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Geological Thermal Energy Storage (GeoTES) Charged with Solar Thermal Technology Using Depleted Oil/Gas Reservoirs and Carnot-Battery Technique Using Shallow Reservoirs

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ABSTRACT

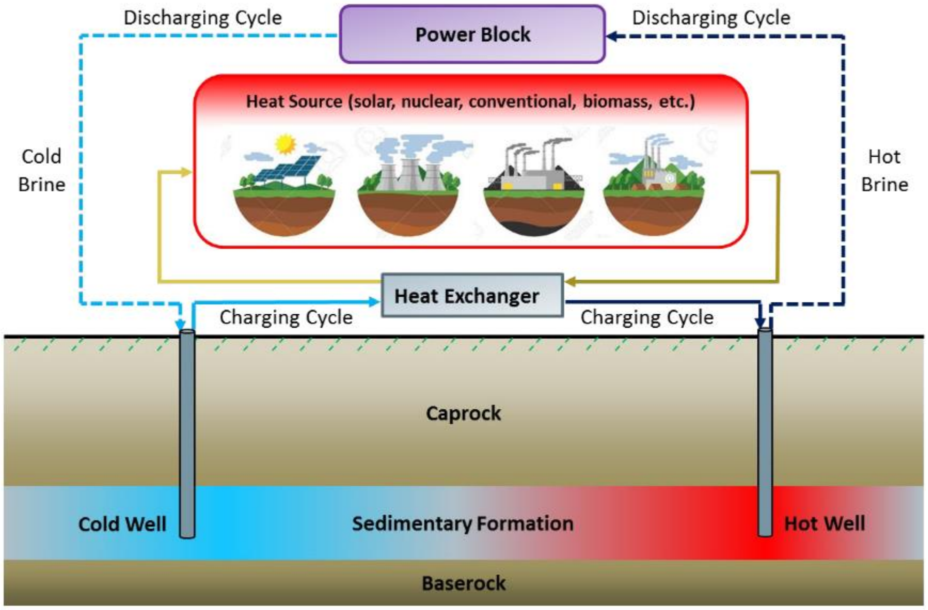
Geological thermal energy storage (GeoTES) utilizes underground reservoirs to store and dispatch energy per a given demand schedule that can span entire seasons. The energy input can be of various sources/forms; in this paper, we investigate 1) GeoTES technology with solar thermal hybridization and using depleted oil/gas reservoirs, and 2) GeoTES technology with heat pumps charged by excess renewable electricity and using low-temperature shallow reservoirs. For each GeoTES technology, we carry out a suitability analysis of candidate reservoirs, develop initial techno-economic models, and validate the model with a selected case study. The paper provides an overview of our technical progress on the topics of concern and aims to promote a wider acceptance of GeoTES technologies in the future energy market.

1. INTRODUCTION

A future zero-carbon energy infrastructure will require not only various renewable energy technologies such as solar, wind, and geothermal for generation, but also their integration with energy storage at various time scales—hourly, weekly, and seasonally (Denholm et al., 2021). It is extremely challenging to develop affordable storage technologies to meet seasonal-scale energy dispatching for the grid (Sharan et al., 2021).

Here, we propose geological thermal energy storage (GeoTES) for seasonal energy dispatching. As illustrated in **Figure 1**, GeoTES can take various energy sources such as solar thermal and excess grid renewable electricity, store the energy with water reservoirs and depleted oil/gas reservoirs, and output electricity, heating, and cooling per energy demands.

In this paper, we will present our preliminary results in analyzing the economic potential of GeoTES with solar thermal and excess renewable electricity.



Energy In	(Thermal) Energy Storage	Energy Out
• Solar thermal • Excess grid renewable electricity • Waste heat from fossil fuel and energy end users • Excess nuclear heat	• Low-temperature water reservoirs • Depleted oil/gas reservoirs	• Electricity • Heating or cooling

Figure 1: Illustration of GeoTES technologies and processes.

