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Capital costs of aquifer thermal energy storage (ATES): a review

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ABSTRACT

For a successful global energy transition, more seasonal thermal energy storage (STES) and district heating and cooling systems are needed. Hence, the economic aspects of STES are essential during the decision-making phase of planning a district heating and cooling system. Until now, only a few studies exist on the capital costs of STES and particular aquifer thermal energy storage systems (ATES). Hence, this study aims to identify and analyse the capital costs of 133 existing ATES systems from the Netherlands, Belgium, Denmark and other countries. Our results show a decrease in capital costs per installed heating and cooling capacity with increasing capacity. Capital costs per installed capacity converge to 300 €/kW after 2 MW of installed heating and cooling capacity. Hence, larger ATES systems should be favoured. Compared with other seasonal thermal energy storage (STES) systems, ATES systems have the lowest capital costs per storage volume (<10 €/m^3) and the lowest per stored energy (130–1,630 €/MWh). Hence, if the hydrogeological conditions at a site are favourable for ATES systems, they should be carefully considered for STES, in particular, if cooling and heating are required in equal proportions.

1. Introduction

To successfully combat climate change and achieve the internationally formulated goal of limiting global warming to 1.5 °C above pre-industrial levels at best, fast reductions of greenhouse gas emissions (GHG) are required worldwide [1]. Hence, decarbonising the heating and cooling sector is of high importance. Since this sector accounts for about one-fifth of the global GHG [2]. However, only 10 % of this energy is supplied by renewable energies, such as solar thermal energy, sustainable bioenergy or geothermal energy, with only minor increases in recent years [3]. At the same time, global heating demand is expected to increase due to rising living standards until 2035 [4]. In particular, the energy demand for cooling could grow 400 % by 2050 [5]. Climate change is driving the increase of cooling degree days by 2080 of 125 %, further increasing cooling demand [6].

The key challenge of increasing the amount of renewable energies in the heating and cooling sector is attributed to the seasonal offset between thermal energy supply and demand. To address this seasonal mismatch, the idea of seasonal thermal energy storage (STES) has attracted increasing attention [7–9]. STES systems could decrease energy consumption and, therefore, GHG emissions by storing thermal energy derived from renewable or other sources during periods of abundance and discharging the storage during scarcity of thermal energy [10,11]. A wide variety of STES systems, such as tank thermal energy storage (TTES), pit thermal energy storage (PTES), borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES), are currently in use and under consideration [8,9,12–14]. Xu et al. [15] provide a comprehensive review of the various STES technologies. For the decision-making process and comparison with other technologies, the capital and operational costs of STES systems are crucial. Hence, various economic studies of STES have been performed in the past and increasingly in recent years [8,14,16,17]. For example, Yang et al. [8] also introduced a decision tree for STES selection, which intends to facilitate practical engineering.

The first studies on the economic performance of ATES systems were performed by Reilly [18], Reilly et al. [19] and Brown [20] after the

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1970s energy crisis. They concluded that the well-related expenses were the largest portion due to the number of wells required for energy storage and retrieval. Reilly [18] concluded that ATES can be highly cost-effective and achieve substantial fuel savings. Initiated by Schmidt et al. [14] and extended by Mangold and Schmidt [21], they compared the capital cost per water equivalent (€/m^3) of various realized STES systems (7 TTES, 4 PTES and 2 BTES) and one high-temperature (HT) ATES system in Germany. Both studies showed that geothermal storage systems such as BTES and ATES systems have the lowest capital cost per water equivalent (<100 €/m^3) and that other STES systems provide the highest storage volume (>10,000 m^3). Yang et al. [8] provide a comprehensive techno-economic literature review of six STES systems such as TTES, PTES, BTES, ATES, latent heat storage (LHS) and also thermochemical heat storage (THS). They analysed the economical feasibility using levelized cost of heat (LCOH), storage volume cost and storage capacity cost. Based on the analysis of 9 BTES and 4 ATES systems, they showed that BTES and ATES have the best economic performance, confirming previous conclusions made by Schmidt et al. [14,22]. Furthermore, in comparison to other heating systems, such as natural gas and solar heating for decentralized systems, only PTES and low-temperature (LT) ATES systems are economically competitive [8]. However, in this study, only 4 ATES systems, 3 HT-ATES systems in Rostock, Germany [14], in Adana, Turkey [23], in Groningen, Netherlands [24] and only one LT-ATES system in Brasschaat, Belgium [25], were considered. Although, of the more than 3000 ATES systems operating worldwide, 99 % are LT-ATES systems with storage temperatures of ≤25 °C [9]. In addition, only two of the considered ATES systems in Rostock (HT-ATES) and Brasschaat (LT-ATES) are realized and in long-term operation (>3 years).

