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Case Study Of Seasonal And Diurnal Borehole Thermal Energy Storage

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ABSTRACT

A Borehole Thermal Energy Storage (BTES) system functions like a thermal battery, preheating or precooling the ground to later provide heating or cooling for buildings. BTES is becoming increasingly popular worldwide due to its versatility across different climates, its ability to minimize surface area usage, and its efficient seasonal energy storage capabilities. However, the capital cost of installing a BTES system remains a significant barrier to its widespread implementation. In this study, we proposed a modular BTES layout designed to better accommodate the growing capacity requirements of the thermal network. In the new layout, each independent module consists of multiple boreholes, each with a specified heating/cooling capacity. These modules can operate simultaneously to meet fluctuating energy demands, allowing for easy expansion of the BTES system as needed. To maximize the effectiveness of BTES in meeting peak demand and improve system efficiency, BTES is integrated with Grid Amplified Building Energy Seasonal Storage (GABESS), in which the ASHP supplies warm or cold water during off-peak hours to heat or cool the BTES. Later, the WSHP extracts the stored heat or cold from the BTES to provide heating or cooling to the buildings within the thermal network. The feasibility of the proposed system is tested at Joint Base Andrews (JBA), where the heating demand from 20 buildings reaches 11,000 kW. The BTES operating scheme is thoroughly tested using the GABESS technique and numerical simulation to effectively meet the energy demands at JBA.

1 INTRODUCTION

Borehole thermal energy storage (BTES) is a type of geothermal energy storage system where a working fluid, such as water, circulates in closed-loop pipes to transfer heat or cold by conduction. Depending on the storage medium, other types of geothermal energy storage include, for example, aquifer thermal energy storage and tank thermal energy storage.

In the traditional BTES system, boreholes are closely packed within a cylindrical volume, such as in the Drake Landing Solar community. In this case study, we proposed a modular BTES system integrated with the Grid Amplified Building Energy Seasonal Storage (GABESS) system (Kitz, 2021). GABESS combines three established technologies in a new configuration to provide significant value to the energy grid: a water source heat pump (WSHP), an air source heat pump (ASHP), and a BTES. In this system, the ASHP operates during off-peak times to heat or cool the BTES. Later, the stored thermal energy is extracted by the WSHP to heat or cool the buildings connected to the thermal network. Integrating BTES with GABESS can improve performance by:

1. Increasing BTES effectiveness during peak demand periods,
2. Improving overall system efficiency, and
3. Reducing the required number of boreholes.

The new BTES configuration was applied at JBA to meet the heating and cooling demands of 20 selected buildings.

2 (HYDR)GEOLOGICAL CONDITIONS AND MODEL PARAMETERS

The borehole depth in the proposed BTES systems ranges from 85 to 120 meters (m), varying by zones. The geologic formations present at this depth mainly include North Keys Sand, Brandywine Sand, and Calvert Clay. The groundwater table is approximately 15 feet deep, and the hydraulic gradient is very small in the limited area of the BTES system and can be ignored in the test (Tehama LLC, 2020). Parameters are summarized in Table 1.

Table 1. **Geological/hydrogeological/thermal parameters for BTES simulation**

Parameter	North Key and Brandywine Sands	Calvert Clay
Hydraulic conductivity (m/d)	0.475	8.64E-6
Thickness (m)	9	122.5
Porosity (-)	0.25	0.15
Solid thermal conductivity (W/(mk))	1.1	1.6
Solid heat capacity (MJ/m3/K)	1.4	0.92

FEFLOW is employed in this study to model heat transport in the BTES system. FEFLOW is a numerical simulator featuring both a Geographic User Interface (GUI) and a Python Application Programming Interface (API). The GUI supports intuitive visualization and analysis of simulation results, while the API allows for flexible integration with other modeling tools and custom functionalities. A special boundary condition known as a Borehole Heat Exchanger (BHE) is developed and implemented in FEFLOW to model the boreholes in the BTES system. In this approach, the borehole is modeled as a 1D boundary embedded within the 3D simulation domain (Diersch et al., 2011a, 2011b), allowing for efficient and accurate thermal interaction modeling between the borehole and the surrounding ground.