2. GEOTES WITH CST HYBRIDIZATION

In this section, we will present our findings on GeoTES with concentrating solar-thermal power (CST) hybridization.

2.1 Suitability of Oil/Gas Reservoirs for Hot Geothermal Energy Storage

Oil and gas fields in central California and east Texas are analyzed as potential candidate formations for high-temperature geothermal energy storage. Reservoir data such as porosity, permeability, thermal conductivity, temperature, pressure, mineralogy, depth and thickness of the formation, brine salinity, and productive area are collected from the California Geologic Energy Management Division (CalGEM) database, California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (1998), Railroad Commission of Texas, and the Texas Bureau of Economic Geology (**Figure 2**). The data for 568 oil and gas fields in central California (Zone I), and 198 abandoned reservoirs in Railroad Commission of Texas Districts 1 through 6 have been characterized for hot geothermal storage. These zones/districts were selected based on their high levels of historical oil and gas activities compared to others within the states. To shortlist the formations for hot geothermal storage, we determined a cut-off value for reservoir properties (**Table 1**) (Glassley et al., 2013). Pressure and temperature data are plotted in **Figure 3**. Porosity and permeability data are plotted in **Figure 4**, and **Figure 5** shows salinity and thickness of the formation. Based on the criteria listed in **Table 1**, oil and gas formations in central California and east Texas have been screened, prioritized, and shortlisted. A detailed thermal-hydraulic-mechanical-chemical (THMC) modeling approach is recommended for the shortlisted formations on a case-by-case basis. This is an integral input to the final investment decision on its application for hot geothermal storage. A roadmap for evaluating and selecting a candidate formation is outlined in **Figure 6**.

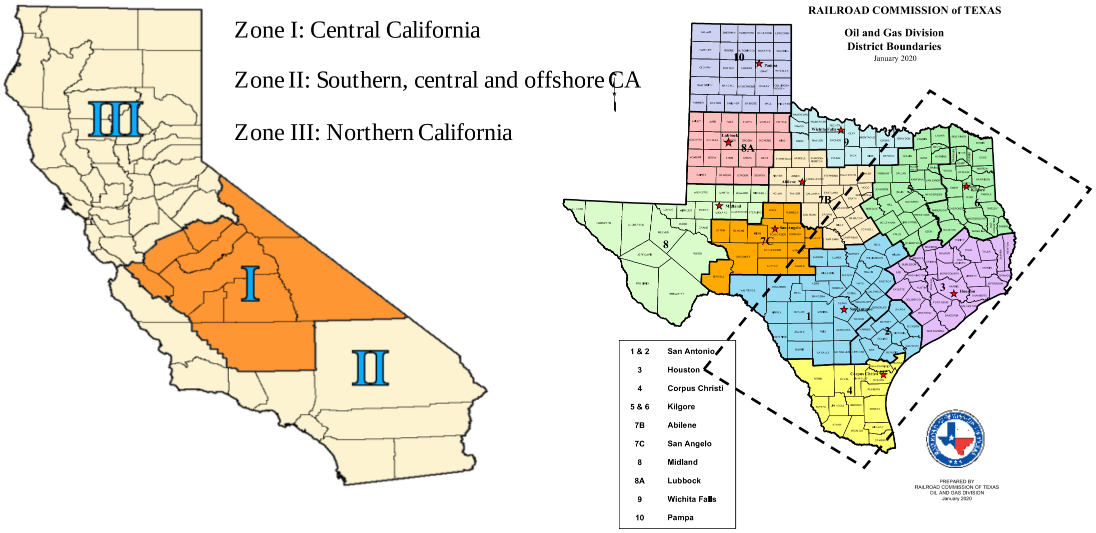


Figure 2: California oil and gas fields (left) and Texas oil and gas districts (right). Source: California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (1998); Railroad Commission of Texas (2020).

