Seasonal Storage of Heat in Boreholes

Technical note

Authors: Wu Gao, Meysam Qadrdan, Modassar Chaudry, Jianzhong Wu, Cardiff University

February 2023

Contents

What is a borehole thermal energy storage, and how does it work?

Significant amounts of heat can be stored in ground materials like soils, rocks, and pore water due to their high volumetric heat capacity. Borehole thermal energy storage technologies uses this capability via an array of boreholes to store excess heat in shallow geological environments and can provide seasonal storage capability.

As shown in Fig. 1(a), drilling boreholes reach a typical depth of 30-100 m (the borehole depth can be determined based on factors such as heating and cooling demands, geological conditions, etc.), are installed with single or double U-tube pipes or casing pipes mostly made from synthetic materials, and are filled by grout materials with high thermal conductivities. Boreholes are not usually grouted in Scandinavian countries, where the geology and hydrology are characterised by hard rock and high groundwater levels, and natural groundwater will fill the borehole to the groundwater table level (Gehlin, 2016). Significant amounts of heat can be stored in ground materials like soils, rocks, and pore water due to their high volumetric heat capacity. Water, which can be mixed with an antifreeze solution, usually circulates in pipes as a heat carrier. Heat predominantly transfers by conduction between the borehole fields and the surrounding ground. Borehole thermal energy storage (BTES) is usually used in combination with solar collectors, heat pumps, and a buffering tank, as shown in Fig. 1(b). The typical ground storage temperature in the core of the borehole field is 30-50 ℃, and the ground temperature at the periphery of the borehole field is much lower, for instance, the mean temperature at the depth of 100 m below ground level in the UK is 13.6 ℃ (Busby et al., 2011), which makes borehole thermal energy storage especially beneficial for the heating demand of commercial and residential buildings in winter and cooling requirements in summer, as shown in Fig. 1(c).

