22nd International Conference on Sustainable Energy Technologies
Kuala Lumpur, Malaysia, 13 to 15 August 2026 · ISBN 978-1-995850-00-9 · ISSN 2978-4387

CONFERENCE PAPER · ENERGY STORAGE & CONVERSION

Effects of Zonal Design for Seasonal Thermal Energy Storage Systems

Mengying Cui[1]*, Yuxi Huang[1], Yonggao Yin[1]

[1] Southeast University, Nanjing, China

RECEIVED 15 May 2026 · REVISED 16 June 2026 · ACCEPTED 29 June 2026
PRESENTED 13 to 15 August 2026 · PUBLISHED 23 November 2026

ABSTRACT

Borehole thermal energy storage offers a viable approach for the large-scale seasonal utilization of low-grade heat sources and the decarbonization of heating systems. In district heating applications, large-scale BTES systems generally involve a considerable storage volume and a spatially non-uniform temperature field within the borehole field. This spatial non-uniformity affects heat transfer and heat loss, making the design of zoning configurations important for system performance. In this study, two zoning configurations are proposed: an inner–outer zoning configuration and a cross-zoning configuration. Long-term simulations are conducted to compare their effects on temperature distribution, heat injection, heat loss, storage efficiency, and system energy consumption against a non-zoned configuration. In addition, borehole fields with different sizes are investigated to evaluate how the effectiveness of zoning strategies changes with BTES system scale. The results show that the two zoning configurations lead to different thermal regulation effects. The inner–outer zoning configuration concentrates more heat in the core region, increasing the core soil temperature by approximately 2 °C to the non-zoned configuration in the eighth cycle, but results in a less uniform temperature field. By contrast, the cross-zoning configuration produces a more uniform temperature distribution and increases cumulative heat injection by 3% compared with the non-zoned configuration. Although both zoning configurations show lower storage efficiency, they reduce total system energy consumption, indicating that the evaluation of zonal operation should consider both underground thermal performance and system energy use. In addition, the energy-saving benefit of zonal operation becomes more pronounced as the borehole-field size increases, while its effect on heat extraction remains relatively stable. These findings provide a theoretical basis for the zoning design and operational optimization of BTES systems under low-grade heat source conditions.

KEYWORDS Borehole thermal energy storage, Seasonal storage, Zoning configuration, Heat loss, System performance

1. Introduction

District heating systems are subject to both short-term mismatches and long-term seasonal imbalances. Seasonal thermal energy storage provides an effective approach to mitigating the long-term mismatch by storing renewable energy or waste heat during the non-heating season and discharging it when heating demand increases. Among the available seasonal thermal energy storage technologies, borehole thermal energy storage (BTES) has attracted considerable attention because the underground soil and rock can be directly used as a large-volume storage medium, offering relatively low costs and stable long-term operation (Pokhrel *et al.* 2021; Sadeghi *et al.* 2024).

BTES systems have been implemented using various heat sources, including solar thermal energy and industrial waste heat (Cui *et al.* 2026). Existing projects cover a wide range of borehole-field sizes, borehole depths, storage volumes, and operating temperatures, demonstrating its engineering adaptability and feasibility of transferring heat across seasons (Guo *et al.* 2017; Sibbitt *et al.* 2012; Zhao *et al.* 2025). According to the storage temperature and heat-supply configuration, BTES systems can

* Corresponding author. Email address: 15733703546@163.com (Mengying Cui)

© 2026 The Author(s).
Published by Caravel Press.

doi.org/10.65582/set.2026.012

generally be classified into high-temperature BTES systems for direct heat supply and low- or medium-temperature BTES systems coupled with heat pumps. Compared with high-temperature BTES systems, low- or medium-temperature BTES coupled with heat pumps shows considerable potential for large-scale heating applications. Low- or medium-temperature BTES systems can utilize a broader range of low-grade heat sources and reduce heat loss because of the smaller temperature difference between the storage volume and the undisturbed ground. In addition, the heat pump provides the required temperature lift to meet heating demand.

