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Techno-economic performance evaluation of Aquifer Thermal Energy Storage

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ABSTRACT

While the share of renewables in the power generation sector steadily increases, less attention is paid to the decarbonisation of the heating and cooling sector. Since most industrial nations are located in the moderate climate zone, the global heating and cooling supply is less a matter of energy shortage than a matter of seasonal storage. Aquifer Thermal Energy Storage (ATES) is considered to bridge this seasonal gap between times of highest energy demand and times of highest energy supply. More than 80 % of all ATES systems are operating in the Netherlands and Scandinavia. This discrepancy in global ATES development is not only attributed to geological and climatic conditions, but also to several market barriers mainly of socio-economic nature. To evaluate the economic and environmental performance of ATES, the present study analysis monitoring data as well as capital costs of more than 100 low-temperature ATES systems currently in operation. With a total abstraction of 30.4 GWh heat and 31.8 GWh cold per year, the data analysis revealed only small thermal imbalances and small temperature losses during the storage period. The abstraction temperatures are around 10 and 15 °C during summer and winter, respectively. However, the temperature difference between abstraction and injection is 3 to 4 K smaller compared to the optimal design value. This indicates insufficient interaction between the energy system and the subsurface by an inadequate charging of the aquifer. Additionally, the financial analysis revealed decreasing specific capital costs from more than 1,200 €/kW for small systems to less than 300 €/kW for large buildings. A case study revealed that direct cooling with ATES systems is the most efficient supply option resulting in an electricity costs reduction of up to 80 % compared to conventional energy systems. The payback times range between 2 and 10 years. ATES is highly cost-effective for large buildings with a high cooling demand such as hospitals, airport, data canters, and hotels.

1. INTRODUCTION

The global community has to face a paradigm shift towards a sustainable energy supply to keep the increase in the global average temperature to within 2°C above pre-industrial levels. The share of renewable energy in the power generation sector is continuously on the rise. However, much less attention is paid to the transition of the heating and cooling sector, which accounted for half of the total world final energy consumption in 2015. Currently, the estimated share of modern renewable technologies only amounts to 8 % (REN21, 2016). With rising prosperity, population and climate change the global energy consumption for heating and cooling further increases. Thus, more attention has to be paid to the decarbonization of the thermal energy sector to achieve the climate change mitigation targets.

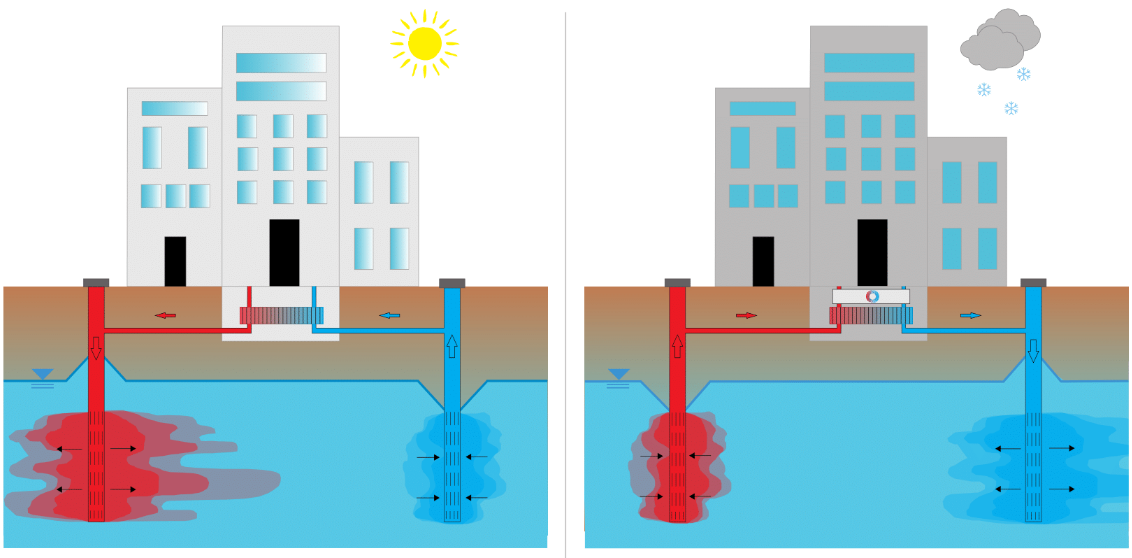

Figure 1: Basic principle of a doublet ATES during heating (summer) and cooling (winter) period.

To increasing the share of renewables in the heating and cooling sector it is indispensable to adapt to the seasonal temperature variations resulting in a seasonal mismatch between thermal energy demand and supply. One approach to tackle this seasonal offset, is the idea of Thermal Energy Storage (TES), which has attracted increasing attention (Dinçer, 2002). However, several parameters including storage capacity, storage duration as well as supply and demand temperatures influence and limit the selection of an appropriate storage method (Lefebvre and Tezel, 2017; Abedin and Rosen, 2011). Underground Thermal Energy Storage (UTES), as part of the sensible TES methods, is the preferred procedure for long-term TES mainly resulting from high storage efficiencies (Li, 2016; Caliskan et al., 2012) and high storage capacities. UTES is distinguished between open-loop, also referred to as Aquifer Thermal Energy Storage (ATES) and closed-loop systems such as borehole thermal energy storage (BTES). ATES temporarily stores sensible heat and cold in the saturated zone of the subsurface through injection and abstraction of the groundwater (Sommer, 2015; Lee, 2013; Dickinson et al., 2009). The basic principle of a bidirectional ATES is illustrated in Fig 1 and involves the seasonal storage of heat and cold. In winter warm groundwater stored from the summer is extracted for heating purposes of the building. The temperature level from the aquifer is increased by heat pumps to the required inlet temperature for space heating (Andersson et al., 2013; Bloemendal and Olsthoorn, 2018; Bridger and Allen, 2005; Bridger and Allen, 2010). The reverse process is observed in summer by using cold groundwater stored from the winter. In many cases, the temperature level is sufficient for direct cooling. The excess heat of the cooling process is reinjected in the warm well and stored in the aquifer (Dinçer and Rosen, 2011; Dickinson et al., 2009).