2.1 Energy load profile

The hourly heating and cooling load profile (Figure 1) is based on amalgamation of multiple years. Negative values represent heat extraction, usually occurring during the winter, and positive values indicate heat injection, mainly during the summer. Based on this load profile, the system displays cooling-dominated behavior, meaning that cooling demand exceeds heating demand. Accordingly, the BTES system should be designed to accommodate a higher cooling load.

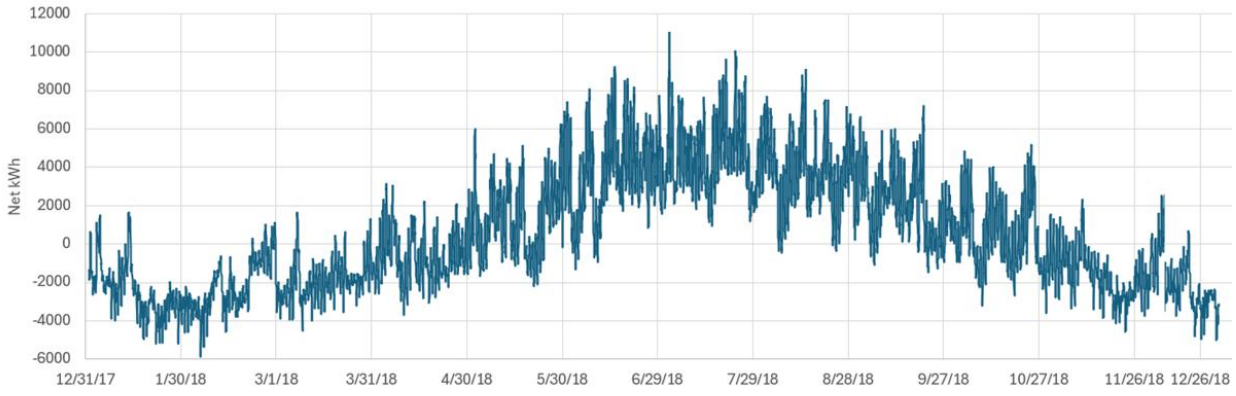


Figure 1. Net hourly heating and cooling load profile from the 20 studied buildings at the JBA Site.

2.2 Modular BTES system

A traditional BTES system is cylindrical with a 1:1 diameter-to-depth ratio to minimize heat loss to the surroundings; however, the load profile at the JBA site indicates the need for a cooling-dominant BTES system, where heat dissipation to the surroundings would enhance system performance. A new BTES layout concept is proposed in this work—rather than a single BTES system, multiple modules are applied where each module

consists of two zones: (1) Zone A, which includes 6 long boreholes with coarse spacing between wells (5 to 6 m); and (2) Zone B, which includes 30 boreholes with dense spacing (3 m), as shown in Figure 2. This module layout features the following advantages:

- The system is easy to scale up by adding more modules (e.g., phase 1, phase 2, and phase 3) to meet future increasing demand.
- The simulation time is reduced by modeling one single module instead of a full BTES system (i.e., the module highlighted in red in Figure 2).
- Deeper and more widely spaced wells in Zone A will facilitate heat dissipation, especially in a cooling-dominant system.
- The module layout fits the surface better than a full-size traditional cylindrical BTES system.

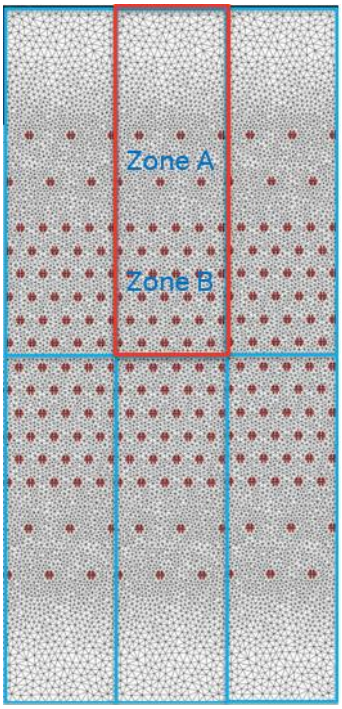


Figure 2. BTES system that consists of six modules. (Only one of the six modules will be modeled with FEFLOW in the numerical simulation.)