For low- or medium-temperature BTES systems, particularly large-scale borehole fields, active regulation of the spatial distribution of stored thermal energy may improve storage efficiency, reduce heat loss to the surrounding ground, and maintain a higher temperature level during the discharging period, thereby enhancing heating system performance (Hu *et al.* 2025; Millar *et al.* 2025). Zonal operation can provide a means of achieving such regulation within a BTES field. By dividing the borehole field into independently controlled regions, the spatial distribution of stored heat can be regulated through different hydraulic connections, operating sequences, or inlet-control strategies. Previous studies have explored several zonal operating strategies for BTES. Concentric zoning has been used to establish radial temperature stratification within the storage volume (Casasso *et al.* 2022). A radial series connection of boreholes can further direct heat transfer from the central region toward the periphery during the charging period (Kumawat *et al.* 2024). In addition, Lim *et al.* (2020) proposed an inlet-position control strategy based on the temperature distributions of both the injected fluid and the storage volume during charging and discharging. The results demonstrated a 24.4% improvement in thermal storage efficiency by the end of the third year, alongside enabling the storage of low-temperature heat during winter. However, improved underground thermal performance does not necessarily translate into lower system energy consumption. A systematic comparison of different zoning strategies over long-term operation is required.

This study compares a conventional non-zoned BTES configuration with two zonal configurations over multiple annual operating cycles. Their long-term performance is assessed from both underground thermal and system energy perspectives, including temperature evolution, storage efficiency, heat loss, and operating energy consumption. Borehole fields of 10 × 10, 20 × 20, and 30 × 30 boreholes are also investigated to evaluate how borehole-field size affects the effectiveness of zonal operation. The results provide a basis for evaluating the long-term applicability of zonal operation in low- and medium-temperature BTES systems.

2. Methods

2.1. System conditions

This study investigates a large-scale, low-temperature borehole thermal energy storage (BTES) system coupled with heat pumps for building heating, as illustrated in Fig. 1. The system consists of a low-grade heat source, a BTES field, heat pump units, and the buildings served by the heating system. The borehole field comprises 900 boreholes, each with a depth of 150 m. The boreholes are arranged in a square array with a spacing of 3.5 m. During the charging period, the heat-transfer fluid supplied by the low-grade heat source is maintained at 30 °C with a total flow rate of 405 m^3/h. The charging period extends from May 1 to September 30, while the heating period extends from November 15 to March 15 of the following year. The BTES system remains in standby mode during the remaining periods.

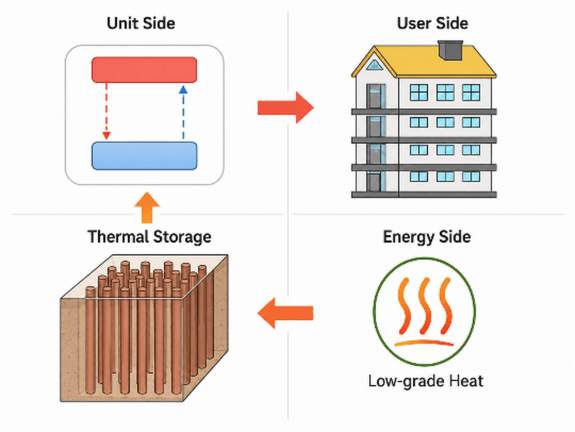

Figure 1. Schematic diagram of low-temperature BTES systems coupled with heat pumps.

During the heating season, the heat stored in the ground is extracted through the borehole heat exchangers and supplied to two heat pump units as the low-temperature heat source. The design supply and return water temperatures on the building side are 45 °C and 40 °C, respectively. The system is simulated continuously for eight annual cycles to evaluate the long-term thermal performance of the BTES system and the variation in system energy consumption under different zonal operating modes.

During the charging and discharging periods, the hydraulic circuits are operated according to the defined zoning strategy. Case 1 is the non-zoned baseline, where all boreholes operate in parallel as a single field. Case 2 uses inner–outer zoning configuration. The field is divided into an inner zone and an outer zone, with distinct hydraulic circuits arranged concentrically. During the standby period, Case 2 will continue to inject lower-grade heat into the boreholes in the outermost layer of the storage volume. Case 3 uses cross-zoning configuration. Boreholes belonging to different hydraulic circuits are spatially interlaced throughout the storage volume.

2.2. System modelling

The BTES model consists of two parts: the ground domain and the borehole domain. For the ground domain, the borehole-field temperature response is calculated based on finite line-source theory, and time-varying loads are handled through temporal superposition. The temperature response of a single borehole is used as a convolution kernel, and two-dimensional discrete convolution is applied to superimpose the temperature responses of all boreholes. A load aggregation method is used to improve the computational efficiency of long-term simulations. At the borehole scale, a quasi-three-dimensional model is used to describe the heat-transfer process inside the borehole. Further details of the modelling method are provided by Zhao *et al.* (2025). The main geometric and thermophysical parameters used in the BTES model are summarised in Table 1.

