direction. All wells are required to supply thermal energy to the different buildings during the warmest and coldest periods of the year.

The simulation results of this case in Figure 4.25-A shows that it takes 15 years before the extraction temperature of the downstream well stays above 13°C (with an infiltration temperature of 15°C), for different pumping schemes. An optimal pumping scheme of 0.65/0.35 is identified using downstream temperature monitoring to control the pumping scheme for the case study, Figure 4.25-C/D. The relatively large mutual distance between the wells causes much lower efficiency compared to the values indicated in Figure 4.19-C/D. The overall efficiency is of course low, due to the many years it takes before the heat reaches the downstream well. The temperature distribution in Figure 4.25-B/D also explains why the last year efficiency is much lower; the surface area of the footprint of the warm water between the wells increases considerably, compared to the situation where wells are located closer to each other. This results in conduction losses at the boundary of the warm zone in the aquifer, causing a lower efficiency. So contrary to the findings in the previous subsection, at very large mutual distance (>2.5 *u*) the increased size of the warm zone in the aquifer, therefore, results in such large conduction losses, that a pumping scheme closer to 0.5/0.5 works better.

The wells were not placed closer together in this case as, A) this research on identifying optimal distance was carried out after the ATES system in Apeldoorn was constructed but mainly as B) the aquifer is phreatic in which a small mutual distance of the wells would result in groundwater head changes that could affect the flora in the adjacent nature reserve. This illustrates that other design aspects may also affect choices in well design/location, which, sometimes unavoidably, result in a suboptimal well lay-out as is the case at this ATES system. However, the principles elaborated in this section do allow for technical optimization with respect to the geohydrological conditions in Apeldoorn.

4.6.4. Discussion & Conclusion

Discussion

The analysis in this section was done with a regular (sine-shaped) energy demand profile of the building and pre-defined pumping schemes. However, in practice the operation of the wells is not as straightforward as presented here. The automatic adjustment of the pumping scheme at runtime based on downstream temperature measurements showed to be an efficient way to optimize the pumping scheme. At the cost of an extra monitoring well with a temperature sensor and transmitter, such a direct control is applicable in practice and will also reduce heat loss (heat pollution) downstream. An important aspect to consider is that the location of the monitoring point should consider the expected volume to be pumped in the downstream well and the stagnation point of the well at low flow rates. Making smart choices during well installation may also help improve efficiency. With the presently applied sine-shaped energy demand profile and a combined pumping capacity of 100% for both wells, around 30% of the required volume has to be pumped at the "wrong" well. When installing wells with a capacity of 75% of the maximum required capacity instead of 50%, the percentage of pumping at the wrong well can be reduced to only around 10%. Especially for larger systems, and ATES systems in areas with groundwater flow velocity larger than 100 m/y, this considerably improves the recovery efficiency.

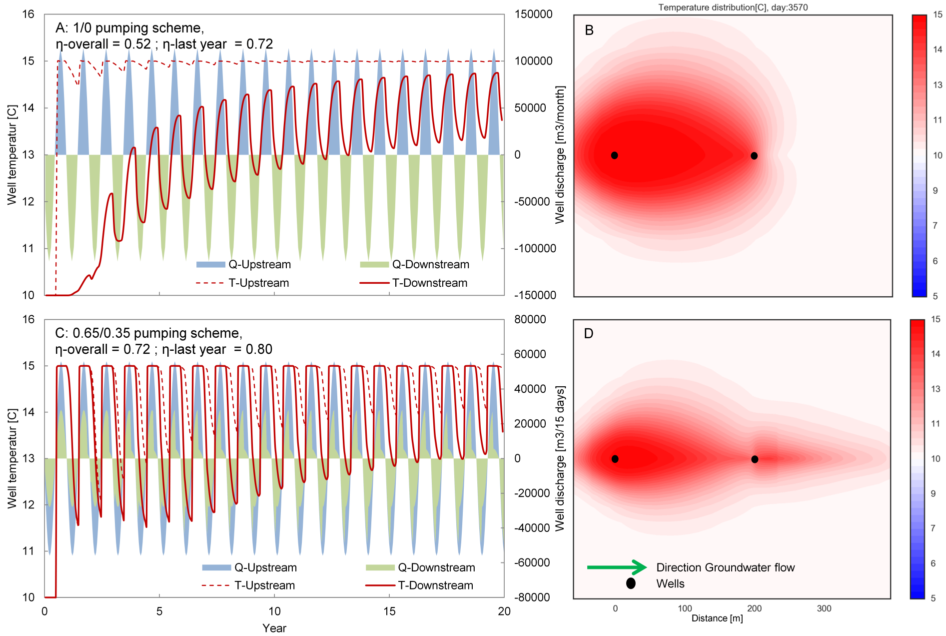


Figure 4.25: Temperature and discharge (A,C) of the warm wells and temperature distribution in the aquifer (B,D) at year 10 for the case site at predefined 1/0 (A,B) and automatically generated pumping scheme with downstream monitoring control (C,D) pumping scheme

In cases where flow direction and velocity change considerably, it is difficult to anticipate on with ATES well design and/or operation.

Despite the legal periodic requirement for energy balance, ATES systems never have exactly the same heating and cooling demand. This affects how efficiently the displacement of heat by groundwater can be compensated. However, under single doublet and no ambient flow conditions, an imbalance would affect operation similarly; more water is extracted from one of the well types, while thermal energy remains in the subsurface at the other well. This then results in a higher efficiency in one, and lower efficiency in the other well. When energy balance is not periodically met, one well type will completely recapture the infiltrated thermal energy, while the other will have a thermal plume downstream of the downstream well. In the condition with high ambient groundwater flow, such situations may even be preferable (when there are no other interests downstream), since the heat accumulation in one of the wells will not affect the other well in the long run.

A detail that was not discussed in this study is the effect of simultaneously injecting and extracting groundwater in the other well pair, regarding the distribution of the warm and cold water in the aquifer. Theoretically, the crosswise injection and extraction pattern as schematically depicted in Figure 4.16 means that the warm and cold groundwater is also pulled towards the downstream well of the other well pair. As such, collecting all the warm and cold groundwater requires the two downstream wells to be closer together than the upstream wells, as exaggerated and schematically represented in Figure 4.26-A. It is difficult to generalize the extent to which this mechanism affects the distribution of warm and cold groundwater, as it depends on local conditions and the position of the wells with respect to each other. For the averaged sized doublet, this appears to be negligible, as the change in efficiency of the warm well is smaller than 1% compared to the situation where the cold wells were not present in the model. This is also shown by the temperature distribution in Figure 4.26-B, where the wells are aligned in the direction of groundwater flow. This confirms the validity of the simulation approach in which only one of the well types was incorporated in the model.

At large distances between the wells, a deviation in flow direction of a few degrees may already result in a situation in which the downstream well can only partly recover the heat. Horizontal anisotropy may often cause the groundwater flow direction to be misinterpreted. Several exploratory simulations were carried out to assess this effect. The results show that a misinterpretation of the flow direction of 25° reduces efficiency by 7%, 17% and 29% for well distances of 0.4, 1 and 2 times the groundwater flow velocity, respectively. This confirms that at small distances between the wells, the recovery efficiency is less sensitive to the ambient groundwater flow direction.

The cost of additional wells may render the application of multiple wells unfeasible, at least for small ATES systems or buildings. For the smallest buildings, this may thus not be affordable. It is therefore wise to develop collective ATES systems in areas with high ambient groundwater flow. For aquifers with sufficient thickness, using two monowells aligned in the direction of the groundwater velocity may be a cost-effective substitute for two doublets.

CONCLUSION

This section provides guidelines for the optimal well placement and operation of ATES wells to counteract ambient groundwater flow. This can be done by using multiple warm and cold wells aligned in the direction of the groundwater flow, and is a suitable alternative for the recirculation systems (Figure 4.15) which are often applied in areas with high ambient groundwater flow velocity. The optimal distance between the wells is 0.4 times the yearly groundwater flow velocity (u). The well distance should at least be 0.2 u, while a larger mutual distance has a considerable negative effect on thermal efficiency during the first years of operation. Also, at larger distances, the heat losses to confining layers and surrounding aquifer increase due to the increase of overall area over which losses occur. Therefore, the well distance should be kept as close to 0.4 u as possible. Another

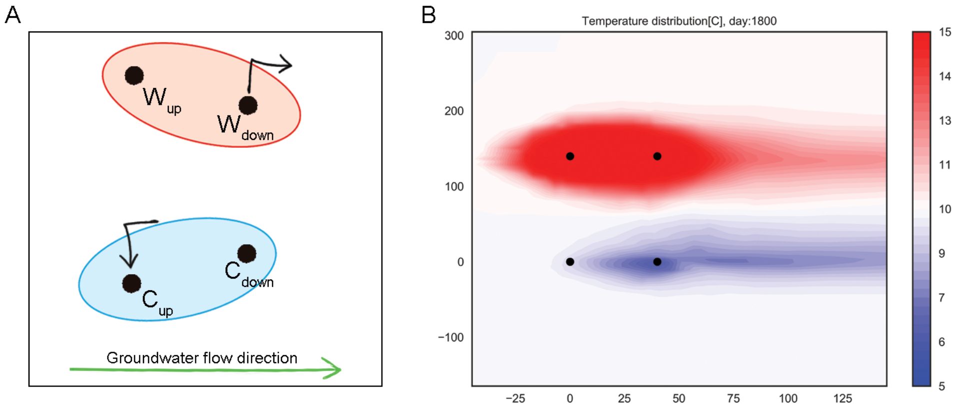


Figure 4.26: Effect of crosswise injection and infiltration and spreading of warm and cold groundwater. A: Schematic representation of the mechanism with exaggerated location of downstream wells, B: Simulation results with wells aligned in groundwater flow direction and $D = 0.4u$, $V = 250,000 m^3/y$, $L = 50m$, $u = 100m/y$, the 1/0 pumping scheme and the distance between warm and cold wells of $3R_{th}$,

advantage of a small mutual distance is that a deviation of the expected direction of the groundwater flow does not have a large impact on the efficiency of the system. Screen length should be chosen shorter compared to when there is no groundwater flow: the ratio between screen length and expected thermal radius should be around 0.5, in order to minimize conduction losses.

While using two wells to counteract the groundwater flow, it is always best to infiltrate upstream and extract downstream. However, during energy demand peaks in mid-winter and mid-summer, it may be needed to also use the upstream well for extraction and the downstream well for infiltration. The highest efficiency is achieved when the upstream well is used preferentially for infiltration and the downstream well for extraction, while using the other wells as little as possible during periods when the required discharge is larger than a single well can deliver.

At low groundwater flow velocities and small ATES systems, the efficiency is less sensitive to the proposed optimal distance and the pumping strategy. The higher the groundwater flow and the larger the thermal radius of the ATES system, the more important it is to stay as close to the 0.4 u distance and to the pumping scheme where infiltration is in the upstream well and extraction in the downstream well.

Animations of the basic simulation scenarios can be found at martinbloemendal.wordpress.com. The used code can be send to you on request to the author, running the code requires python and flopy.

APPENDICES SECTION 4.6

APPENDIX 4.6-A: DERIVATION PARTICLE TRACKING

The specific discharge q_x [m/d] by a well in an aquifer with a uniform ambient flow along a line through the well parallel to the ambient flow in direction x equals:

$$q_x = \frac{Q}{2\pi Lx} + q_0 \tag{4.19}$$

With $Q > 0$ injection [m^3/d] and $q_0 > 0$ the ambient specific discharge in the positive x direction, and the well location is $x = 0$. This automatically implies that A) $q_x > 0$ when $Q > 0$, $x > 0$ and $q_0 = 0$ and B) $q < 0$ when $Q > 0$, $s < 0$ and $q_0 = 0$ and vice versa when $Q < 0$. The stagnation point x_s is where $q_x = 0$ so:

$$0 = \frac{Q}{2\pi Lx_s} + q_0 \tag{4.20}$$

$$x_s = -\frac{Q}{2\pi Lq_0} \tag{4.21}$$

In this expression the direction of the ambient groundwater flow along the x-axis automatically deals with the location of the stagnation point. When infiltrating ($Q > 0$) the stagnation point is always upstream from the well, while when extracting ($Q < 0$) it is always downstream. The flux can, therefore, be written as:

$$\frac{q_x}{q_0} = 1 - \frac{x_s}{x} \quad and \quad q_x = q_0\left(1 - \frac{x_s}{x}\right) \tag{4.22}$$

which is the same as:

$$\frac{u_x}{u_0} = 1 - \frac{x_s}{x} \quad with \quad u = \frac{dx}{dt} : \quad \frac{dx}{dt} = \left(\frac{x - x_s}{x}\right) u_0 \tag{4.23}$$

Which can be rearranged / rewritten as follows:

$$\left(\frac{x}{x - x_s}\right) dx = u_0 dt \tag{4.24}$$

$$\left(\frac{x-x_s}{x-x_s}+\frac{x_s}{x-x_s}\right)dx = u_0 dt \tag{4.25}$$

$$dx+\frac{x_s}{x-x_s}dx = u_0 dt \tag{4.26}$$

Allowing integration on both sides, which then yields:

$$x + x_s ln(x-x_s) = u_0 t + C \tag{4.27}$$

The integration constant C can be solved from the boundary condition $x = x_0$ at $t = 0$, so that

$$C = x_0 + x_s ln(x_0 - x_s) \tag{4.28}$$

So that

$$x - x_0 + x_s ln\left(\frac{x-x_s}{x_0+x_s}\right) = u_0 t \tag{4.29}$$

Check: Taking the derivative of Equation 4.29 again yields Equation 4.23 (Equations 4.30 to 4.34)

$$\frac{dx}{dt}+\frac{x_s}{x-x_s}\frac{dx}{dt} = u_0 \tag{4.30}$$

$$\left(1+\frac{x_s}{x-x_s}\right)\frac{dx}{dt} = u_0 \tag{4.31}$$

$$\left(\frac{x}{x-x_s}\right)\frac{dx}{dt} = u_0 \tag{4.32}$$

4

$$u = \left(\frac{x - x_s}{x}\right) u_0 \tag{4.33}$$

$$u = \left(1 - \frac{x_s}{x}\right) u_0 \tag{4.34}$$

To determine x as a function of t numerical root-finding can be done with the Newton-Raphson method. For this, Equation 4.29 is turned into a function y of x for which we seek x such that $y = 0$.

$$y = x - x_0 + x_s ln\left(\frac{x - x_s}{x_0 + x_s}\right) - u_0 t \tag{4.35}$$

The Newton Raphson method also requires the first derivative of y with respect to x:

$$y' = 1 + \frac{x_s}{x - x_s} \tag{4.36}$$

With y and y', x can be determined iteratively as follows:

$$x_{t+1} = x_t - \frac{y_t}{y'_t} \tag{4.37}$$

The first thing to notice in the Equation 4.29 and 4.35 is that the argument of the logarithm must be larger than 0 for it to exist. This means that that the numerator and the denominator have the same sign, which can be physically interpreted by that x is always on the same side of the stagnation point as x_0. Both during extraction and infiltration time goes to infinity when $x \rightarrow x_s$, because then the argument of the logarithm approaches 0 and hence the logarithm approaches to +/- infinity for infiltration and extraction respectively. During extraction the sign changes because Q is then negative.