Table 1: Criteria for shortlisting oil and gas reservoirs in California and Texas for hot geothermal energy storage

Reservoir properties	**Cut-off value**
Temperature	>50℃
Pressure	Bars; depth dependent (regressed from the compiled data)
Average thickness of the formation	>150 feet (ft)
Average depth	>1,500 ft
Porosity	>10%
Permeability	>100 millidarcy (md)
Salinity	<30,000 parts per million (ppm)
Productive area	>100 acres

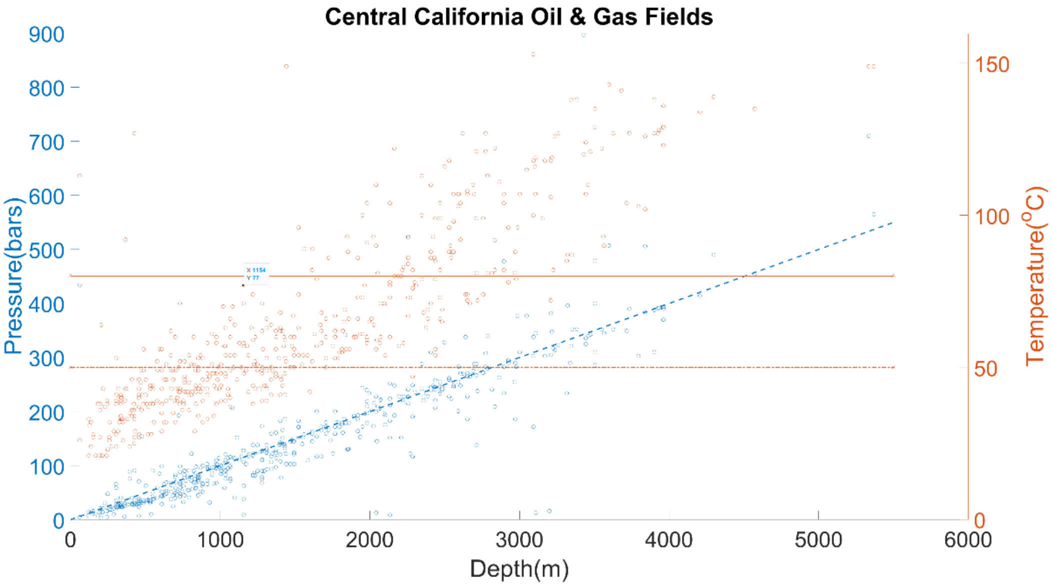


Figure 3: Pressure vs. depth for all reservoirs in central California. Hydrostatic pressure vs. depth is plotted as a solid line. Temperature vs. depth is plotted in an orange color, and solid lines represent temperature at 50°C and 80°C.

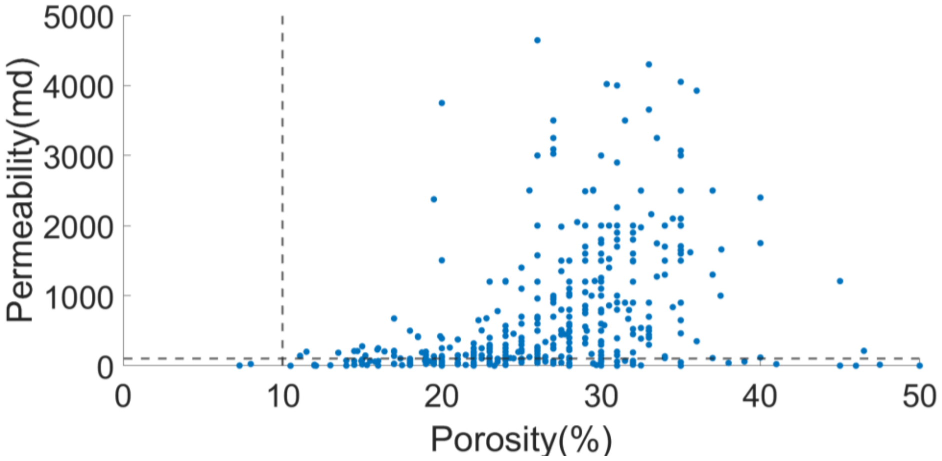


Figure 4: Permeability and porosity for all oil pools in central California. Dashed line at x=10 represents porosity cut-off, and y=100 represents permeability cut-off at 100 millidarcy.