Table 1. Main parameters of the BTES model.

Parameters	Unit	Value
Borehole depth	m	150
Borehole number	/	900
Borehole spacing	m	3.5
Soil thermal conductivity	W/(m·K)	1.31
Volumetric heat capacity of soil	kJ/(m³·K)	2100

2.3. Performance indicators

The evaluation indicators for BTES systems include the temperature of the thermal storage medium, thermal storage efficiency, and heat loss ratio.

Storage efficiency is the ratio of the system's heat extraction to its heat injection during a complete operating cycle, and is calculated using the Equation 1.

$$\eta_{se} = \frac{Q_{ext}}{Q_{in}} \tag{1}$$

Where:

- η_{se} = storage efficiency (%)
- Q_{ext} = heat extraction of BTES system (GJ)
- Q_{in} =heat injection of BTES system (GJ)

The heat loss ratio is the ratio of the heat lost by the storage volume to the heat injection during a complete operating cycle, and is calculated using the Equation 2.

$$\eta_{loss} = \frac{Q_{loss}}{Q_{in}} \tag{2}$$

Where:

- η_{loss} = heat loss ratio (%)
- Q_{loss} = heat loss of BTES system (GJ)

3. Results

3.1. Temperature field evolution

Figure 2 compares the temporal evolution of the average, core, and edge temperatures for the three cases. All cases exhibit periodic temperature fluctuations superimposed on a gradually rising baseline, indicating progressive thermal accumulation over repeated storage–recovery cycles. By the eighth cycle, the peak average temperatures of Cases 1–3 reach approximately 23.5, 24.0, and 23.8 °C, respectively. Case 2 maintains the highest core temperature, which is about 2.0 °C higher than that of Case 1. This indicates that Case 2 preferentially concentrates and retains heat in the core region, thereby reducing the decline in temperature grade during heat extraction. In contrast, Case 3 exhibits the highest edge temperature, reaching approximately 20.2 °C at the final peak, about 0.3–0.4 °C higher than the other cases, demonstrating a stronger outward redistribution of heat and a more uniform temperature field. Therefore, Case 2 is more effective in preserving the core temperature grade, whereas Case 3 provides better spatial temperature uniformity.

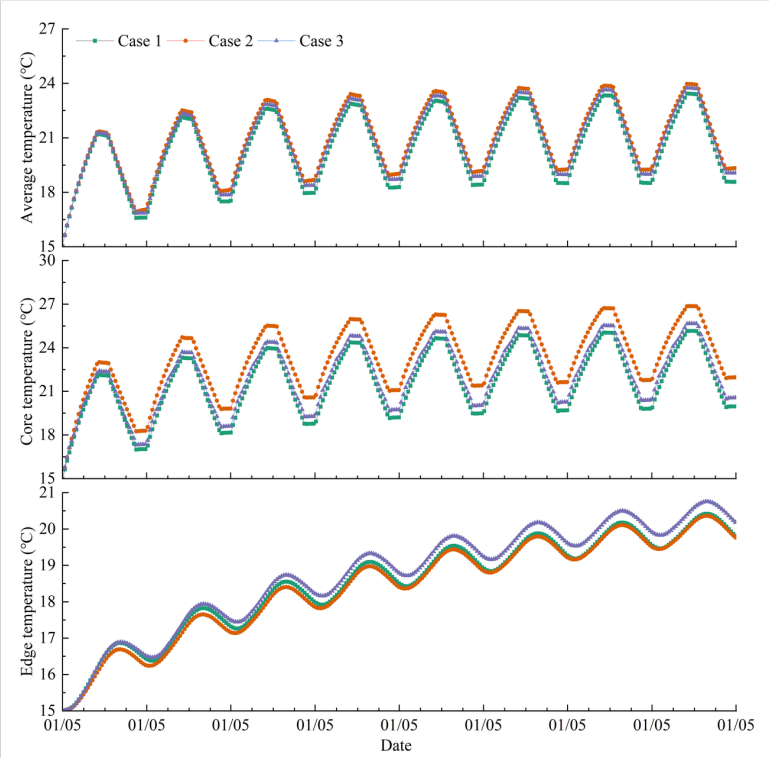

Figure 2. Variations of average temperature, core temperature, and edge temperature for three cases over eight years.