The effect of a density gradient in groundwater on ATES system efficiency and subsurface space use

Everything should be made as simple as possible, but not simpler

Albert Einstein

Aquifer Thermal Energy Storage Systems (ATES) are often placed in aquifers in which salinity increases with depth. This is the case in coastal areas where also the demand for ATES application is high due to high degrees of urbanization in those areas. The seasonally alternating extraction and re-injection between ATES wells disturbs the preexisting ambient salinity gradient causing horizontal density gradients, which trigger buoyancy flow, which in turn affects the recovery efficiency of the stored thermal energy.
This section uses analytical and numerical methods to understand and explain the impact of buoyancy flow on the efficiency of ATES in such situations, and to quantify the magnitude of this impact relative to other thermal energy losses. The results of this research show that losses due to buoyancy flow may become considerable at (a relatively large) ambient density gradients of over 0.5 kg/m^3/m in combination with a vertical hydraulic conductivity of more than 5 m/d. Monowell systems suffer more from buoyancy losses than do doublet systems under similar conditions.

Section 4.7 is submitted for publication in peer reviewed conference proceedings. The introduction section has been modified to prevent repetition and to fit within the storyline of this thesis.

4.7. ATES wells in aquifers with a salinity gradient

4.7.1. Introduction

Motivation and goal

ATES systems concentrate in urban areas, because their wells have to be placed in close vicinity to their associated building to limit connection costs and heat losses during transport. The world's largest urban areas continue to expand near seas and oceans, making them future hot spots for ATES systems, Chapter 2. Yet, groundwater in coastal areas is often brackish to saline with increasing salinity and, therefore, increasing density with depth [43, 107, 108]. Because ATES wells penetrate aquifers over substantial depths, groundwater with different salt concentrations enters the well screens and is subsequently mixed inside these wells and the piping circuit. After heat exchange with the associated building, the groundwater is injected into the same aquifer with a uniform but possibly time-varying salt concentration. This re-injection disturbs the preexisting ambient density distribution. It also causes horizontal density gradients, which trigger buoyancy flow. This buoyancy flow influences the spatial distribution of the injected water and heat and, therefore, also has an impact on the recovery efficiency of the thermal energy stored in the subsurface. The influence of an initially vertical ambient density gradient on the immediate and long-term recovery efficiency of ATES systems has not yet been studied in detail. As a consequence, it has hitherto not been taken into account in the design and operation of ATES systems. Only Caljé [43] identified the problem and used numerical simulations to analyze the density impact for one specific ATES system in Amsterdam. The current study aims to systematically evaluate how disturbance of the pre-existing salinity distribution in the aquifer that is caused by ATES operations affects their thermal efficiency and their use of subsurface space. This analysis requires identification of which parameters affect the buoyancy most; these parameters can then also be used to identify possible controls to limit the associated heat losses.

Buoyancy flow around ATES wells

Warm and cold ATES well screens can either be separated horizontally, in which case each pair is called a doublet, or vertically in a single borehole, in which case the screen pair is called a monowell (Figure 4.15). The buoyancy flow behaves differently at doublets compared to monowells. The two systems are, therefore, discussed separately. The behavior of the buoyancy flow is schematically shown in Figure 4.27 for both types of ATES wells, where Figure 4.27-A) illustrates a doublet and Figure 4.27-B a monowell.

Doublets

The yellow gradient color in Figure 4.27-A, indicates that the ambient groundwater density becomes larger with depth. The injected water has a uniform density as is indicated by the uniform yellow, which is the result of mixing of the water, pumped from the paired well of the doublet. The injected water is, therefore, lighter than the groundwater near the bottom of the aquifer and heavier than the groundwater near the top of the aquifer. Hence, the interface tilts towards the well, both at the top and the bottom of the aquifer. This mechanism causes the interface between injected and ambient water to remain vertical in the middle of the aquifer, where the density of the injected water practically equals that of the ambient groundwater at that depth. When the injected water does not mix with the ambient groundwater, the injected water will eventually end up in the middle of the aquifer where ambient and infiltrated densities match. However, after the seasonal storage period, the infiltrated water is extracted again (Figure 4.27-A3), at least to the extent possible.

The red color marks where the groundwater and aquifer temperature is changed by the injection. Note that the temperature interface lags behind that of the density interface, due to thermal retardation (section 4.2). The thermal retardation adds complexity; it separates the temperature and salinity interfaces. Both interfaces are illustrated in Figure 4.27-A. The buoyancy-induced flow is strongest at the density interface, and does not fully exercise its tilting effect at the temperature interface. Nevertheless, the buoyancy flow during infiltration, storage and recovery has as a consequence that not all the previously stored water and heat can be later extracted; some is left behind and at least some water with ambient density and temperature is extracted instead, which affects the temperature of the extracted water.

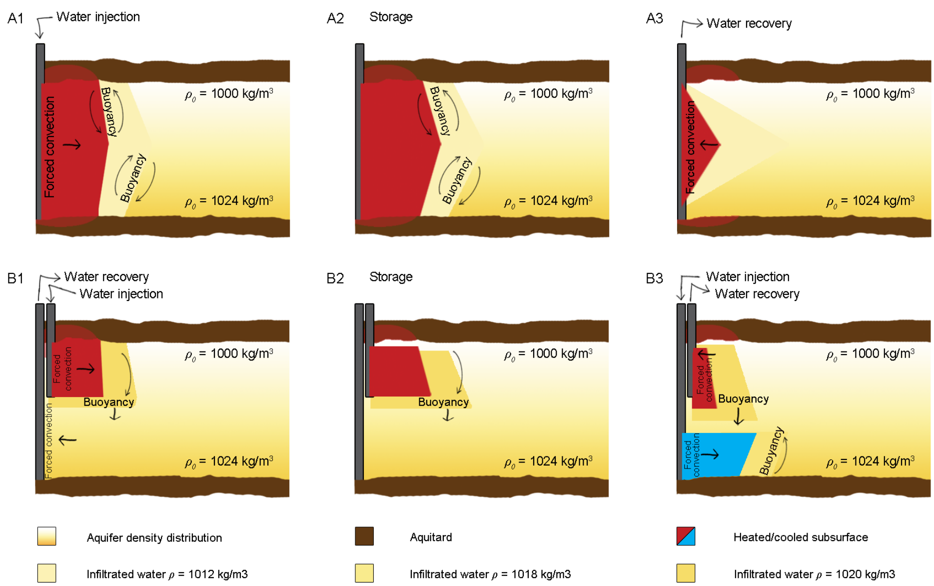


Figure 4.27: Schematic representation of disturbance of a density gradient by warm well of a doublet (A) and monowell (B) ATES system.

MONOWELL

Due to the well screens at the top and bottom of the aquifer, the density differences between the ambient and infiltrated water are larger than in the case of a doublet. This results in stronger buoyancy flow. The water extracted from the lower screen has a higher density than the ambient groundwater opposite the upper screen through which it is re-injected. Therefore, the interface between injected and ambient groundwater tilts inward near the top of the screen and outward near the bottom. This water also sinks because of its higher density with respect to the ambient water between the upper and lower screens, Figure 4.27-B1 and B2. The interface tilts faster near the top of the upper screen than near its bottom where the density difference between injected and ambient groundwater is less. The opposite happens when the mixed water from the top screen is injected through the bottom screen, where it encounters heavier ambient groundwater. The interface will tilts faster towards the well near the bottom of the screen than near its top where the density difference between the injected and ambient groundwater is less. At the same time the injected bubble tends to float upwards. The tilting causes early entry of native groundwater into the extracting screens. This is associated with a loss of thermal energy and, therefore, with a loss of thermal efficiency of the ATES system involved. At the same time, such mixing dilutes the interface into a transition zone, which will also reduce the tilting velocity over time, and with a growing number of seasonal cycles. In the longer run, the buoyancy flow and its associate energy losses may, therefore, become negligible.

Approach

This section is divided into three parts to identify the main drivers, parameters and possible controls of buoyancy flow around ATES wells.

- The specific working conditions are identified first. Both ATES systems and geohydrological characteristics are considered, which define the scenarios to be analyzed. Next to defining an assessment and simulation framework, this first part provides the parameter values necessary to identify the strength and effect of buoyancy flow around ATES wells.
- The second part applies analytical tools to determine the magnitude of the buoyancy flow and its expected effect on the thermal efficiency of the wells. This part serves to provide insight into which parameters affect buoyancy flow most, and when buoyancy may be neglected.
- Numerical simulation is used to deal with the complex behavior of the combined processes of buoyancy, heat conduction, hydro-dynamical dispersion, mixing, repetitive storage and injection, and retardation of the thermal front.

4.7.2. Method and Materials

Working conditions and scenarios

ATES systems characteristics

ATES systems in The Netherlands cover a wide range of subsurface thermal energy storage capacity, which mainly depends on the size of the associated building. In sufficiently thick aquifers, like the 150 m thick one below the city of Amsterdam, around 40% of the ATES systems are monowells, see summary in Table 4.7. The storage volumes of these

Table 4.7: ATES-well properties in Amsterdam (rounded) [109], *V*=seasonal storage volume, *L* = screen length, *z* = depth of top of screen

	Monowells				Doublets		
	V	L	z_{warm}	z_{cold}	V	L	z
	[m^3]	[m]	[m-sl]	[m-sl]	[m^3]	[m]	[m-sl]
Perctile 0,1	40,000	10	60	90	75,000	15	70
Average	100,000	20	75	125	250,000	50	90
Percentile. 0,9	160,000	30	85	170	500,000	85	100

Table 4.8: Geohydrological conditions in Amsterdam [43]

Layer	Depth	k_{xy}	k_z	Salt concentration	Density
	[m-sl]	[m/d]	[m/d]	[kg/m^3]	[kg/m^3]
Aquitard	0 to -70	1	0.1	1	1001
Aquifer	-70 to -170	35	3.5	1-10	1001 – 1010
Aquitard	-170 to -175	0.0001	0.00001	10	1010

systems correspond with those presented in section 4.3. However, due to the large thickness of the aquifer and the larger buildings served, ATES systems in Amsterdam tend to be larger and to have longer screens than those elsewhere in the Netherlands, where aquifers are thinner and cities smaller.

Geohydrological conditions

In the Netherlands, ATES is applied in aquifers with a thickness between 10 and 150 m (section 4.3). This wide range overlaps with that in most other countries, which allows generalizing the Dutch experience. The horizontal hydraulic conductivity in those aquifers ranges from 5 to 50 m/d (section 4.3), vertical anisotropy ratio between 2 and 20 [110], which results in a vertical hydraulic conductivity range from 0,25 to 25 m/d. The salinity gradient strongly depends on local geohydrologic conditions and the material and geologic history of the aquifer. Aquifers near the coast to the extent that they have sufficient continuous recharge, have a relatively sharp interface between fresh and saline water. Aquifers with zero or little recharge tend to have a smooth, up to an almost constant vertical density gradient [111, 112].

Scenarios

To obtain insight under what circumstances a vertical density gradient in the aquifer may have a considerable impact on thermal energy performance of ATES systems, the analysis in this study uses the conditions identified in Table 4.7 and Table 4.8:

- Storage volumes per well are between 40,000 and 500,000 m^3/ year. The storage and recovery is distributed over a year following a block or sine function to represent the seasonal operation scheme.

- The infiltration temperature is 5 and 15°C for the cold and warm well respectively.
- Well-screen lengths and aquifer thickness are between 10 and 150 m.
- The vertical density gradient is linear and varies from 0.05 to 1 kg/m^3/m. The smallest gradient represents a thick aquifer with fresh water at the top and brackish water at the bottom; the largest gradient represents the extreme case of a thin aquifer of about 35 m thickness with fresh groundwater at the top and seawater at the bottom.
- The vertical hydraulic conductivities studied are low (0.5 and 1 m/d), medium (5 and 10 m/d) and high (25 m/d) respectively.
- Losses due to interactions between wells are not taken into account in this section; wells are assumed to be placed at sufficiently large distance from each other, i.e. on at least 3 times the thermal radius for doublets [24] and on 1/3rd of the aquifer thickness for monowells [113].

ASSESSMENT FRAMEWORK

THERMAL RECOVERY EFFICIENCY

In this study, focusses on storage of heat, but the results also apply to storage of cold water used for cooling. As in other ATES studies [82, 96], the recovery efficiency (η_{th}) of an ATES well is defined as the amount of injected thermal energy that is recovered after the injected volume has been extracted (Equation 4.1, section 4.2.1). The recovery efficiency is used as parameter to compare the simulation results of the scenarios outlined above to identify how much buoyancy flow affects the performance of ATES systems.

THERMAL RADIUS

The planning and organization of ATES systems is based on thermal radius of the wells as design criterion. Because buoyancy flow disturbs the dominant horizontal flow field around the wells, density driven convection may also affect the extent of these thermal radii. The change in thermal radius caused by buoyancy proves mainly important for doublet wells (Figure 4.27). The thermal radius identified in Equation 4.5.

NUMERICAL MODELING OF DENSITY AND TEMPERATURE

While the buoyancy flow causes energy losses, also conduction, dispersion and diffusion affect the efficiency of the ATES wells. SEAWAT [114] not only dynamically couples MODFLOW [64] and MT3DMS [65], that is flow and transport [63, 115], but adds viscosity and density coupled to temperature and salt concentration. To gain insight in these intertwined mechanisms, a basic model was set up, without neighboring wells and ambient groundwater flow. An axisymmetric SEAWAT model with a high vertical discretization was applied to simulate in detail the vertical flow components in the entire aquifer and along the well screen [83, 116]. Lopik et al. [83] calibrated an axisymmetric model of a high temperature (80°C) ATES system against monitoring data, in which buoyancy flow was a dominating process. The model set-up and parameter values in this study follow their work.

- Discretization. The grid applied with SEAWAT is a vertical section of one row, with distance along the columns and depth along the layers. The wells screen(s) are in different layers in the first column. A doublet is represented by 3 rows, where the two outer rows, model the warm and cold well, while the middle row was set to inactive to prevent interaction between the outer rows. The horizontal discretization is 2 m at the well face, cell size grows logarithmically with radial distance to a maximum of 250 m at the outer boundary of the model, in 50 steps. The Courant number is the ratio transport distance during one time step over the cell size, [117] and should be smaller than 1 for accurate calculation. In this set-up it is larger than 1 close to the well, with an applied time step of five days, and smaller than one at several meters away from the well and onwards, where buoyancy flow, conduction, dispersion matter.

- Model layers. To allow for sufficient detail and insight in the vertical buoyancy flow component, the layers are also discretized at high resolution; 0.5 m thickness, irrespective the thickness of the aquifer that is simulated. The model can be thought of to consist of an aquifer that is confined by 10 m thick aquitards at its top and bottom. No recharge was applied. Constant head, temperature and salinity boundaries were applied at outer boundary. The inner and lower boundary at $r = 0$ were closed. The top of the upper confining layer has a constant temperature.
  The aquifer thickness varies over the simulated scenarios. The wells screens of the doublets were always fully penetrating and those of the monowells always penetrated the top and the bottom third of the aquifer. The flow from the injection screen entering different model layers is calculated proportionally to the transmissivity of each model layer.

