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An overview of aquifer thermal energy storage system performance studies

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Abstract

Because of its huge storage capacity and natural availability, an underground aquifer made of water and sand is thought to be an excellent option for thermal energy storage. Numerous nations have adopted and built aquifer thermal energy storage (ATES) since it was first proposed. Researchers are very interested in the ATES's system performance. The purpose of this study is to provide a brief overview of recent research on the economic, environmental, and thermal performance of ATES systems, particularly that done after 2010. The definitions of the thermal performance indicators were provided. The features of the available simulation techniques for assessing thermal performance were compiled. According to the review, the most often used indicators are the thermal recovery ratio and the thermal interference intensity. The right thermal interference intensity should be chosen in order to increase energy supply in a particular region at a reasonable cost. ATES systems have a payback period of less than five years and can save between forty and ninety percent of the energy.

Keywords: Aquifer thermal energy storage (ATES); thermal performance; economic and environmental performance; thermal recovery ratio; thermal interference intensity

1. Introduction

Thermal energy storage (TES) is always required to fully utilise thermal energy and minimise the mismatch between energy supply and demand in both time and space. When Aquifer Thermal Energy Storage (ATES) was initially presented in the early 1960s [1, 2], it was thought to be a viable solution because to its enormous storage capacity, ease of deployment, and good economics [3, 4]. Aquifers are geological formations made up of rock, gravel, or sand and water. As shown in Fig. 1, an ATES system typically employs a water-saturated restricted aquifer with aquitards above and below it for TES, as well as at least a hot well and a cold well. During the summer, cold water is drawn from an aquifer using cold wells, heated, and then injected back into the same or a different aquifer using warm wells. The procedure is reversed in the winter, when warm water is drawn from warm wells, heated, and then reintroduced through cold wells.

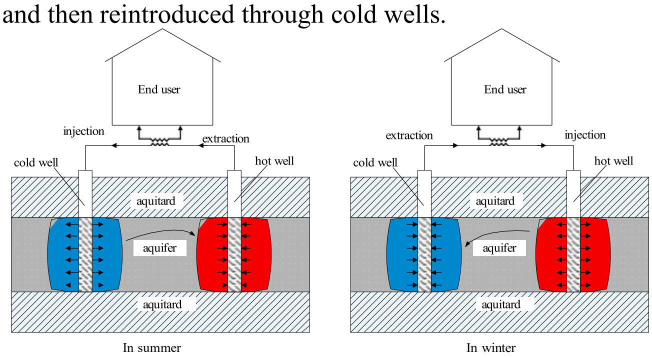

Fig. 1 Scheme of an ATES system

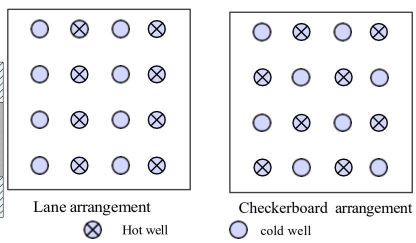

Fig. 2 Arrangement of multi-wells in ATES systems

At the moment, the Netherlands is the technological leader in the construction and use of ATES systems, followed by

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Sweden, Canada, France, Germany, the US, and so forth [5-7]. Hesaraki et al. and Xu et al. summarised a few ATES-related initiatives [4, 8]. In the Netherlands, between 3500 and 18,000 systems are anticipated to be operational by 2020 [9, 10]. Heat sources for ATES systems include solar energy, industrial waste heat, and excess heat from cogeneration facilities [3, 4, 11]. Additionally, ATES systems have been utilised for the heating and cooling of factories, greenhouses, hospitals, universities, offices, and more [1, 4, 12, 13].

System performance is the primary consideration when designing and using ATES systems. In order to help designers and users, this paper provides a brief overview of the most recent ATES system performance studies. Included are the economic and environmental performance as well as the thermal performance. A summary of the definitions of the thermal performance indicators is provided. A list of influencing factors is provided. The characteristics of the various simulation techniques for assessing thermal performance, particularly for subterranean heat accumulators, were compiled.