Figure 3 presents the mid-depth horizontal temperature fields of the three cases at four representative operating stages. In all cases, heat progressively accumulates in the central region during charging and diffuses toward the field boundary, while the temperature decreases during heat extraction. Case 1 exhibits the typical radial temperature distribution of conventional operation, with a warm central region and noticeable cooling near the boundary. Case 2 develops the most pronounced high-temperature core and the steepest radial temperature gradient; the central high-temperature region remains clearly visible even after heat extraction, indicating stronger heat concentration and better preservation of the stored-energy temperature grade. By contrast, Case 3 produces smoother temperature contours and higher peripheral temperatures, demonstrating enhanced outward heat redistribution and a smaller centre-to-edge temperature difference. These spatial characteristics are consistent with the temporal results: Case 2 favours core-temperature retention and increases the heat-pump source-side temperature, whereas Case 3 promotes a more uniform temperature field and reduces excessive local heat accumulation.

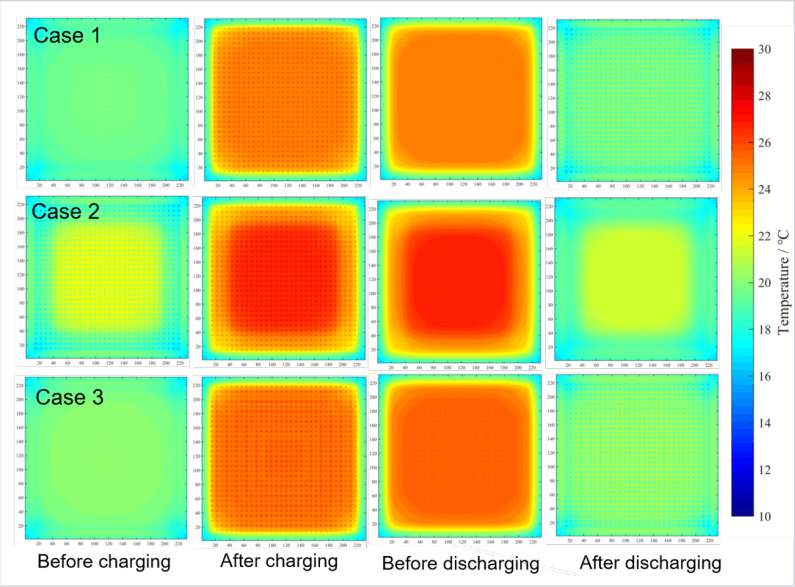

Figure 3. Mid-depth horizontal temperature fields of the three cases at four operating stages in the seventh cycle.

3.2. Energy and storage efficiency

Figure 4 compares the annual energy balance and storage efficiency of the three cases. The extracted heat remained nearly constant at approximately 23–24×10³ GJ, whereas the required heat injection decreased from about 33.5–36.5×10³ GJ in the first cycle to approximately 25×10³ GJ in the eighth cycle. Consequently, the storage efficiency increased from approximately 62%–68% to 91%–92%, with the most pronounced improvement occurring during the first four cycles and gradually levelling off thereafter. Compared to Case 1, the two zoning operations increase the heat injection. Case 3 increases cumulative heat injection by 3% compared with the Case 1. Case 1 exhibited a slightly higher efficiency during the initial cycles because it required less injected heat for a comparable amount of heat extraction, while the differences among the cases diminished as the storage approached a quasi-periodic thermal state. This trend results from progressive underground thermal accumulation, which reduces the fraction of injected heat required to establish and maintain the storage temperature field.

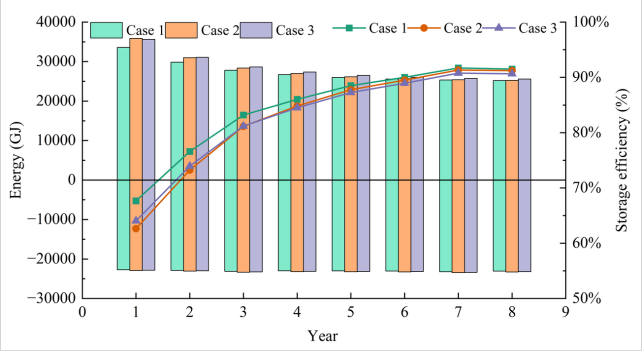

Figure 4. Annual energy balance and storage efficiency of the BTES system for the three cases.

