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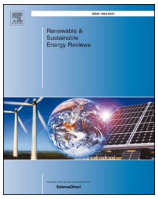

Worldwide application of aquifer thermal energy storage – A review

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ABSTRACT

To meet the global climate change mitigation targets, more attention has to be paid to the decarbonization of the heating and cooling sector. Aquifer Thermal Energy Storage (ATES) is considered to bridge the gap between periods of highest energy demand and highest energy supply. The objective of this study therefore is to review the global application status of ATES underpinned by operational statistics from existing projects. ATES is particularly suited to provide heating and cooling for large-scale applications such as public and commercial buildings, district heating, or industrial purposes. Compared to conventional technologies, ATES systems achieve energy savings between 40% and 70% and CO_2 savings of up to several thousand tons per year. Capital costs decline with increasing installed capacity, averaging 0.2 Mio. € for small systems and 2 Mio. € for large applications. The typical payback time is 2–10 years. Worldwide, there are currently more than 2800 ATES systems in operation, abstracting more than 2.5 TWh of heating and cooling per year. 99% are low-temperature systems (LT-ATES) with storage temperatures of $< 25\,^{\circ}\mathrm{C}$. 85% of all systems are located in the Netherlands, and a further 10% are found in Sweden, Denmark, and Belgium. However, there is an increasing interest in ATES technology in several countries such as Great Britain, Germany, Japan, Turkey, and China. The great discrepancy in global ATES development is attributed to several market barriers that impede market penetration. Such barriers are of socio-economic and legislative nature.

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. While the share of renewables in the power generation sector increases continuously, less attention is paid to the decarbonization of the heating and cooling sector. In 2015, heating and cooling accounted for half of the total world final energy consumption, with three-quarters produced from fossil fuels. The share of modern renewable technologies is currently estimated at only 8% [1]. At the same time, global energy consumption for heating and cooling is expected to further increase with rising prosperity, population growth, and climate change. According to IPCC (Intergovernmental Panel on Climate Change), power consumption for air conditioning alone is expected to rise 33-fold by 2100 [2]. To achieve the climate change mitigation targets, increasing attention has to be paid to the decarbonization of the thermal energy sector.

The key challenge of increasing the share of renewables in the heating and cooling sector is attributed to the seasonal offset between thermal energy demand and supply. To tackle this seasonal mismatch, the idea of Thermal Energy Storage (TES) has attracted increasing attention [3]. The selection of an appropriate storage method depends on several factors such as storage capacity, storage duration, and supply and demand temperature [4,5]. Underground Thermal Energy Storage (UTES) is a sensible TES method, characterized by high storage efficiencies [6,7] and high storage capacities and is therefore the preferred choice for long-term TES. The most popular sensible seasonal UTES techniques are illustrated in Fig. 1. UTES can be further subdivided into open-loop or closed-loop systems. In open-loop systems, also referred to as Aquifer Thermal Energy Storage (ATES), sensible heat and cold is temporarily stored in the subsurface through injection and withdrawal of groundwater [8–10].

Closed-loop systems are more or less independent of the permeability of the subsurface and are called Borehole Thermal Energy Storage (BTES). In Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), and Cavern Thermal Energy Storage (CTES),

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Abbreviations: AR, Artificial Recharge; ATES, Aquifer Thermal Energy Storage; BTES, Borehole Thermal Energy Storage; CCS, Carbon Capture and Storage; CTES, Cavern Thermal Energy Storage; ECES, Energy Conservation through Energy Storage; GHG, Greenhouse Gas; GSHP, Ground Source Heat Pump; HT, High Temperature; HVAC, Heating, Ventilation, and Air Conditioning; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; LT, Low Temperature; PTES, Pit Thermal Energy Storage; TES, Thermal Energy Storage; TRL, Technical Readiness Level; TTES, Tank Thermal Energy Storage; UTES, Underground Thermal Energy Storage