The goal of this study is to give an overview over the historical development and the current global application status of ATES. Additionally, the technical performance is analyzed based on the monitoring data of 73 Dutch ATES systems from 2016 to 2018. Valuable conclusions are drawn both on the technical performance of ATES and also on the quality of the building-subsurface interaction. Since the literature lacks on economic studies the financial performance of low temperature ATES is evaluated based on the capital costs of running ATES systems and a techno-economic case study.

The present work presents an updated summary of our recently published studies as listed below:

- Fleuchaus P, Godschalk B, Stober I, Blum P. Worldwide application of aquifer thermal energy storage—a review. Renewable and Sustainable Energy Reviews. 2018 (Fleuchaus et al., 2018)
- Schüppler S, Fleuchaus P, Blum P. Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage in Germany. Geothermal Energy. 2019 (Schüppler et al., 2019)
- Fleuchaus P, Schüppler S, Godschalk B, Bakema G, Blum P. Performance Analysis of Aquifer Thermal Energy Storage. Renewable Energy. 2019 (Fleuchaus et al., 2019)

2. WORLDWIDE APPLICATION STATUS

2.1 Historical development

The timeline in Fig. 2 visualizes ATES development over time, highlighting important research projects as well as experimental and commercial ATES milestones. The first ATES activity can be traced back to the industrialization of China in the mid-1960s (Sun, Li Qin-fen and Wu, 1991; Gao et al., 2009; Shen, 1988; Zhou et al., 2015; Sun and Li, 1993; Tsang and Hopkins, 1982). Several textile companies in Shanghai started to inject cold groundwater into the aquifers to reuse the stored cold for summer cooling. Given the high demand for industrial cooling, the number of ATES applications increased gradually in the following years. The utilization of ATES peaked in the mid-1980s in China, when about 20 cities installed more than 400 wells to actively store heat and cold in groundwater (Morofsky, 1995; Sanner, 2001; Shi et al., 2016; Tsang, 1978). After the first big oil crises in the early-70s, the International Energy Agency (IEA) initiated several research projects in North America and Europe. During that time, several field experiments were designed and conducted at several universities such as Auburn University, Texas A&M University, or the University of Neuchâtel (Stottlemyre et al., 1979; Tsang, 1978; Saugy et al., 1984).

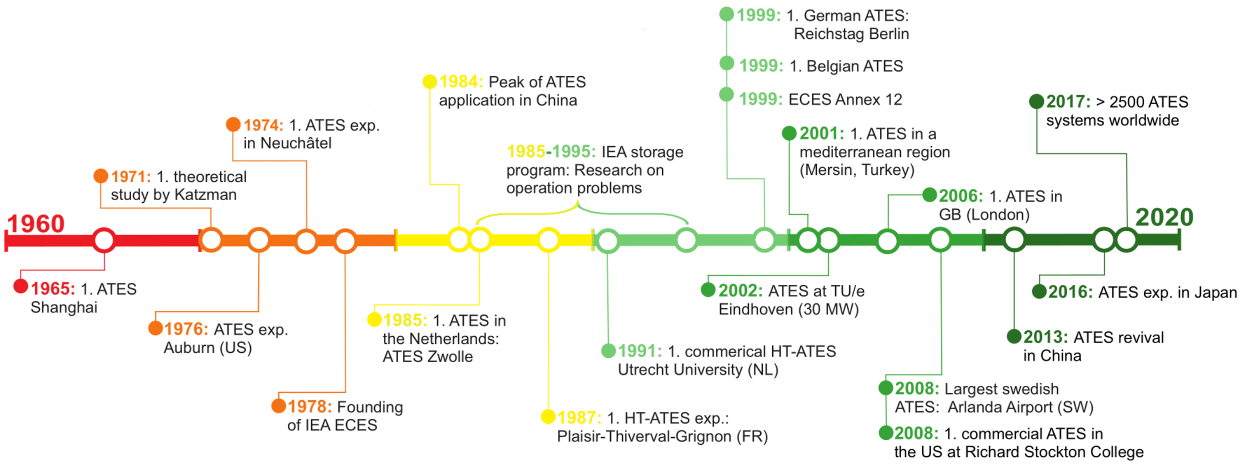

Figure 2: Historical development of ATES.

The scope of these early storage projects was less to supply thermal energy for the university campus, but to investigate the storage of high temperatures in the subsurface. Other countries such as France, Japan, Germany, or Canada started participating in ATES research with own experimental field sites. While many of these early projects focused on the storage of high temperatures (> 80 °C), significant operational problems especially due to geochemical problems were reported from the test sites (Molz et al., 1979; Molz et al., 1981; Jenne, 1993; Jenne, 1990; Sanner and Knoblich, 1998; Tsang, 1980). Thus, all early high temperature test sites were abandoned after several years. At the same time, fewer problems were encountered for the storage of lower temperatures and engineering feasibility was demonstrated in the Netherlands and Sweden. Subsequently, the interest shifted from high temperature (HT) ATES (>40°C) to low temperature (LT) ATES (<40°C) especially in North-western Europe (Snijders, 2005; Nordell et al. 2015). With the first LT project in the Netherlands in the 1980s, ATES established in the energy markets of the Netherlands. Driven by market incentive programs, ATES technology experienced a boom in the Netherlands in the 20st century. With more than 2500 ATES in operation, 85% of all systems are located in the Netherlands. However, also other countries, such as Sweden, Denmark or Belgium initiated first ATES projects in their countries the last 20 years. Recently, there is also growing interest in ATES technology in China, Japan and the US.