Fleuchaus et al. [9] and Schüppler et al. [16] collected the capital costs of 16 ATES systems with an estimated average payback time of 7 years and typical payback times between 2 and 10 years. However, these reported payback times are often discussed without mentioning the reference technology [16] or comprehensively reporting operational costs. Vanhoudt et al. [25], who investigated the existing LT-ATES at the Klina Hospital in Brachschaat, Belgium, is one of the few studies, that reported the capital and also operational costs. Hence, most of the provided economic analyses on LT- and HT-ATES systems are based on hypothetical case studies [16,26–29]. Hitherto, only a few detailed and well-documented economic studies exist on realized and operating LT-ATES. A similar conclusion on STES, including ATES, was drawn by Yang et al. [8].

Thus, the objective of the current study is to identify and analyse capital costs of existing implemented ATES systems with a focus on LT-ATES. Overall, the capital costs of 132 LT-ATES systems are comprehensively analysed, with 102 systems from the Netherlands, 8 from Belgium, 5 from Denmark and 18 from various European and North Amercian countries reported in the literature. The account composition of the capital costs, the capital cost per installed capacity (€/kW), the capital cost per storage volume in water equivalent (€/m^3) according to Schmidt et al. [14] and stored energy (€/MWh) are determined. This economic analysis of ATES systems is subsequently compared and discussed with other STES systems such as TTES, PTES [17,30], BTES [31,32] and geothermal systems such as ground source heat pump (GSHP) systems [33] and deep geothermal systems [34] provide the conclusion of the most economic STES system with respect to capital costs and the basis for future economic studies. The results of this study also aim to support decision-makers for choosing the appropriate STES system, in particular for ATES systems in emerging markets.

2. Material and methods

2.1. Capital costs

2.1.1. Aquifer thermal energy storage (ATES)

In total, the capital costs of 132 LT-ATES systems are studied, 102 systems from the Netherlands, 8 from Belgium, 5 from Denmark and 17 from various European countries reported in the literature, summarised by Schüppler et al. [16]. The capital cost data from the Netherlands are provided by realized ATES projects from the consultancy company IF Technology based in Arnhem, these include capacity, well depth and flow rates. The installed capacities from the 102 Dutch ATES systems range between 0.05 and 11 MW covering a broad range of ATES installations. The maximum capital cost is 5.5 million €. These systems were installed from 2002 until 2007.

The capital cost data of the 8 ATES in Belgium originate from the company IFTech based in Beringen, which designs, constructs and also operates geothermal energy systems. The capital costs of these 8 Belgian ATES systems are also subdivided into two categories: (1) subsurface and (2) surface installations, providing further insights into the account composition. The surface installation consists of all horizontal piping, the corresponding groundwork from the wellhead to the building or heating station, and the necessary building integration consisting of the heat pump and heat exchanger. The subsurface installation consists of the drilling of the wells and the well piping including all essential well installations such as pumps and all necessary installations for the monitoring and production wells. This also includes pumping tests for the determination of the hydraulic properties of the aquifer. The installed capacities of these 8 systems range between 0.3 and 8 MW so in a similar range as the Dutch systems. The company Energy machines based in Copenhagen provides the capital cost data from the 5 Danish ATES systems. The company provides services of integrated energy systems, including ATES systems, from design to implementation and operation. The capacities of these 5 systems, installed between 2010 and 2024, range between 0.6 and 5 MW.

This unique data set from realized and still operating ATES systems in three European countries, the Netherlands, Belgium and Denmark, is complemented by data from the literature. Table 1 summarises this data, which consists of 14 LT-ATES and 4 HT-ATES systems from the Netherlands, Belgium, Denmark, Sweden, Norway, Germany, United States of America and Canada covering countries, with 99 % of all installed LT-ATES systems and all market development levels from emerging, growth to mature phases [9]. For studied systems, the capacity includes heating and cooling. ATES systems, which only stated the heating capacity, were assumed to be balanced, and therefore, the equivalent cooling capacity was added. If the capital costs did not include the heat pump, costs of the heat pump were also added, corresponding to the system's heating capacity [35].

2.1.2. Other thermal energy storage and geothermal systems

Other STES and geothermal systems are also considered for a comprehensive comparison and discussion. Hence, 9 TTES systems from Germany, 8 PTES with 2 from Germany and 6 from Denmark and 7 BTES from Denmark, Germany, Sweden, Norway and Canada are also included. Table 2 summarises the relevant data such as location, year of installation, storage volume in water equivalent, storage temperature, stored energy, capital costs in the reference year 2022 and the data source (reference).

In addition to the ATES and STES data, two additional data sets of shallow geothermal systems, ground source heat pump (GSHP) and groundwater heat pump (GWHP) systems located in Germany, are also included. The data set of GSHP systems consists of 1100 individual and small installations typical for one-family houses with an average heating demand of 11 kW ± 3 kW [33]. In addition, the capital costs of 3 groundwater heat pump (GWHP) systems from Germany are included. This data set is provided by the consultancy company tewag based in Regensburg, Germany. These systems range between 0.7 and 1.3 MW. Two of these systems operate in heating and direct cooling mode, similar to a typical ATES system. Because the capital costs of the surface data such as heat pump and heat exchanger, were not available, these costs are completed by data from the literature [16,33,35].