2. The thermal performance of ATES system

2.1. The thermal performance indicators

The efficiency of ATES systems is determined by the thermal performance of the subterranean aquifer, which is the system's central component. The subterranean portion of ATES systems is the subject of several research, and some performance metrics are suggested. Table 1 summarises the definitions of the most often used thermal performance indicators for the subterranean portion in the literature, such as thermal interference intensity, thermal recovery ratio, exergy efficiency, energy balance ratio, etc. The phenomena where the water temperature in the vicinity of one well varies as a result of the water temperature of another well is frequently referred to as thermal interference [14–16]. Additionally, system design can be optimised by utilising the intensity of thermal interference. It should be avoided between wells with different temperatures because it can typically result in a decrease in the thermal recovery ratio. However, other studies contend that thermal interference may be advantageous for economically boosting the amount of energy supplied in a certain region and improving the effectiveness of a well or system with a comparable temperature in several systems [5, 17, 18]. In contrast to the scenario without negative thermal interference, Sommer et al.'s study [5] demonstrated that permitting a small amount of thermal interference between ATES systems could cost-effectively increase energy provided in a given area by 30–40%. Thermal recovery ratio, also known as thermal efficiency, or η, is a key measure of the subterranean portion of the ATES system's energy performance [5, 17, 19]. Thermal recovery ratios of heat and cold can be used to categorise it. However, because the thermal recovery ratio indicator just uses energy amount as the foundation, it could be deceptive. Consequently, energy efficiency (ε) The second rule of thermodynamics is developed for assessment, and it is thought to be a more effective approach than energy analysis [20, 21]. The remaining heat or cold will build up in the aquifer as operation time increases if the thermal recovery ratio is less than 1. When the ATES system is utilised for both heating and cooling, residual heat or cold buildup may lower the system's appropriateness and efficiency. Both the heating and cooling systems must achieve thermal balance in order for the long-term operating ATES system to have an acceptable efficiency [22]. The better the system, the closer the thermal balance ratio is to zero.

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Table 1 Indicators for ATES system thermal performance

Indicator	Definition	Equation or representative parameter	Reference
Thermal interference intensity	Water temperature change degree of the area near one well changes due to the water temperature of another well	The thermal breakthrough time: $t_b = \frac{\pi H d^2 (\rho c)_{aq}}{3QQ(\rho c)_w}$ Onset time of thermal breakthrough or ratio of the length of thermal front to the distance between two wells	[1, 14-16, 23-25]
Thermal recovery ratio/thermal efficiency	The ratio of energy extracted from the subsurface to energy injected into the subsurface. Usually the natural aquifer temperature is taken as the calculation base.	$\eta = \frac{E_{extracted}}{E_{iniiected}} = \frac{\int_{extraction} c_{extracted} \cdot m_{extracted} \cdot (T_{extracted} - T_{natural}) \cdot dt}{\int_{iniiection} c_{iniiected} \cdot m_{iniiected} \cdot (T_{iniiected} - T_{natural}) \cdot dt}$	[5, 17-19, 26-28]
Exergy efficiency	The ratio between exergy that is extracted from the subsurface and that is stored within the subsurface.	$\epsilon = \frac{Ex_{extracted}}{Ex_{iniiected}}$	[19, 28]
Energy balance ratio	The ratio of the difference between the energy that are extracted in cooling and heating mode to the total extracted energy over a certain period of time.	$\psi = \frac{E^{extracted}_{coolincc} - E^{extracted}_{heatincc}}{E^{extracted} + E^{extracted}}$	[18, 27]

As for the whole ATES system, seasonal performance factor (SPF) is taken as the thermal performance indicator. The SPF is the ratio between energy supplied to the end user and energy consumed by pumps (and heat pumps). When the temperature range is below 50 ºC, heat pumps (HPs) are always used in the ATES system for temperature adjustment according to the required heating temperature level for end user needs. And then, the COP of the HP and the system, and the SPF of the system are the indicators [29] [30].

2.2. The influence factors of thermal performance

As for the underground part of the ATES system, the thermal performance study is focused on parameter sensitivity and many simulation codes are proposed. The simulation codes and their characteristics are summarized in Table 2. Most codes are available for 3-D simulating of both fluid flow and heat transfer in the aquifer. Among them, the most commonly used maybe FEFLOW. And commercial COMSOL is becoming more and more popular.