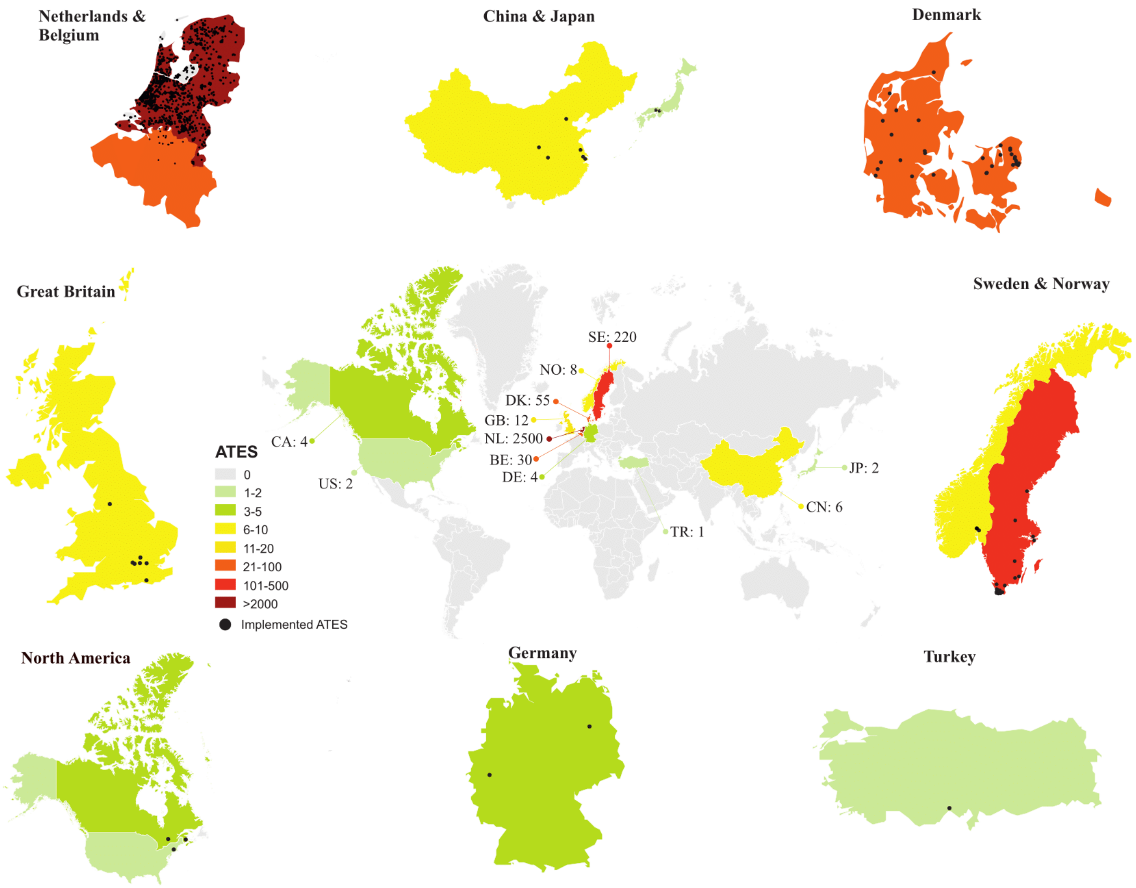

Figure 3: Global distribution of low temperature ATES. Please note that the map makes no claim to completeness.

Fig. 3 illustrates the global application statistics and global spatial distribution of ATES. To our knowledge, more than 2800 ATES projects have been successfully implemented worldwide. Regardless of the great discrepancy in global ATES application, the number of ATES systems is expected to increase further. High growth rates are reported from the Sweden, Denmark, Belgium and in particular the Netherlands (Gehlin and Andersson 2016; Anibas et al., 2016). All ATES systems abstract more than 2.5 TWh of thermal energy for heating and cooling per year. This equals the average thermal energy consumption of 150,000 households in Central Europe. More than 99% of all ATES are low-temperature systems (LT-ATES) with storage temperatures below 25°C. In the Netherlands, around 70 % of the buildings supplied by ATES are public or commercial buildings (e.g. offices, shopping malls, hospitals, hotels). The remaining 30% are installed in residential and industrial facilities (Hendriks et al., 2008; Nordell et al., 2015). Similar proportions are reported from Sweden (Andersson et al., 2013) and Denmark (Sørensen, 2017). Recently, ATES has been increasingly considered for greenhouses and data centers (Courtois et al., 2007; Turgut et al., 2009; Wong et al., 2011). The lifetime of an ATES system is estimated at 25 years by Hartog et al. (2013) and at 30-50 years by Bloemendal et al. (2014). The capacity of a small ATES ranges between 0.1 and 0.3 MW. Larger system supply between 5 and 30 MW. The largest ATES system worldwide is operated at Eindhoven University of Technology (TU/e). Here, 36 wells provide a cooling and heating capacity of about 20 MW (Snijders and van Aarssen, 2003). The supplied buildings are connected by a district heating and cooling grid with the ATES. With CO_2 savings of about 13,000 t of CO_2 per year, the invest of 15 million Euro amortized after 6-10 years (Worthington, 2011).