- Model extent and time horizon. To prevent boundary conditions from influencing simulation results, several test runs were carried out. These showed that the outcomes changed less than 1% with the outer boundary set at 1500 m. The time horizon was set to 10 years as these test runs showed was sufficiently long to evaluate the effect of multiple years of operation until stable recovery efficiency was achieved and to fully assess the buoyancy flow impact and its dynamics.

- Parameter values. The parameter values follow Lopik et al. [83] adapted to axisymmetric flow according to Langevin [116]. These values are given in Table 4.9. The viscosity and density dependency on temperature and salt concentration was implemented following Equations 4.39 and 4.40. The extraction temperature and salt concentration as calculated by SEAWAT for every cell representing the well screen, are averaged in proportion to cell transmissivity. The thus computed extracted salinity is used as infiltration salinity of the coupled well screen.

- The groundwater flow was solved using the PCG 2 package. The standard finite-difference method with upstream or central-in-space weighting was applied in the advection package.

Table 4.9: SEAWAT simulation parameters

Parameter	Value	Package
Solid heat capacity*	710 kJ/kg °C	RCT
Water reference density	1,000 kg/m^3	RCT
Solid density*	2,640 kg/m^3	RCT
Water thermal conductivity	0.58 W/m/°C	RCT
Solid thermal conductivity	2.55 W/m/°C	RCT
Thermal distribution coefficient#	$1.7 \cdot 10^{-4}$ m^3/kg	RCT
Thermal retardation+	2.21	RCT
Porosity	0.3	BTN
Specific storage aquifer	$6 \cdot 10^{-4}$ /m	LPF
Longitudinal dispersion	0.5 m	DSP
Transversal dispersion	0.05 m	DSP
Vertical dispersion	0.005 m	DSP
Effective molecular diffusion heat#	0.15 m^2/day	DSP
Effective molecular diffusion salt	$8.64 \cdot 10^{-6}$ m^2/day	DSP

THE EFFECT OF SALT CONCENTRATION AND TEMPERATURE ON DENSITY AND VISCOSITY

Both the density and viscosity of the water are a function of salinity, temperature and pressure. However, for the depth range of interest, the dependency of pressure is negligible [83, 118]. The geohydrological conditions and ATES characteristics identified in the sections above are now used to determine to what extent density and viscosity are affected by changes in salt concentration and temperature. In groundwater modeling the often-used equation [114] of state for density (ρ [kg/m^3]) as a function of temperature and salt concentration is;

$$\rho(S,T) = 1000 + 0.78S - 0.375T \tag{4.38}$$

where T is the temperature of the water [°C] and S the total salt concentration [kg/m^3] [119–121]. However, the slope of this linear approximation for the temperature influence is too steep over the range of 5 to 15°C in which ATES operate. Figure 4.28-A shows this by plotting Equation 4.38 in grey contour lines together with the non-linear density relation as described by Sharqawy et al. [118] as shown in colored filled contours. For this study Equation (4.38) is replaced by;

$$\rho(S,T) = 1000 + 0.78S - 0.1T \tag{4.39}$$

to correct the density- temperature slope for the 5 to 15°C temperature range, from -0.375 to -0.1. This yields the white contour lines in Figure 4.28-A. Salt concentration and temperature also affect fluid viscosity (μ [kg/m/d]), to which the hydraulic conductivity is proportional [110]. The relation between viscosity, salt concentration and temperature may be approximated following Voss [122];

$$\mu(S,T) = 2.394 \cdot 10^{-5} \cdot 10^{\frac{248.8}{T+133.2}} + 1.923 \cdot 10^{-6} S \tag{4.40}$$

Figure 4.28-B shows that viscosity depends much stronger on temperature than on salt concentration over the range of temperature and salt concentration identified for this study. Around warm wells, flow in the subsurface is enhanced by the increased hydraulic conductivity caused by the reduction of viscosity with higher temperatures [110]

This research neglects the geothermal gradient. At common values for the geothermal gradient like also present in The Netherlands (0.03 °C/m), the density change is dominated by the increasing salt concentration. The geothermal gradient has a larger influence on the viscosity change, it is still neglected because the thermal front is retarded with respect to injected water front, the dominating buoyancy flow occurs at the injected water front, so without a significant viscosity difference [6].

4.7.3. ANALYTICAL ANALYSIS OF BUOYANCY FLOW

The mechanisms involved in the heat transport are described in section 4.2. The effect of horizontal ambient groundwater flow on the recovery efficiency of water stored in aquifers has been studied extensively e.g. [85, 86] and previous sections of this chapter. Vertical flow components as a consequence of buoyancy flow have also extensively studied, e.g. [107, 108, 123, 124]. In the next subsection the usability of analytical relations found in these studies is evaluated for the purpose of establishing the magnitude of buoyancy flow around ATES wells and its most important parameters.

MIXED CONVECTION RATIO

Massmann et al. [107] define the mixed convection ratio (M) to identify which processes dominate during the periods of infiltration, extraction and storage in situations where buoyancy flow is involved.

$$M = \frac{D}{\Delta h} \frac{\rho_{in} - \rho_0}{\rho_0} \tag{4.41}$$

[6] Also after several storage cycles the temperature distribution around the well is mainly determined by the losses in previous cycles rather than the geothermal gradient, in simulations with long well screens the viscosity effect would be stronger than with short screens which complicates comparison of simulation results across different scenarios and the density changes also with depth which again makes it difficult to distinguish between both processes.

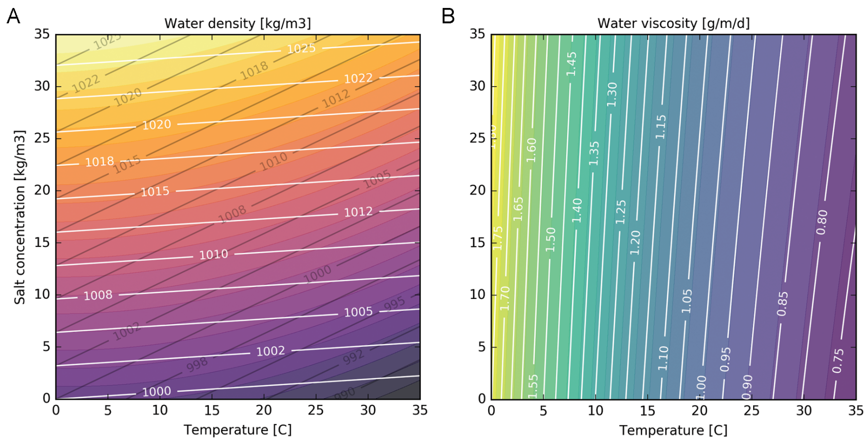


Figure 4.28: A: Water density as a function of temperature and salt concentration. Color filled contours are Sharqawy et al. [118] grey lines: Equation (4.38), white lines: Equation (4.39). B: Water viscosity as a function of temperature and salt concentration, Both colored filled contours and white lines: Equation (4.40)

with Δh the difference in hydraulic head between the screens of the wells [m] and D is horizontal distance between the screens [m]. The first factor in Equation 4.41 is proportional to the forced convection while the second is proportional to the buoyancy. According to Massmann et al. [107], mixed convection ratios larger than 1 indicate dominance of buoyancy flow, while $M < 1$ indicates dominance of forced convection. This metric was used to identify to what extent buoyancy flow dominates during the storage phase only or during storage, infiltration and extraction. Because the density of the ambient groundwater varies with depth, the largest occurring density difference between injected and ambient groundwater along the well screen, was used in Equation 4.41 to determine the mixed convection ratio. For monowells the vertical distance between the bottom of the top and the top of the bottom screen is used for the D in Equation 4.41. The results are plotted in Figure 4.29 for the full range of combinations in density gradient and vertical hydraulic conductivity defined in section 4.7.2. The monowells generally have a higher mixed convection ratio, which indicates that buoyancy losses are larger for monowells than for doublets. At the largest density gradient (1 kg/m^3/m) the mixed convection ratios are little over 1, indicating that only under extremely large density gradient conditions the buoyancy flow may have a large impact on thermal efficiency of the ATES wells.

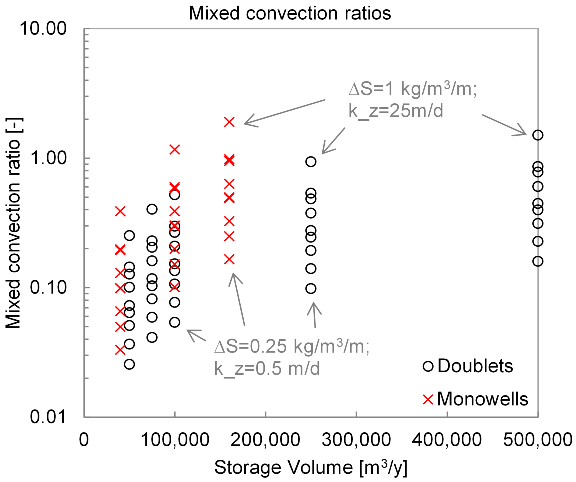


Figure 4.29: Mixed convection ratios for ATES systems conditions following Table 4.7 and Equation 4.41. The head difference between the two wells was estimated conservatively to not underestimate the mixed convection ratio; for doublets 10, 7 and 5 m, for monowells 6, 4 and 2 m for k-values of 0.5, 10 and 25 m/d respectively. The distance between the well for doublets is set to $3R_{th}$, and $1L$ for monowells.

Characteristic tilting time of the density difference interface

Because the density-forced tilting of the interface between the injected and ambient groundwater continues until the equilibrium situation is reached, the time this tilting process takes relative to the storage cycle length is an important measure to identify how strong the losses due to buoyancy flow are. Hellström et al. [123] derived an expression that quantifies the characteristic tilting time of an axially symmetric interface between fresh and salt water:

$$t_0 = \frac{1}{\omega_0} = \frac{c_{aq}}{c_w} \frac{L}{\sqrt{\kappa_h \kappa_v}} \frac{\pi^2(\mu_0 + \mu_1)}{32Gg(\rho_0 - \rho_1)} \tag{4.42}$$

With ω_0 the initially vertical front rotation angular velocity, t_0 the characteristic tilting time [s], κ_h and κ_v the horizontal and vertical aquifer permeabilities [m^2], μ_0 and μ_1 the viscosities of the ambient and the injected water [kg/m/s], ρ_0 and ρ_1 the densities of the ambient and the injected water, G the Catalan's constant [7] [0.915 -] and g the gravitational constant [9.81 m/s^2]. However, due to three aspects, this relation is not completely valid for calculating the tilting time of the injected water or thermal front in the case of ATES systems;

1. At the condition of interest, the initial ambient density increases linearly with depth and, therefore, also across the interface between the injected and ambient ground-

[7] Catalans constant is a mathematical constant used in estimates of finite or countable discrete structures.

water, while Hellström et al. [123] assume homogenous ambient density. Due to the ambient density gradient, it is expected that rotation of the interface varies with aquifer depth because the density difference between injected and ambient water increases towards both the top and the bottom of the aquifer (Figure 4.30-A), which results in increasing rotation speeds towards the top and bottom of the aquifer. This increasing rotation speed towards the top and bottom of the aquifer results in a curved interface between injected and ambient groundwater, see Figure 4.30-B. For this study, the largest density difference at the top and bottom of the aquifer is used to compute the tilting times with Equation 4.42. This results in an overestimation of the average characteristic tilting time of the water interface.

2. Hellström et al. [123] assume that the interface of density difference coincides with that of viscosity, but around an ATES well the jump in viscosity is at the thermal front, which lags behind the water front, as can be seen from Figure 4.28-B and Figure 4.30-B. The computed tilting times are, however, not corrected for this thermal retardation effect, which results in an underestimation of the characteristic tilting time of the front of the injected water.
   The tilting at the thermal interface is less strong than at injected water front because the buoyancy flow components decline with distance to injected water front. According to Hellström et al. [123] the width (w_c) of a free convection cell around the tilting interface is the aquifer thickness (L) over the anisotropy factor (a_v). The amount of decline is expressed by the ratio (d_r) of the width of the free convection cell over the distance between the thermal and the injected water front ($0.33R_h$, Equation 4.5):

$$d_r = \frac{w_c}{0.33R_{th}} \tag{4.43}$$

   This distance ratio (d_r) expresses the extent to which the thermal front lies within the convection cell of the injected water front. When d_r is close to 1 the tilting is strongly excersized on the thermal front, when it is close to 0 the thermal front is hardly affected by buoyancy flow.
   For small storage volumes and/or long screen lengths, the tilting of the injected water front affects tilting of the thermal front stronger than in the case of large storage volumes and/or short screens. In the case of a sufficiently large thermal radius relative to the aquifer thickness, the width of the free convection cell may become smaller than $0.33R_h$, in which case tilting of the thermal front will not occur at all. With anisotropy factors ranging from 2 to 10 and aquifer thicknesses from 10 to 150 m, the widths of the free convection cells that occur around ATES wells vary between 1 to 150 m.

3. Due to thermal retardation, any tilting of the thermal interface rotates at about half the speed of the tilting rate of the water front.

Despite the limited validity of Equation (4.42), it is still valuable to get an indication of the order of magnitude of the characteristic tilting times relative to the length of the storage-

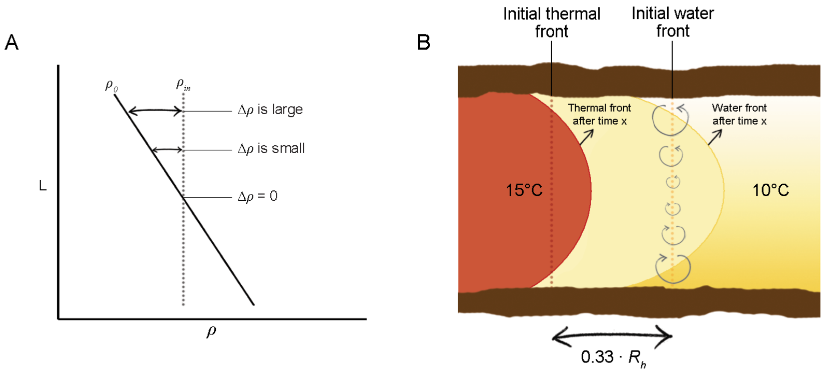


Figure 4.30: A: schematic representation of the differences in density of injected and ambient groundwater along the screen (L). B: Schematic representation of development of tilting along an interface between infiltrated water with a constant density in an aquifer with a density gradient along aquifer depth.

