International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0349

STATE OF THE ART REVIEW OF SEASONAL SENSIBLE HEAT STORAGE

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ABSTRACT

This paper reviewed seasonal sensible heat storage which is the most mature storage concept from technical and economic points of view. The results showed that tank storage and pit storage have higher storage capacity and less geological requirements, while borehole storage and aquifer storage are more economically effective.

Keywords: seasonal thermal energy storage, sensible heat, solar thermal, levelized cost of heat, storage volume cost

1. INTRODUCTION

Seasonal thermal energy storage (STES) is the technology to store heat in summer for winter use, and the storage method, depending on the materials, can be sensible heat, latent heat and thermochemical heat. It can be the supplement and adjustment of heat supply system and an economical and feasible way to coordinate the mismatch between the supply and the demand of thermal energy in time and intensity. This paper aims to learn the recent developments of seasonal sensible heat storage (SSHS) and identify the role of that in energy transition. To achieve this aim, different technologies and applications of seasonal sensible heat storage were firstly summarized, classified and compared, and a levelized cost of heat analysis was implemented to see the economic feasibility of different seasonal sensible heat storage concepts.

2. SEASONAL SENSIBLE HEAT STORAGE

2.1 Tank thermal energy storage

In a tank thermal energy storage (TTES) system, a storage tank which is normally built with reinforced concrete or stainless steel, as shown in Fig 1(a), is buried under the ground fully in case of the heat loss or partially in order to save the excavation fee. The tank is surrounded by thermal insulation layers at least along the vertical walls and the roof [1].

A solar assisted district heating system was built in a living area of 300 accommodation units in Munich, Germany with a 5700 m^3 storage tank and a solar collector area of 3600 m^2 [2]. The system had the durability for the temperatures up to 90 °C and could cover 47% of the annual heat demand. In Hannover, a cylindrical concrete tank with a volume of 2750 m^3 was used for STES in combination with 1473 m^2 roof-integrated solar collectors. The system could cover 39% of the total annual heat demand [3].

2.2 Pit thermal energy storage

In a pit thermal energy storage (PTES) system, a mix of water and gravel is used as the thermal energy storage medium, which is normally buried underground, as shown in Fig 1(b). Heat is charged into and discharged out of the store either by direct water exchange or by plastic pipes installed in different layers inside the store [1].

The first large-scale PTES project was developed in Stuttgart University in 1984 [4]. A hole dug in the ground was lined with a 2.5 mm thick high density polyethylene foil, and was filled with 4 m high pebbles and about 3.75 m of these pebbles were flooded with water. The entire store volume is 1050 m^3. A solar fraction of 62% and a recovery efficiency of 82% were achieved in the 1986-1987 heating season. A PTES unit with a storage volume of 1600 m^3 was developed in Steinfurt, Germany [5]. The storage unit lined with two layers of 2 mm thick polypropylene and insulated with granulated recycling

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

glass was charged and discharged via cross-linked PE water tubes with a total length of 7000 m. The system had the durability for the temperatures up to 90 °C and could cover 34% of the annual heat demand.

2.3 Borehole thermal energy storage

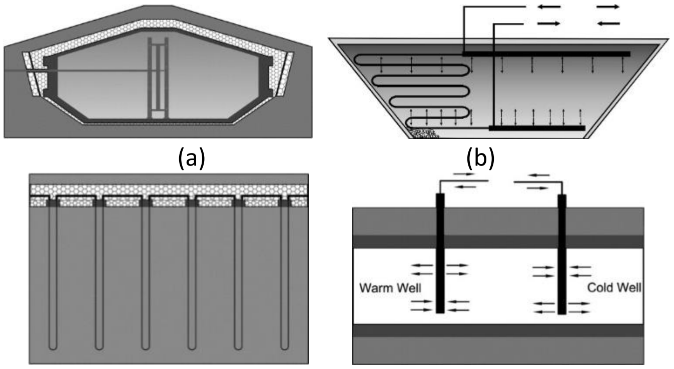
In a borehole thermal energy storage (BTES) system, several vertical or horizontal boreholes into which heat exchangers are inserted are drilled into suitable geological formations, as shown in Fig 1(c), forming a huge heat exchanger. There is always a layer of insulation between the storage area and ground surface in case of heat loss.