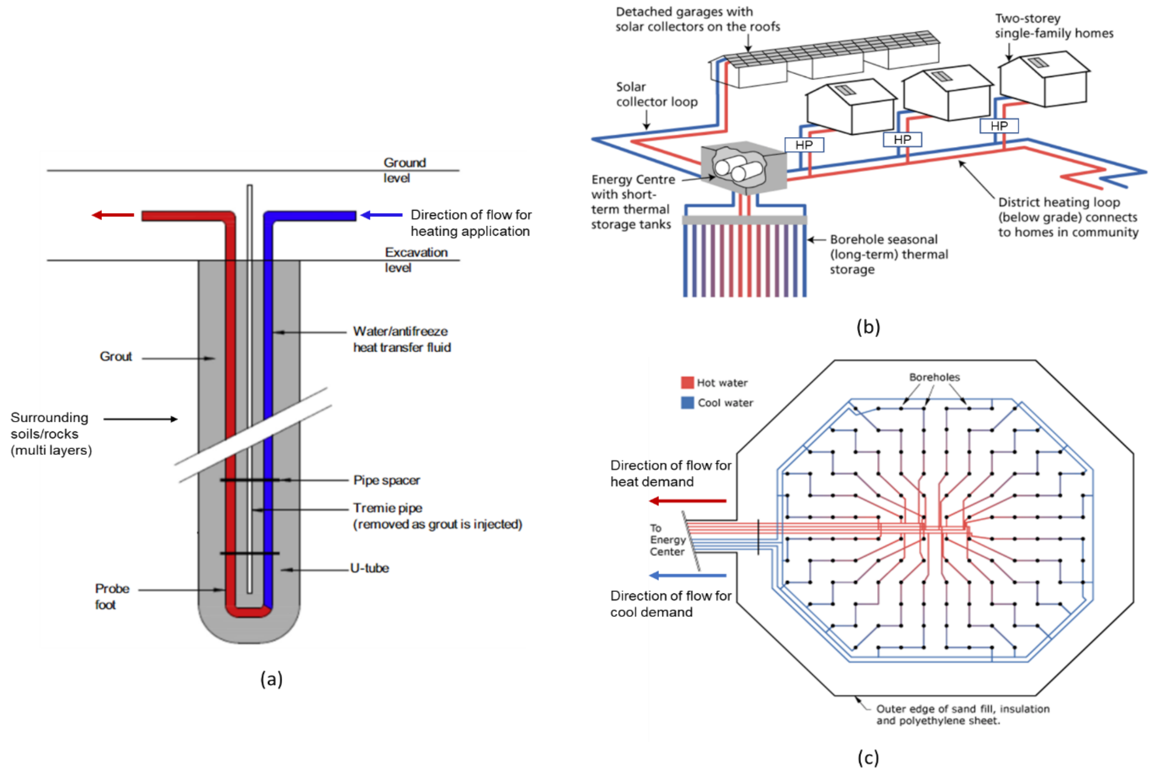

Fig. 1 Schematic diagram of (a) a borehole with single U-tube pipe (Velraj, 2016), (b) a borehole thermal energy storage system (Mesquita et al., 2017), and (c) flow directions for heat and cooling demands and ground storage temperature distribution (McClenahan et al., 2006).

Fig. 2 shows the temperature evolutions in a high-temperature borehole thermal energy storage system and an ambient (low-temperature) borehole thermal energy storage system serving balanced heating and cooling demands. As shown in the figure, for the high-temperature borehole thermal energy storage system, there is an initial transient “charging” phase during the initial years of operation, which often involves heat injection to the ground significantly more than is extracted, and the performance of the high-temperature borehole thermal energy storage system improves over time. Typically, after 3-6 years, a long-term steady state would be reached under the balanced heating and cooling demands. For the ambient borehole thermal energy storage system, a steady state would be reached when the extracted heat is comparable to the injected heat, and the long-term average temperature is stable and close to the surrounding ground temperature.

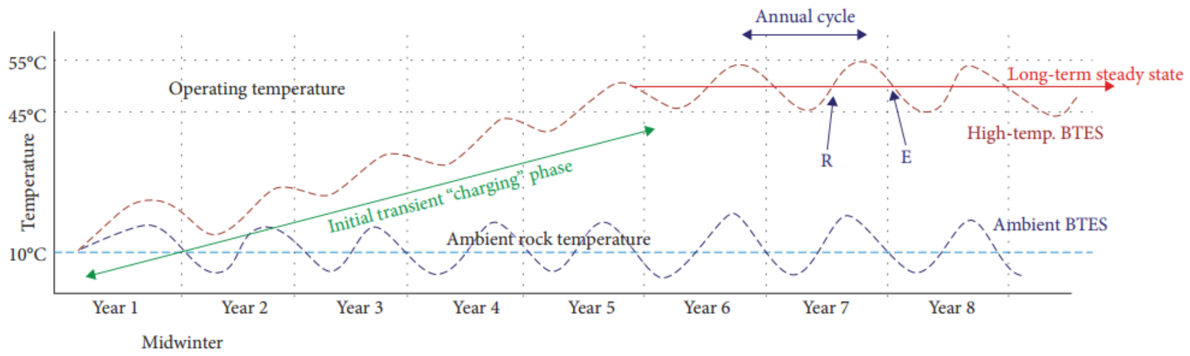

Fig. 2 Schematic diagram of temperature evolutions in a high-temperature borehole thermal energy storage system and an ambient borehole thermal energy storage system serving balanced heating and cooling demands. R = recharge of heating during summer and autumn; E = extraction of heat in winter and spring (Skarphagen et al., 2019)

Table 1 lists the operational performances of representative borehole thermal energy storage systems. In the table, the storage temperature varies widely from project to project: it can be around 10 ℃, such as in several projects in China, which belong to low-temperature borehole thermal energy storage systems, or as high as 90 ℃, such as in the Crailsheim project, Germany, which is a high-temperature system.