3.3. Heat-loss of BTES system

As shown in Fig. 5, both the annual heat loss and heat-loss ratio decreased continuously with operating cycles. The heat loss of Case 1 declined from approximately 4.7 TJ in the first cycle to 1.9 TJ in the eighth cycle, while those of Case 2 and Case 3 decreased from about 5.8 and 5.7 TJ to approximately 2.0 TJ. Correspondingly, the heat-loss ratio decreased from approximately 14.1%–

16.2% to 7.6%–8.2%. Case 2 and Case 3 exhibited larger heat losses during the initial cycles because zoned operation redistributed heat over a wider or higher-temperature region, increasing transient heat diffusion toward the surrounding soil. As the underground temperature field gradually stabilised and the required annual heat injection decreased, the incremental heat diffusion into the far-field soil weakened, resulting in lower absolute and relative heat losses and smaller differences among the three cases.

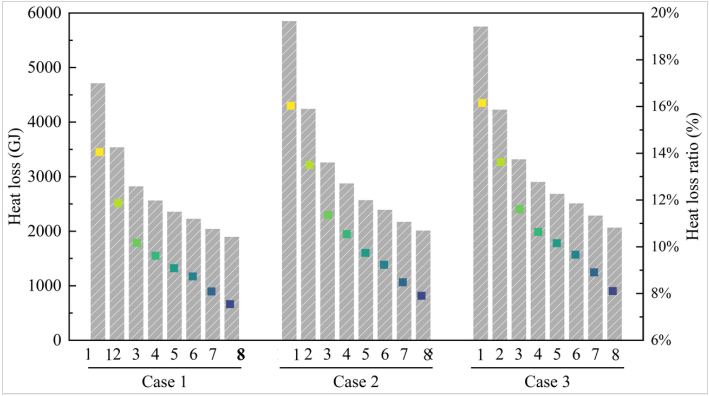

Figure 5. Heat loss and heat loss ratio of the BTES system for three cases.

3.4. Energy consumption

Figure 6 compares the annual heat-pump and pumping energy consumption of the three cases. The heat pump accounts for the dominant share of the total system energy consumption, whereas pumping energy represents a considerably smaller but non-negligible contribution. With increasing operating cycles, heat-pump energy consumption generally decreases because progressive thermal accumulation raises the source-side temperature and reduces the compressor work required to meet the heating demand. Case 2 exhibits the lowest heat-pump energy consumption owing to its stronger preservation of the core temperature and the resulting higher heat-pump source temperature. However, its additional zonal circulation, particularly during the standby period, increases pumping energy and partially offsets the heat-pump energy savings. Case 1 requires less pumping energy but has the highest heat-pump energy consumption, while Case 3 exhibits intermediate heat-pump, pumping, and total energy consumption among the three cases. Consequently, the differences in total system energy consumption are smaller than those observed for heat-pump energy alone, demonstrating that the energy benefit of zoning should be evaluated by considering both thermal improvement and the associated hydraulic penalty.

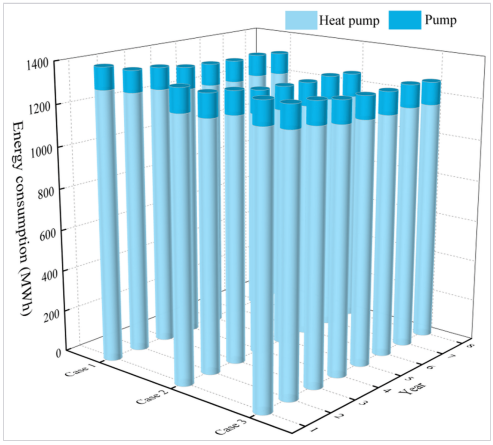

Figure 6. Energy consumption of BTES system coupled with heat pump system.

3.5. Effect of borehole field scale

Borehole-field models of three scales (10 × 10, 20 × 20, and 30 × 30) were established to analyse the impact of borehole field scale on the effectiveness of zoned operation. Using Case 1 as the baseline, the study compared the changes in various indicators for Case 2 and Case 3 relative to Case 1 across different borehole field scales. The changes in heat injection, heat extraction, heat-pump energy consumption, and total energy consumption are calculated relative to Case 1 and presented in percentage terms. For storage efficiency and heat-loss rate, the differences from Case 1 are given in percentage points. The signs are defined consistently for all indicators, with positive values representing better performance than Case 1 and negative values representing poorer performance.