Table 4.10: Characteristic tilting times of water interface of two different densities, according to Equation (4.42), corrected for heat retardation. The screen lengths (L) follow the corresponding values of Table 4.7. Maximum ratio of width of the free convection cell and distance between water and thermal front for the range of conditions identified in Table 4.7, values>1 indicate that the buoyancy at the water front affect the thermal front.

k_z		*0.5*			*5*			*25*		*[m/d]*
L & V	*0.1 perc.*	*avg.*	*0.9 perc.*	*0.1 perc.*	*avg.*	*0.9 perc.*	*0.1 perc.*	*avg.*	*0.9 perc.*	*(Table 1)*
ΔS	0.1	0.25	1	0.1	0.25	1	0.1	0.25	1	*[kg/m^3]*
Monowells										
t_0	2726	1097	284	273	**110**	**28**	**55**	**22**	**6**	*[d]*
max d_r	0.5	0.8	**0.9**	0.5	0.8	**0.9**	0.5	0.8	**0.9**	*[-]*
Doublets										
t_0	8171	3286	307	817	329	**85**	**55**	**66**	**17**	*[d]*
max d_r	0.3	0.7	0.8	0.3	0.7	0.8	0.3	0.7	0.8	*[-]*

cycle. The characteristic tilting times calculated, are initial tilting times, which progressively increase. So, at a characteristic tilting time equal to, or smaller than the storage period, heat loss due to buoyancy can be considerable. Storage periods of ATES systems last typically about a quarter year, so that with characteristic tilting times of 90 days or shorter, buoyancy flow may considerably reduce the recovery efficiency of ATES wells.

The obtained tilting times are presented in Table 4.10, together with the values of the distance ratio (d_r) for the range of conditions identified in Table 4.7 and Table 4.8. The identified tilting times and distance ratios (d_r) show that buoyancy flow may have a considerable effect on recovery efficiency at only some of the most extreme conditions, i.e. combination of high conductivity, large density gradient and long screens. In general buoyancy has a stronger impact on monowells, due to the larger density differences as a consequence of the position of the screens in the top and bottom of the aquifer.

4.7.4. NUMERICAL SIMULATION OF BUOYANCY FLOW

Despite the limited validity of the analytical approximations worked out in the previous section, it is concluded that, at high vertical conductivity combined with a large ambient salinity gradient, the buoyancy flow may affect ATES efficiency, especially for monowells. However, the analytical solutions only take into account the initial situation and disregard feedbacks of the spreading of dissolved salt and heat with time propagating over multiple storage cycles. In this section, numerical simulations are used to study such propagation effects over several ATES cycles. These simulations also quantify the effect of buoyancy flow on the recovery efficiency as well as the effects of mechanical dispersion and conduction. This is done for the ranges in monowell and doublet systems and geohydrological conditions identified in section 4.7.2. The losses are compared to those under the same circumstances, but with a constant density in the aquifer.

IMPACT OF THE AQUIFER'S DENSITY GRADIENT ON ATES EFFICIENCY

MONOWELLS

Table 4.11 shows the density and temperature distribution around an average-sized monowell at 4 moments in the first year of operation, these figures are used to discuss the processes of buoyancy flow and heat loss around the monowell screens.

The average recovery efficiencies of both warm and cold screens after 10 cycles are shown in Figure 4.31-A for different vertical conductivities as a function of the vertical salinity gradient. The losses due to buoyancy flow are negligible for small vertical hydraulic conductivities and/or small salinity gradients, while the losses increase for increasing salinity gradients and vertical conductivities, reaching over 50% under the most extreme conditions. In all scenarios, the recovery efficiency stabilizes after 4 to 6 storage cycles.

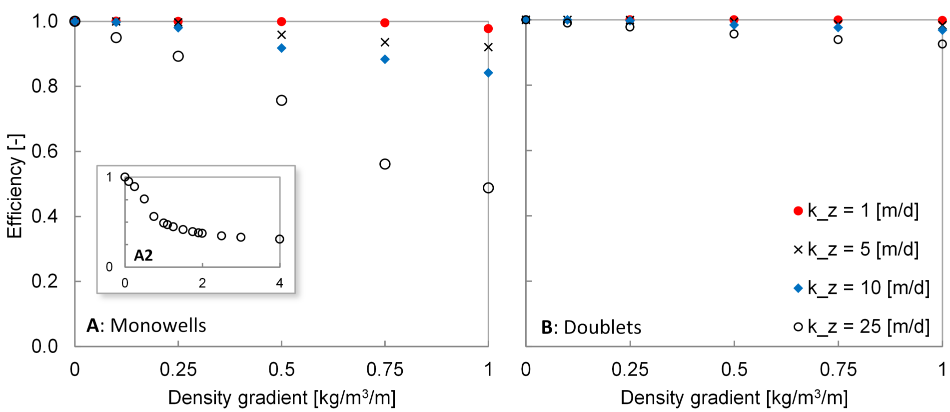
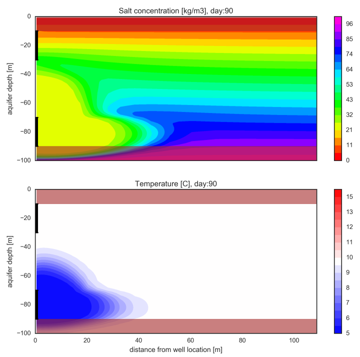


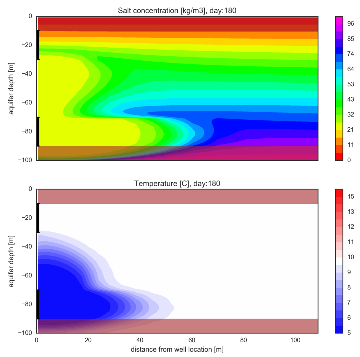
Figure 4.31: The average recovery efficiency after 10 year simulation period as a function of density gradient and different geohydrological properties, for average sized A) Monowell and B) Doublet systems.

The short description and cross sections shown in Table 4.11 are now used to discuss

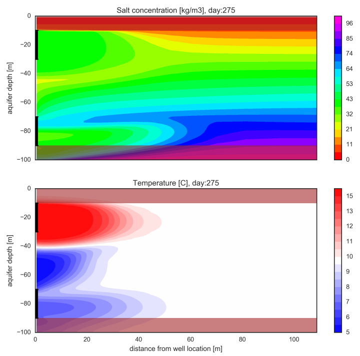
Table 4.11: Cross-sectional overview of density and temperature change for a monowell with: storage volume = 100,000 m^3, vertical conductivity = 10 m/d, density gradient = 1 kg/m^3/m, the screens are located on the Y-axis; top 10-30 m-sl, bottom 50-70 m-sl. N.B. the relatively large vertical conductivity causes the infiltrated water to also move in between the two wells due to short circuit flow during simultaneous infiltration and extraction.



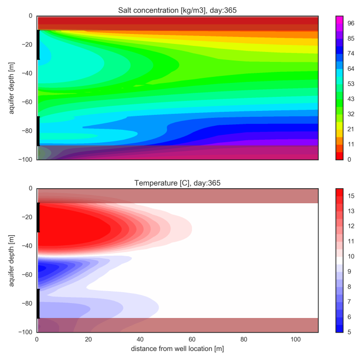
1. Cold-water injection - end of winter During the first storage period (winter) relatively light water extracted from the upper (warm) screen, is stored through the deeper screen. The thermal retardation can be seen from the difference in the propagation of heat compared to that of salt concentration. This figure shows that already during infiltration water starts to move upwards. This may not only be caused by the buoyancy, but also by the short-circuit flow between the two screens.



2. Cold-water storage - begin of summer During the storage of cold water, buoyancy causes the cold water to flow towards the top of the aquifer; this water may not be retrievable by the lower screen during cold-water extraction during summer. The thermal retardation limits the speed at which the cold front migrates to the upper screen.



3. Warm-water injection - end of summer The water extracted from the deeper screen and infiltrated in the upper screen, no longer has the low density that it had when it was previously infiltrated. It has become denser compared to when it was infiltrated, due to the buoyancy flow during storage. At the end of the warm water infiltration period, ambient salt concentration from the deeper parts of the aquifer is infiltrated through the upper screen.



4. Warm water storage - end of autumn During the storage of warm water, buoyancy causes the warm water to flow towards the bottom of the aquifer, which may not be retrievable by the upper screen during winter. The downward movement of the heat is, however, much less compared to the upward movement of the cold water during the storage period. This is caused by the smaller density difference between the extracted water from the bottom screen and the ambient water at the top screen, because the previously stored water in the bottom screen came from the top screen.

the relations shown in Figure 4.31-A. The relations in Figure 4.31-A can be best explained following the discussion in step 2 of Table 4.11: The ambient vertical density gradient and the vertical conductivity determine the extent at which the infiltrated water is affected by buoyancy flow. In the example in Table 4.11, both are relatively large, which results in strong upward flow during cold-water storage and also in strong downward flow during warm-water storage. But when the vertical conductivity and ambient density gradient are small, then during cold-water storage, buoyancy flow is low, and the extracted water from the lower screen during summer has a density that is still much closer to the ambient density at the upper screen, which results in smaller changes of the density differences during storage in the upper screen and fewer losses than is the case in Table 4.11, step 4.

This discussion explains why in Figure 4.31-A the relation between efficiency and ambient density gradient has a flat slope when the vertical conductivity is small. At first, the losses at the both screens remain limited, but become aggravated as the conductivity and density gradient continue to increase, which results in a steeper slope. This can be seen in Figure 4.31-A for the simulation results with k_z=25m/d. For the case k_z=25m/d, simulations were carried out for (hypothetical) ambient density gradients up to 4 kg/m^3/m just to show how the relation between ambient density gradient and efficiency propagates beyond 1 kg/m^3/m (see sub-plot Figure 4.31-A2). The flattening of the slope of the efficiency versus density gradient with higher ambient density gradients in Figure 4.31-A2 is caused by the following mechanism: the upward movement of the light water (yellow in step 2 of Table 4.11) injected in the lower screen can only reach the lower part of the upper screen, because ambient groundwater of a higher density (green in step 2 of Table 4.11) enters the middle part of the upper screen.

DOUBLETS

Both wells of the doublet usually have their screen at the same depth. Therefore, their thermal energy losses are equal. The efficiency of both the warm and the cold well over 10 cycles are shown in Figure 4.31-B. The figure shows that also for doublets, both the vertical conductivity and vertical density gradient affect the losses due to buoyancy, however, less strongly than for monowells. Also, all doublet wells reach stable recovery efficiencies after 4 to 6 cycles. The results of these numerical simulations did not show any considerable changes in the maximum extent of thermal radius over the 10-cycle simulation period. Figure 4.32 shows the density and temperature distribution around the warm well after the first warm-water storage period for both 0 and 1 kg/m^3/m ambient density gradients. Figure 4.32-D confirms the gradual tilting of the thermal front that was discussed in section 4.7.2 and schematically indicated in Figure 4.30.

THE EFFECT OF WELL DESIGN ON BUOYANCY LOSSES

Next to buoyancy flow, the spreading of heat by conduction and dispersion at the boundary of the thermal cylinder and advection by groundwater flow are the dominant processes that cause energy to be unrecoverable for the ATES well [43, 81, 91]. Different design strategies are now evaluated to firstly identify the relative contribution of conduction, dispersion and buoyancy losses and secondly, to identify possible controls to maximize overall efficiency.

Doughty et al. [82] and Bloemendal and Hartog [81], use the ratio of screen length

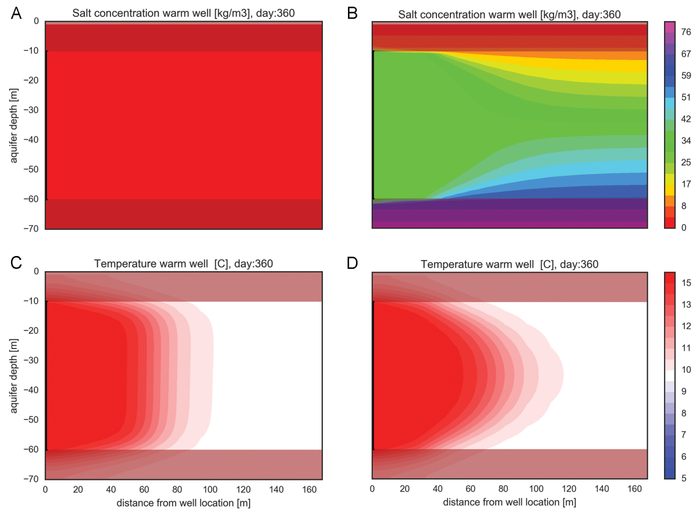


Figure 4.32: Cross-sectional overview of density (AB) and temperature (CD) distribution after one year of operation of a warm well, k_z = 10 m/d, storage volume = 250,000 m^3, fully penetrating screen located on the y-axis at 10-60 m-sl. AC. no density gradient, DB. a gradual density gradient of 1 kg/m^3/m.

over thermal radius (L/R_{th}) as a design criterion to ensure maximum heat-recovery efficiency. They found that this ratio should be between 1 and 4. Next, it is identified what values of this L/R_{th}-ratio lead to optimal well design when buoyancy flow contributes to the heat losses. The contribution of buoyancy to the heat losses is investigated by simulating scenarios with and without a vertical density gradient. The increase of dispersion caused by buoyancy flow is considered negligible.

Earlier in this section it was shown that the losses due to a vertical density gradient are only important when both this gradient and the vertical hydraulic conductivity are high. Therefore, the relative influence of conduction, dispersion and buoyancy is considered only at the maximum ambient density gradient of 1 kg/m^3/m and vertical conductivity of 5 m/d for the range of ATES system sizes and screen lengths indicated in Table 4.7. The average ATES system size is used as a base case and altered systematically over the ranges identified in section 4.7.2.

MONOWELLS

Figure 4.33 shows the simulation results. Distinction is made between the recovery of heat on the one hand and losses due to conduction-dispersion and buoyancy on the other.

Figure 4.33-A shows the result of a stepwise increase of the screen length for a constant storage volume. Simulations for other storage volumes are not shown because the results show the same trend. The smallest screen length yields the smallest buoyancy losses because the density difference between the upper and the lower screen is then smallest. N.B. the screen length of the simulated monowell is one third of the aquifer

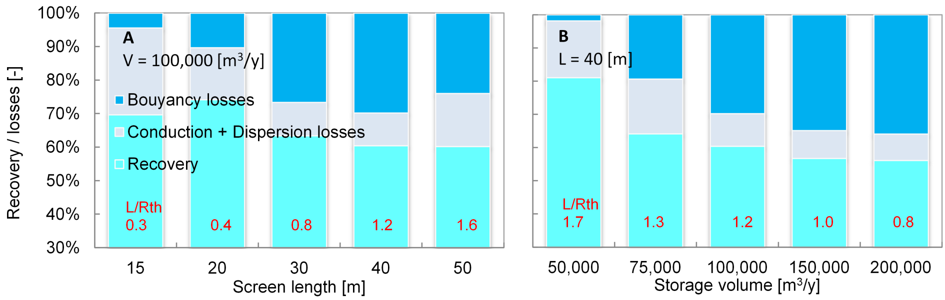


Figure 4.33: Heat recovery, buoyancy, conduction & dispersion losses, relative to monowell design and storage volume at 1 kg/m^3/m density gradient and vertical conductivity of 10 m/d. Short circuit flow between wells contribute to losses as well, those could not be separated from the results. At the smallest screen lengths and largest storage volumes the conduction and dispersion part is likely to also contain the losses to short circuit flow. This also explains the low recovery efficiency in those cases.

thickness. Therefore, small screens imply smaller density differences both at and between the screens. The conduction and dispersion losses are large because of the low L/R_{th}-ratio, which results in large conduction losses to the confining layers.