Thermal losses of STES are an essential factor for storage efficiency.

Table 1
Literature data on capital costs of LT- and HT-ATES systems.

Location	Capacity [kW]	Year of installation	Storage temperature [°C]		Depth of wells [m]	Flow rate [m^3/h]	Storage volume in water equivalent [m^3]	Stored energy [MWh]	Capital costs in reference year 2022 [€]	Capital costs per capacity [€/kW]	Reference
			Warm well	Cold well							
Low-temperature ATES											
Agassiz, CA	560	2001	15	6	60	40	–	–	341,000	607	[36,37]
Amersfoort, NL	2,000	1996	–	–	240	–	–	–	1,750,000	892	[37]
Amsterdam, NL	20,000	2015	–	–	–	1,100	–	–	30,700,000	1,535	[37]
Arlanda, SE	10,000	2009	20	5	20	720	1,150,000[a]	20,000	6,300,000	631	[38,39]
Brasschat, BE	1,200	2000	18	6	65	–	525,000[a]	6,125	1,150,000	959	[25,40]
Copenhagen, DK	7,000	2015	–	–	130	–	1,500,000[a]	22,000	9,100,000	1,301	[41,42]
Eindhoven, NL	60,000	2002	16	6	80	3,000	5,400,000[a]	63,000	22,180,000	370	[37,43, 44]
Frösundavik, SE	3,000	1994	–	–	–	–	–	–	783,000	261	[45]
Kristianstad, SE	750	1985	25	10	–	40	100,000[a]	1,800	330,000	439	[46]
Malle, BE	820	2002	13	7	67	90	61,000a	429	540,000	659	[40]
Malmö, SE	1,300	2001	–	–	75	120	280,000[a]	3,900	510,000	659	[37,47]
New Jersey, US[d]	2,800	2005	18	6	35–70	272	325000	2025	1,300,000	464	[48]
Oslo, NO	13,500	1998	30	4	45	–	720,000[a]	22,000	4,500,000	334	[49–51]
Solna, SE	2167	1987	15	8	–	1,000	640,000[a]	5,200	1,400,000	620	[45,46]
High-temperature ATES											
Middenmeer, NL	12,000	2021	85	30	380	150	650,000	28,000	5,750,000	479	[52,53]
Rostock, DE	102[b]	2000	50	10	–	15	5,266	245	250,000	2,520	[37,54, 55]
Utrecht, NL	2,600	1991	90	50	260	100	130,000	6,000	2,250,000	868	[45]
Zwammerdam, NL	600	1998	90	–	150	20	24,000	1,400[c]	2,250,000	3,728	[37,56]

[a] Storage volume calculated from stored energy using Equation (2).
[b] capacity calculated from stored energy with 2400 full load hours.
[c] stored energy calculated from the storage volume and temperature difference using Equation (2).
[d] System only provides cooling.

Thermal losses for most of the ATES systems are unavailable and highly dependent on regional hydrogeological conditions [67]. Thus, thermal recovery rates were not included in the economic evaluation of this study. According to Bolton et al., 2023 [68], seasonal thermal recovery of ATES ranges from 67 to 90 %, PTES from 54 to 90 %, BTES 20–60 %, and TTES around 50 %.

2.2. Harmonized Index of Consumer Prices

Since almost all considered ATES systems are located in Europe (except two ATES systems in Canada and the United States of America) and no data is available on operation and maintenance costs, the Harmonized Index of Consumer Prices (*HICP*) is used for the comparison of the capital costs of the various systems from distinct years. The *HICP* is country-specific, an indicator for prize stability and enables the comparison of inflation rates and capital costs across the European Union [68]. Thus, the location of the studied energy system is required and provided in Tables 1 and 2. The calculated and referenced capital cost (CC_r) for cost comparison is determined using the Harmonized Index of Consumer Prices (*HICP*) as follows:

$$CC_r = \frac{HICP_r}{HICP_y} \times CC_y \tag{1}$$

with $HICP_r$ for the chosen reference year of 2022, $HICP_y$ for the year of system installation, both values can be obtained by eurostat [69] and the capital cost for the year of installation (CC_y). Using this index, it is possible to compare different energy systems from distinct years and countries. The Canadian Consumer Price Index (CPI) is used for the Canadian ATES system and the CPI of the USA for the US American ATES system.