The country statistics give rise to the question for the reasons for the great discrepancies in ATES development worldwide. Even though the techno-economic viabilities have been demonstrated, only a small share of ATES potential has been tapped yet. In most industrial countries, except for Sweden or the Netherlands, ATES is not in the focus yet. This can be explained since the development of ATES technology is not only influenced by underground and climate conditions, but also by several market barriers, which are of socio-economic, regulatory, technical and political natures. The kind of market barrier, influencing ATES development in a country is a function of the market development level: in an emerging market phase, the main barrier is less a matter of technical nature than a lack of awareness of the technology. Since no experiences were made with ATES, politicians, stakeholders and HVAC (heating, ventilation, and air conditioning) installers often do not consider ATES and, therefore, this technology is not part of the new energy design. A promising way to promote an innovative technology is the successful realization of pilot projects (Hicks and Stewart, 1988; Hattrup and Weijo, 1989). Such projects not only draw public attention but also prove technical and often economic feasibility. Entering the commercialization stage, the type of potential barrier shifts from socio-economic to more regulatory issues. As experiences gained with ATES are rare in most countries, many legal questions have to be addressed, discussed, and finalized in regulations (Reilly, 1980). Experience gained in the Netherlands have illustrated that courage of the authorities to create a proper legislative framework is important to facilitate technology growth in a country (Godschalk and Bakema, 2009). Authorities have to find the right balance between the protection of groundwater and an acceptable limitation of ATES application. With a successful establishment in the energy market and a steadily increasing number of implemented systems, a scarcity of subsurface space, especially in an urban environment can also be a limiting factor. In the Netherlands, the increasing demand for ATES exceeds the available subsurface space in many cities. Hence, there is an increasing demand for a cross-sectoral subsurface management.

3. TECHNICAL PERFORMANCE

The performance analysis is based on the monitoring data of 73 Dutch ATES systems. The data were gathered by an energy management software (EMS) called Lift and comprise of the following parameter:

• Volume of pumped groundwater [m³]

• Abstracted thermal energy for heating and cooling [MWh]

• Abstraction temperature heating and cooling [°C]

• Injection temperature heating and cooling [°C]

• Minimum and maximum injection temperature for heating and cooling [°C]

The capacity, the location as well as the type of building of the analyzed ATES systems are illustrated in Fig 4. The capacity ranges between less than 0.5 GWh for small and more than 1.5 GWh for large systems. 42 % of the ATES systems supply commercial buildings such as offices or hotels. Public buildings such as universities, museums and governmental buildings as well as hospitals make up 21 % and 20 %, respectively. The remaining 16 % are multi-functional or residential buildings.

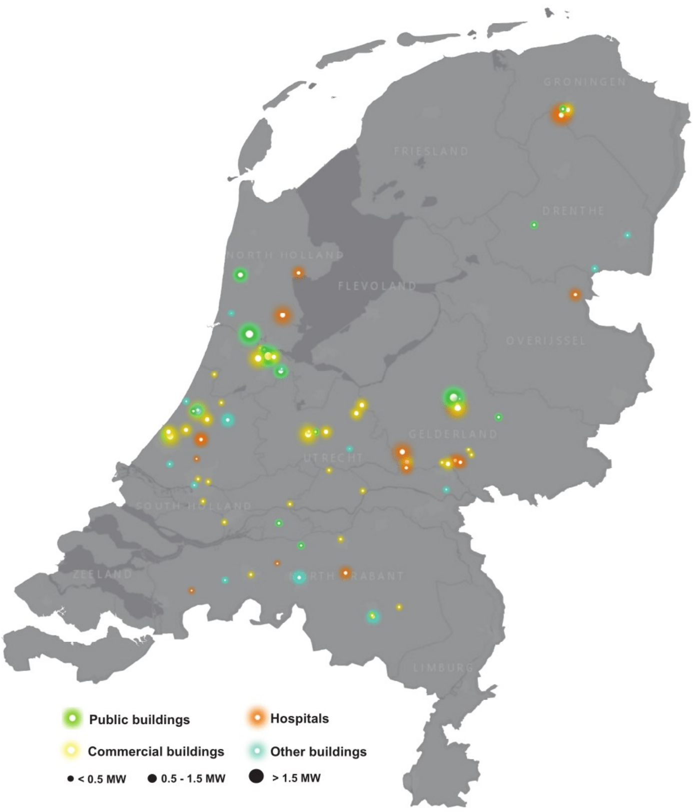

Figure 4: Location, heating and cooling capacity as well as type of building of the analyzed ATES systems.

With an annual abstracted amount of thermal energy for heating and cooling of 30.4 GWh and 31.8 GW, respectively, the average pumped energy per system was measured as 455.8 (± 484.9) MWh for heating and 477.0 (± 575.4) MWh for cooling. The high standard deviation (±) indicates a large range of the system capacities. Fig. 5 shows the average amount of abstracted thermal energy per system per month from 2016 to 2018. The dashed line shows the mean abstracted thermal energy for heating (orange) and cooling (purple) of all systems. With around 2,500 ATES systems in operation, the supplied thermal energy can therefore be estimated to more than 2 TWh in the Netherlands per year. At the same time, ATES contributes only to 2 % of the thermal energy demand (127

TWh) of the built environment in the Netherlands (CBS, 2017). With an average volume of 153,000 (± 146) m³ of pumped groundwater per year, the total abstracted annual volume can be estimated to 384 million m³ in the Netherlands per year. In addition, Bonte et al. (2011) calculated the total amount of pumped groundwater to be 350 million m³ per year based on licensing data. In comparison, the amount of abstracted groundwater for drinking water supply in 2016 was estimated to be 692 million m³ (Vevin, 2017). 9 and 15 % are attributed to the industry and the agriculture, respectively (OECD, 2015). Hence, around 27 % of the pumped groundwater is used for ATES application in the Netherlands. While the groundwater extraction steadily decreases (Vevin, 2017), the share of ATES on the total groundwater abstraction is expected to further increase. However, it is important to note that the net abstraction volume is close to zero as the abstracted groundwater is injected back into the aquifer by the ATES system after passing the heat exchanger. The monitoring data revealed that the amount of injected thermal energy of the 73 ATES was almost in balance (imbalance of -2.3 %) in the period from 2016 to 2018. Hence, the net groundwater temperature is only minimally affected by ATES activity in the Netherlands. Even though a balanced energy ratio is required by the authorities, the monitoring data revealed at least a slight thermal imbalance for most systems. However, some systems (about 15%) also showed a strong thermal imbalance. The latter results from an insufficient monitoring and energy management and can negatively affect the performance the ATES and the optimal usage of the subsurface.