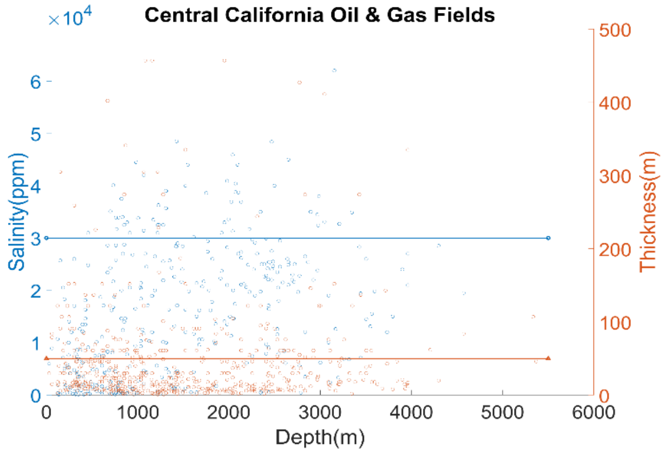


Figure 5: Salinity (ppm) and average thickness (m) for all oil pools in central California. Blue solid line represents 30,000 ppm salinity and orange solid line represents 50 m thickness.

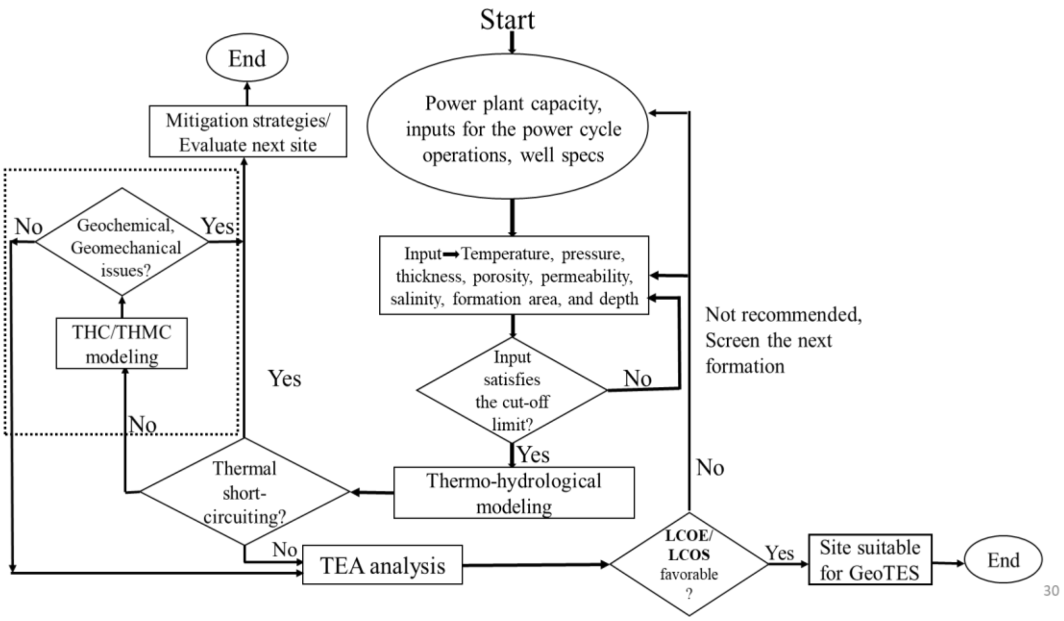


Figure 6: A flow chart for site characterization approach for GeoTES applications.