2.3 BTES system operating schedules

After analyzing the energy load profile (Figure 1), we proposed operating schedules for the BTES system that are both seasonal and diurnal, considering peak and off-peak hours, as well as integration with GABESS. We assume that the BTES starts running in the winter.

- Winter (6 months: November through April)
  - 4 a.m. to 10 a.m. and 4 p.m. to 10 p.m. (12 hours per day): power = 1/75 of real load
    - Zone A: flow rate = 40 m^3/d per borehole
    - Zone B: flow rate = 35 m^3/d per borehole
  - 10 a.m. to 4 p.m. and 10 p.m. to 4 a.m. (12 hours) (start from the end of the 4th year to balance heat storage in zone A)
    - Zone A: power = - 600 MJ/d
  - In the last 30 days, both Zones A and B have been operated 24 hours per day (instead of 12 hours per day) to cool down both zones to prepare for the summer cooling season.
- Summer (6 months: May through October)
  - 5 a.m. to 1 p.m.: run Zone A, inlet temperature = 30 °C, flow rate = 40 m^3/d per borehole. By operating Zone A at this temperature, heat can be dissipated into the formation, and the WSHPs still provide reasonable efficiency for the WSHP.
  - 1 p.m. to 9 p.m.: run Zone B, power = 1/75 of real load, flow rate = 35 m^3/d per borehole. This is the period of maximum cost on the electric grid, so the lower the temperature of the thermal energy network, the more efficient the WSHPs.
  - 9 p.m. to 5 a.m.: run Zone B, heat extraction (cooling down of Zone B), inlet temperature = 10°C, flow rate same as heat storage (1 p.m. to 9 p.m.). This provides diurnal recharge of the BTES.

- In the last 40 days, do not cool Zone B so it is warm for the winter heating season.

Each single module is responsible for 1/75 of the total load, which equals 2,100 boreholes. The building's cooling and heating demands are substantial, requiring many boreholes to satisfy the annual heat and cold requirements, especially during peak periods. The total number of boreholes could be lowered if alternative heat and cold sources are added for days with the highest demand.

3 RESULTS

3.1 Outlet temperature and underground temperature

Figure 3 illustrates the daily average inlet and outlet temperature at Zone A over a 7-year simulation period. During the first 4 years, Zone A operates 12 hours each day; in the final 3 years, the operation extends to 24 hours per day. In the first 4 years, the outlet temperature steadily increases, indicating a thermal imbalance in the BTES system—specifically, excessive heat accumulation. Following this adjustment, the outlet temperature stabilizes, demonstrating improved thermal balance and system performance in the subsequent years.