Techno-economic comparison with alternatives

Table 2 compares key technical characteristics of different types of seasonal thermal energy storage systems. Compared with tank thermal energy storage, which is the most popular approach for storing heat with the highest heat recovery efficiency, borehole thermal energy storage needs 2-5 times larger storage volume, but it can be used for supplying both heating and cooling and the heat recovery efficiencies can range from 70% to 90%. Pit thermal energy storage has almost twofold greater thermal density than borehole thermal energy storage, but it can only be used for heating and there is a risk of water leakage. Aquifer thermal energy storage, like borehole thermal energy storage, can be used for heating and cooling. However, it requires special geological conditions, such as a natural aquifer layer with high hydraulic conductivity and low permeability layers on top and below. It also has higher thermal loss than borehole thermal energy storage due to the lack of thermal insulation, and it is susceptible to clogging.

Based on existing projects, Fig. 3 compares the economic characteristics of different types of seasonal thermal energy storage in terms of storage volume cost (SVC) and storage capacity cost (SCC), which are calculated by dividing the cost of storage by the thermal volume and thermal capacity, respectively. From Fig. 3, it can be seen that tank thermal energy storage has the highest average values of storage volume cost and storage capacity cost (over 1790 €/m^3 and approximately 3 €/kWh_{th}, respectively), followed by pit thermal energy storage (around 135 €/m^3 and 2

€/kWhth, respectively), and borehole thermal energy storage and aquifer thermal energy storage are equivalent and the lowest, with storage volume costs of less than 13 €/m^3 and storage capacity costs lower than 1 €/kWhth.