2.2 System Techno-Economic Model

GeoTES systems comprise several distinct subsystems (such as the subsurface, wells, power cycle, and solar field) that each require detailed modelling in order to capture their distinct characteristics. A techno-economic model has been developed that uses specialist tools for each sub-system, as described in McTigue et al. (2023). For instance, concentrating solar thermal is modeled using the System Advisor Model (SAM) ("System Advisor Model (SAM)" 2022), while power cycles are modeled using the flow-sheeting tool IPSEpro ("IPSEpro: Process Simulation and Heat Balance Software," n.d.), which allows the off-design behavior to be obtained. Methods are extracted from the Geothermal Electricity Technology Evaluation Model (GETEM) to calculate parameters relating to the subsurface equipment, such as drilling and exploration costs, production and injection pump costs and power requirements, and operations and maintenance costs. The outputs of the individual models are combined in MATLAB, and the performance and cost of the full system are subsequently calculated. (Uncertainty and sensitivity can also be evaluated in the integrated MATLAB model). For CST-GeoTES, the electrical power output and relative solar field size are first defined. MATLAB calls SAM and calculates the solar field size to deliver the required thermal input given the individual properties of the location and solar collector design. The thermal energy is then calculated for each hour of the year based on the solar collector optical properties and the solar resource at the chosen location. A simple dispatch model is then used to determine whether thermal energy drives the heat engine or is injected or produced from the GeoTES. Once the thermal input to the power cycle is known, then the electrical output is calculated by interpolating the off-design performance map generated from IPSEpro. The energy flows are calculated over the course of a year, and subsequently the annual energy production is evaluated, and economic metrics such as the levelized cost of electricity (LCOE) are calculated.

As an example of the capabilities of the techno-economic model, consider a contrived scenario that illustrates the unique characteristics of GeoTES—namely, the ability to store large quantities of energy and deliver energy over both daily and seasonal scales. This example is based on the energy generation characteristics in California—namely, the observation of the daily and seasonal variations in energy produced by solar photovoltaics, wind, and hydro-electric. Figure 7 indicates that these electricity sources exhibit considerable seasonal variability, with the average energy generation in summer months roughly 75% greater than that in winter months. Furthermore, the so-called "duck curve" phenomenon is a well-known feature of the Californian electricity system that describes daily energy supply and demand; in particular, late afternoons in the spring and summer are characterized by the requirement for power generation to ramp rapidly while there is decreasing solar generation as the sun sets. A CST-GeoTES system is conceived with the aim of delivering energy continuously in the winter months, and also for several hours in summer evenings, therefore stabilizing the grid against daily and seasonal variations in energy supply.

In this example, the power cycle delivers 100 $\mathrm{MW_e}$ at an efficiency of 20% as solar heat is generated at a temperature of 200°C. The solar field is oversized, so that at peak solar irradiance the solar field generates three times as much heat as is required by the power cycles—i.e., 1500 $\mathrm{MW_{th}}$. Therefore, during summer months, considerable excess quantities of solar thermal energy are injected into the GeoTES. During the winter months, energy is drawn almost continuously from the GeoTES in order to generate power constantly, as shown in Figure 8. This example shows the maximum energy capacity of the GeoTES reaches over 1,272 $\mathrm{GWh_{th}}$ which is sufficient to drive the 100 $\mathrm{MW_e}$ power cycle for 2,580 hours, thus demonstrating the vast storage capacities achievable by GeoTES. Simple calculations indicate this capacity of storage could be provided by a cubic region of the subsurface with a side-length of 280 m. Power flows between the different subsystems that are illustrated in Figure 9, which clearly shows that heat is delivered to the power cycle all day and all night during winter months, as the GeoTES discharges. Conversely, large flows of heat that occur during the summer months are used to charge the GeoTES. Heat is only sent to the power cycle for a few hours in summer evenings, requiring only small quantities of energy to be discharged allowing the GeoTES to manage the daily demand while also charging during summer months.