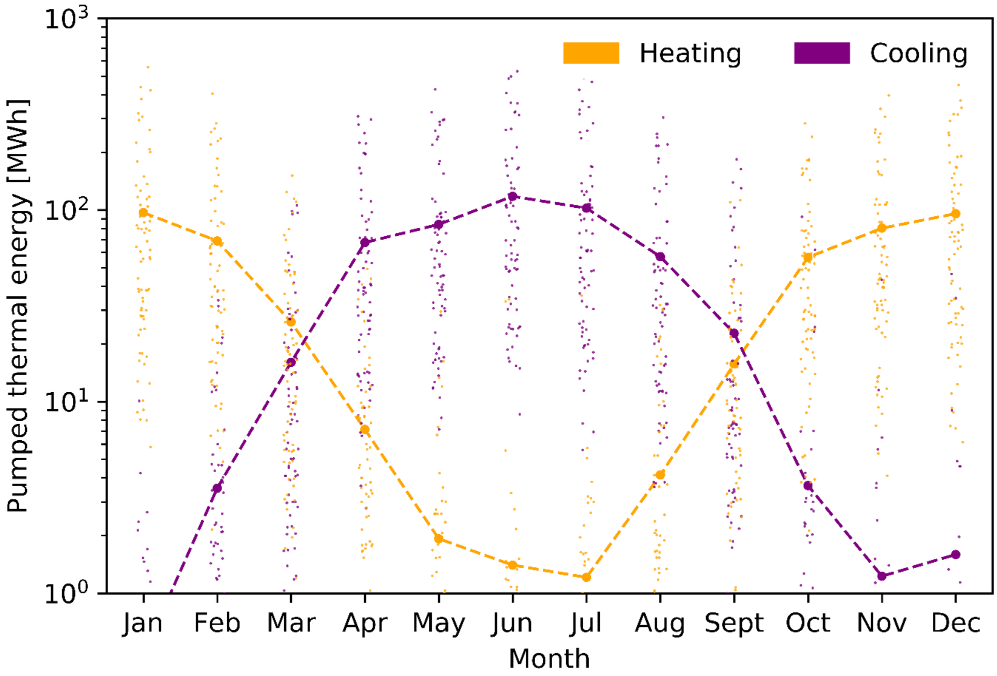

Figure 5: Average pumped thermal energy per month of 73 studied Dutch ATES systems. The average pumped energy for cooling and heating is indicated by the dotted line.

Fig. 6 shows the injection and abstraction temperature for heating (left) and cooling (right) season. The temperature was measured before and after the heat exchanger once per hour. As the hourly data were averaged to monthly values, peak injection and abstraction temperatures are not illustrated in Fig. 6. The average abstraction temperature drops from 15 to 14 °C during winter and increases from 10 to 11 °C during summer. Compared to the ambient groundwater temperature in the Netherlands, which typically ranges between 10 and 12 °C (Bloemendal, 2018), the storage effect is reflected by a 2 to 3 K colder (summer) or warmer (winter) production temperature. However, for around 15 % of the analyzed systems, the abstraction temperatures are close to the ambient groundwater temperature. These ATES operate more like standard GWHP systems using natural groundwater temperature instead of actively storing energy. However, it is important to note that some of the monitored injection and abstraction temperatures are impacted by different kind of urban infrastructures such as buildings, railways or other geothermal systems. Even though hourly peak-time values can go up to 20 K, the average ΔT was measured 5.2 K (± 1.8) K for heating and 5.4 (± 1.8) K for cooling. Thus, the ΔT are around 3-4 K smaller than initially designed. This can be explained by an inefficient charging of the subsurface by the HVAC system. The lower ΔT are typically compensated by higher pumping rates. Therefore, an optimization here would not only result in a reduced electricity demand for pumping, but also in lower specific storage volumes (kWh/m³) and hence, a more efficient utilization of the subsurface. The average temperature losses during the storage period of all analyzed system was measured as 1.3 (± 1.2) K. Hence, in order to facilitate ATES efficiency in the Netherlands, it is not only crucial to enhance subsurface storage efficiency, but to ensure an efficient integration of the ATES system into the energy system. In addition, the monitoring data also indicated an inefficient use of the available subsurface space. Particularly in city centers, the available space is already limited by different kind of subsurface users such as geothermal energy, underground infrastructure or buildings. To allow a future growth of shallow geothermal energy in an urban environment, it is essential to use the available space in a sustainable way. However, the analyzed ATES systems use less than 50 % of the licensed capacity. To guarantee a sustainable ATES application, both owners and authorities should strive to minimize unused subsurface space. In some Dutch provinces, the authorities started to negotiate with permit holders to reduce the licensed capacity in case it is not fully used.