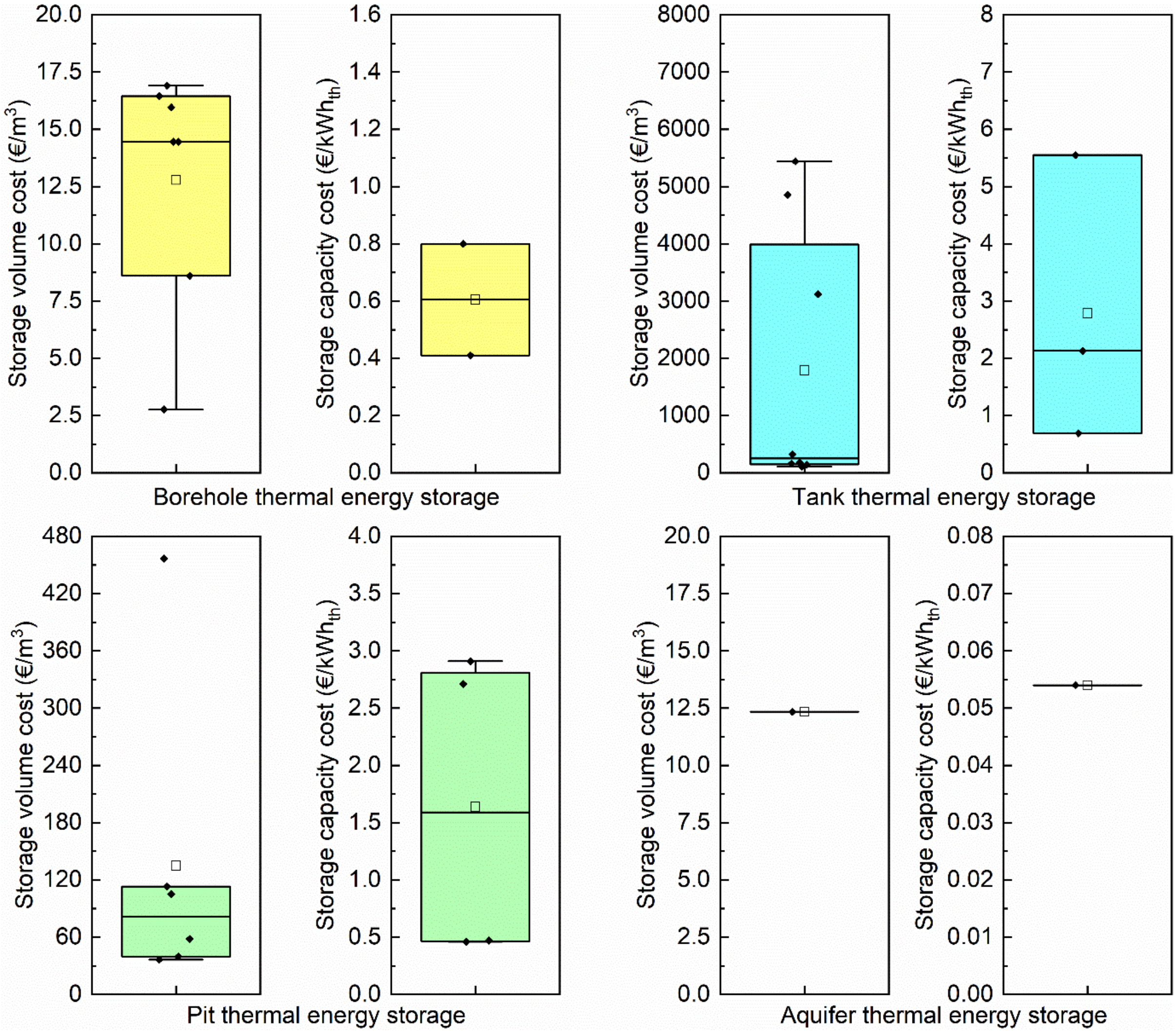

Fig. 3 Economic viability of different types of seasonal thermal energy storage: storage volume cost and storage capacity cost (2019 €, Yang et al., 2021)

Table 1 Operational performance of borehole thermal energy storage systems

Project	Temperature (ground storage temperature/heating supply temperature) (℃)	Details of borehole thermal energy storage	Storage volume (m³)	Storage capacity (MWh_{th})	Heat recovery efficiency (%)	Reference
Neckarsulm, Germany	15-65/-	528 boreholes, 15 cm diameter, 30-100 m depth	63360	–	50-65	Nußbicker-Lux et al., 2009; Schmidt et al., 2004; Bauer et al., 2010
Crailsheim, Germany	3-90/-	80 boreholes, 55 m depth (mudstone and limestone)	37500	–	50	Bauer et al., 2016
Attenkirchen, Germany	85/-	90 boreholes, 30 m depth	10500	–	55	Reuss et al., 2006; Shah et al., 2018
Brædstrup, Demark	17-50/80	48 boreholes, 3 m spacing, 45 m depth, 16 parallel, 6 series, mussel shells used for top insulation (clay/till)	19000	400	37	Schmidt and Sørensen, 2018
Anneberg, Sweden	30-45/32-55	99 boreholes, 11.5 cm diameter, 65 m depth, 3 m spacing (crystalline rock)	60000	–	58	Nordell and Hellström, 2000
Emmaboda, Sweden	40-45/-	140 boreholes, 150 m depth, 4 m spacing (glacial till, granodiorite, amphibolite)	280800	–	72	Nordell et al., 2015
Torino, Italy	–	1 double-U piped borehole, 3 single-U piped boreholes, 27 m depth (gravel, sand, pebble)	180	–	–	Giordano et al., 2016
Andalusia, Spain	–	–	18000	375	60	Lizana et al., 2017
GEOSOL, France	4-16/-	2 boreholes, 90 m depth (limestone with marl veins, no underground water flow)	–	–	–	Trillat-Berdal et al., 2006
Melbourne, Australia	30-45/-	2 boreholes, 11.5 cm diameter, 40 m depth	554	–	30	Lhendup et al., 2012; Lhendup et al., 2014
Okotoks, Canada	30-75/37-55	144 boreholes, 35 m deep, 24 parallel, 6 series (sand silt, clay)	34000	–	54	McCleanahan et al., 2006; Sibbitt et al., 2012; Mesquita et al., 2017
Oshawa, Canada	-/52.5	384 boreholes, 213 m deep (limestone, hard rock, and water-filled)	–	–	–	Wong et al., 2006
Sussex, Great Britain	– (low-temperature storage)	30 boreholes, 100 m deep (chalk)	–	–	–	Witte and van Gelder, 2007
Harbin, China	3.4-7.7/27.1	12 boreholes, 50 m depth	–	–	76	Wang et al., 2010
Shanghai, China	15–37.4/23.6–50	130 boreholes, 10 m depth, 1.4 m spacing	4970	–	62.9	Xu et al., 2014
Tianjin, China	8-10.3/43.2	580 boreholes, 120 m depth	2400000	133	–	Zhu et al., 2015
Tianjin, China	–	60 double U pipes boreholes with 20 m depth, 48 double U pipes boreholes with 120 m depth (8 boreholes for thermal storage)	–	–	–	Li et al., 2010
Shijiazhuang, China	11-16/-	5 boreholes, 21 m depth, 5 m spacing	–	–	–	Xi et al., 2011
Chifeng, China	10-55/20-30	13-468 boreholes, 80 m depth (0-30 m: silt, 30-40 m: silty clay, 40-110m: silty clay, gravel, and boulders)	6652.8-518918.4	–	–	Guo et al., 2020