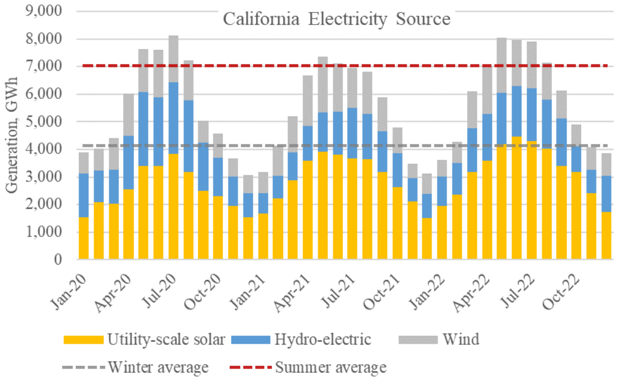


Figure 7: Electricity generation from variable renewable sources in California over several years. Data from https://www.eia.gov/opendata

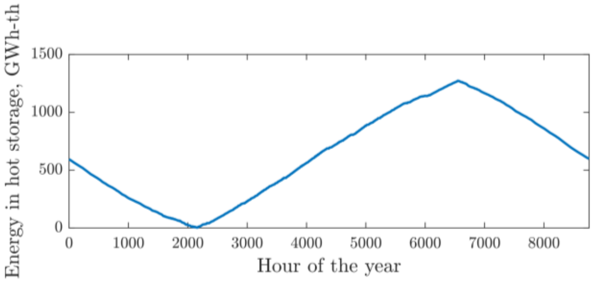


Figure 8: Energy capacity of the GeoTES during one year of operation. The GeoTES is depleted in winter months and recharged in summer months.

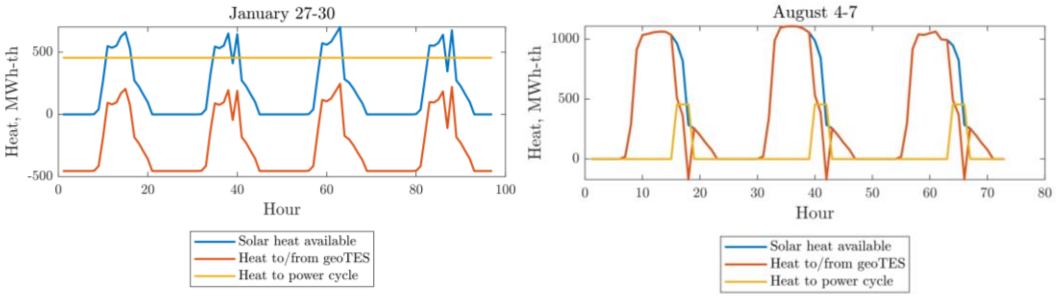


Figure 9: Energy flows between the concentrating solar thermal system, the GeoTES, and a low-temperature power cycle for several days in January and August. Heat is delivered continuously in winter months, whereas power is only generated in the late afternoon in summer months.

Some techno-economic results are shown for several reservoir depths in Table 2. These results indicate that the GeoTES provides daily and seasonal storage at very low cost—typically less than 0.5 $/kWh$_{th}$. This is due to the large energy capacity and the low cost of this capacity: the GeoTES capital cost depends predominantly on drilling costs and pump costs, which are functions of the power capacity. Therefore, increasing the storage duration of the GeoTES acts to reduce the capital cost per unit storage duration, as the containment effectively has no cost. Pumping fluid into and out of the reservoir can contribute significantly to the energy balance and operational costs. In this example, the electricity to drive pumps during charge is bought from the grid, since generally the power cycle is not operating. During discharge, the net power output of the system is reduced as some of the power generated is used to power the pumps. These factors act to increase the operational costs and reduce the storage efficiency and is particularly significant for deeper reservoirs. Therefore, it is important to find suitable geological formations that are close the surface to increase the feasibility of GeoTES.