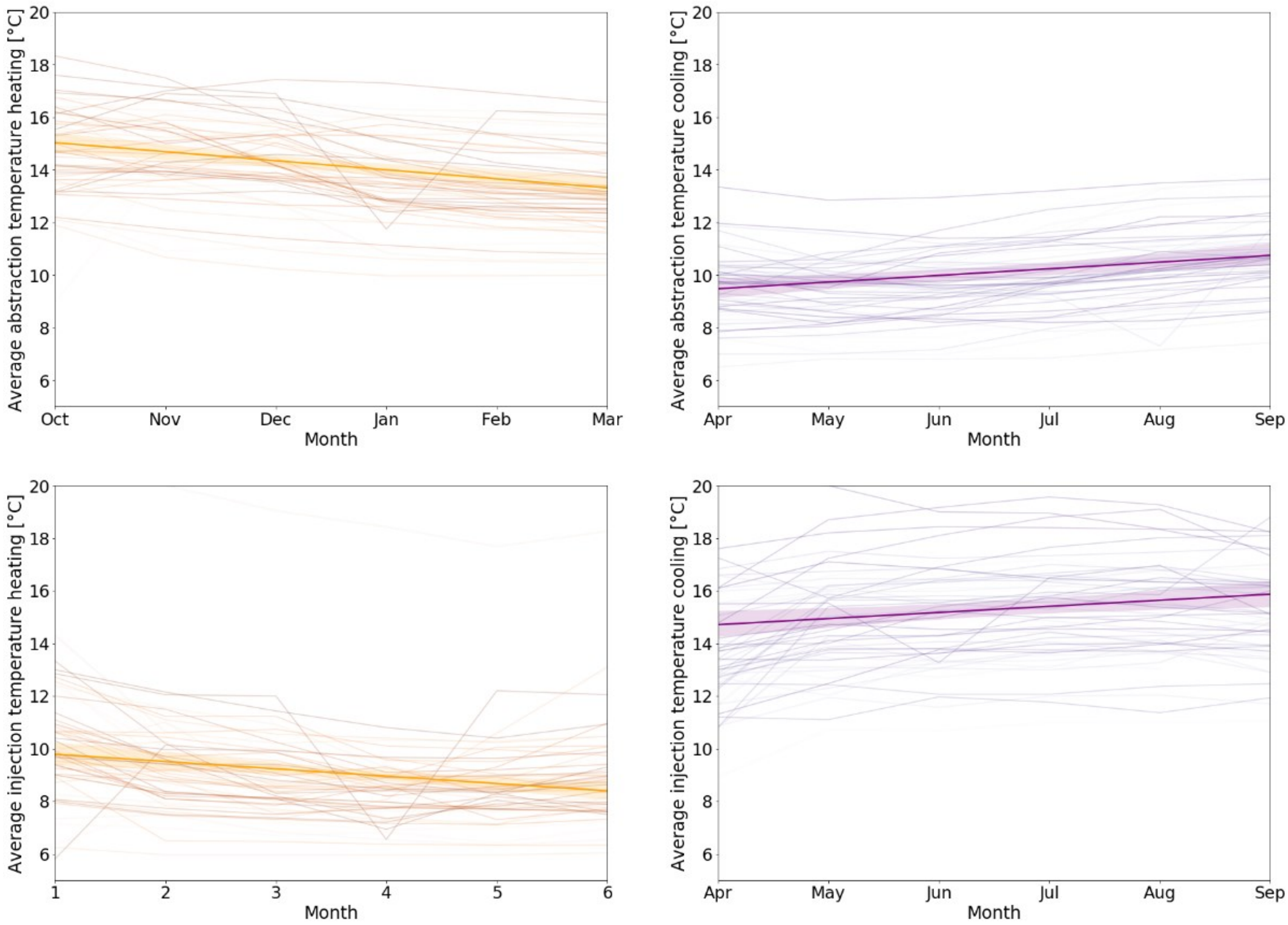

Figure 2: Injection and abstraction temperature of the 73 monitored ATES systems.

4. FINANCIAL PERFORMANCE

The awareness of the capital costs of ATES systems are important for clients and stakeholders. The high capital costs of ATES, which are often twice the price compared to common supply technologies, often appear less attractive when it comes to the decision of either using ATES or another common supply technology. In general, the capital costs of ATES range between 0.2 M€ for small and 2 M€ for large systems. However, the determination of the specific capital costs (€/kW) of ATES is more suitable for comparison with other ATES or different supply technologies. The expected additional specific capital for ATES systems compared to common supply technologies is between 130 €/kW and 265 €/kW (Chant and Morofsky, 1993). Fig. 7 illustrates the correlation between the specific capital costs (€/kW) and the thermal storage capacity of 77 Dutch ATES systems currently in operation. The average specific capital costs and capacities of all systems amount to 545 ± 396 €/kW and 1,200 ± 1,500 kW, respectively. The specific capital costs strongly decrease from more than 1,200 €/kW for small systems to 300 €/kW for systems with large storage capacities. One reason for this is that high up-front investments regarding feasibility studies or transportation of the single components to the construction site are nearly independent from the system size. In addition, Fig. 7 shows the decrease of the specific capital costs with increasing flow rate per well-doublet. The storage capacity and the pumping rate is expected to be proportional. Systems with smaller capacities are designed to supply buildings with low heating and cooling demand resulting in a reduced flow rate compared to large applications with flow rates up to 200 m^3 per well-doublet. Thus, ATES are in general more suitable for large storage capacities and should therefore be implemented for buildings with large heating and cooling demands (> 1.0 MW).