Table 2 Key technical characteristics of different types of seasonal thermal energy storage

Category	**Borehole Thermal Energy Storage**	**Tank Thermal Energy Storage**	**Pit Thermal Energy Storage**	**Aquifer Thermal Energy Storage**	**Reference**
Storage medium	Ground saturated or unsaturated rock/soil	Water	Gravel and water mixture	Groundwater and ground material	Schmidt et al., 2003
Maximum storage capacity	15-30 kWh/m^3	60-80 kWh/m^3	30-50 kWh/m^3	30-40 kWh/m^3	Schmidt et al., 2003
Storage volume compared to 1 m^3 water	2-5 m^3	1 m^3	1.3-2 m^3	1.5-3 m^3	Schmidt et al., 2003; Lanahan and Tabares Velasco, 2017
Heating/Cooling application	Heating/Cooling	Heating	Heating	Heating/Cooling	Lanahan and Tabares-Velasco, 2017
Charing/discharging rate	Low with buffer required	High. Direct (pumping medium in/out); Indirect (heat exchanger)	High. Direct (pumping medium in/out); Indirect (heat exchanger)	Low/medium with buffer required	**Lyden et al., 2022**
Operating temperature	5-90 ℃, limited by heat loss and source temperature	< 100 ℃ (limited by insulation materials)	< 80 ℃, limited by material of floating lid	Low temp: 13-25 ℃, Medium temp: 25-50 ℃, High temp: > 50 ℃	Lyden et al., 2022
Highest heat recovery efficiency	70%-90%	90%-98%	50%-90%	65%-95%	Lanahan and Tabares-Velasco, 2017
Depth below ground	30-100 m	<50 m due to economic infeasibility	5-15 m	Typical aquifer thickness: 20-50 m; Typical aquifer depth: shallow (<30 m) or deep (> 30 m)	Schmidt et al., 2003; Lyden et al., 2022
Geological requirements	Drillable ground Favourable groundwater High heat capacity High thermal conductivity Low hydraulic conductivity ($k_f < 1 \cdot 10^{-10}$ m/s) Natural groundwater flow < 1 m/year	Enough ground spaces Stable ground Preferably no groundwater	Enough ground spaces Stable ground Preferably no groundwater	Natural aquifer layer with high hydraulic conductivity ($k_f > 1 \cdot 10^{-5}$ m/s) Confining low permeability layers on top and below No or low groundwater flow Suitable water chemistry at high temperatures	Schmidt et al., 2003

Performance and potential cost reductions

The performance and feasibility of borehole thermal energy storage depend on several factors, including the design and arrangement of boreholes, material properties, ground properties, and operating parameters. A suitable geometric dimension and capacity of borehole thermal energy storage considering local geological conditions, such as groundwater flow and soil/rock characteristics will reduce heat loss (DEEL, 2016; Gehlin, 2016). A design with small surface-to-volume ratio is desirable, and the most commonly used storage geometries are the cylinder or parallelepiped shapes (Gehlin, 2016). To limit heat loss to the atmosphere, top insulation of boreholes is usually used (Reuss, 2020). In addition, as borehole thermal energy storage is a part of the network, the heat charging and discharging process should be operated considering the synergy between the network components, including utilisation of renewable energy sources, heating and cooling demand ratios, and electrical network balancing (Lyden et al., 2022).