Table 2: Annual energy and installed cost results for a CST-GeoTES system that provides daily and seasonal energy storage. Three different well depths are considered.

Depth	m	500	1000	1500
Solar thermal energy generated	GWh$_{th}$	2318	2318	2318
Heat delivered to GeoTES	GWh$_{th}$	1539	1539	1539
Max. GeoTES capacity	GWh$_{th}$	1272	1272	1272
Energy delivered to the grid*	GWh$_{e}$	487	483	479
Energy consumed by pumps in charge	GWh$_{e}$	10	10	172
Energy consumed by pumps in discharge	GWh$_{e}$	33	36	40
System capital cost	$/kW$_{e}$	8210	8456	8980
GeoTES capital cost	$/kWh$_{th}$	0.13	0.15	0.19
LCOE	$/kWh$_{e}$	0.154	0.160	0.187
LCOE (inc. 30% Investment Tax Credit)	$/kWh$_{e}$	0.108	0.112	0.131
* This is the energy produced by the power cycle minus the energy consumed by production and injection pumps during discharge. Charging pump power is assumed to be bought from the grid.				

3. GEOTES WITH CARNOT-BATTERY TECHNIQUE HYBRIDIZATION

In this section, we present our findings on GeoTES with Carnot-battery technique hybridization. A Carnot Battery is an electricity storage device. Electricity is converted into thermal energy during charge using a heat pump or electric heater, and the thermal energy is stored. Later, the thermal energy is recovered and converted to electricity using a thermal power cycle.

3.1 Suitability of Shallow Reservoirs

Vast subsurface reservoirs are key to the success of a GeoTES project. This requires favorable subsurface characteristics such as porosity, permeability, geochemistry, formation thickness, temperature, etc. Depth also plays a substantial role in the economics of the project as in most cases increasing depth brings higher drilling costs. For this reason, we evaluated shallow reservoirs (<1,500 ft) and aquifers for their feasibility of storing waste heat for seasonal or on-demand use in the Texas and California regions.

State and national datasets were analyzed to understand the various reservoirs and aquifers that could potentially be used for GeoTES. In Texas, 15 brackish aquifers (Meyer, 2020) were identified as potential GeoTES reservoirs because they 1) are shallow compared to deep depleted oil fields, 2) contain low-quality fluids (brackish) that will not be used for potable water sources, and 3) cover large areas within the state. Similarly, 53 shallow reservoirs in the central California region (CA Division of Oil, Gas, and Geothermal Resources, 1998) were evaluated to understand which reservoirs have the highest potential for GeoTES operations.

By using formation depth, estimated drilling costs, and storage capacity assumptions, aquifer properties such as permeability, porosity, mass, density, thermal conductivity, and specific heat capacity were translated into preliminary techno-economic parameters to down-select the top-performing shallow reservoirs. Specifically, these aquifer properties were translated into two parameters: cost per storage capacity (i.e., the ratio of total capital cost over total capacity) and steady-state self-discharge rate. Because drilling cost is the largest cost driver, we modeled the total capital cost as a function of aquifer depth (Daniilidis et al., 2022). The total capacity was determined based on aquifer thickness and bulk specific heat. The self-discharge rate of an aquifer was defined as the ratio of its annual heat loss over its storage capacity. We estimated the self-discharge rates of all aquifers by considering heat loss by thermal conduction, following similar models as in Pepin et al. (2021) and Burns et al. (2020). We then pinpoint all aquifers on a two-dimensional plane to evaluate their overall performance (Figure 10). In this preliminary evaluation, the Carrizo-Wilcox, Yegua-Jackson, and Dockum brackish aquifers were identified as having the highest potential for further investigation in Texas. Similarly, the White Wolf, Belridge South Tulare, and Belridge South Reef Ridge exhibit the highest potential for further study in the central California region. Future work will focus on these reservoirs and aquifers to perform higher level techno-economic analysis for understanding how economically feasible these could be under a variety of operational scenarios.