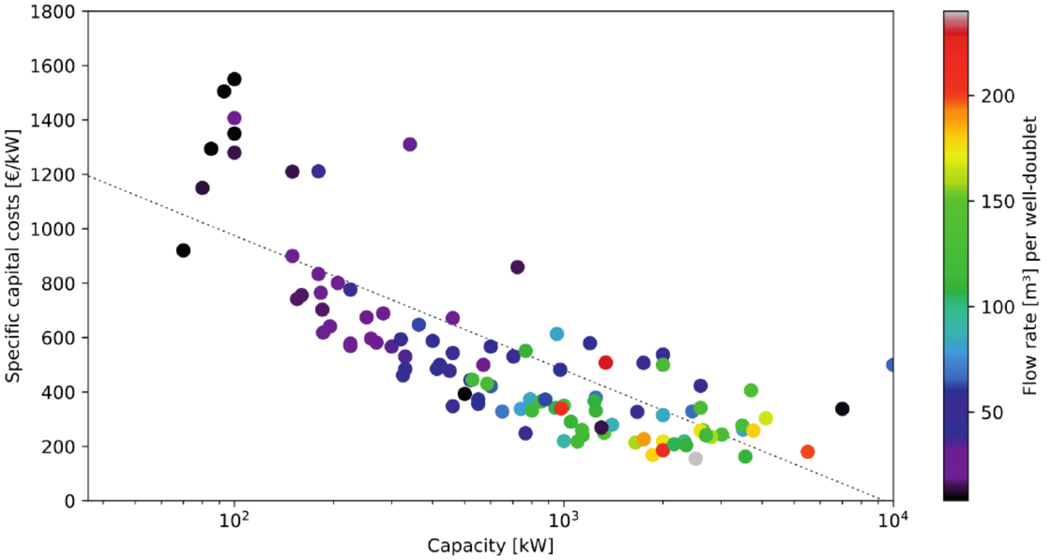

Figure 7: Specific capital costs of ATES systems as a function of the thermal storage capacity.

4.2 Operational expenditure (Opex)

Considering the high capital costs of ATES systems it is of particular importance to analyze the costs and economic benefits of ATES during operation. However, the operating costs are often not sufficiently considered in the decision-making process. The operating costs of ATES mainly result from the electricity consumption of the heat pump and the submersible pumps in the wells (Sommer, 2015; Bloemendal et al., 2018). The smaller the operational costs, the faster the compensation of the capital costs resulting in small payback times. Thus, looking at the payback times as a function of the capital costs allows conclusions on the efficiency of ATES operation. Fig. 8 summarizes the expected average payback times of 16 ATES systems comprehensively described in literature. The payback times range between two and 15 years with an average value of seven years. ATES with payback times of more than seven years are related to research projects (Agassiz, New Jersey) or are among the very first systems, which were implemented during the 1980s or early 1990s (e.g. Utrecht, Klippan, Falun). This suggests that a focus on scientific issues or lack of experience could lead to less efficient operation resulting in payback times above the average. Fig. 8 shows that the payback times of hybrid ATES systems used for heating and cooling supply with an average value of 6 years are potentially much lower than ATES system only for heating and cooling, respectively. Hence, ATES for heating and cooling is the most efficient application and should be the first priority when it comes to the implementation, in particular in regions where ATES in not yet common.

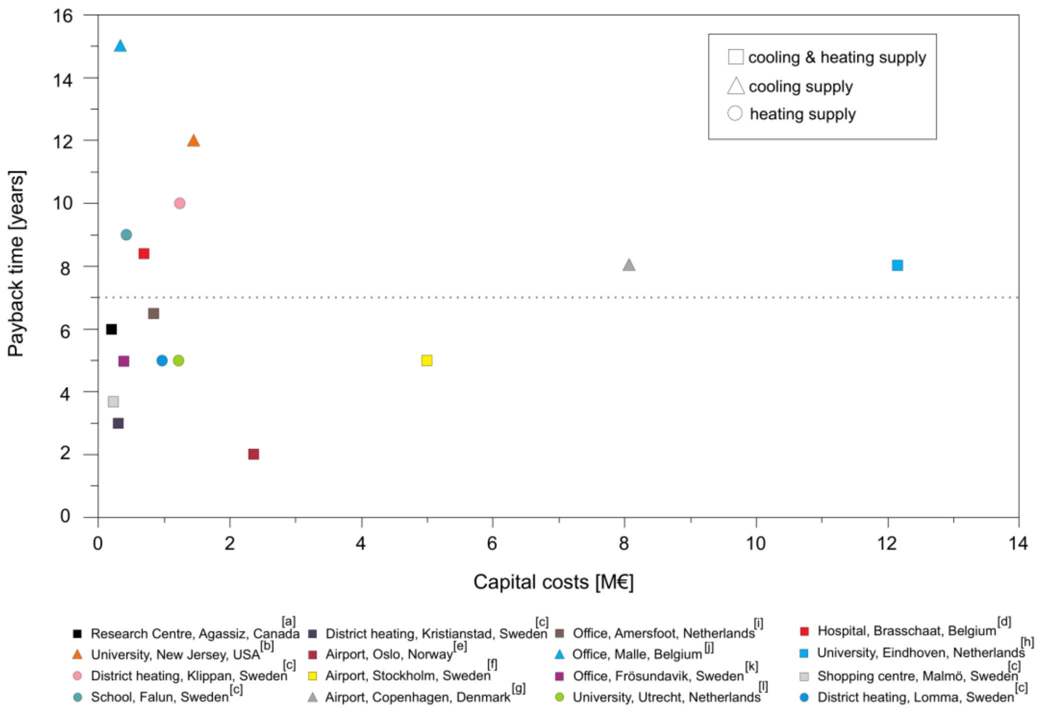

Figure 8: Payback times of ATES systems as a function of the capital costs (Bridger and Allen, 2010; Stiles et al., 2009; Andersson and Sellberg, 1993; Vanhoudt et al., 2011; Eggen and Vangsnes, 2005; Wigstrand, 2009; Worthington, 2011; Baxter et al., 2018; Hoes et al., 2006; Bakema et al., 1995; Sanner, 2000; Dinçer and Rosen, 2011)