In terms of investment in borehole thermal energy storage systems, the upfront/initial investment is much higher than the operation and maintenance (O&M) cost. The annual fixed O&M cost is about 1%-3.5% of the initial investment (Yang et al., 2021). The borehole cost varies from site to site. The deeper the borehole, the higher the drilling cost; the harder the rock, the higher the drilling cost (Lanahan and Tabares-Velasco, 2017; Welsch et al., 2018). Normally, the cost of boreholes can be as high as 50% of the total initial investment of the project (Lyne et al., 2019). For example, the borehole cost in the Neckarsulm project, Germany, which has 528 boreholes with depths varying from 30 m to 100 m, accounts for 45% of the project's initial investment. The cost of a borehole varies and can range from £4000 to £6000 for small commercial applications (DEEL, 2016) and from £10220 to £16000 for a 60-m-deep borehole in the UK (Checkatrade, 2022). Meanwhile, as shown in the Attenkirchen project, Germany (90 boreholes with an equal depth of 30 m), drilling is the most expensive composition of a borehole, which is more than 40% of the total cost of a borehole. Therefore, reducing the drilling cost of boreholes can significantly help reduce the cost of borehole thermal energy storage. The development of new and efficient drilling technologies will help reduce costs. For example, advances were made to air-lift reverse circulation drilling technology, which is commonly used in geothermal borehole drilling, to overcome problems along with drilling depth increasing. Using this new drilling technology, the drilling depth was up to 4200 meters, the deepest recorded in China (Zhang and Zhang, 2014). Electro-Pulse-Boring (EPB), a valuable option to Rotary drilling (modest minimum costs for a borehole in a sedimentary formation are usually estimated to be about 2000 €/m), is developed for industrialisation. EPB shows low costs for drilling: 100 €/m for a borehole with a large diameter of 50 cm, and it is independent of the borehole depth and applicable for sediments and crystalline rocks, such as granite (Schiegg et al., 2015). In addition, the Down the Hole (DTH) method, which is based on the air-lift reverse circulation drilling method, shows good results in drilling hard rock and a low environmental impact (Sliwa et al., 2020).

Technology status in the UK?

The ground temperature in the UK is suitable for low-temperature borehole thermal energy storage. The mean temperatures at depths of 100, 200, 500, and 1000 m below ground level in the UK are 13.6, 17.3, 24.7, and 38.7 ℃, respectively (Busby et al., 2011). It is estimated that there is a geothermal gradient of 28 ℃/km for the upper 1000 m of the sedimentary curst. Elevated temperatures have been observed in eastern and southern England, owing to convection within some of the thicker Permo-Triassic sandstones and the thermal blanketing effect of Triassic and Jurassic argillaceous rocks. In addition, the geological conditions in the UK are not inherently restrictive for borehole thermal energy storage, provided adverse geological conditions are avoided, such as fast groundwater flow (DEEL, 2016).

However, compared to countries, such as Denmark, Germany, and Sweden, the deployment of borehole thermal energy storage in the UK is lagging in the context of low heat network deployment. Despite this, borehole thermal energy storage can be an affordable option, especially for large scale applications. Currently there are just a few installations in the UK, with around 10 projects for commercial and/or apartment buildings carried out each year (DEEL, 2016). The UK market status of borehole thermal energy storage technologies is between system prototyping and demonstration (Technology Readiness Level of 6-8). It should be noted that the development of borehole thermal energy storage in the UK is inseparable from the development of distributed heating and cooling networks, such as the deployment of solar collectors and heat pumps. Achieving the net zero target by promoting heat pumps across the country is a positive driver for the development of the borehole thermal energy storage market.

References

Bauer, D., Marx, R. and Drück, H., 2016. Solar district heating systems for small districts with medium scale seasonal thermal energy stores. Energy Procedia, 91, pp.537-545.

Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W. and Müller-Steinhagen, H., 2010. German central solar heating plants with seasonal heat storage. Solar Energy, 84(4), pp.612-623.

Busby, J., Kingdon, A. and Williams, J., 2011. The measured shallow temperature field in Britain. Quarterly Journal of Engineering Geology and Hydrogeology, 44(3), pp.373-387.

Checkatrade, 2022. https://www.checkatrade.com/blog/cost-guides/cost-drill-borehole-uk/

DEEL (Delta Energy & Environment Ltd.), 2016. Evidence Gathering: Thermal Energy Storage (TES) Technologies. BEITS, London, UK.

Gehlin, S., 2016. Borehole thermal energy storage. Advances in Ground-Source Heat Pump Systems, edited by Rees, S.J., Woodhead Publishing.

Giordano, N., Comina, C., Mandrone, G. and Cagni, A., 2016. Borehole thermal energy storage (BTES). First results from the injection phase of a living lab in Torino (NW Italy). Renewable Energy, 86, pp.993-1008.

Guo, F., Zhu, X., Zhang, J. and Yang, X., 2020. Large-scale living laboratory of seasonal borehole thermal energy storage system for urban district heating. Applied Energy, 264, p.114763.

Lanahan, M. and Tabares-Velasco, P.C., 2017. Seasonal thermal-energy storage: A critical review on BTES systems, modeling, and system design for higher system efficiency. Energies, 10(6), pp.743.

Lhendup, T., Aye, L. and Fuller, R.J., 2012, December. Experimental study of coolth charging of an inter-seasonal underground thermal storage system. In Proceedings of the 50th Annual Conference, Australian Solar Energy Society, Melbourne.

Lhendup, T., Aye, L. and Fuller, R.J., 2014. Thermal charging of boreholes. Renewable energy, 67, pp.165-172.

Li, X.G., Zhao, J., Wang, J., Lv, Q., Wang, Y.P., Jia, Y.M., 2010. Application and experiment on solar-ground coupled heat pump with heat storage. In Proceedings World Geothermal Congress.

Lizana, J., Ortiz, C., Soltero, V.M. and Chacartegui, R., 2017. District heating systems based on low-carbon energy technologies in Mediterranean areas. Energy, 120, pp.397-416.

Lyden, A., Brown, C.S., Kolo, I., Falcone, G. and Friedrich, D., 2022. Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches. Renewable and Sustainable Energy Reviews, 167, pp.112760.

Lyne, Y., Paksoy, H. and Farid, M., 2019. Laboratory investigation on the use of thermally enhanced phase change material to improve the performance of borehole heat exchangers for ground source heat pumps. International Journal of Energy Research, 43(9), pp.4148-4156.

McClenahan, D., Gusdorf, J., Kokko, J., Thornton, J. and Wong, B., 2006. Okotoks: Seasonal storage of solar energy for space heat in a new community. In Proceedings of ACEEE.

Mesquita, L., McClenahan, D., Thornton, J., Carriere, J. and Wong, B., 2017, February. Drake landing solar community: 10 years of operation. ISES Solar World Congress 2017, IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry, Abu Dhabi, United Arab Emirates.

Nordell, B., Andersson, O., Rydell, L. and Scorpo, A.L., 2015. Long-term performance of the HT-BTES in Emmaboda, Sweden. In Greenstock 2015: International Conference on Underground Thermal Energy Storage.

Nordell, B.O. and Hellström, G., 2000. High temperature solar heated seasonal storage system for low temperature heating of buildings. Solar energy, 69(6), pp.511-523.

Nußbicker-Lux, J., Bauer, D., Marx, R., Ochs, F., Heidemann, W. and Müller-Steinhagen, H., 2009. Monitoring results from German central solar heating plants with seasonal thermal energy storage. EFFSTOCK 2009, Stockholm, Sweden, June, pp. 14-17.

Reuss, M., Beuth, W., Schmidt, M. and Schoelkopf, W., 2006, June. Solar district heating with seasonal storage in Attenkirchen. In Proceedings of the IEA Conference ECOSTOCK.