2.3. Stored energy

Unfortunately, some of the collected literature data does not state the stored energy or the stored water volume. If this is the case, the following equation is used to calculate the missing data:

$$E_{th} = c_w \times \rho_w \times \Delta T \times V_w \tag{2}$$

E_{th} is the stored thermal energy, c_w is the specific heat capacity of water, ρ_w is the density of water, ΔT is the temperature difference of the storage system and V_w is the storage volume in water equivalent. If no data on the temperature difference is available, the following typical values are assumed: 40 K for BTES, 60 K for TTES, 50 K for PTES and 45 K for HT-ATES, according to Driesner [64]. For LT-ATES, the average temperature difference from the literature data was used (12.4 K) (Table 1).

2.4. Storage volume of ATES (water equivalent)

To compare various STES systems according to Schmidt et al. [14], the stored energy (MWh) and storage volume in water equivalent (m^3) are used. For TTES and PTES, the storage fluid is water. For ATES and BTES, however, the storage volume also consists of rock material. For ATES systems, the pumped water volume of one heating and cooling storage cycle is used as stored volume. If no data is available, the storage volume is calculated using the stored energy given in Equation (2).

3. Results and discussion

3.1. Account composition of the capital costs

Using the Belgian ATES and German GWHP data sets, both are subdivided into two categories, (1) subsurface and (2) surface, it is

Table 2
Literature data of tank thermal energy storage (TTES), pit thermal energy storage (PTES) systems and borehole thermal energy storage (BTES).

Location	Year of installation	Storage volume in water equivalent [m³]	Storage Temperature [°C]	Stored Energy [MWh]	Capital costs in the reference year (2022) [€]		Reference
					Storage system	Total costs	
Tank thermal energy storage (TTES)							
Hanover, DE	2000	2,700	-	128[a]	990,000	–	[57–59]
Berlin, DE	2016	10,000	-	300	–	3,310,000	[60,61]
Friedrichshafen, DE	1996	12,000	55	800	2,250,000	–	[58,59]
Hamburg, DE	1996	4,500	–	210[a]	1,480,000	–	[58,59]
Hanover, DE	2000	2,700	–	128[a]	990,000	–	[57–59]
Mannheim, DE	2013	43,000	–	1,500	8,400,000	32,500,000	[60,62]
Munich, DE	2007	5,700	–	330	1,140,000	–	[58–60]
Nürnberg, DE	2015	33,000	113	1,500	–	14,240,000	[60–62]
Potsdam, DE	2016	41,000	–	1,200	–	13,700,000	[60,61]
Pit thermal energy storage (PTES)							
Steinfurt, DE	1998	1,000	–	70[a]	623,00	–	[58]
Chemnitz, DE	2000	8,000	–	560[a]	1,500,000	–	[58]
Dronningslund, DK	2013	60,000	–	4,200[a]	2,700,000	–	[52]
Eggenstein, DE	2008	3,000	80	175	575,000	–	[12,58,63]
Marstal 1, DK	2003	10,000	–	700[a]	1,120,000	–	[58,59]
Marstal 2, DK	2012	75,000	–	5,250[a]	2,700,000	–	[52,59]
Toftlund, DK	2017	85,000	–	5,950[a]	3,500,000	–	[59]
Vojens, DK	2015	210,000	–	14,700	4,450,000	–	[59]
Borehole thermal energy storage (BTES)							
Braedstrup, DK	2012	5000	–	233[a]	275,000	–	[52,64]
Crailsheim, DE	2008	10,000	–	465[a]	770,000	–	[58]
Emmaboda, SE	2010	65,000[b]	40–60	3,800	1,540,000	–	[65,66]
Lorenskog, NO	2007	210,000[b]	–	13,600	28,000,000	–	[51,67]
Neckarsulm 1, DE	1997	10,000	50	465[a]	695,000	–	[58,66]
Neckarsulm 2, DE	1997	30,000	–	1,350	2,100,00	–	[58,59]
Okotoks, CA	2007	18,000	–	837[a]	448,000	–	[59]

[a] Stored energy calculated from storage volume using Equation (2).
[b] Storage volume calculated from stored energy using Equation (2).

possible to assess the account composition of the capital costs (Fig. 1). These two categories typically correspond to the two contractor groups, i.e. heating and drilling contractors, during the construction phase. The results show that the capital costs for the surface installations, including the heat pump at 55 %, are marginally larger than for the subsurface installations at 45 %. A similar cost distribution was previously observed for the capital costs of GSHP systems [33]. The average capital costs for monitoring are minor with 4 % of the total.

3.2. Capital cost per installed capacity

The capital costs of operating geothermal systems with increasing capacity is shown in Fig. 2. In comparison with GSHP systems with smaller capacities (<30 kW), ATES systems with larger capacities (>60 kW) reveal much lower capital costs per installed capacity (€/kW). Inside the ATES systems, a further decrease in capital costs is observed. With increased installed capacity, the capital costs per capacity of ATES systems decrease and converge to a minimum of about 300 €/kW at a capacity of around 2 MW. The results indicate that the larger the system, the lower the specific capital cost. Hence, larger ATES systems (>2 MW) should be built. Reilly et al. (1980) estimated the economic break-even point of ATES systems to be around 340 USD_{2022}/kW (76 USD_{1978}/kW) compared to conventional fossil-based heating solutions. This showed already in the 1970s that ATES systems can be highly cost-effective.