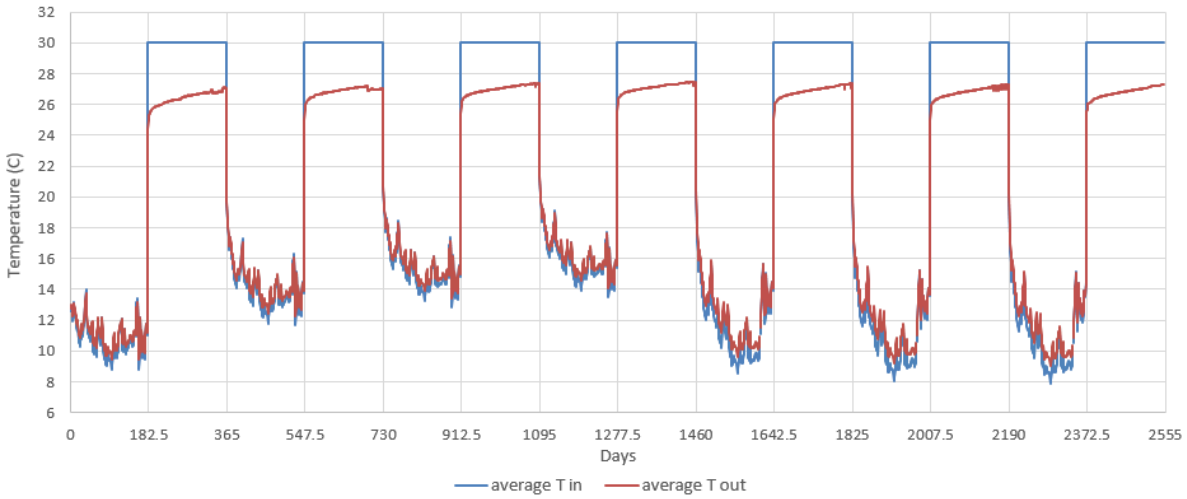
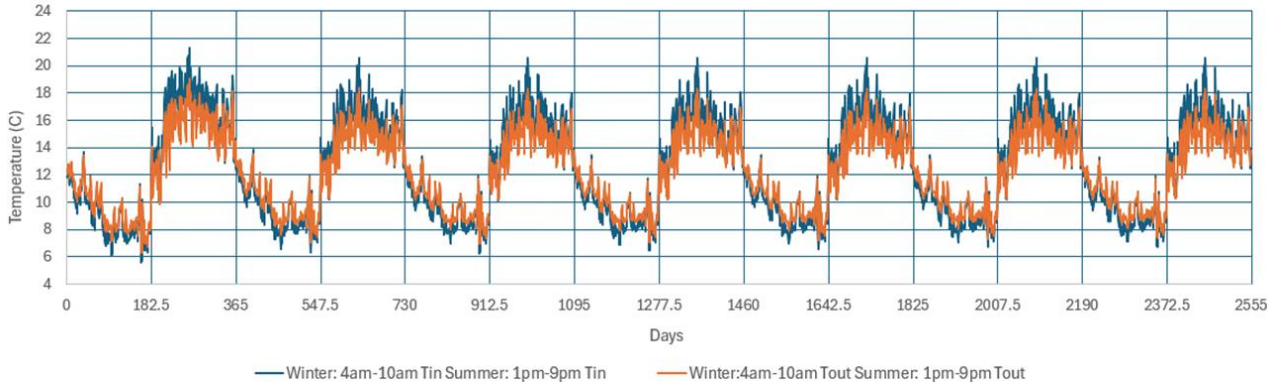


Figure 3. Daily average inlet and outlet temperature of zone A.

Figure 4 presents the average inlet and outlet temperatures of Zone B. Blue lines represent the inlet temperature, and orange lines indicate the outlet temperature. The two plots in Figure 4 represent average temperatures over different periods. The top plot shows the average between 4 a.m. and 10 a.m. in the winter and between 1 p.m. and 9 p.m. (peak hours) in the summer. The bottom plot shows the average for winter from 4 p.m. to 10 p.m. and summer from 9 p.m. to 5 a.m. As mentioned in the operating schedules for summer, no diurnal cooling down of Zone B is conducted for the last 40 days of each summer season, which is illustrated in the bottom plot (blank curve near the end of each year, for example, days before 365). The temperature shows stable in the 7-year cycle.



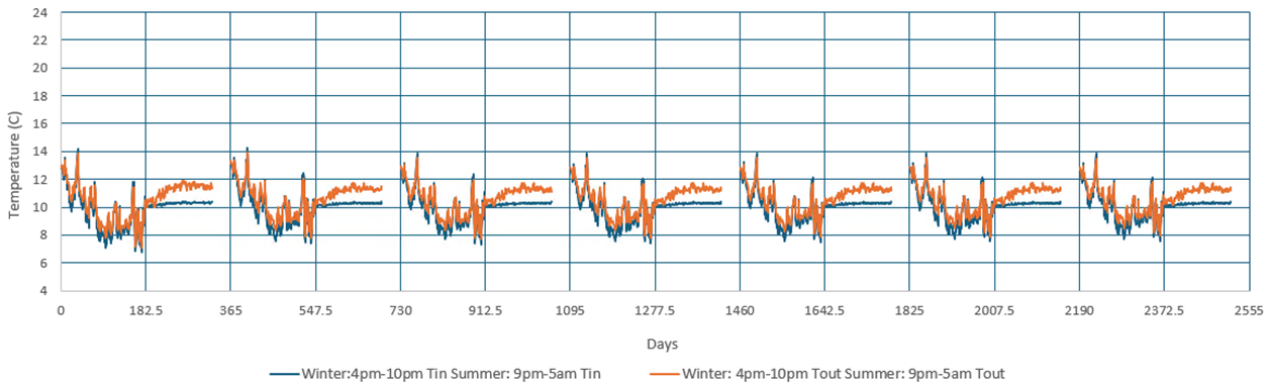


Figure 4. Daily Average Inlet and Outlet Temperature of Zone B. (Top: Average for winter from 4 a.m. to 10 a.m., and summer 1 p.m. to 9 p.m. Bottom: Average for winter from 4 p.m. to 10 p.m. and summer 9 p.m. to 5 a.m.).

