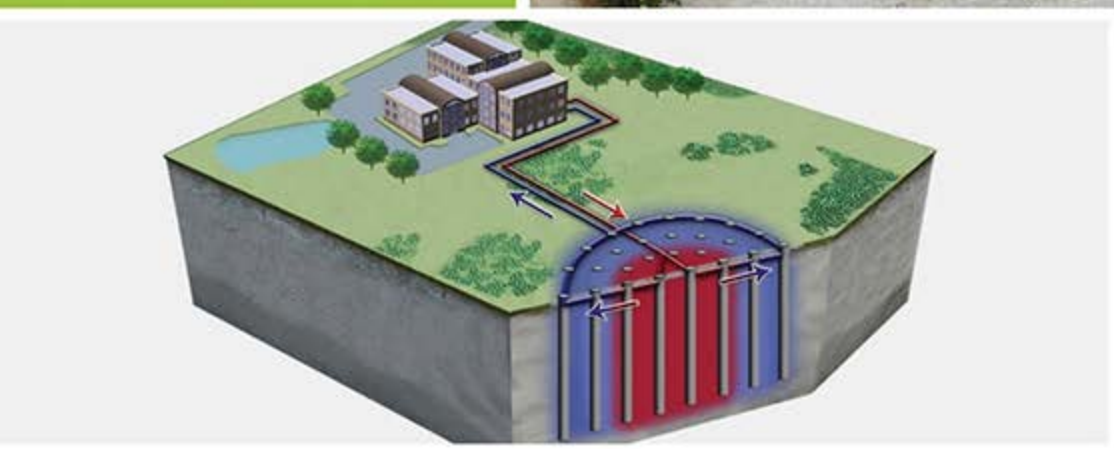
Application Guide for Large Thermal Energy Storage



PIT THERMAL ENERGY STORAGE

TANK THERMAL ENERGY STORAGE





BOREHOLE THERMAL ENERGY STORAGE

Application Guide for Large Thermal Energy Storage



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Executive Summary

Thermal energy storage (TES) is a critical tool in the overarching energy system architecture in that it allows the use of intermittently generated energy, the energy available during certain periods (e.g., wind, solar), or energy waste streams from industrial processes, when needed for air-conditioning or process needs. TES can be designed to charge, store, and discharge energy daily, weekly, or seasonally. Examples of daily cycling of TES include hot water storage in the domestic hot water system, and chilled water storage designed for load shifting to reduce the peak demand and the size of cooling equipment. Seasonal TES is typically used to store heat in the months with high solar radiation to be used for heating needs in the colder months. TES can be designed to be used in heating or cooling system configurations with a several-day or several-month capacity based on the user load profile. It can be charged using waste heat, e.g., generated by combined heat and power (CHP), cooling equipment, or collecting heat from solar receivers. Interest in large-scale and long-term TES is growing with new plants being planned and built in Denmark and Germany; the number of countries interested in this technology is growing as indicated by a recently completed International Energy Agency (IEA) Energy Storage Technology Collaboration Programme, Task 39 that brought together researchers and practitioners from Austria, Denmark, France, Germany, the Netherlands, Sweden, and the USA to analyze the use of large TES facilities for district heating. Most of the large TES built to date have been considered pilot or demonstration projects and have been subsidized as such. The analysis presented in the current book has been performed within IEA Task 39 to determine under which circumstances large-scale TES improves energy supply systems' resilience, reduces CO_2 emissions and is cost effective in different climates and at different energy prices and economic incentives. This analysis was conducted by an international team of researchers and practitioners led by the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) and was sponsored by the office of the Deputy Assistant Secretary of the Army for Energy and Sustainability.

Chapter 1 introduces this project. Chapter 2, Thermal Energy Storage, discusses general TES applications and specific case studies. This chapter presents the construction, storage medium characteristics, working principles, and real-world applications of TES. Specific types of TES included in the analysis are tank thermal energy storage (TTES), pit thermal energy storage (PTES), and borehole thermal energy storage (BTES). Aquifer thermal energy storage (ATES) requires very specific geological conditions. The allowable temperatures in ATES are typically very limited compared to other TES types. Due to these limitations ATES is not included in this book.