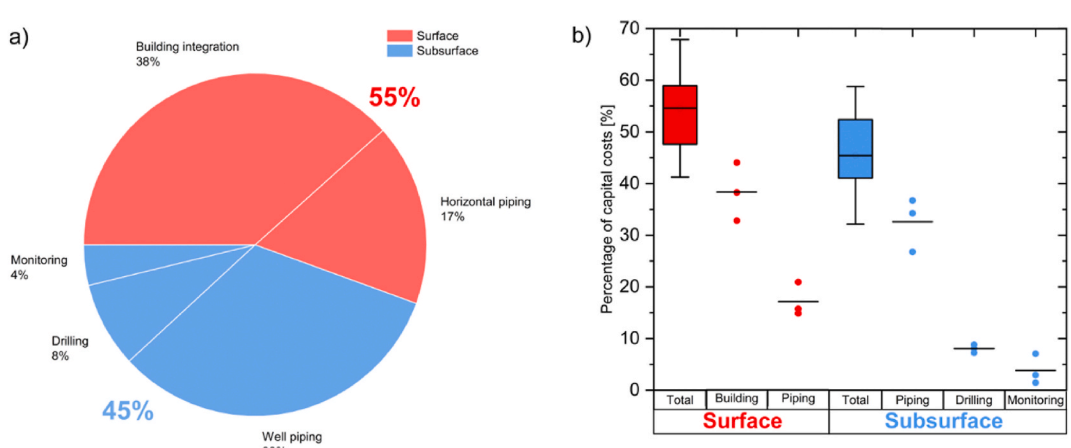

Fig. 1. The account composition of the capital costs of ATES systems is divided into surface and subsurface installations with 8 ATES systems from Belgium and 3 GWHP systems from Germany.

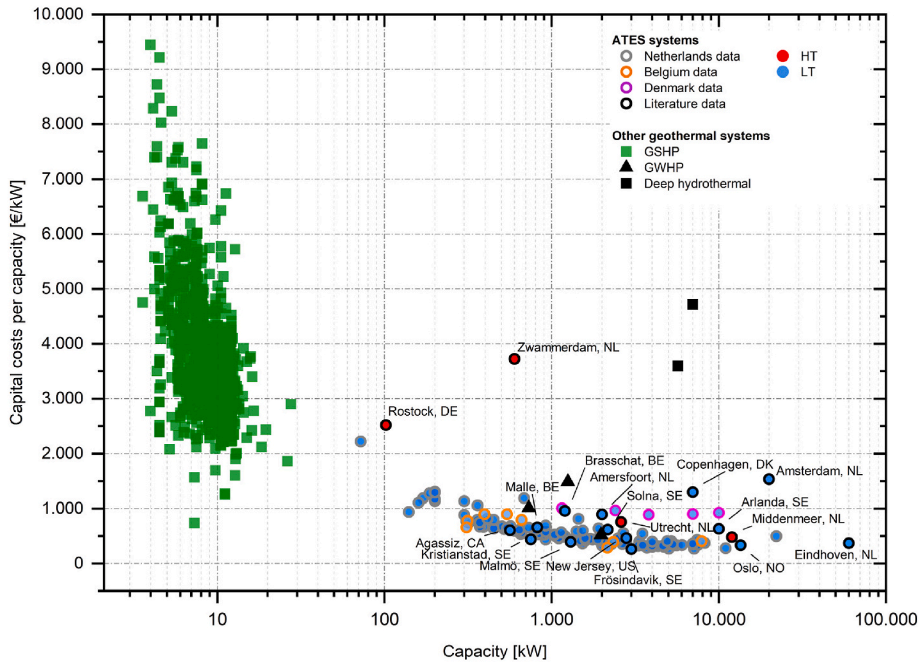

Fig. 2. Capital costs of about 1,100 ground source heat pump (GSHP) systems [33], 132 aquifer thermal energy storage (ATES) systems (this study and literature, Table 1), 3 groundwater heat pump (GWHP) systems (this study) and 2 hydrothermal geothermal systems [34,76].

Instead of individual solutions for single-family houses or buildings, integrated solutions for entire districts and cities should be implemented [70,71]. Stemmle et al. [72] studied city-scale heating and cooling with ATES systems in the city of Freiburg, Germany. They could demonstrate that for ATES heating alone, 40 % of the current greenhouse gas emissions (GHG) caused by space and water heating could be saved in the residential building stock. Hence, considering also cooling even larger GHG and cost savings could be obtained. Since 2024, in Germany, for example, for communities with >45,000 inhabitants, municipal heat planning is mandatory and legally binding. Unfortunately, cooling, which will become increasingly more important, is currently not addressed in this heat planning law [73].