With the stepwise increase of the screen length, Figure 4.33-A shows that at the first steps, the buoyancy losses increase due to the greater density differences between the upper and the lower screen. The conduction and dispersion losses become smaller due to the increased L/R_{th}-ratio, which reduces the total area of the circumference of the heat volume in the aquifer and thus the losses due to conduction and dispersion.

At the largest well-screen lengths conduction and dispersion losses increase again, where the optimum L/R_{th}-ratio is exceeded. For the smallest storage volume conduction and dispersion even dominate the buoyancy losses.

In situations without a density gradient, increasing the storage volume results in a higher efficiency. Remarkable is the observation that recovery decreases with increasing storage volume as shown in Figure 4.33-B. This is explained by the fact that at larger storage volumes more heat can flow towards the other screen. Because the thermal radius is larger, any vertical buoyancy flow results in larger heat losses. With same the well-screen length an increasing storage volume, also the short-circuit flow increases. For monowells, larger storage volumes are more sensitive to losses caused by buoyancy flow and short-circuit flow than to dispersion and conduction. Despite the lower relative dispersion and conduction losses expected at larger storage volumes, larger storage volumes may lead to lower recovery rates than smaller storage volumes in these specific conditions.

Both the losses due to buoyancy and those due to conduction are strongly affected by the applied length of the screens of the monowells. For short screens, dispersion and conduction losses are largest as a result of large conduction losses to confining layers. For the longest screens, buoyancy losses generally dominate because then density differences between the top and the bottom screen are larger. The highest efficiency is attained for intermediate screen lengths, where neither type of losses dominates.

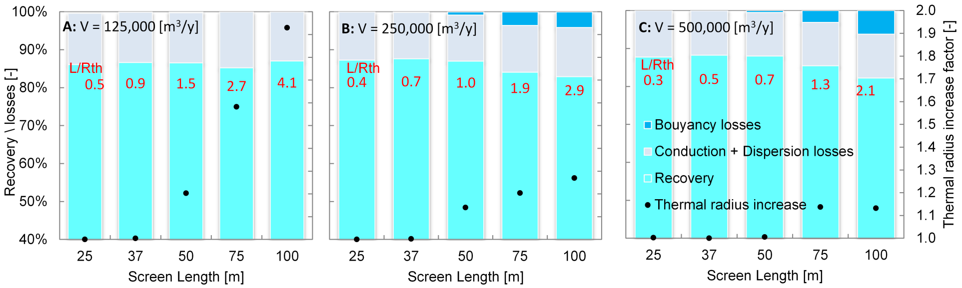


Figure 4.34: Heat recovery, buoyancy and conduction & dispersion losses, relative to doublet well design and storage volume at 1 kg/m^3/m density gradient and vertical conductivity of 10 m/d

DOUBLETS

Similar to the monowells, longer well screens cause larger buoyancy losses for doublets, see Figure 4.34. For doublets, the buoyancy flow does not affect efficiency as much as for monowells. The small buoyancy losses that characterize doublets, also limit the increase in thermal radius that is caused by the buoyancy flow. Counter-intuitively, the increase in thermal radius is only considerable for the smallest storage volume (Figure 4.34-A), with its characteristic high ratio of screen length over thermal radius. The buoyancy-induced change in thermal radius is more or less constant over the range of simulations carried out for doublets; it varies from hardly noticeable for a short screen, to about 15 m for the longest screen (100 m).

CASE STUDY AMSTERDAM

To also include practical aspects in this evaluation, design and monitoring data were obtained for a monowell system in the city of Amsterdam. The local density gradient of 0.28 kg/m^3/m was derived from water-quality samples taken at the installation, see Table 4.12. Xynogalou [113] found an anisotropy of 8 for the aquifer below Amsterdam boiling down to a vertical hydraulic conductivity of 6 m/d with some variations at different depths, which is consistent with earlier work from Caljé [43]).

The axisymmetric model was adapted to the conditions for this monowell system and simulated for the situation with and without the ambient density gradient. Because the two screens are relatively far apart and short, also scenarios were simulated where screens are twice as long (14 m) and placed closer together (20 m instead of 28 m). Thick aquifers like the one used in this case are often intersected by thin clay layers. The effect of such layers was also explored by adding a 2 m thick clay layer between the two wells. The first two simulation results in Table 4.13 show that for the situation as installed, the density gradient in the aquifer under Amsterdam does not affect the efficiency much.

Adding a thin clay layer in between the screens results in an overall efficiency improvement, due to the improved thermal efficiency of the cold screen. Following the mechanisms discussed in this section it can be expected that in this case the warm screen suffers from the largest buoyancy flow, which hardly depends on a clay layer in between the screens. This clay layer prevents the heat from moving close to the cold

Table 4.12: Monowell characteristics provided by ATES contractor Installect B.V.

Screen	Upper	Lower	
Type	Warm	Cold	
Top screen	65	100	*[m -sl]*
Screen length	7	7	*[m]*
Salt concentration	1.2	11.1	*[kg/m^3]*
Seasonal storage	10,000	15,000	*[m^3]*
Average infiltration temperature	19.5	8.5	*[°C]*

Table 4.13: Average extraction temperatures and overall efficiency of the 3 year simulation of the case study ATES system at different alternative well designs and aquifer conditions

Case	Warm *[°C]*	Cold *[°C]*	η *[-]*
No density gradient	16.1	11.4	0.71
As installed	15.9	11.4	0.7
Clay layer	15.9	11.2	0.72
Screens closer together	15.2	12.9	0.6
Longer screen	15.7	11.2	0.7

screen, which results in an improved efficiency of the cold screen.

The two cases with the altered screens (last two lines in Table 4.13) suggest that the short-circuit flow between the two screens has a larger effect on efficiency than the losses due to buoyancy flow. In the previous subsection, the spacing between the screens was kept the same as the screen length. The effect of the distance between the screens was evaluated, for several scenarios described in Table 4.14, for a monowell with average storage volume. The results in Table 4.14 confirm that short-circuit flow between the two screens has a larger influence than the buoyancy.

Table 4.14: Average extraction temperatures and overall efficiency of the 3 year simulation of the average Monowell system at different alternative well spacing distances and aquifer conditions. V = 100,000 m^3/y, k_v = 6 m/d.

	Screen Spacing	Warm *[°C]*	Cold *[°C]*	η *[-]*
no gradient	1L	17.2	10.1	0.82
	2L	17.3	9.2	0.87
Amsterdam	1L	17.1	10	0.82
	2L	17.3	9.2	0.87
1 kg/m^3/m	1L	16.5	10.1	0.79
	2L	17	9.2	0.85

Conclusions numerical simulations

The thermal losses due to buoyancy for monowells affect recovery efficiency by more than 5% at a vertical density gradient over 0.5 kg/m^3/m combined with a vertical hydraulic conductivity over 5 m/d. Doublets are not sensitive to heat losses caused by buoyancy flow, even under the most extreme conditions is the efficiency decrease less than 10%. Within the conditions pertaining to the Netherlands, buoyancy losses caused by a vertical ambient density gradients are negligible for both monowells and doublets.

4.7.5. Discussion and Conclusion

This study shows that within the conditions pertaining to coastal aquifers in the Netherlands (described in section 4.7.2), an ambient vertical density gradient has a negligible effect on the thermal recovery efficiency of ATES systems. An ambient density gradient of over 0.5 kg/m^3/m, combined with a vertical conductivity over 5 m/d, has a considerable impact on the efficiency of monowell ATES systems, but these do not occur in the Netherlands.

The largest vertical ambient density gradient of 1 kg/m^3/m evaluated in this research, leads to a groundwater density that exceeds seawater density in the lower part of aquifers with a thickness larger than 35 m. Although groundwater with salinities of several times that of seawater also occurs in parts the Netherlands at depths larger than 1000 m, this is not the case for the shallow aquifers used for ATES. Therefore, it is not likely to encounter considerable thermal energy losses due to buoyancy flow in low-temperature ATES practice in brackish or saline aquifers in the Netherlands, as well as other coastal areas.

Well design can help reduce heat losses caused by buoyancy flow; a longer screen increases the density differences between upper and lower (part of the) screens, thus aggravating buoyancy losses. This is, however, compensated for by a smaller thermal radius, which limits these buoyancy losses, especially for monowell systems. To obtain the highest recovery efficiency, the results indicate that in case of buoyancy flow, the optimal L/R_{th}-ratio needs to be chosen smaller than the thresholds identified by Doughty et al. [82] and Bloemendal and Hartog [81]. For monowells it is more important to prevent short-circuit flow between the screens, which requires sufficient spacing between the top and bottom screen.

Animations of the basic simulation scenarios can be found at martinbloemendal.wordpress.com. The used code can be send to you on request to the author, running the code requires python and flopy.

5

METHODS FOR PLANNING OF ATES SYSTEMS

For every MWh_{th} spent in organizing, a GJ_{th} is earned

adapted from Benjamin Franklin

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 chapter 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.

This chapter is published in Applied Energy journal **216**, 534-557 (2018)[125]. The introduction and methods sections have been modified to fit within the storyline of this thesis and to prevent repeating statements/explanations.

5.1. INTRODUCTION

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. Chapter 2 showed 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 [12, 22]. 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 [23]. 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 [9], 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 [57, 58], due to which a spacious safety margin around the wells is obligatory so as to prevent mutual interaction. On top of that, monitoring data show that ATES systems generally use less than 50 % of their permitted capacity [22]; 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 [26, 44, 104]. 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 Figure 5.1.

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 [103], but application of this method is not enforced. A benchmark of the 24 ATES plans available in the Netherlands (Appendix 5-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 5-B) showed that these critical elements (substantiation and benefit) are also missing in the ATES planning method set up by Arcadis et al. [103].

An approach to organize ATES systems in busy urban areas was introduced chapter 3. It was proposed to apply ATES-systems with 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. 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 chapter 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.

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 up-dated to meet changes in real-estate developments in the area at hand (e.g. the ATES plan in Utrecht, Appendix 5-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 5.1), while the current general rules are uniform for the whole country, which was desired by the legislator to stimulate ATES adoption [58]. 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

[1] at the time of 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.

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.

GOAL OF THIS CHAPTER

The goal of this chapter 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 and 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.

5.2. METHODS AND MATERIALS

5.2.1. LITERATURE REVIEW ATES PLANNING

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 (section 4.2, Equation 4.5 and Figure 4.1). Longer screens reduce the areal footprint because it reduces the well's thermal radius. In chapter 4 it was shown 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 5.1: A 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).

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 [57, 58], 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 [26, 44, 104]. 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 Figure 5.1. 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 [126]. 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. [44] 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 chapter 4 and uncertain and limited well placement opportunities at surface level). In chapter 3 is 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. [127]. 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 work 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.

5.2.2. ANALYSIS THROUGH SIMULATION

5

A theoretical basis for the organization of ATES wells was provided by Sommer et al. [44], 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. [128, 129]). However, scenario evaluation can be used to identify robust solutions under uncertainty [130].

An agent-based model to simulate ATES adoption and ATES operation in dense settings was implemented using NetLogo [131]. The involved groundwater dynamics are modeled using the MODFLOW / SEAWAT codes [64, 119]. Both models are widely applied, but have not been combined through a bi-directional coupling as in this study e.g. [63, 94, 132, 133]. MODFLOW/SEAWAT and NetLogo were linked through an object oriented architecture written in Python. Python objects form the interface between the two models. Figure 5.2 illustrates the basic architecture and shows the data exchanges. The two coupled models run inside the Exploratory Modeling and Analysis (EMA) workbench package [134, 135]. 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.

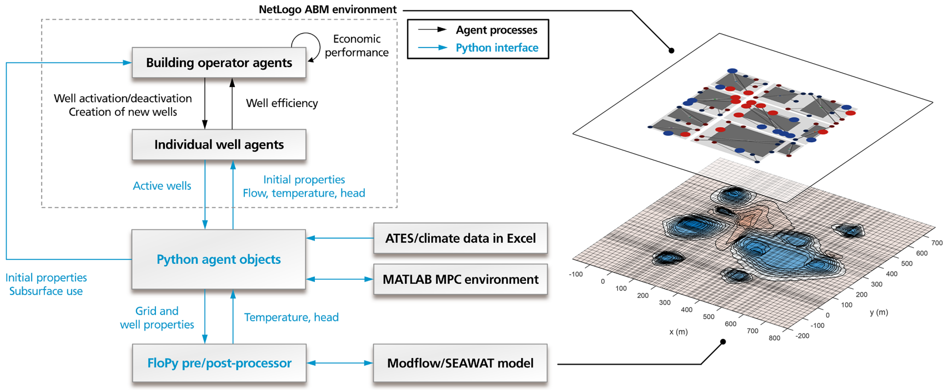


Figure 5.2: Coupled simulation architecture [26]

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 in chapter 4.

- 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 the benchmark (Appendix 5-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 [81]. 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. [96] 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 [44].

- 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 homogeneous, the effect of heterogeneity on ATES well efficiency has been studied by Calje [43], Sommer et al. [50], Possemiers [136]

Table 5.1: MODFLOW simulation parameters [43, 63, 119]

Parameter	value
Longitudinal dispersion	1 m
Transversal dispersion	0.1 m
porosity	0.3 -
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

and Xynogalou [113], 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 [81, 82, 91]. Because hydraulic conductivity has negligible effects on thermal losses under homogeneous and no buoyancy flow [81], 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 5.1.

5.2.3. 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 [126]. The analysis of the ATES planning method resulted in the identification of four parameters that determine the success of an ATES plan (Appendix 5-B).

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 building 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 system, 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-emission.

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 [26].

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 accommodation of new systems. Available space also allows for temporary energy imbalances because some winters are colder than others as was indicated in chapter 4. 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,

5.2.4. 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 [137];

$$P_h = P_{ATES} + P_e \quad \& \quad COP_{hp} = \frac{P_h}{P_e} \tag{5.1}$$

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 5.1 shows that all electric power fed to the heat pump contribute 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

5

$$E_{h,ATES}(t_0 \rightarrow t) = c_w \int_{t_0}^{t} P_{ATES} dt = c_w \Delta\bar{T}_h \int_{t_0}^{t} Q dt = c_w \Delta\bar{T}_h V_h \tag{5.2}$$

with

$$P_{ATES} = c_w Q(T_w T_c) = c_w Q \Delta T_h \tag{5.3}$$

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, 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 5.1 and 5.3, Equation 5.4 yields the heat E_h [J] delivered to the building over the heating season:

$$E_h = c_w \Delta\bar{T}_h V_h \frac{COP_{hp}}{COP_{hp} - 1} \tag{5.4}$$

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:

$$E_c = c_w \Delta \bar{T}_{c,fc} V_{c,fc} + c_w \Delta \bar{T}_{c,hp} V_{c,hp} \frac{COP_{hp} - 1}{COP_{hp} - 2} \tag{5.5}$$

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, which follows from the heat pump relations in Equation 5.1. The total energy consumption of the ATES system (E_{ATES}) is completed by including the pump energy consumption. Substituting equations 5.1) into 5.4 and 5.5 yields:

$$E_{ATES} = \frac{E_h}{COP_{hp} - 1} + \frac{E_{c,hp}}{COP_{hp} - 2} + \frac{(V_h + V_{c,fc} + V_{c,hp})\Delta p}{\eta_p} \tag{5.6}$$

where Δp is the lifting pressure generated by the groundwater pump and η_p its nominal efficiency. The total GHG emission is retrieved by calculating the CO_2 emissions of the considered ATES systems:

$$GHG_{ATES} = \sum_{i=1}^{n} E_{e,i} e_{fe} \tag{5.7}$$

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.