Chapter 3, Methodology, delineates the parameters, system architectures, and demand profiles used for the simulations. The demand profiles are based on a representative U.S. Army Brigade Combat Team (BCT) complex of buildings, which include a variety of buildings with different uses. The demand profiles for these buildings have been generated using Energy Plus modeling for representative U.S. public/military locations in the 18 U.S. Department of Energy (DoE) climate zones (section 3.3). Section 3.3 also includes the TMY3 weather data that form the basis for the temperatures, solar radiation, wind speed, humidity, and precipitation ranges used in this analysis. Section 3.4 outlines the system architectures of the simulated alternative energy systems. Although these architectures are divided into cold/moderate climate zones and hot climate

zones, they share the same baseline system architectures that form the basis for the criteria used to compare the results. The baseline system architecture is comprised of a boiler to satisfy demand for heating and domestic hot water needs, an electric chiller to satisfy cooling demand, and sourcing electricity from the public grid to satisfy overall electricity demand, encompassing the usage of the electric chiller. The seven cold/moderate climate system architecture scenarios include the ones used to demonstrate the advantage of TES use in combination with different sizes and architectures of systems with CHP plants and a solar water heating (SWH) field. In these scenarios, CHP plants generate all or a fraction of electrical and heat loads with the grid and a boiler providing the remaining fractions of loads, when necessary, in each cold/moderate climate zone. While the hot climate system architecture is similar to the one used for cold/moderate climates, it differs with the addition of absorption chiller(s) for cooling energy production and TES for storing cooling energy. The simulations for the hot climate zones are also structured differently in that they include eight simulation scenarios in which elements of the system architecture were gradually added and replaced.

Chapter 4, Input Data and Boundary Conditions, details the parameters and data used in the simulation framework. This section encompasses various elements such as energy prices, heating values, emission rates for imported electricity, equipment maintenance costs, equipment efficiencies, and capital expenses (CAPEX) associated with equipment and TES capacities (Foley 2022). Additionally, it provides graphical representations of CAPEX for different TES technologies across varying capacities. These insights are derived from thorough research and informed industry expertise contributed by the involved stakeholders, with proper references cited for each category. The energy prices are divided into three categories for both the import of electricity and purchase of natural gas, except for Fairbanks, which was assigned a fourth category, extra high (Alaska) prices, denoted to accommodate the higher energy prices in Fairbanks given to the less integrated gas infrastructure and higher electricity transmission costs. The emission rates for the imported electricity were similarly divided into three categories that denote the potential emissions levels associated with the imported electricity (MWh). Due to the legal complexity of exporting electricity, the simulations do not include the export of electricity. The feasibility of the CAPEX and operational expenses (OPEX) associated with the alternative energy systems rely solely on the savings that these system solutions yield. Different coefficients of performance (COPs) were used for electric chillers and absorption chillers because different cooling technologies are used in the system architectures for the cold/moderate and the hot climate zones.

Chapter 5, Results, presents and explains the results of the simulations performed for different climate zones, starting with the results for the coldest climate zone (c.z.) 8 (Fairbanks) and proceeding to the hottest climate zone 0A (Guam) along with general recommendations regarding the practical implementation of TES technologies.

In cold to moderate climate zones, simulation results consistently demonstrate that TES used in combination with CHP results in the lowest total energy costs, indicating significant total cost savings. This application proves to be most beneficial in scenarios with high winter heat demand and lower heat demand in summer. Without TES, CHP systems often cease electricity production during summer months once heat demand is met, leading to reliance on imported electricity to meet remaining demands. However, with TES integration, excess heat produced by CHP during summer can be stored for later use in winter when CHP alone may not suffice, increasing resilience and reducing reliance on supplementary heating sources like boilers. Consequently, this leads to decreased natural gas consumption, enhanced energy efficiency, and overall larger savings. This effect is particularly pronounced in Minneapolis (c.z. 6A) and Chicago (c.z. 5A), where integrating TES enables the same CHP capacities to effectively double both electricity and heat production. In contrast, in climate zones with high winter heat demand but moderate summer demand, such as Duluth (c.z. 7), Helena (c.z. 6B), Vancouver (c.z. 5C), Denver (c.z. 5B), Seattle (c.z. 4C), Albuquerque (c.z. 4B), and Baltimore (c.z. 4A), the impact of TES is less pronounced. In these climate conditions, TES increases heat production from the same CHP capacity by only a third, indicating that surplus heat production is more effectively used in summer months. Conversely, in regions like San Francisco (c.z. 3C), where heat demand remains consistent year-round, TES has minimal impact on heat production.

Across all cold/moderate climate zones, the integration of TES along with CHP, and a SWH plant consistently results in the lowest overall emissions at every emission rate with a grid power generation. Despite the varying emission rates, these zones generally maintain a reduction in total energy costs. Notably, heat gener-

ated from the SWH plant is prioritized over that from the CHP due to its emissions-free nature. As the size of the SWH field and TES capacity gradually increases in the scenarios, the load generated by CHP and boiler decreases, leading to reduced local emissions but a higher reliance on imported electricity. For scenarios with low emission rates, overall emissions steadily decline as the SWH field and TES used to meet a larger portion of the heating demand, eventually fulfilling the entire demand in the final scenario. However, as the electricity demand must increasingly be met with imported electricity, medium and high emission rate scenarios experience an uptick in overall emissions. This trend indicates that scenarios where the entire heat demand is satisfied by a SWH plant and TES result in higher overall emissions at higher emission rates. Consequently, scenarios with the lowest overall emissions at every emission rate feature a combination of CHP, TES, and a SWH plant. The solar field supplements heat production sufficiently to eliminate the need for the boiler but does not render the CHP redundant, thereby minimizing reliance on imported electricity.