The Drake Landing Solar Community in Okotoks, Canada has the first STES system in North America, with over 90% of residential space heating needs being met by solar thermal energy [6]. It used two water-based buffer storage tanks, 34000 m^3 of BTES system and 2300 m^2 of solar collectors to supply the space and water heating needs of 52 houses with a heated living area of 7410 m^2. With ten-years reliable operation, the solar fraction was calculated as an average of 96% for the period 2012-2016 [6]. Nordell and Hellström [7] investigated a solar heated seasonal storage system with 3000 m^2 of roof-mounted solar collectors and a BTES system of 60000 m^3 in Anneberg, Sweden. The results showed that the system could provide 60% of the total heat demand of 90 single-family houses including space heating and domestic hot water. They also found that a larger system could lead to a lower annual heating cost.

2.4 Aquifer thermal energy storage

In an aquifer thermal energy storage (ATES) system, there are two wells or two groups of wells which are drilled into a suitable aquifer respectively to extract and reinject groundwater, as shown in Fig 1(d). The cold groundwater is extracted from the cold well, heated up by alternative heat sources like solar energy and reinjected into the warm well during the charging process in summer. It is reversed during the discharging period in winter.

Kabus et al. [8] introduced an ATES system using the modified geothermal wells in Neubrandenburg, Germany. A storage efficiency of 46% and a renewable energy fraction of 48% were achieved after three cycles. An ATES system combined with a heat pump was built in a Belgian hospital. After three-years monitoring, the results showed that the primary energy consumption was 71% lower than a reference conventional system and the overall seasonal performance factor was 5.9 [9].



(a) (b) (c) (d)

Fig 1 Schematic of (a) TTES [10]; (b) PTES [1]; (c) BTES [10]; (d) ATES [10]

2.5 Comparation

Different sensible heat storage methods are compared in Table 1. TTES and PTES have advantage in storage capacity and can be built at almost everywhere, while BTES and ATES can be used for both heating and cooling and have fewer problems in heat loss and leakage. The relationship between storage temperature and storage volume in water equivalent is given in Fig 2. It is noticed that BTES enjoys a large range of both storage volume and storage temperature, while TTES gets the highest storage temperature and ATES gets the largest storage volume.

Table 1 Comparison of sensible heat storage methods [10-12]

Storage methods	TTES	PTES	BTES	ATES
Storage medium	Water	Water and gravel	Ground material (soil/rock)	Ground material (sand/gravel…-water)
Storage capacity (kW h/m^3)	60-80	30-50	15-30	30-40
Storage volume in water equivalent (m^3)	1	1.3-2	3-5	2-3
Geological requirements	• Stable ground conditions • Preferably no groundwater • 5-15 m deep	• Stable ground conditions • Preferably no groundwater • 5-15 m deep	• Drillable ground • Groundwater favorable • High heat capacity • High thermal conductivity • Low hydraulic conductivity • Natural groundwater flow < 1 m/a • 30-100 m deep	• Natural aquifer layer with high hydraulic conductivity • Confining layers on top and below • No or low natural groundwater flow • Suitable water chemistry at high temperatures • Aquifer thickness 20-50 m deep

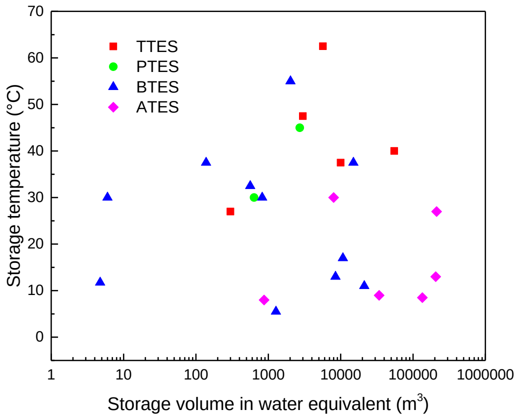


Fig 2 Relationship between storage temperature and storage volume in water equivalent. Calculated by author with the data from [1, 10-13]

3. ECONOMIC FEASIBILITY

3.1 *Levelized cost of heat*

The levelized cost of energy (LOCE) is a popular method of cost-benefit analysis in the energy field as a tool for comparing the costs of different electricity generation technologies over the long term. Adapting the LCOE formulation for heat storage, the levelized cost of heat (LCOH) can be expressed as:

$$LCOH_s = \frac{I_s + \sum_{t=1}^{n} \frac{OM_s}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_s}{(1+r)^t}} \qquad (1)$$

where I_s is the initial investment of the storage (€); r is the real discount rate; n is the lifetime of the storage; OM_s is the annual operation and maintenance cost of the storage (€) and E_s is the heat annually discharging from the storage ($\mathrm{MWh_{th}}$).