Figure 5 displays ground temperature distribution at the end of the 7th year along with the locations of six observation points used for temperature monitoring. The temporal evolution of ground temperature at these locations is shown in Figure 6. The ground temperature measurements in Zone A (obs8, obs9, and obs10 in Figure 5) exhibit continuous increase during the first 4 years, which is consistent with the rising outlet temperature trends observed in Figure 3. After the schedules are modified at the end of the 4th year, resulting in increased heat extraction from Zone A, the ground temperature stabilizes over the final 3 years of the simulation, reflecting improved thermal equilibrium.

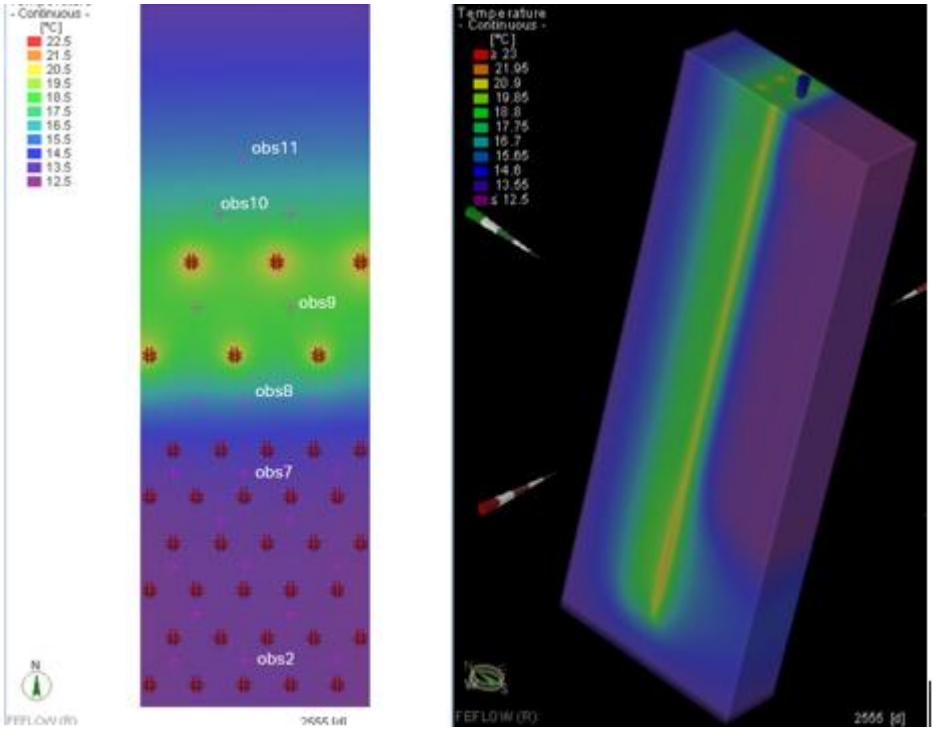


Figure 5. Ground temperature at the end of the 7-Year Simulation. (Left: Top view at a depth of 40 m. Right: 3D view.)