[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 the 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.

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. The 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:

$$E_{boiler} = \frac{E_h}{COP_b} \quad \& \quad E_{chiller} = \frac{E_c}{COP_c} \tag{5.8}$$

Their GHG emissions equal:

$$GHG_{ATES} = \sum_{j=1}^{m} (E_{boiler,j} e_{fg} + E_{chiller,j} e_{fe}) \tag{5.9}$$

in which e_{fg} and e_{fg} are the emission 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, Equation 4.1. The thermal efficiency taken over all the wells in the model (η_{tot}) is the average of the individual efficiencies determined from Equation 4.1 weighted by the individual total storage volume of the wells ($V_i = V_{h,i} + V_{c,fc,i} + V_{c,hp,i}$)

$$\eta_{tot} = \frac{\sum_{i=1}^{n} \eta_i V_i}{\sum_{i=1}^{n} V_i} \tag{5.10}$$

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 5-A, the following characteristics are defined to allow comparison between plans:

1) 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:

$$F_s = \frac{\sum_{i=1}^{n} V_i}{L_a A_{Ap}} \tag{5.11}$$

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

2) 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:

$$F_A = \frac{\sum_{i=1}^{n} \pi R_{th,i}^2}{A_{Ap}} = \frac{c_w}{c_{aq}} \frac{\sum_{i=1}^{n} \frac{V_i}{L_i}}{A_{Ap}} \tag{5.12}$$

5.3. SIMULATION RESULTS

5.3.1. 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 [104] was the first to identify such parameters; her set of parameters is extended here and discussed in appendix 5-B, and summarized in Table 5.2. 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.

With the design parameters of the ATES plan of Table 5.2, 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 5.2 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 [43, 49], 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 5-C; this fraction varied between 3 and 37%, equal to the range in the ATES plan benchmark (Appendix 5-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 combine 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. [82] who optimized the ratio L/R_{th}, which was reformulated to $L = V^{1/3}$ by Bloemendal and Hartog [81] 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 5-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 5-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 [22].

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 5-A) and in Bloemendal and Hartog [81].

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

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Table 5.2: 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.

5.3.2. 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 5.3. It gives the efficiencies and GHG savings for the different allocated aquifer space fractions. Figure 5.3 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 5.3 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 5.3 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 [44, 138]. 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 (3^{rd} 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 5.3) 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.

WELL DESIGN SCENARIOS

Figure 5.4 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 5.3, 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 in chapter 4; 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 ($m/1{,}000\ m^3$). Row 3 shows the results with only doublets when their length is determined according to the Doughty [82] 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 5.3 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.

LANE PLACEMENT SCENARIOS

In these scenarios, warm and cold wells were placed in separate, parallel lanes. Each marker in Figure 5.5 shows the average result of the 64 realizations computed for each

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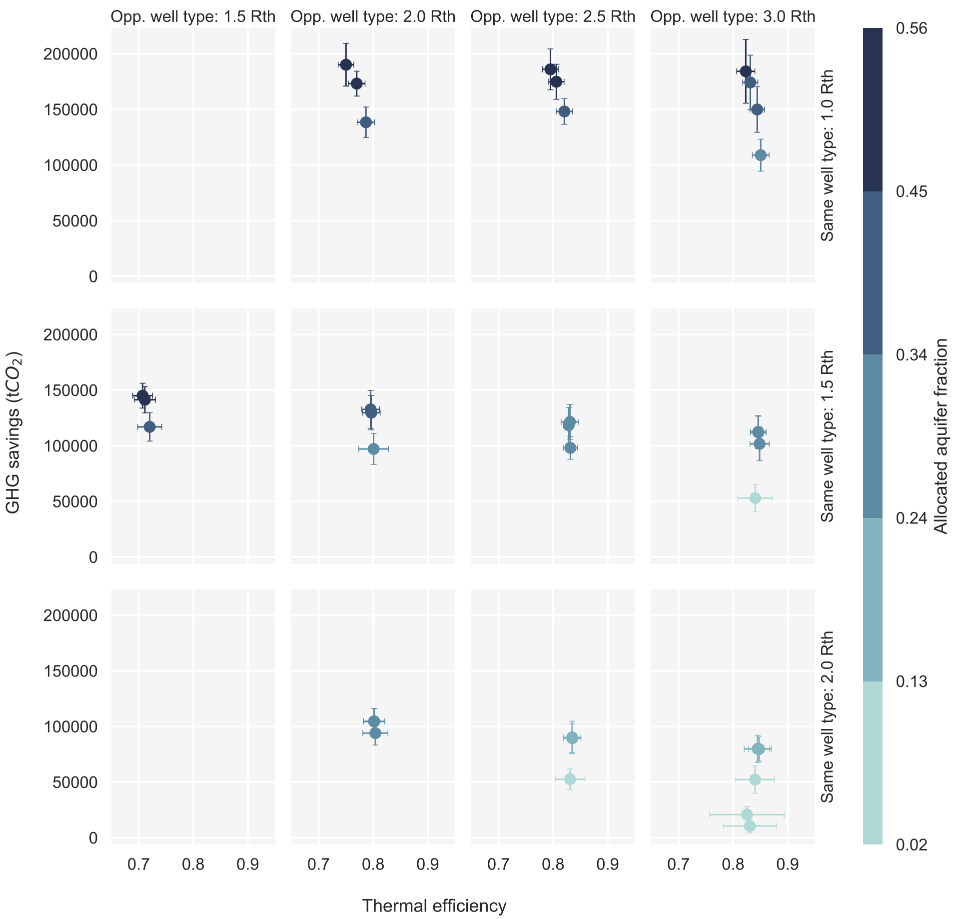

Figure 5.3: The average of all model realizations for the self-placement scenarios, grouped by same and opposite type of well distance policy. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

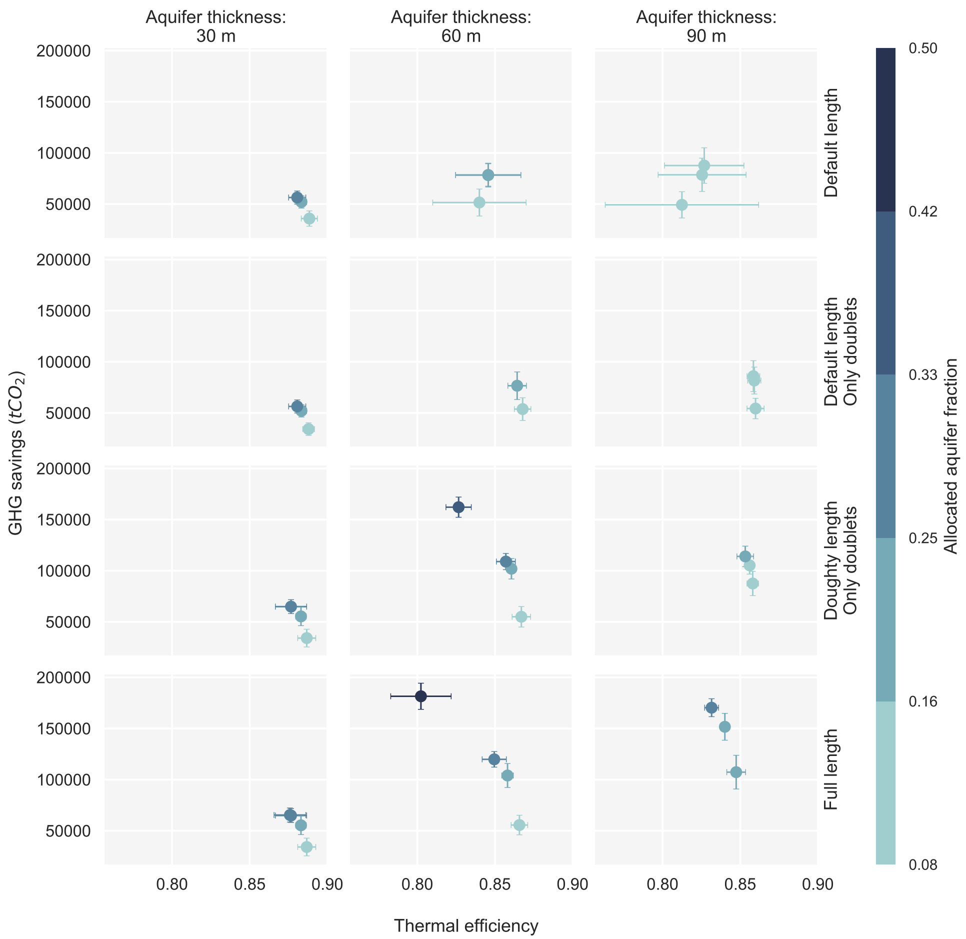

Figure 5.4: The average result of all model realizations for the scenarios where well design is varied, grouped by aquifer thickness and well design parameters. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

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 5.5 easily exceed the values achieved with self-placement in Figure 5.3. 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 5.5 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 [81].

It follows that also the width of the lanes is important as smaller widths limit the positive effect of clustering wells of same type. Narrow lanes hinder finding well locations, which limits the attainable allocated aquifer fraction. Figure 5.5 also illustrates this lane-width effect.

AMBIENT GROUNDWATER FLOW

Figure 5.6 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 5.6, respectively. The results of the zero groundwater velocity for the self-organized scenarios can be found in Figure 5.3 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 5.6. The results of the lane scenarios for zero groundwater flow can be found in Figure 5.5 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%).

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 work, the impact

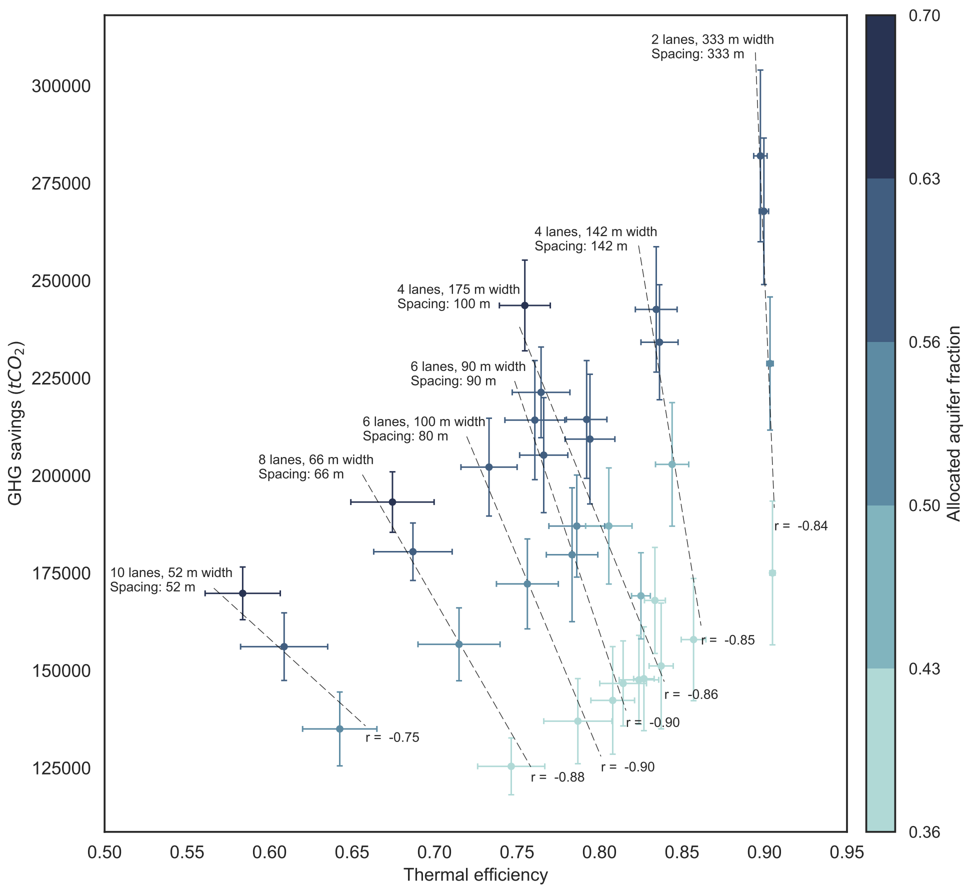

Figure 5.5: The average of all model realizations for the lane placement scenarios where wells are placed in lanes with given distance and width (details in appendix 5-C). The linear trend lines indicate the correlation between thermal efficiency and GHG savings for each simulated lane width and spacing 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.

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 5.3 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 cooling capacity, long term use of the aquifer for ATES is not possible.

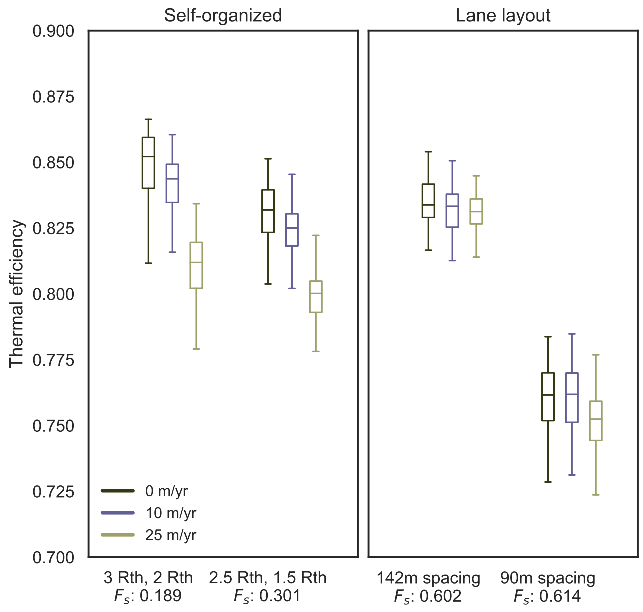

Figure 5.6: Boxplots for thermal efficiency in a set of representative policies, across three scenarios for ambient groundwater flow.

Table 5.3: 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 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 5.7 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 in chapter 4. Collective (i.e. larger) systems lead to a higher allocated aquifer space fraction as indicated by darker markers in Figure 5.7. 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.

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 5-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.