The cost of each SSHS project is converted to 2018 constant prices in € using inflation rates and currency conversion factors derived from Organization for Economic Co-operation and Development (OECD) [14, 15]. The operation and maintenance cost of the storage is assumed as 1% of the investment when that is unknown. The real discount rate is considered as constant which is 5%.

The results of LCOH of seasonal sensible heat storage are listed in Table 2. The LCOH of the project in Groningen is very low because the main heat resource of that is geothermal energy which is relatively continuous and steady, while other projects use solar thermal energy. And the LCOH of the project in Brædstrup is relatively high; that can be explained by its low storage efficiency.

Table 2 LCOH of the storage of reference projects (2018€). Calculated by author

STES concept	Project	Initial investment (€)	Annual operation and maintenance cost (€)	Annual heat production ($\mathrm{MWh_{th}}$)	Lifetime (years)	Reference	LOCH (€/$\mathrm{MWh_{th}}$)
TTES	Copenhagen, DK	1361	13.61	0.85	30	[16]	120.09
	Marseille, FR	21000	210	11.4	30	[17]	138.16
PTES	Marstal, DK	2724111	27940	4445	20	[18]	55.31
	Osijek, HR	1594821	125022	2397	14	[19]	20.55
BTES	Anneberg, SE	173309	1733	700	25	[7]	20.05
	Brædstrup, DK	279807	2798	163	20	[20]	154.49
ATES	Brasschaat, BE	623742	6237	1142	25	[9]	44.24
	Groningen, NL	1480883	14809	11389	15	[21]	13.78

Legend: DK = Denmark, FR = France, HR = Croatia, SE = Sweden, BE = Belgium, NL = Netherlands.

3.2 *Storage volume cost*

The storage volume cost (SVC) is a specific indicator to evaluate the economic acceptance of a storage concept, which can be expressed as:

$$SVC = \frac{COS}{SVe} \qquad (2)$$

where SVe is the storage volume in water equivalent (m^3) and COS is the cost of the storage (€), including the costs of storage materials, container as well as charging and discharging device.

Fig 3 shows the relationship between investment cost per storage volume and storage volume in water equivalent. It is clear that the investment cost per storage volume decreases with the decrease of storage volume in water equivalent. BTES and ATES are always applied in large projects, while TTES and PTES are mostly applied in small projects. And the investment cost can be very high when applying TTES in small projects.

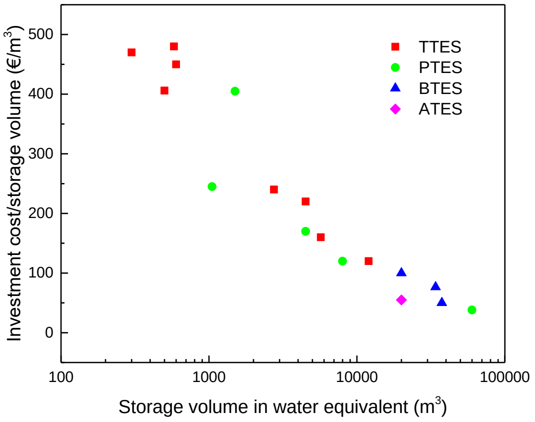


Fig 3 Relationship between investment cost per storage volume and storage volume in water equivalent. Calculated by author with the data from [7, 13, 16-20]

4. CONCLUSION

Seasonal sensible heat storage is the most mature STES concept which is an economical and feasible way to store the extra heat in summer for winter use. A review work of SSHS from technical and economic points of view was conducted in this paper. The results showed that TTES and PTES have higher storage capacity and less geological requirements, while BTES and ATES are more economically effective and have less worry about heat loss and leakage. Besides, the investment cost per storage volume of seasonal sensible heat storage was found decreasing with the decrease of storage volume.

ACKNOWLEDGEMENT

The financial support from China Scholarship Council (No. 201806220072) is gratefully acknowledged.

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