Reuss, M., 2020. The use of borehole thermal energy storage (BTES) systems. Advanced in Thermal Energy Storage Systems - Methods and Applications, edited by Cabeza, L., 2nd edition, Woodhead Publishing.

Schiegg, H.O., Rødland, A., Zhu, G. and Yuen, D.A., 2015. Electro-pulse-boring (EPB): Novel super-deep drilling technology for low cost electricity. Journal of Earth Science, 26(1), pp.37-46.

Schmidt, T. and Sørensen, P.A., 2018, April. Monitoring results from large scale heat storages for district heating in Denmark. In 14th International Conference on Energy Storage, pp.25-28.

Schmidt, T., Mangold, D. and Müller-Steinhagen, H., 2003. Seasonal thermal energy storage in Germany. ISES Solar World Congress 2003, Gothenburg, Sweden.

Shah, S.K., Aye, L. and Rismanchi, B., 2018. Seasonal thermal energy storage system for cold climate zones: A review of recent developments. Renewable and Sustainable Energy Reviews, 97, pp.38-49.

Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J. and Kokko, J., 2012. The performance of a high solar fraction seasonal storage district heating system–five years of operation. Energy Procedia, 30, pp.856-865.

Skarphagen, H., Banks, D., Frengstad, B.S. and Gether, H., 2019. Design considerations for borehole thermal energy storage (BTES): A review with emphasis on convective heat transfer. Geofluids, 2019, pp. 1-26.

Sliwa, T., Jarosz, K., Rosen, M.A., Sojczyńska, A., Sapińska-Śliwa, A., Gonet, A., Fąfera, K., Kowalski, T. and Ciepielowska, M., 2020. Influence of rotation speed and air pressure on the down the hole drilling velocity for borehole heat exchanger installation. Energies, 13(11), pp.2716.

Trillat-Berdal, V., Souyri, B. and Fraisse, G., 2006. Experimental study of a ground-coupled heat pump combined with thermal solar collectors. Energy and Buildings, 38(12), pp.1477-1484.

Velraj, R., 2016. Sensible heat storage for solar heating and cooling systems. Advances in Solar Heating and Cooling, edited by Wang, R.Z. and Ge, T.S., Woodhead Publishing.

Wang, X., Zheng, M., Zhang, W., Zhang, S. and Yang, T., 2010. Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas. Energy and Buildings, 42(11), pp.2104-2110.

Welsch, B., Göllner-Völker, L., Schulte, D.O., Bär, K., Sass, I. and Schebek, L., 2018. Environmental and economic assessment of borehole thermal energy storage in district heating systems. Applied energy, 216, pp.73-90.

Witte, H.J.L. and Van Gelder, A.J., 2007. Three years monitoring of a borehole thermal energy store of a UK office building. In Thermal energy storage for sustainable energy consumption, pp.205-219.

Wong, B., Snijders, A. and McClung, L., 2006, May. Recent inter-seasonal underground thermal energy storage applications in Canada. In 2006 IEEE EIC Climate Change Conference, pp.1-7.

Xi, C., Hongxing, Y., Lin, L., Jinggang, W. and Wei, L., 2011. Experimental studies on a ground coupled heat pump with solar thermal collectors for space heating. Energy, 36(8), pp.5292-5300.

Xu, J., Li, Y., Wang, R.Z. and Liu, W., 2014. Performance investigation of a solar heating system with underground seasonal energy storage for greenhouse application. Energy, 67, pp.63-73.

Yang, T., Liu, W., Kramer, G.J. and Sun, Q., 2021. Seasonal thermal energy storage: A techno-economic literature review. Renewable and Sustainable Energy Reviews, 139, pp.110732.

Zhang, Y. and Zhang, J.J., 2014. Technical improvements and application of air-lift reverse circulation drilling technology to ultra-deep geothermal well. Procedia Engineering, 73, pp.243-251.

Zhu, N., Wang, J. and Liu, L., 2015. Performance evaluation before and after solar seasonal storage coupled with ground source heat pump. Energy conversion and management, 103, pp.924-933.