TES plays a crucial role in enhancing the resilience of solar energy systems by enabling the storage of excess heat generated from solar fields during periods of ample sunlight. This stored heat can then be used during periods of low or no sunlight, ensuring continuous heat supply even when solar energy production is limited. Essentially, TES acts as a buffer, allowing the surplus heat captured on sunny days to be efficiently stored and later deployed to meet heating demands when sunlight is not available. This capability enhances the reliability and resilience of solar energy systems, contributing to their overall effectiveness and viability as sustainable energy solutions.

Hot climate zones are characterized by low heat demand, even during the winter months, and significant cooling needs in the summer. Given that solar radiation peaks during the summer when heat demand is minimal, it is more beneficial to use solar energy for cooling purposes, typically through absorption chillers (ABS). In these regions, most simulated scenarios incorporating CHP, ABS, and TES demonstrate the lowest total energy costs. However, unlike in moderate climate zones, the implementation of TES in hot climates has a lesser impact on heat production from the CHP. Instead, it often results in a modest increase in heat production from the same capacity CHP, typically by about a tenth.

In hot climate zones like Las Vegas (c.z. 3B), Atlanta (c.z. 3A), and Phoenix (c.z. 2B), the simulation results consistently trend towards gradually expanding the SWH fields and increasing the capacity of absorption chillers. This approach serves to bolster cooling capabilities while reducing reliance on electric chillers and their associated electricity consumption. Notably, scenarios featuring CHP, ABS and TES lead to a significant reduction in overall emissions, particularly at higher emission rates. This reduction is attributed to decreased usage of electric chillers and boilers, with the CHP fulfilling a larger portion of the electricity demand. As SWH field sizes, TES and absorption chiller capacities are incrementally increased, emissions continue to diminish. This decline is facilitated by the use of solar heat in absorption chillers to meet cooling demands, enabling the CHP to meet electricity needs and resulting in the lowest overall emissions.

In Miami (c.z. 1A) and Guam (c.z. 0A), where heating demands are minimal but cooling demands are substantial year-round, the introduction of CHP and TES initially leads to an increase in emissions at low emission rates. This uptick is primarily due to heightened fuel consumption, resulting in emissions surpassing those of the baseline scenario, where only a boiler, an electric chiller, and imported electricity are used. However, at higher emission rates, the electricity generated by the CHP replaces imported electricity, resulting in lower emissions compared to the baseline. The most effective emission reduction strategies in these climates involve the integration of CHP, ABS, TES, and SWH fields. In these scenarios, overall emissions are minimized as electricity import is minimized, electric chillers are underused, and TES effectively stores surplus heat generated by the solar field.

The simulation results underscore the pivotal role of CHP and TES in optimizing energy systems across diverse climate zones. In moderate climates with pronounced seasonal variations, TES emerges as a game-changer, allowing surplus heat to be stored during periods of low demand and then used during peak demand seasons. This dynamic helps alleviate strain on heat-producing systems, leading to significant economic benefits by reducing the need for additional natural gas purchases and imported electricity.

Additionally, scenarios incorporating CHP, TES, and SWH plants consistently exhibit the lowest overall emissions across different emission rates. This strategic combination minimizes reliance on external electricity sources, leverages solar energy to meet heating and cooling needs, and enhances system resilience by

enabling the storage of excess energy for future use. By harnessing the synergy between CHP and TES alongside renewable energy sources like solar heating, these scenarios not only optimize energy use but also contribute to environmental sustainability by mitigating emissions. However, the drawback of implementing these technologies is often an increased total energy cost due to higher CAPEX and maintenance costs, which consequently leads to longer payback periods.

The analysis also investigates how variations in energy prices, and the availability of tax credits influence the economic viability of different scenarios, providing comprehensive insights into the interplay between financial incentives and energy economics across diverse climate zones.