The capital costs of ATES systems in the Netherlands and Belgium are comparable and display a similar trend with increasing capacity (Fig. 2). In both countries, where most of the ATES systems are operating, have comparable subsurface conditions such as alluvial deposits made of sands and silts and deeper Chalk aquifers. The two Belgian systems with 580 and 660 kW installed capacities that use a chalk aquifer and a fractured basement aquifer, respectively, tend to be more expensive than other systems. They also follow a similar trend to the other Dutch systems. The ATES systems in Denmark also show higher capital cost per capacity at about 1000 €/kW (939 ± 44 €/kW), which could be caused by the different geology, hydrogeological conditions like the chalk as one of the main aquifer in Denmark and also the economy of scale as Denmark's market development level is still emerging and in contrast the Netherlands is a mature market for ATES [9]. The range of capital costs for ATES systems in the literature is wider. This can also be explained by the different subsurface conditions and economies of scale as the market development levels are dissimilar in the studied countries.

The few analysed HT-ATES systems, and in particular the HT-ATES systems in Rostock [74] and Zwammerdam, which is no longer in operation [75], show much higher capital costs per capacity (>2500 €/kW) compared to LT-ATES systems. Furthermore, the two operating deep hydrothermal systems reveal much higher capital costs per capacity with 3600 €/kW in Schwerin-Lankow (Mecklenburg-Western Pomerania, North Germany; [76]) and 4720 €/kW in Poing (Bavaria, South Germany; [34]), which is mainly caused by the increased drilling costs of the deeper wells with 1300 m in Schwerin-Lankow and 3000 m in Poing (Fig. 2).

In contrast, considering only the capital costs of LT-ATES (Fig. 3), the well depth does not strongly correlate with higher capital costs per capacity, as the drilling costs only account for 8 % of the total capital costs (Fig. 1). However, the capitals costs per capacity highly correlates with the flow rate, i.e. higher flow rates result in lower capital costs per capacity. Yet again, these results clearly demonstrate that the larger the installed LT-ATES systems, lower investment costs per installed capacity can be achieved.

3.3. *Capital cost per storage volume in water equivalent*

Fig. 4 summarises the capital costs per stored volume in water equivalent for different thermal energy storage systems (TES). The lowest capital costs per stored volume (<10 €/m^3) is achieved by LT-ATES systems, which confirms previous results by Schmidt et al. [14, 22]. In contrast to the other STES systems, ATES systems need no constructed storage as natural aquifers are used to store the energy, which is one of the main advantages compared to other STES. The only requirements for ATES systems with respect to storage are wells. Despite providing the largest storage volumes, ATES systems occupy the smallest surface area. Furthermore, by using an aquifer, larger storage volumes for cooling and heating can be assessed. The two main limiting factors are the size and groundwater flow velocity of the aquifer system. The groundwater flow velocity is crucial for the thermal recovery of an ATES system, as larger groundwater flow velocities tend to lower the thermal recovery. High groundwater flow velocities of >1 m/d indicate small thermal recoveries of <50 % [72].

The capital costs per stored volume of HT-ATES is also higher than for LT-ATES (Fig. 4). The difference could be even higher, as in the provided data of HT-ATES, the capital costs of the heat source is not included. The heat sources for HT-ATES can be various types of renewable energies (solar, geothermal, biomass, power to heat, incineration plants) or waste heat from industry. Fleuchaus et al. [77] concluded that the loss of heat source is one of the key risks in operating HT-ATES systems. Hence, the type and additional costs of the heat source have to be carefully considered.