The comparison results for the eighth year are shown in Table 2. As the borehole number increases, the increase in annual heat injection for Case 2 and Case 3 relative to Case 1 gradually decreases, indicating that zonal operation has a more pronounced effect on the heat injection process in smaller borehole fields. In terms of storage efficiency and heat-loss rate, both zonal operation schemes perform worse than Case 1, but the differences gradually decrease as the number of boreholes increases. This is associated with the scale effect of BTES systems. As the borehole-field size increases, the surface-area-to-volume ratio of the storage volume decreases, resulting in an overall reduction in heat loss caused by the diffusion of stored heat into the surrounding ground. For the same borehole-field size, the total heat supplied to the buildings remains the same for all three cases. The improvements in annual heat extraction and heat pump energy consumption for Case 2 and Case 3 remain relatively stable across different borehole field scales. The total energy-saving rates for both Case 2 and Case 3 increase as the borehole field scale expands, from 1.2% to 3.9% for Case 2 and from 1.6% to 2.7% for Case 3, indicating that zonal operation has greater potential to improve system energy efficiency in larger-scale BTES systems.

Table 2. Performance differences of Case 2 and Case 3 relative to Case 1 in the eighth cycle for different borehole field scales.

	Case 2 relative to Case 1			Case 3 relative to Case 1		
Borehole number	**100**	**400**	**900**	**100**	**400**	**900**
Heat injection	2.0%	1.4%	1.3%	2.5%	1.8%	1.6%
Heat extraction	0.9%	1.0%	1.0%	0.6%	0.6%	0.6%
Storage efficiency	−0.9%	−0.4%	−0.3%	−1.3%	−1.1%	−0.9%
Heat-loss ratio	−1.0%	−0.5%	−0.4%	−1.2%	−0.8%	−0.6%
Heat-pump energy consumption	4.6%	5.0%	4.9%	3.1%	3.3%	3.4%
Total energy consumption	1.2%	3.8%	3.9%	1.6%	2.5%	2.7%

4. Conclusion

Zonal operation can modify BTES performance by redistributing stored heat within the storage volume. This study compares two zonal configurations with a conventional non-zoned configuration over eight annual operating cycles. Their long-term thermal and system energy performance was compared for 10 × 10, 20 × 20, and 30 × 30 borehole fields to examine how borehole-field size affects the effectiveness of zonal operation. The main findings are as follows:

Case 2 concentrates more heat in the core region, resulting in the highest core temperature but a less uniform temperature field, whereas Case 3 provides a more uniform temperature distribution and higher heat injection.

Both zonal configurations show lower storage efficiency but lower total energy consumption, indicating that both thermal performance and energy consumption should be considered when evaluating different zonal strategies.

Zonal operation shows greater energy-saving potential as the BTES scale increases, while its effect on heat extraction remains relatively stable.

Future work will further investigate the effects of key design and operating parameters on the performance of different zonal configurations.

Declarations

Author contributions. Mengying Cui: Writing (original draft), Investigation, Methodology, Conceptualization, Visualization, Funding acquisition, Data curation. Yuxi Huang: Writing (review and editing), Visualization, Investigation. Yonggao Yin: Writing (review and editing), Supervision, Methodology.

Funding. This work was supported by the Postgraduate Research & Practice Innovation Program of Jiangsu Province under Grant No. 26CXJH0666.

Conflicts of 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.

Data availability. Not applicable. This study did not generate or analyse any datasets.