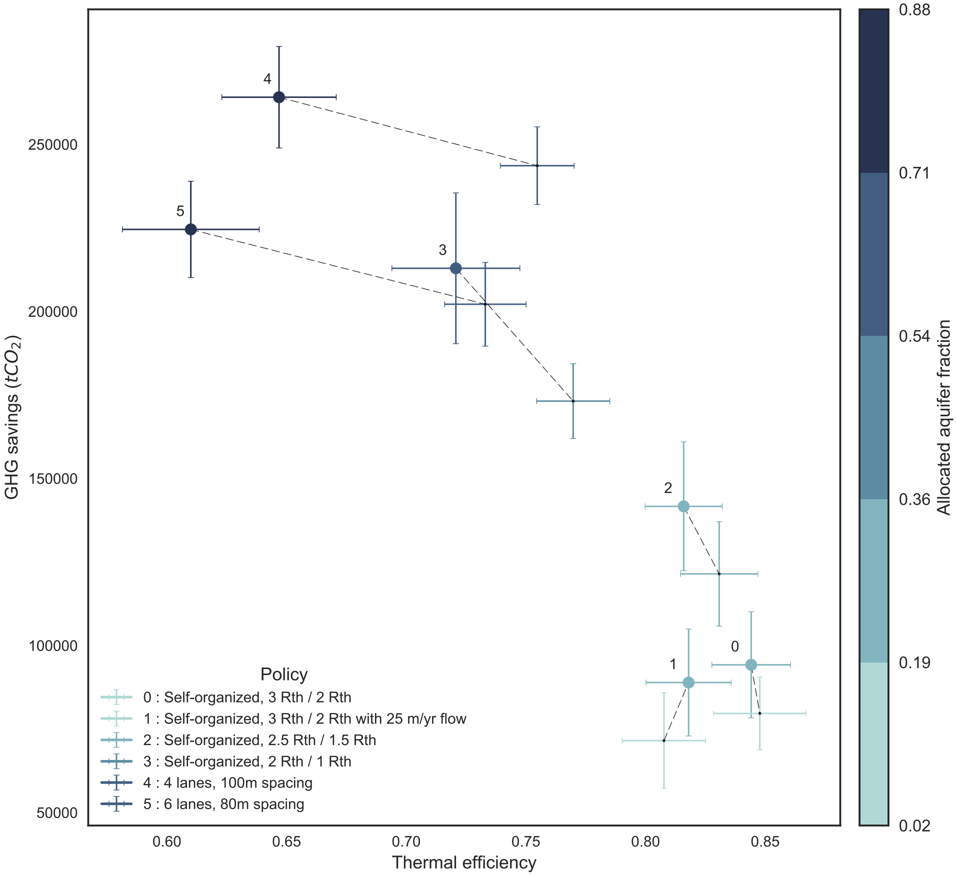

Figure 5.7: The average of all model realizations for the scenarios with collective ATES system, compared to policies with normal sized ATES systems. Each result in the figure is the average of all operational wells of all the 64 simulation realizations of the policy under consideration. The error bars indicate the inter quartile range (IQR) among realizations with the same policy.

- 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.

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 5.3 shows this, because the scenarios following the current rules/practice reach a maximum allocated subsurface fraction of only 24%.

The other subplots in Figure 5.3 and Figure 5.4 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 5.5 and Figure 5.6 show that only lane placement combined with a coordinated approach to minimize well size (Figure 5.7) 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 modeling 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 modeling 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 [12, 22]. 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 [139]. Of course, variations between years in the use of the allocated aquifer space should be taken into account [81]. 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 [81].

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 [140]. 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. [50] 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 [113] 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 [113]; 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 [141, 142], fresh water storage and recovery [41] or de presence of contamination [94, 143]. 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. [144].

5.4. ATES PLANNING METHOD FOR USE IN PRACTICE

5.4.1. ATES PLANNING GOALS AND CONSIDERATIONS

The goal of ATES plans is to ensure maximum utilization the available aquifer space by to 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.

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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 [145] 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 5.4).

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 5-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.

Table 5.4: 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 10%. 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, to choose themselves	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
All monowells	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
All 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

5.5. 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.

APPENDICES CHAPTER 5

5-A BENCHMARK 24 ATES PLANS

5-A.1 THE ANALYZED ATES PLANS

Subsurface planning is not limited to ATES [146–148], 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 dissertation. 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

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5-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 5.8. 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.

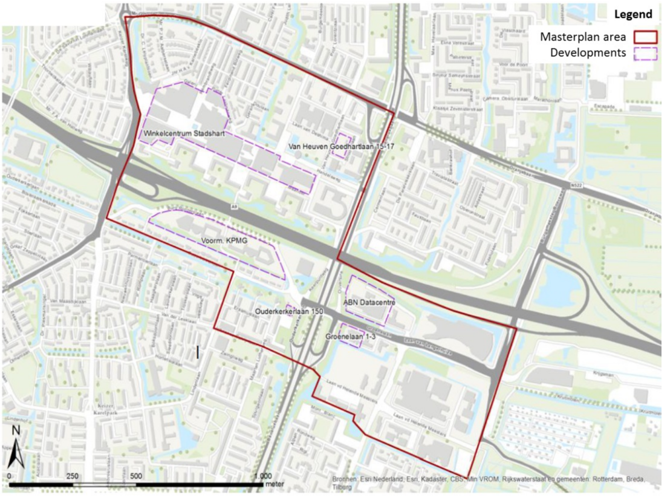

Figure 5.8: Example of ATES plan area demarcation. (Figure 4 from ATES-plan Amstelveen)

Table 5.5: 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 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 [81]. In thick aquifers where well screens are generally partially penetrating, this assumption may underestimate the thermal radius and, therefore, the ATES footprint.

5-A.3 BENCHMARK RESULTS

Table 5.4 presents the metrics introduced in section 5A.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 5.6: 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						
Surface area of ATES-plan area (A_{Ap})	0.52	1					
Total thermal energy storage (*E*)	0.88	0.64	1				
Aquifer thickness (t_a)	0.21	0.14	0.23	1			
Floor space index (*FSI*)	0.18	-0.41	0.12	0.29	1		
Allocated aquifer space fraction (F_s)	-0.12	-0.45	0	-0.46	0.49	1	
Allocated surface area fraction (FA)	-0.08	-0.55	-0.1	-0.3	0.61	0.8	1

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.

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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 ($r_{x,y} = cov(x, y)/\sigma_x \sigma_y$) 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 data set the correlations identified are not statistically significant, but may point towards reasons why the allocated subsurface space and surface area differ between ATES plans. Table 5.5 shows the Pearson correlation coefficients of different ATES plan area characteristics.

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 [81].

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 5.8.

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.

5-B CURRENT ATES PLANNING METHOD

5-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 [58, 103], 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 [58]. There currently exists only one formal ATES planning method in the Netherlands, the guidelines by Arcadis [103]. 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 5-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 [103] 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 to manipulate 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 [26, 49, 81, 94, 104]. 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 [58]. 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.

5-B.2 SUGGESTIONS FOR IMPROVEMENTS

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;

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- Thresholds of subsurface space use beyond which planning is needed.
- Design variables that can be used to plan the ATES wells (discussed in 5B.3).
- An assessment framework to compare alternative ATES plans (discussed in 5B.4).

5-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 [19, 58]. 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 [12]. 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 [22]. Bloemendal & Hartog [81] 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.

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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 [24, 81, 82]. Rules for requiring minimal filter screen lengths may reduce ATES footprint where aquifers are thick [149]. Minimum filter screen lengths could be set dependent on expected storage volume using the rule proposed by Bloemendal and Hartog [81]. 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 [43, 49]. 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 [26, 138]. 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 [81].
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.

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5-B.4 Assessment framework

Commonly accepted assessment frameworks for subsurface space functions does not exist [126]. 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 [13]. 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 [26, 49, 94] 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 [104] 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 with local authorities and real-estate developers from an ATES plan (Lelystad airport [145]) 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

5-C DESCRIPTION OF SIMULATION 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 4 is used; 1 km x 1 km. Also the average aquifer thickness of the 24 ATES plans is used in the reference case; 60 m. Ambient groundwater flow is zero.
Specific energy storage: The allocated aquifer space fraction varies between 7% to 54% 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 [22], 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 [150].
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 [81]. 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 [113].

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. [82] and Bloemendal and Hartog [81]; $L = V^{1/3}$, 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 5-A.

D Evaluation of different lay-out;
Well placement: Sommer et al. [44] 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 ($R_{th}D_{opposite}$) 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 layouts (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 64 times 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.

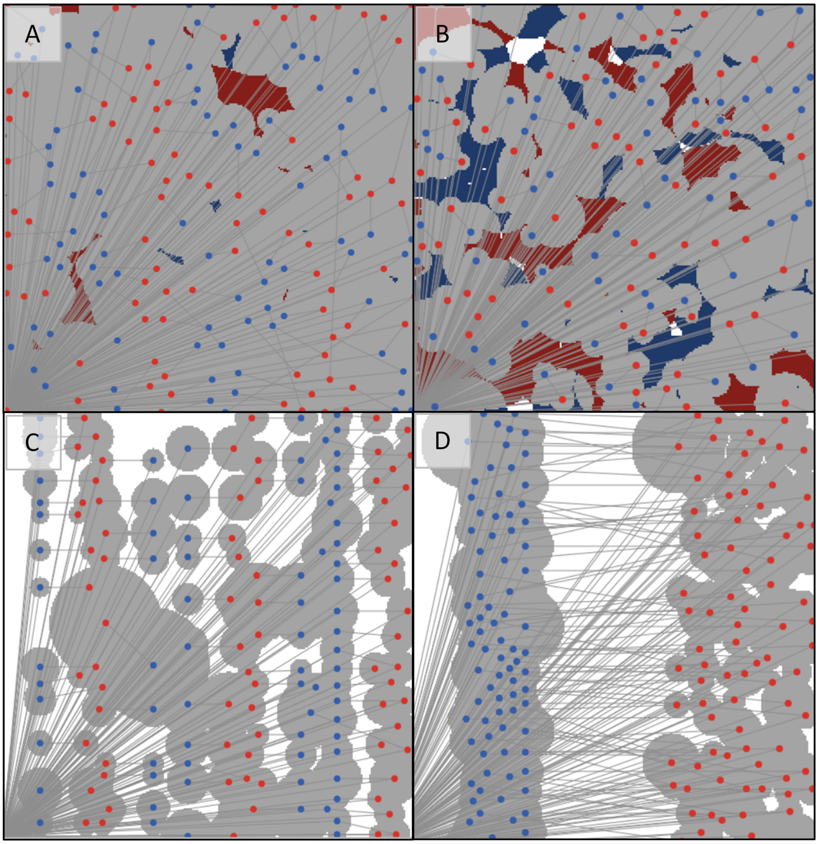

Figure 5.9: Well placement by the agent-based model for 50 % allocated subsurface fraction for ATES. Red/blue markers = warm/cold wells. White space = search area for new well, grey area= allocated surface space, blue/red area = search area for new warm/cold wells. A= current practice, screen length 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.

5-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.

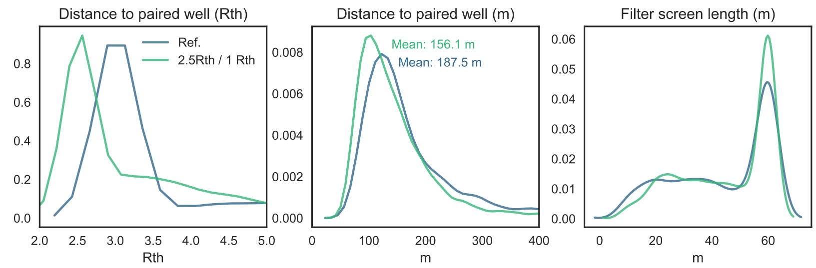

Figure 5.10: Distribution of well distances and screen lengths for A and B scenarios

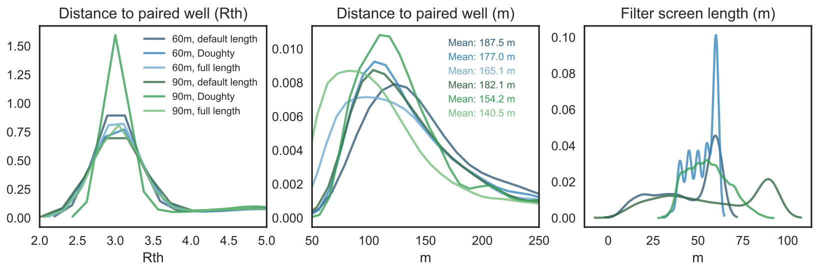

Figure 5.11: Distribution of well distances and screen lengths for C scenarios

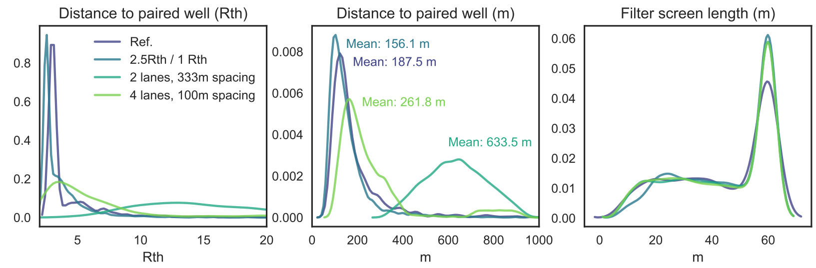

Figure 5.12: Distribution of well distances and screen lengths for A, B, D scenarios

6

CONCLUSIONS, DISCUSSION AND OUTLOOK

I'd put my money on geothermal, what a source of heat storage. I hope we don't have to wait until fossil runs out before we tackle that

adapted from Thomas Edison

Aquifer Thermal Energy Storage (ATES) systems provide sustainable space heating and cooling for buildings. In the future 25% of buildings in moderate climates may rely on ATES for their space heating and cooling. The subsurface space available for thermal energy storage is limited and on top of that there is a trade-off between individual ATES efficiency and maximizing greenhouse gas emission reduction by facilitating as much ATES systems as possible. Therefore, it is important to explore how aquifers can be utilized sustainably and to its full potential to maximize energy saving with ATES.
To achieve this, methods for governance, design and planning of ATES systems are presented in this dissertation. It is also identified where in the world suitable aquifers and climatic conditions coincide with urban areas: the future hot-spots for ATES where such methods are needed. Aquifer as well as operational conditions affect recovery efficiency and distribution of heat in the subsurface, a framework for optimal design of ATES wells, addressing both aspects is also presented.

6.1. CONCLUSIONS

ATES systems help save energy which make them increasingly popular. In the future, 25% of the buildings in moderate climates may rely on ATES for their space heating and cooling. Efficient use of subsurface space in urban areas, where demand for such systems is largest, is of crucial importance for its long-term energy savings and profitability. In this dissertation, design methods and organizational concepts were introduced for dense urban settings. Use of these methods result in the most effective and sustainable use of subsurface space by ATES systems. Because ATES design, installation and operation is a multidisciplinary field, expertise and concepts from the fields of geohydrology, building energy systems, spatial planning and legislation were combined in this work. An important part of the research in this dissertation was done from the Dutch perspective, which allowed to use and evaluate the extensive experience and data from practice, which was lacking in international literature before this study.

- Firstly, a method to determine the potential for ATES was developed, which was then used to identify where in the world potential for ATES exists. This revealed that ATES potential is present in many North American, European and Asian urban areas. Demand for ATES may exceed the suitable aquifer space available in those areas.

6

- Secondly, a framework for governance of ATES is proposed for urban areas where demand for ATES approaches or exceeds available aquifer space. This indicated the need for an organizational and operational framework that optimizes local and regional energy savings rather than individual autonomously operating ATES systems, like it the case in current practice.