The influence factors on the thermal performance include physical properties, design and operation parameters and background parameters. To avoid severely thermal intensity and maintain a good thermal recovery ratio or thermal recovery load, suitable well distance and well arrangement should be satisfied. Bloemendal et al. [7] theoretically showed that thermal interference can be p revented when the well distance between the warm and cold wells is about 1.4 R_{th} (the thermal radii, $R_{th} = \sqrt{(c_{ww} \cdot V)/(c_a \cdot \pi \cdot H)}$). The study of Sommer et al. [18] demonstrated that when the well distance of a doublet well system increased from $2R_{th}$ to $3R_{th}$, thermal recovery ratio increases was less than 4%. And continuously increasing the well distance almost had no effect on the thermal recovery ratio. For the many ATES systems in Hague, Netherlands, the thermal interference which was affected by the distributions of wells and the well distance had a positive effect on some wells and a negative effect on other wells and the well efficiency of the systems was increased by 3.2% by thermal inference on average [17]. While Zeghici et al. [31] indicated that for a five identical mono-well ATES system, when the well distance decreased from $3R_{th}$ to $0.2R_{th}$, the overall energy recovery ratio of the mono-well ATES system would increase by 5%. Commonly used well arrangement for large-scale or multiple ATES systems in an area with limited space are checkerboard pattern and lane pattern (see Fig. 2).

As for the whole ATES system, emphasis is put on the monitoring or prediction of thermal performance. The performance of the doublet ATES/HP system for heating and cooling of ventilation air in Brasschaat, which is one of the first and largest ATES systems in Belgium was monitored. The three years monitoring results indicated that the average COP of the HP was 5.6 in winter and 5.0 in summer, and the overall SPF was 5.9 for heating and 26.1 for cooling [43]. Ghaebi et al. [26] compared the COP and aquifer recovery of three systems with ATES. The three systems were doublet ATES systems for direct cooling alone, for cooling and heating with HPs, and for heating alone together with flat plate solar energy collectors for a residential complex in Tehran, Iran. The results indicated that the system combining ATES with HP to meet both cooling and heating needs of the complex was the best with the COP of 17.2 for cooling process and 5 for heating process. Andersson et al. [30] declared that in Sweden, HPs supported ATES systems had a SPF of 6-7 and the direct heating/cooling ATES systems had an SPF of 40-60.

Caliskan et al. [44, 45] first developed a novel integrated system which combined thermochemical and ATES systems for building heating application, and then incorporated latent TES into the building wall. The results of energy and exergy analysis at dead state temperature of 8 ºC, 9 ºC and 10 ºC made clear that the ATES system was the most exergetically efficient one among the different tTES methods. Kılkış et al. [46] conducted a energy and exergy comparison of two building clusters (8 buildings at the KTH Royal Institute of Technology and those in the Albano district) with present energy supply system and new devised energy supply systems. The exergy match increased from 0.49 to 0.80 and 0.78 respectively in scenarios that large-scale ATES and that large-scale ATES, solar collector and photovoltaic thermal arrays were used. For overall system thermal performance, Zeghici et al. [47] studied the performance of an integrated system of a gas-driven micro-turbine, HP and HT- ATES to substitute the initially district heating system in Bucharest, Romania. Kranz and Frick [48] monitored the thermal performance of the whole ATES cooling system with five wells for the German Parliament Buildings. The calculated COP of the system was 3.6 to 7.8 in the year of 2005 to 2011. They also carried out parameter study for the improvement and optimization potential of the ATES system using TRNSYS together with TRNAST based on yearly demand data and ambient air conditions of the storage period of 2005/2006. The simulation indicated that the system COP could be increased with proper operating conditions and design parameters.