References

Casasso, Alessandro; Giordano, Nicolò; Bianco, Carlo; Sethi, Rajandrea (2022) 'UTES - Underground Thermal Energy Storage', *Encyclopedia of Energy Storage*. Elsevier, pp. 382-393. Available at: https://doi.org/10.1016/b978-0-12-819723-3.00078-0

Cui, Mengying; Yin, Yonggao; Zhao, Donglin; Cao, Bowen; Chen, Xin; Bu, Gen (2026) 'Seasonal borehole thermal energy storage for zero-carbon city heating: Mechanisms, optimization, and application challenges', *Renewable and Sustainable Energy Reviews*, 232, pp. 116793. Available at: https://doi.org/10.1016/j.rser.2026.116793

Guo, Fang; Yang, Xudong; Xu, Luyi; Torrens, Ignacio; Hensen, Jan (2017) 'A central solar-industrial waste heat heating system with large scale borehole thermal storage', *Procedia Engineering*, 205, pp. 1584-1591. Available at: https://doi.org/10.1016/j.proeng.2017.10.274

Hu, Zhiru; Li, Tianshuang; Mao, Ruofeng; Xiong, Teng; Du, Ruiqing; Tao, Yao; Tu, Jiyuan; Yang, Qizhi; Wang, Yong; Yang, Lizhong; Romagnoli, Alessandro (2025) 'Experimental study on an innovative borehole thermal energy storage system: Improving performance through effective allocation of low-grade energy', *Energy Conversion and Management*, 346, pp. 120479. Available at: https://doi.org/10.1016/j.enconman.2025.120479

Kumawat, Piyush Kumar; Zhou, Haiyan; Kitz, Kevin; McLennan, John; Powell, Kody; Deo, Milind; Panja, Palash (2024) 'Sensitivity analysis of borehole thermal energy storage: examining key factors for system optimization', *Energy Storage and Saving*, 3(3), pp. 218-230. Available at: https://doi.org/10.1016/j.enss.2024.04.003

Lim, Hwan Suk; Ok, JungSoo; Park, Jin Soo; Lee, Seung Joo; Karng, Sarng Woo; Kang, Yong Tae (2020) 'Efficiency improvement of energy storage and release by the inlet position control for seasonal thermal energy storage', *International Journal of Heat and Mass Transfer*, 151, pp. 119435. Available at: https://doi.org/10.1016/j.ijheatmasstransfer.2020.119435

Millar, C.; Lightstone, M.F.; Cotton, J.S. (2025) 'Validation and conceptualization of thermal zones: A new method of efficiently utilizing borehole thermal energy storage systems', *Energy Conversion and Management*, 346, pp. 120470. Available at: https://doi.org/10.1016/j.enconman.2025.120470

Pokhrel, Sajjan; Amiri, Leyla; Zueter, Ahmad; Poncet, Sébastien; Hassani, Ferri P.; Sasmito, Agus P.; Ghoreishi-Madiseh, Seyed Ali (2021) 'Thermal performance evaluation of integrated solar-geothermal system; a semi-conjugate reduced order numerical model', *Applied Energy*, 303, pp. 117676. Available at: https://doi.org/10.1016/j.apenergy.2021.117676

Sadeghi, Habibollah; Jalali, Ramin; Singh, Rao Martand (2024) 'A review of borehole thermal energy storage and its integration into district heating systems', *Renewable and Sustainable Energy Reviews*, 192, pp. 114236. Available at: https://doi.org/10.1016/j.rser.2023.114236

Sibbitt, Bruce; McClenahan, Doug; Djebbar, Reda; Thornton, Jeff; Wong, Bill; Carriere, Jarrett; Kokko, John (2012) 'The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation', *Energy Procedia*, 30, pp. 856-865. Available at: https://doi.org/10.1016/j.egypro.2012.11.097

Zhao, Donglin; Cui, Mengying; Yang, Shuchuan; Li, Xiao; Huo, Junqing; Yin, Yonggao (2025) 'Rapid Temperature Prediction Model for Large-Scale Seasonal Borehole Thermal Energy Storage Unit', *Energies*, 18(19), pp. 5326. Available at: https://doi.org/10.3390/en18195326

HOW TO CITE THIS PAPER

Cui, M., Huang, Y. and Yin, Y. (2026). Effects of Zonal Design for Seasonal Thermal Energy Storage Systems. In: *Proceedings of the 22nd International Conference on Sustainable Energy Technologies (SET2026)*, Kuala Lumpur, Malaysia, 13 to 15 August 2026. Caravel Press, pp. 147–156. ISBN 978-1-995850-00-9. ISSN 2978-4387. https://doi.org/10.65582/set.2026.012

COPYRIGHT AND LICENCE

© 2026 The Author(s). This is an open access paper distributed under the terms of the Creative Commons Attribution (CC BY 4.0) licence, which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

WSSET World Society of Sustainable Energy Technologies Organised by the World Society of Sustainable Energy Technologies. Published by Caravel Press.