BTES systems, however, also indicate low capital costs per stored

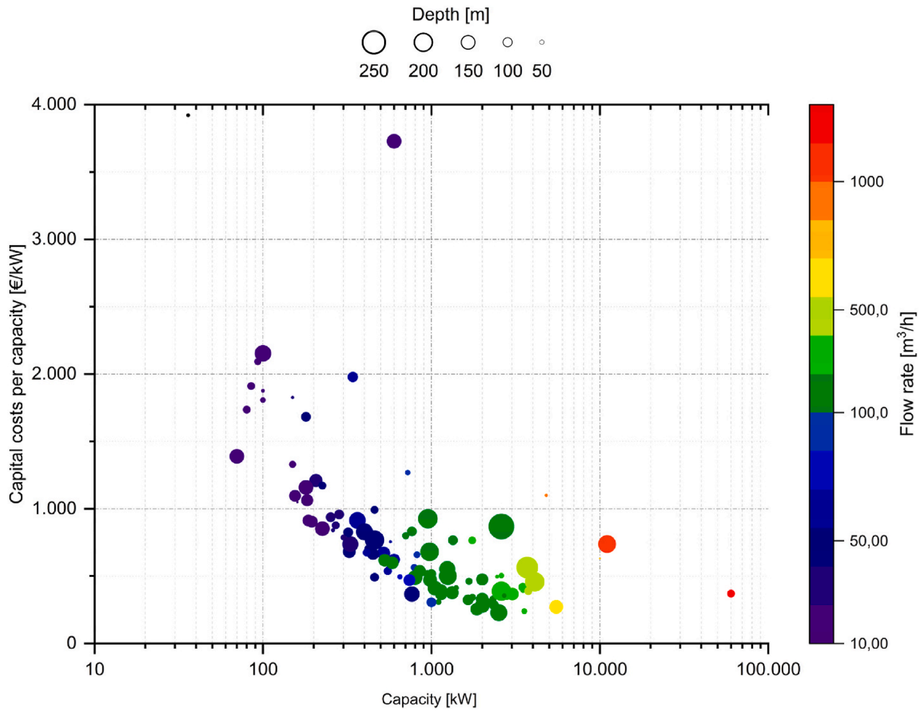

Fig. 3. Capital costs of operating low-temperature aquifer thermal energy storage (LT-ATES) systems with increasing capacity, including drilling depth and flow rate. Data consists of literature data (Table 1) and data from the Dutch ATES systems.

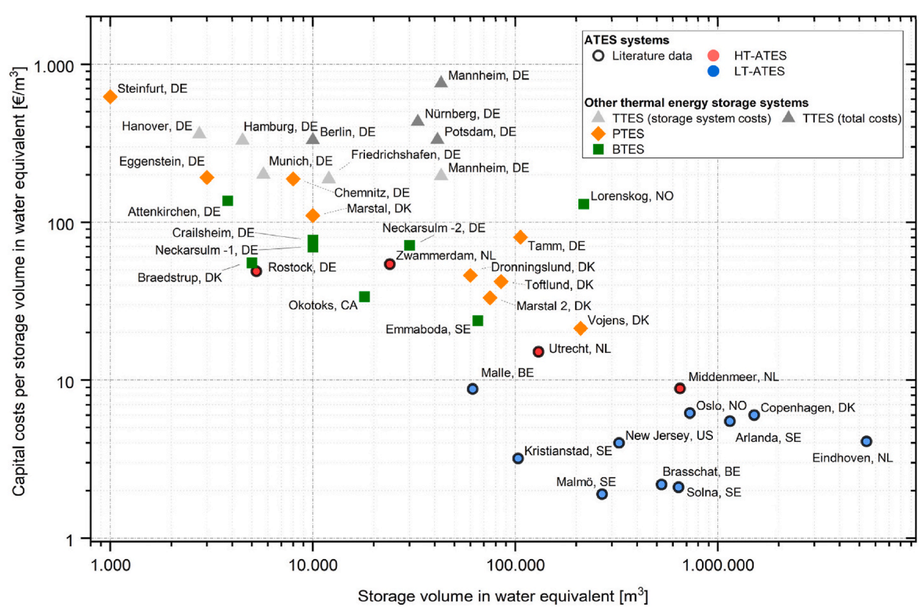

Fig. 4. Comparison of capital costs per stored volume in water equivalent for different thermal energy storage systems (TES). This figure includes literature data on aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage (TTES), and pit thermal energy storage (PTES) systems (Table 1, Table 2).

volume in water equivalent, ranging between 25 and 130 €/m^3. In contrast to ATES systems, the storage volume is smaller, as BTES like GSHP systems are closed systems [78]. However, the main advantage of these closed systems is that they can be built almost everywhere without having an aquifer below. The typical payback time of BTES is 10 years [32] and, therefore, only slightly higher than that of ATES [9].

As for the HT-ATES systems, the given capital costs of the TTES and PTES systems are incomplete. For PTES only the costs of the storage systems are provided. Piping, heat generation or heat source and the connection to the district heating system will increase the investment costs. Thus, their economic performance in comparison to both geothermal storage systems, such as BTES and ATES, gets even worse. For example, for the TTES system in Mannheim, the costs of the storage systems are only about 35 % of the total capital costs, indicating that the data given for TTES and PTES will severely increase (Figs. 4 and 5) and therefore, lower the economic performance.

In contrast to ATES and BTES systems, TTES and PTES systems can be charged and discharged multiple times per year and therefore, can also be used as short-term or midterm storage. Especially TTES systems are often used as short-term storage to optimize the use of renewable heat