In Chapter 6, Discussion, the analysis delves into several critical aspects of energy system viability and resilience. It underscores the importance of assessing the payback savings generated by alternative energy systems, emphasizing that large equipment investments must yield subsequent savings or income to be feasible over the equipment's lifetime. The study's focus on savings-driven economics, omitting energy export considerations, highlights the significance of energy prices in shaping investment incentives. Particularly, lower energy prices diminish the economic appeal of alternative energy sources, impacting the feasibility of TES implementation. Additionally, the chapter sheds light on the surprising disparity between greenhouse gas emissions associated with imported electricity and those locally produced by CHP. Despite the perceived intricacies of modern power plants, CHP systems typically emit fewer greenhouse gases per unit of energy compared to electricity imported through the grid.

A key aspect explored in the discussion is the role of TES in enhancing system resilience by decoupling energy generation and consumption. TES systems facilitate flexible energy supply by storing excess thermal energy during off-peak periods or when renewable generation exceeds demand, ensuring continuous energy availability during fluctuating demand or renewable source intermittency. Furthermore, the discussion addresses the technical nuances of TES systems, including optimal temperature settings and efficiency considerations. Comparisons with Danish PTES systems highlight the potential for higher overall efficiency and reduced total energy costs by adopting alternative temperature settings. In hot climate zones like Guam, the inefficiency of using solar fields for cooling prompts exploration of alternative solutions, such as leveraging photovoltaics to assist CHP systems in supplying electricity to electric chillers. This approach offers a less complex and potentially more cost-effective means of meeting cooling demand. Moreover, the section explores the potential of BTES in scenarios requiring extensive TES. BTES is noted for its space efficiency, making it a viable solution where space constraints exist. The discussion underscores the advantages of BTES in energy efficiency for seasonal heating and cooling, its extended operational life of 100 years, and minimal maintenance requirements, which enhance overall system economy compared to PTES. However, successful BTES implementation is contingent upon favorable geological conditions, necessitating meticulous planning to overcome terrain and drilling supply challenges. Effective management of drill-related factors, such as noise mitigation and rigorous quality control, is deemed essential for successful vertical borehole construction.

Chapter 7, Conclusion, outlines the methodological process which generated the results, together with the key findings from every simulated climate zone. Key findings from each simulated climate zone are distilled into actionable recommendations, delineating optimal technology combinations and capacities that either drive favorable economics or achieve significant emission reductions. Furthermore, the technology recommendations regarding TES, given the simulated capacities, are summarized together with geological and hydrological considerations in relation to potential BTES use.

A pivotal component at the end of the conclusion is the presentation of a summarizing table that encapsulates technology combinations used in the analysis that either excel in economic performance or emission reduction outcomes. This visual aid summarizes the findings in more easily digestible insights that help stakeholders to make better informed decisions involved in energy system planning and implementation.

Abbreviations

ABS	absorption chiller
ATES	aquifer thermal energy storage
BCT	Brigade Combat Team
BTES	borehole thermal energy storage
CAPEX	capital expenses
CHP	combined heat and power
COP	coefficient of performance
CZ	climate zone
DoE	Department of Energy
GHG	greenhouse gas
GWHP	ground water heat pump
HTF	heat transfer fluid
HVAC	heating, ventilation, and air-conditioning
OPEX	operational expenses
PTES	pit thermal energy storage
SWH	solar water heating
TES	thermal energy storage
TSP	thermal solar plant
TTES	tank thermal energy storage

1 Introduction

1.1 BACKGROUND

This book presents the analysis of the possibilities of transitioning traditional energy supply systems to more environmentally friendly alternatives, with a particular emphasis on exploring thermal energy storage (TES) as a resource conservation and resilience measure. The study aims to investigate various energy system architectures capable of meeting facilities' energy demands, leveraging TES implementation across 18 U.S. Department of Energy (DoE) climate zones.

For the fair comparison of TES, the book establishes a baseline for simulations, assumptions, boundary conditions, technical and economic characteristics of components, and other parameters used in the analysis. Subsequently, it identifies variations within each climate zone and conducts simulations of each scenario accordingly. The outcomes inform recommendations for alternative energy solutions and technologies, including tailored equipment combinations for each climate zone.

Conclusions drawn from the simulations allow formulating recommendations for TES and technical scenarios of its application in the studied climate zones. The study endeavors to explore the conditions under which TES contributes to viable, beneficial, and sustainable energy solutions. By examining various factors influencing TES environmental and cost-effectiveness, the goal is to uncover practical applications and identify optimal implementation scenarios crucial for maximizing energy efficiency and advancing sustainable energy systems.

Analysis of key technological aspects such as system integration, scalability, cost effectiveness, and environmental impact provides valuable insights for decision-making and evaluating TES technologies across different applications. Ultimately, the findings contribute to a better understanding of TES and its role in optimizing energy management for sustainability goals, without endorsing a specific "best" TES technology.

1.2 SUPPORTING DATA

Note that Appendices A and B are included in a full version of this document, available at:
https://safe.menlosecurity.com/doc/docview/viewer.