- Thirdly, insight is given in the processes that contribute to heat losses in the subsurface under operational and geohydrological conditions that are specific for ATES. Such a general framework for subsurface heat losses was lacking in literature, but increasingly important when the number of ATES wells per unit of aquifer space keeps growing. New methods were developed and new relations identified to optimize the recovery efficiency of ATES wells under varying conditions. It was found that thermal energy losses by hydrodynamic dispersion may be neglected under conditions under which ATES operate. For ATES systems, the conduction losses dominate. This causes the thermal recovery efficiency to correlate linearly with the circumference area of the storage volume over the volume itself (A/V). An analytical expression for the impact of ambient groundwater flow on recovery efficiency for single ATES wells was derived for low groundwater flow velocities (<25 m/y). Also, the use of multiple wells was demonstrated to compensate for displacement losses that are associated with ATES wells in areas with high groundwater flow velocity (>25 m/y). It was also found that a salinity gradient, which is often present in coastal aquifers, has negligible effect on the thermal efficiency of ATES wells under practical conditions.

- Finally, methods for spatial planning of ATES systems were developed. It was shown that current practice aimed at optimizing aquifer space use for ATES is ambiguous. A benchmark of 24 ATES plans showed that characteristics of existing plans vary strongly and are poorly substantiated. Analysis of the method that was used to make the ATES plans, revealed that steps were missing to unambiguously identify the optimal strategy for ATES planning. The ATES planning method as applied in the Netherlands was improved by adding 4 missing components: 1) An assessment framework to evaluate and compare different planning strategies. 2) Parameters for the design of ATES plans. 3) Thresholds that determine when an ATES plan is needed or not. 4) General rules that, when applied, make ATES planning superfluous for allocated aquifer space fractions less then 50 %. The result of this study provide insight on how to make design choices for ATES wells to optimize the use of aquifer space. This study also quantifies the trade-off between thermal efficiency of individual ATES systems and the overall emission reductions of ATES systems in an ATES plan area. The improved ATES-planning method fosters planning and design rules that ensure optimal and sustainable use of aquifer space, which is maximizing energy savings by accommodating as many ATES systems as possible while maintaining the thermal efficiency of individual ATES wells.

The results presented in this dissertation enable both governments, companies and users to successfully implement ATES systems. These results build on the methods and experience of 25 years of Dutch ATES practice presented in this dissertation. The Netherlands aim to increase the number of ATES system by a factor 100 by the year 2050, compared to the approximately 2,000 systems in 2015. This can only be realized with comprehensive design methods and straightforward planning strategies like the ones presented in this dissertation.

6.2. Discussion and Outlook

The future looks bright for sustainable energy as targets for sustaining the energy system are higher on the (political) agenda then they have ever been. Geothermal energy storage can contribute considerably to the reduction of greenhouse-gas emissions in moderate climates because it reduces the energy required for generation of heating and cooling of the built environment. But facilitating ATES systems put pressure on the use of the subsurface, which is a common-pool resource. Therefore, it is important that the use of the subsurface be sustainable and efficient. It was already known that the impact of ATES on groundwater quality is negligible. This study adds to this that ATES systems are relatively robust against mutual interaction. The concepts for design, planning and governance of ATES systems developed in this dissertation form a solid basis for a strong increase of subsurface space utilization for ATES.

In practice, other aspects than the ones presented in this dissertation also affect well design and placement. Often, practical and cost considerations prevail, which often results in suboptimal use of aquifer space and in limited overall GHG emission reductions. This research showed that design and placement of an ATES well has a large influence on the long-term energy savings of its associated building. Because an ATES well is not easily and cheaply replaced, it is of crucial importance to make a profound design and location choice. The concepts and insights presented in this dissertation help convince stakeholders to adopt them. The strategies proposed in this dissertation come at little extra cost, but result in a much more robust network of ATES systems compared to current practice. With the expected operational life time of an ATES system and all the inherent uncertainties regarding the subsurface space use during that time-span, these extra costs always pay out on the long run.

The approach to organize ATES systems in dense urban settings was evaluated in chapters 3 and 5. In chapter 3 it was proposed to equip ATES systems with a model-predictive control strategy that facilitates real-time and automated negotiation among them over the use of subsurface space. This leads to self-organization, but requires a radical change of the legal framework. Because of the many theoretical and practical challenges, widespread implementation of this combined approach is not expected within the next decade. Therefore, chapter 5 pursues assessing and improving current design and governance practices, which are essential for ongoing, near-future adoptions of ATES in dense urban settings.

Many gaps remain despite the work done in this dissertation that suggest several topics for future research:

- The appealing concept of self-organizing ATES systems that was presented goes beyond the possibilities of the current legal and practical framework. Ongoing research in which experts from the field of geohydrology, control and policy management delivered a proof of concept. They are currently working on a pilot in Amsterdam in which this self-organization will be demonstrated. Recent results showed that the developed artificially intelligent controllers that implement the policies and communication framework indeed leads to a more optimal use of aquifer space as well as to less GHG emissions. Next steps should be to develop additional pilots, to make the controllers suitable to handle more complex building systems and to identify a transition path for the adoption of this concept.
- This dissertation focused on ATES systems, which are usually applied in utility buildings. But also the small-scale BTES (Borehole Thermal Energy Storage section 1.2) systems are required and expected to grow in number at the same rate as ATES systems. Because BTES systems do not require an aquifer, they are more widely applicable than ATES systems. Although, their small scale also makes their thermal influence much smaller, they too may suffer from negative interaction and/or scarcity of space in dense urban settings. So similar issues as were tackled for ATES in this dissertation, also need to be solved for BTES. As an added complexity, BTES systems are often applied at the same depths as the ATES systems. Therefore, in areas with both small and large buildings also see ATES and BTES systems side by side. Little is still known about their mutual interaction, which can be negative as well as positive, depending on the local conditions.
- The methods developed to identify potential for ATES can be further elaborated by adapting them to different categories of buildings. These methods can also be further developed to quantify the potential energy savings for heating and cooling

in buildings in different countries as recently published by the IPCC. The method developed in chapter 2 may also be applicable for other types of subsurface functions, e.g. High-Temperature ATES or freshwater storage and recovery.

- The heat pump plays a crucial role in ATES systems, it simultaneously produces the heat and cooling capacity consuming over 50% of the energy needed to run an ATES system. Making the heat pump abundant would have two large benefits: Firstly, it would disconnect the production of heat and cooling capacity. Secondly and foremost, less power would be needed to run the system. Modern buildings require around 40°C for heating, while buildings with an old/leaky envelope may need more than 60°C, even after improved insulation. In urban areas, these temperature levels are abundantly available as waste heat or can be produced sustainably with solar collectors or geothermal mining. Any temporal mismatch between demand and supply can still be overcome by storage in aquifers, for which it is then required to store temperatures higher than the 25-30°C, which is currently the legal maximum in many countries [75]. High-temperature ATES systems may be one of the few cost-effective enablers for sustainable space heating of older buildings. Successful application of high-temperature ATES systems faces three main challenges: 1) Preventing heat losses through buoyancy flow. 2) Preventing calcium-carbonate precipitation. 3) Preventing negative chemical and microbiological effects.
  To limit the buoyancy losses, the insight in the mechanisms discussed in section 4.7 can be used. An increasing salt concentration with aquifer depth may compensate density change associated with high-temperature ATES systems, this is preferable over adding salt to the warm infiltrated water suggested by Lopik et al. [83]. The positive impact of the density gradient was already shown for an high-temperature ATES system at the TUDelft campus by Wegman [151]. The buoyancy flow may also be counteracted by multiple partially penetrating well screens [152].

- Climate change alters the ambient temperature; in combination with the urban heat island effect this may have a considerable impact on ATES systems. But the largest effect from climate change comes from the change in energy-demand profile of buildings. The varying imbalances over multiple storage cycles, are likely to end up in a permanent surplus of heat in the warm well. This will eventually cause breakthrough of warm water to the cold well and strongly reduce the efficiency of the cold well. Solving this problem requires comprehensive evaluation of the building climate system controls. This can be done either by reducing the cooling demand, or by obtaining additional cooling capacity during winter. The latter can, for example, be achieved by discharging the surplus heat in cold surface water. This preserves extra aquifer space for cooling. This discharge of surplus heat to surface water during winter is already regularly applied in the Netherlands to meet legal energy balance requirements.

The work presented in this dissertation provides a valuable base to further improve the controls of the thermal efficiency ATES systems and governance under more complex conditions: e.g. in aquifers that are stratified, are highly irregular and/or anisotropic, are under influence of tide, are fissured or consist of bedrock. The work is also valuable to evaluate more complex storage conditions: e.g. where BTES and ATES systems occur alongside or under higher storage temperatures where buoyancy flow contributes to heat losses.

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Curriculum Vitæ

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Education

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PhD	Aquifer Thermal Energy Storage
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2000-2007 **Delft University of Technology**
MSc Civil engineering

Experience

2013-present **KWR watercycle research institute**
Scientific researcher geothermal energy storage

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Board member (Legislation and R&D)
Dutch geothermal energy storage branch of industry organization

2010-present **Delft University of Technology**
Scientific researcher geothermal energy storage

2007-2014 **Tauw**
Consultant geothermal energy storage & geohydrology

LIST OF PUBLICATIONS

Peer reviewed journal papers

7. **Jaxa-Rozen, M., Bloemendal, M., Kwakkel, J.**, *Assessing the large-scale potential of Underground Thermal Energy Storage for energy savings in the built environment*, (Submitted).
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13. **Bloemendal, M., Jaxa-Rozen, M.,Rostampour, V.**, *The Role of Heat pumps in ATES Smart Grids*, 12^{th} IEA Heat pump conference, Rotterdam, The Netherlands, 2017.
12. **Rostampour, V., Bloemendal, M., Keviczky, T.**, *A Model Predictive Framework of Ground Source Heat Pump coupled with Aquifer Thermal Energy Storage System in Heating and Cooling Equipment of a Building*, 12^{th} IEA Heat pump conference, Rotterdam, The Netherlands, 2017.
11. **Bloemendal, M., Hoogendoorn, J., Rijk, J.**, *Bodemenergie & Drinkwaterwinningen*, H2O wetenschap en Techniek, November 2016.
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12. **Bloemendal, M.**, *Spatial challenges in the subsurface for ATES*, Energy & spatial changes, Pakhuys de Zwijger, Amsterdam, December 2017.
11. **Bloemendal, M.**, *Optimal use of subsurface space with ATES requires 'smart energy grids'*, Aqua Con Soil conference, Lyon, June 2017.
10. **Bloemendal, M., Jaxa-Rozen, M.,Rostampour, V.**, *Use it or lose it, Adaptive governance of aquifers with ATES*, 12^{th} IEA Heat pump conference, Rotterdam, The Netherlands, 2017.
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7. **Bloemendal, M.**, *Optimal use of the subsurface with ATES Smart Grids*, Darcy lecture symposium, Delft, September, 2015.
6. **Bloemendal, M.**, *Determining world potential for Aquifer Thermal Energy Storage*, Aqua Con Soil conference, Copenhagen, June 2015.
5. **Bloemendal, M.**, *WKO het laatste wilde westen van Nederland*, Retirement symposium of Prof. dr. ir. T.N. Olsthoorn, Amsterdam, May 2015.
4. **Bloemendal, M., Olsthoorn, T.N.**, *Optimal and Sustainable Aquifer Thermal Energy Storage*, Groundwater Quality conference, Gainesville USA, April 2013.
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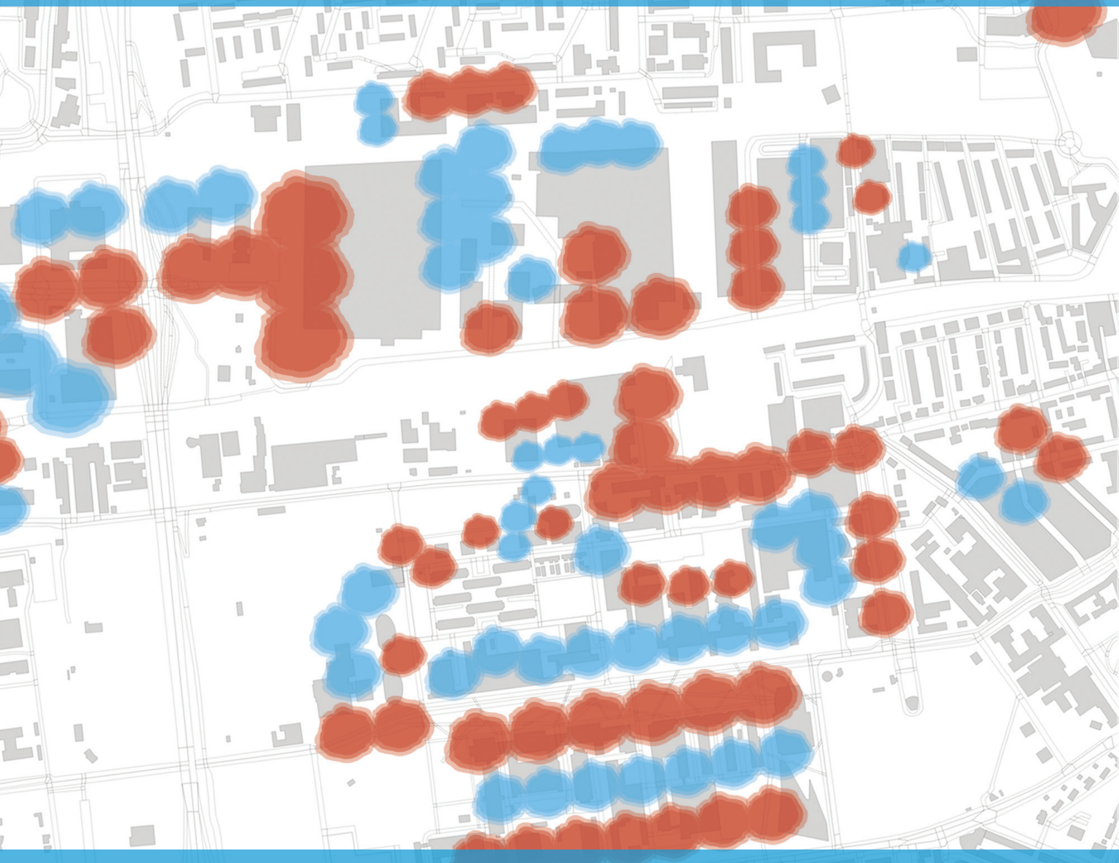
2. **Bloemendal, M., Olsthoorn, T.N.**, *Bodemenergie Smart Grids,*Dutch National conference geothermal energy, Maarssen October 2011.

1. **Bloemendal, M., Olsthoorn, T.N.**, *Facilitating optimal and sustainable subsurface use for Aquifer Thermal Energy Storage by innovative governance,*International Water Week Amsterdam (Royal Dutch Water Network, IWA and NWP) Water related to sustainable energy, Amsterdam, November 2011.

Aquifer Thermal Energy Storage (ATES) systems provide sustainable space heating and cooling for buildings. In future, many buildings in moderate climates rely on ATES for their space heating and cooling.

However, the subsurface space available for heat storage is limited and there is a trade-off between individual ATES system efficiency and minimizing greenhouse gas emissions in an area by facilitating as much ATES systems as possible. Therefore, it is important to explore how aquifers can be utilized sustainably and to its full potential to maximize energy saving with ATES. In this dissertation methods for governance, planning and design of ATES systems in busy areas are presented. It is also identified where in the world suitable aquifers and climatic conditions coincide with urban areas; the future hot-spots for ATES, where these methods are needed.



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