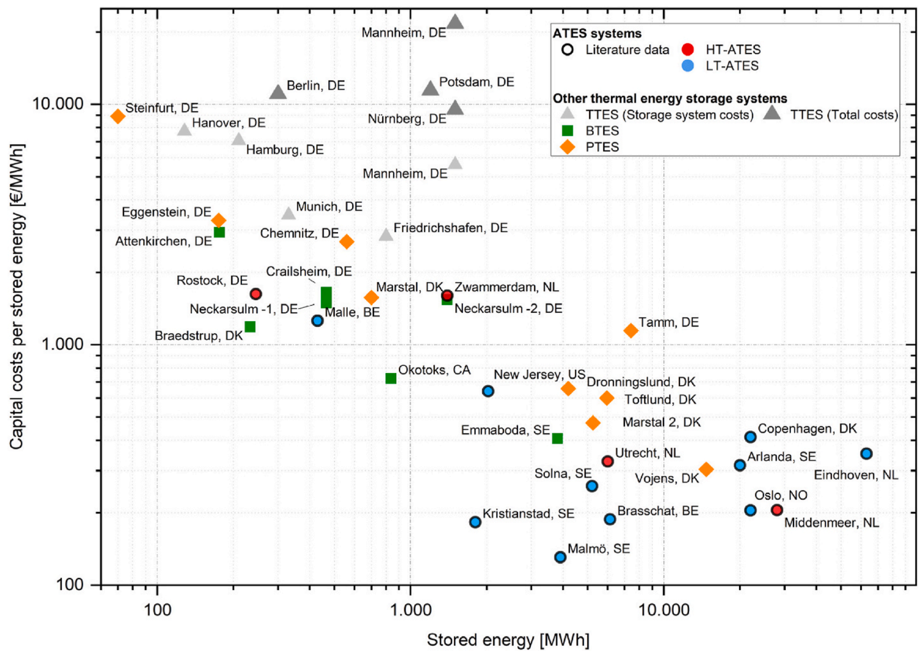

Fig. 5. Comparison of the capital costs per stored energy with increasing stored energy for different thermal energy storage (TES) systems. This figure includes literature data on aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage (TTES), and pit thermal energy storage (PTES) systems (Table 1, Table 2).

sources in district heating systems [61].

3.4. Capital cost per stored energy

The capital costs per stored energy with increasing stored energy are provided in Fig. 5, which shows similar decreasing capital costs with increasing capacity (Fig. 3) and storage volume (Fig. 4). Once more, ATES have the lowest capital costs per stored energy ranging from 130 €/MWh to 1,630 €/MWh. For higher stored energy (>1800 MWh), geothermal storage systems, such as BTES and ATES, reveal the lowest capital costs per stored energy (≤400 €/MWh). The LT-ATES in Malmö, Sweden, has the lowest capital costs per stored energy at 130 €/MWh. This LT-ATES is part of the district heating and cooling system and has 5 warm and 5 cold wells 70–80 m deep. The cold is also taken from the nearby Baltic Sea (Öresund) and cooled water from the heat pump is stored from winter to summer. This system delivers free cooling to the district cooling system at low-temperature levels < +6–8 °C [79].

The HT-ATES in Middenmeer, Netherlands, is a high-temperature demonstration site with one of the lowest capital costs per stored energy (205 €/MWh) due to its storage temperature of 85 °C. The site stores excess heat from a nearby deep geothermal power plant during summer in an aquifer at 360 m–380 m depth and provides peak heating demand for local greenhouses in winter [53,80]. However, HT-ATES systems, like PTES and TTES systems, require an external heat source, which is not included in the stated capital costs, reducing cost-efficiency.

4. Conclusion

Previous studies in the 1980s have already demonstrated that aquifer thermal energy storage (ATES) systems are cost-effective [18,19] and in comparison to other seasonal thermal energy (STES) systems, they also show the best economic performance [8,14,22]. Our study confirms these outcomes regarding capital costs. However, better economic performance has not been demonstrated yet, as operational costs are not considered here. Nevertheless, we could show that with increasing installed capacity, the capital costs of ATES systems decrease and converge to a minimum of about 300 €/kW at a capacity of around 2 MW. Larger low-temperature ATES systems for heating and cooling have the lowest capital costs than any other STES system. Hence, larger LT-ATES systems (>2 MW) for heating and cooling should be ideally considered, planned and built. Therefore, integrated energy solutions for entire districts and cities should be implemented. LT-ATES systems should be compulsorily considered for any future municipal energy plan whenever the subsurface is suitable for ATES, i.e. local aquifer with low groundwater flow velocities of <1 m/d.

Different geological and hydrogeological conditions can, however, increase the capital costs per installed capacity for LT-ATES up to ~1000 €/kW, like in Denmark, where the main aquifer is made of chalk. Nevertheless, LT-ATES systems still provide the cheapest STES solution regarding capital costs per capacity, stored energy and storage volume. It is inexplicable that many developed countries like Austria, Canada, France, Germany, Italy, Norway, the United Kingdom and the USA are lagging in the extensive application of this technology. Like Reilly [18] already stated in his report in the 1980s for the USA, "it appears that it is technically feasible to supply about 7.5 % of the nation's total energy demand through aquifer thermal energy storage (ATES), with about a third of this energy initially supplied by industrial waste heat." Last but not least, the ATES potential is excellent in the USA and also in other countries worldwide [81]. In Germany, for example, more than 50 % of the total land area is suitable for ATES applications [82].

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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