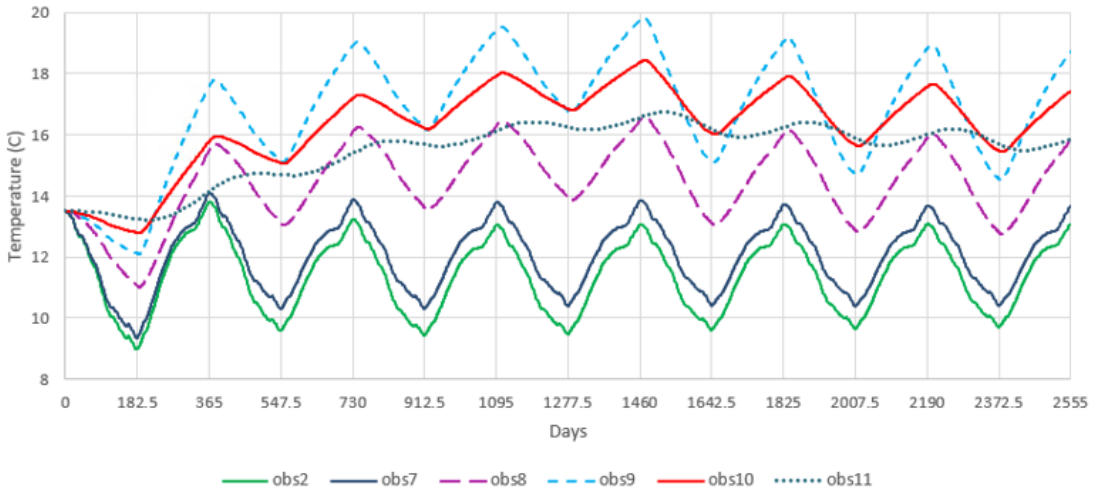


Figure 6. Ground temperature at some observation points. (Locations of the observation points are shown in Figure 5.)

3.2 Capacity Verification

The simulated capacity is determined based on the final year of the simulation (7th year). It is then compared with actual load data to evaluate whether the proposed system can meet the energy demand. For instance, Figure 7 shows a comparison between the simulated capacity (blue dots) and real loads (red dots) during peak hours of the summer season. The results indicate that the simulated capacity can usually meet the real load during peak hours when using Zone B. Most of the time, the proposed BTES system satisfies the energy demand; however, during certain periods, additional support is necessary to meet the load. For example, from 9 p.m. to 5 a.m. in summer, Zone B is storing cold, but some heat needs to dissipate during this time.

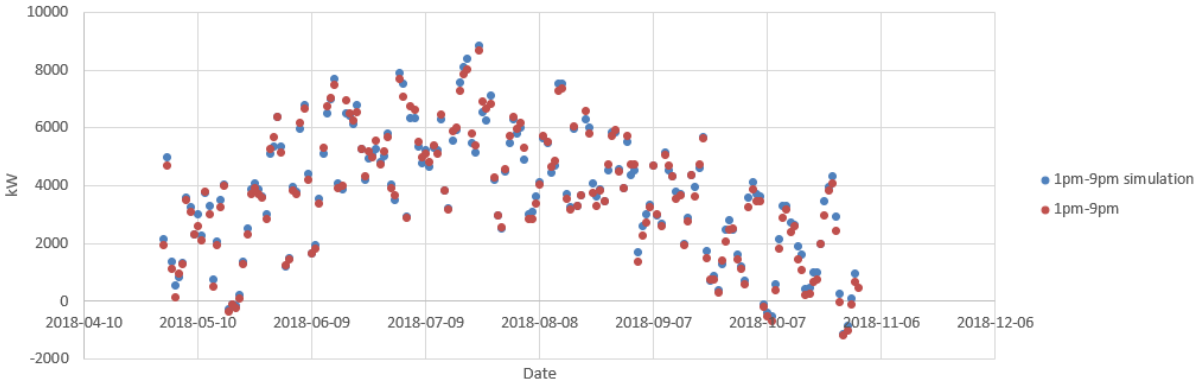


Figure 7. Simulated versus real load from 1 p.m. to 9 p.m. (Peak Hours) in the summer.

4 CONCLUSSION

In this study, we proposed a modular BTES layout and integrated the BTES into the GABESS framework. The concept was applied in a real case study at the JBA site, using an hourly load profile. The proposed design features the following characteristics.

- The system can meet the heating and cooling needs. While many boreholes are required, this is mainly because of high cooling demand during a few peak days. The number of boreholes could potentially be reduced by adding supplemental technologies or strategies.
- Each BTES module zone operates independently, allowing for flexible scheduling that can be adjusted according to real-time load demands.
- When integrated with the GABESS framework, the BTES system can effectively shift peak load demands to off-peak hours through diurnal thermal energy storage, improving system efficiency and reducing strain during peak periods.

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