Since comprehensive analyses or data about the operational costs of ATES are rarely published, the present chapters emphasize the potential economic viability of ATES compared to common supply technologies based on a representative case. A new building complex of the municipal hospital in Karlsruhe, Germany consists of seven floors and has a heating and cooling demand of 3,685 MWh and 4,800 MWh, respectively. Currently, the hospital uses magnetic bearing compression chillers for cooling and district heating from the district heating network of the city. Since these specific types of chillers are frequently used in hospitals and data centers, they are representative for a standard cooling supply technology. The district heating network in Karlsruhe is fed with over 770 GWh of heat, mostly supplied by industrial waste heat of a mineral oil refinery (MiRo). The economics of ATES for heating and cooling of the hospital building are compared to the currently used supply technology. The expenses are the total costs of the ATES, while the revenues are the total costs of the current supply technology of the hospital. For a more detailed description of the methods used, reference is made to Schüppler et al. (2019). Fig. 9 compares the total costs of the current supply technology and the ATES over an observation period of 30 years. The comparison clearly demonstrates the potential economic benefit of ATES. The estimated capital costs of the ATES system are about 50 % higher than the capital costs of the current supply technology. Despite the higher capital costs, the expected net present value (NPV) of the ATES for heating and cooling is 3.1 ± 1.0 million € after an observation time of 30 years. Thus, the investment in the ATES system for heating and cooling is rather positively evaluated in comparison to the currently used supply technology. The estimated saved amount of energy is almost 3,500 MWh, which corresponds to 80 %. This saved amount of energy is equal to 120 hospital beds or 240 single-family houses. Due to the lower energy consumption, a potential average payback time of 2.7 years is achieved. Even though Fig. 9 shows promising results, each case must studied individually to figure out which supply technology meet the current requirement.

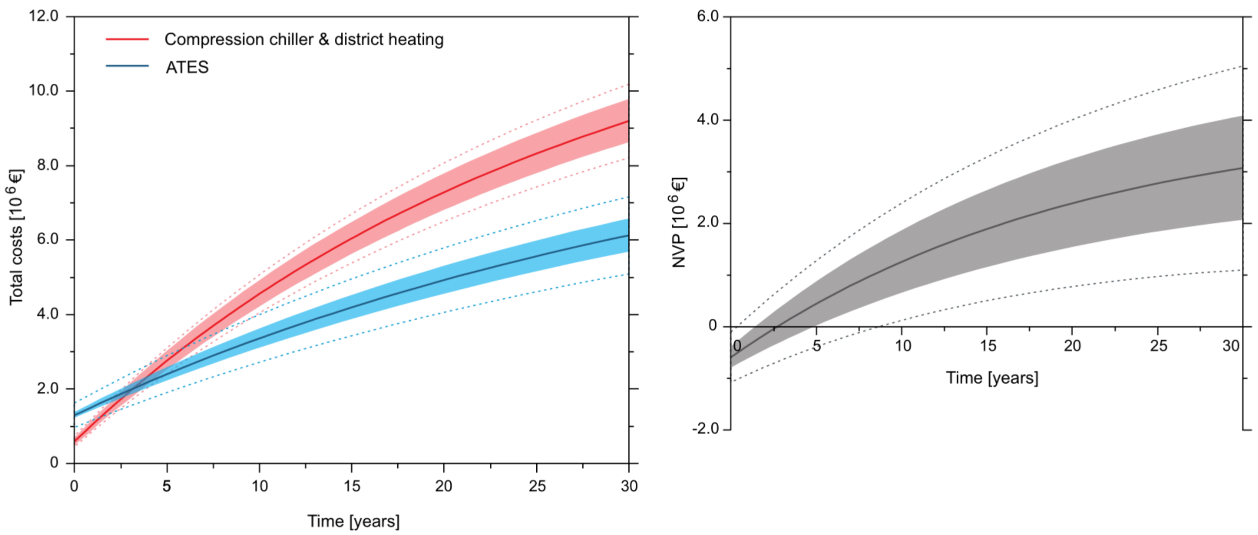

Figure 9: Economic analysis of ATES for heating and cooling and compression chillers for cooling and district heating.

5. CONCLUSION

With more than 2800 systems in operation worldwide, ATES technology has proven its ability to efficiently tackle the seasonal mismatch between periods of highest energy supply and highest energy demand. This success story is almost entirely limited to the Netherlands and Scandinavia. However, there is a high potential for ATES technology in almost all developed countries. In order to promote ATES worldwide, it is important to increase the awareness for the technology among politicians, stakeholders, and HVAC designers. Research supported demonstration projects already proved in several countries the potential to not only draw public attention but also prove technical and often economic feasibility. The monitoring data of 73 Dutch ATES systems showed a good technical performance of the analyzed systems. Nevertheless, there is still room for optimization, which is in particularly the case for the interaction between the subsurface and the supplied building as well as a more sustainable use of the available subsurface space. In addition, the financial analysis showed that the high capital costs can be amortized after several years. In order to further enhance ATES application the following topics should be addressed in future research activity:

- Techno-economic analyses and energetic performance of ATES compared to other shallow geothermal application such as GWHP or BTES systems or storage technologies including Pit Thermal Energy Storage (PTES) and Tank Thermal Energy Storage (TTES);
- Life cycle assessment (LCA) to provide more detailed information about the potential environmental benefits of ATES;
- Evaluation of the ATES potential on urban, regional and national scale, considering hydro(geological), geographical, regulatory and climatic boundary conditions;
- Optimizing the interaction between different kinds of urban subsurface users such as subways, underground utilities or buildings with thermal energy storages considering the effect of subsurface urban heat islands (SUHI).

- Optimizing the interaction between the built environment and shallow geothermal energy applications by linking building energy models to subsurface models.

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