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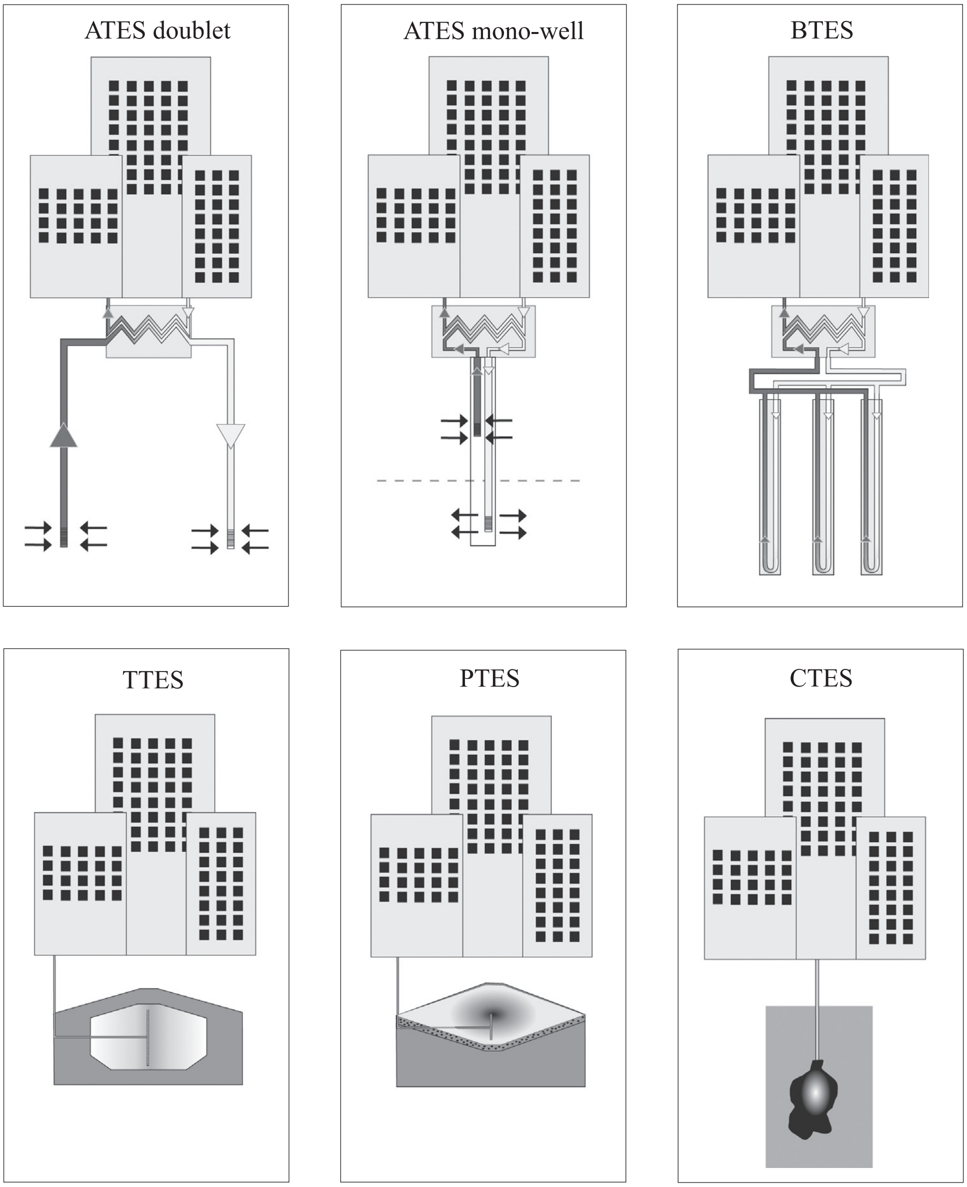

Fig. 1. Seasonal sensible UTES techniques. BTES, Borehole thermal energy storage; TTES, Tank thermal energy storage; PTES, Pit thermal energy storage; CTES, Cavern thermal energy storage.

Table 1
Comparison of seasonal Underground thermal energy storage (UTES) concepts (+ + + high; + + moderate; + low).

	PTES / TTES	ATES	BTES
Storage medium	Water; water/ gravel	Groundwater/ sediments	Groundwater/ sediments
Subsurface requirements	+	+ + +	+ +
Required pre-investigation	+	+ + +	+ +
Maximum storage capacity (kwh/m^3)	+ + +	+ +	+
Storage volumes	+	+ + +	+ +
Space requirement	+ + +	+	+
Investment costs	+ + +	+	+ +
Maintenance	+	+ + +	+
Environmental interaction	+	+ + +	+ +

heat and cold is stored in thermally stratified storage tanks, dug pits filled with gravel and water, or naturally occurring cavities, respectively. Table 1 compares these UTES techniques regarding technical and subsurface-related aspects.

Among different seasonal UTES concepts, ATES is characterized by the highest storage capacities and is therefore most suitable for large-scale applications [11]. However, ATES application requires the presence of an aquifer and suitable hydrogeological conditions such as a low groundwater flow, high permeabilities, and geochemical conditions that prevent clogging and corrosion of wells. Compared to standard open-loop geothermal systems, ATES systems require a more complex pre-investigation and are typically more sensitive to groundwater flow and aquifer heterogeneities. The seasonal storage of heat and cold, however, enables a more efficient operation.

The objective of this work is to review the historical development and the current global application status of ATES. Based on the reviewed literature, system designs, trends, and ideas developed over time are summarized with special attention on operational parameters of successfully implemented ATES systems. Since the literature lacks statistics on the number of implemented ATES systems, the review of

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