3. The economic and environmental performance of ATES systems

Good economic and environmental performance is one of the basic conditions for ATES system to be expanded utilized, and energy saving, CO_2 emission reduction and payback time are always taken as indicators. According to Kılkış et al. [46], in the new devised energy supply scenarios that large-scale ATES and that large-scale ATES, solar collector and photovoltaic thermal arrays were used, the energy saving amounted to 12 GWh and 16 GWh, respectively, and the exergy saving was 7.4 GWh and 9.6 GWh, respectively, while the CO_2 reduction reached up to 2663 t and 2654 t, respectively, compared with that of the present energy supply system. Andersson et al. [30] concluded that the energy savings for integrating ATES into energy supply in Sweden can amount to above 85% for HP supported ATES system and direct heating/cooling with ATES system. And the payback time is less than 4 years. Compared with the reference installation (gas-fired boilers + cooling machines), ATES/HP system of the Klina Hospital [43] obtained an average primary energy saving of 71% and a CO_2 reduction of 1280 t after three years of operation. The system had a payback time of 8.4 years and an annual cost reduction of k€ 54. Hill and DeHouche [49] studied a doublet ATES system with water to air HP in Expeditionary Campaign Infrastructure in Helmand Province, Afghanistan. The system was used for heating from October to March of next year and cooling from March to October. The results indicated that heating and cooling loads were reduced by approximately 16 GJ per year per accommodation tent with the largest comparative reduction being associated with heating (55%) followed by cooling (48%) compared with the original system, and that for a single 250 person ECI Camp, using ATES could achieve payback in less than 2 years and see a net reduction in CO_2 of 39.1 t/y.

The simulation study of Réveillère et al. [50] showed that combining a HT-ATES to the district heating network in Paris basin would increase the geothermal energy share in the network from 50% to 70%. The TRNSYS modeling of Data center cooling system with ATES in Germany [51] demonstrated that the ATES operation could reduce energy consumption by 16.8 %, 1.4% and 20.6% in Berlin, Hamburg and Munich respectively. With proper control, the system efficiency and the economics could be increased. The comparison of the first ATES application in Turkey with a conventional system indicated that the ATES system reduced 60% electrical energy consumption in cooling mode in 2001 [13]. The TRNSYS simulation comparison of the integrated system of ATES in Bucharest, Romania showed that the integrated systems could reduce primary energy consumption by about 43.56%, reduce CO_2 emission by 82%, and switched the initially D-energy class buildings to B-energy class [47]. The exergy cost analysis results indicated that the ATES system was the most exergetic efficient and sustainability one [52]. Taking cost reduction and CO_2 emission reduction as indicators, the economic benefit of large-scale application of ATES under hydrogeological conditions in Amsterdam, Netherlands to that of conventional heating and cooling systems largely depended on hydrological and economic conditions, especially changes in gas price and storage temperatures [5]. Tomasetta et al. [53] compared sustainability of a 250kW ATES system and BTES (borehole TES) system with a boiler burning natural gas for heating. The results from life cycle assessment and energy balance calculation showed that the ATES and BTES system was better and the ATES system was the best. The energy demand of the ATES system is lower than BTES system by 23% and lower than the boiler by 40%, respectively. It can be concluded that using ATES system instead of conventional energy supply systems could save energy by about 40-90%. This is of great importance to decrease the primary energy consumption and realize a cleaner future.

4. Discussion and conclusion

In recent years, ATES has rapidly developed as a cost-effective solution for seasonal TES, particularly in European nations. Additionally, a significant number of ATES investigations are carried out. The most recent ATES system's thermal, economic, and environmental performance studies are briefly reviewed in this paper. The frequently used simulation techniques and thermal performance indicators are shown. Since the performance of the ATES system is largely determined by the selection of an adequate aquifer and well distance, research is now concentrated on the elements that affect the subterranean portion of the system. Additionally, the thermal interference intensity and the thermal recovery ratio are the most often employed indicators for thermal performance research. In a doublet system, thermal interference should be avoided to maximise the thermal recovery ratio; in a system with several wells or multiple systems, the appropriate thermal interference intensity should be chosen to economically increase the amount of energy supplied in a certain region. The ATES SPF with an HP system is typically greater than 5.0, whereas the SPF of the direct cooling ATES system is typically greater than 20. When compared to standard energy supply systems, ATES systems may save 40–90% of energy, and they always have a payback period of fewer than five years. However, long-term monitoring for more in-depth research on ATES systems is still lacking, and simulation studies are consistently conducted without taking end users' varying load requirements into account. In order to optimise system performance, future research may focus on the dynamic coupling modelling of both aboveground and subsurface subsystems as well as system operation control. Furthermore, the saline aquifer for TES should receive greater attention given the issues with subterranean water.

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