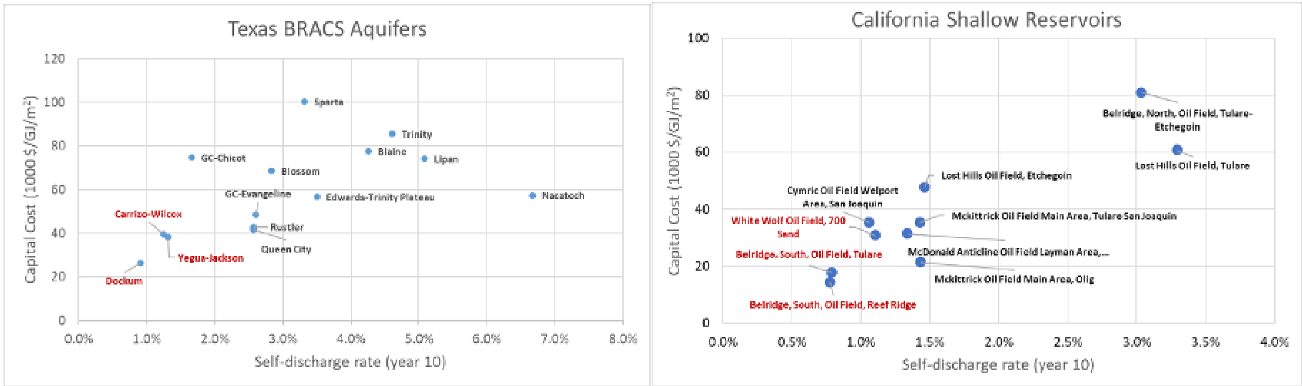


Figure 10: Preliminary evaluation of BRACS (Brackish Resources Aquifer Characterization System) aquifers in Texas (left) and California (right) in terms of their cost per capacity and steady-state self-discharge rate. Note that we use the self-discharge rates at year 10 as an approximation of steady-state self-discharge rates by assuming the aquifers are in thermal equilibrium with ambient temperatures.

3.2 System Techno-Economic Model

The techno-economic model for analyzing Carnot Battery (CB)-GeoTES was developed following the same approach as that described in Section 2.2 System Techno-Economic Model—namely, using specialist software to model each subcomponent, and then integrating the data inputs, outputs, energy flows, and economics using MATLAB. In addition, electricity pricing data was obtained for two years for specific locations in California and Texas. The electricity price is used to determine when the CB-GeoTES should charge and discharge. The simplest approach is to simply observe the median electricity price, and charge the system when prices are lower and discharge the system when prices are higher. This results in a storage device that operates continuously—either charging or discharging. Interestingly, in many cases, this leads to a system that provides *seasonal* electricity storage. For example, in California, electricity prices are typically lower during the summer, which provides more opportunities to charge the GeoTES, whereas it is predominantly discharged in the winter. Figure 11 shows the energy stored in the hot GeoTES of a CB-GeoTES system with 100 MW_e discharging capacity installed in California which demonstrates the large, seasonal energy storage behavior of the system. It should be noted that opportunities for earning revenue from arbitrage are limited in this case, and arbitrage revenue can be increased by restricting the charge and discharge to periods of lowest and highest prices. However, arbitrage is generally considered to provide a limited market for electricity storage, and storage instead provides grid value by other mechanisms, such as deferring grid expansion, reducing curtailment of renewable energy, and displacing fossil-fueled generation. Therefore, the discussion here concentrates on the levelized cost of storage. Electricity prices still play an important role as electricity is bought from the grid for storage and this contributes to the yearly operational cost.

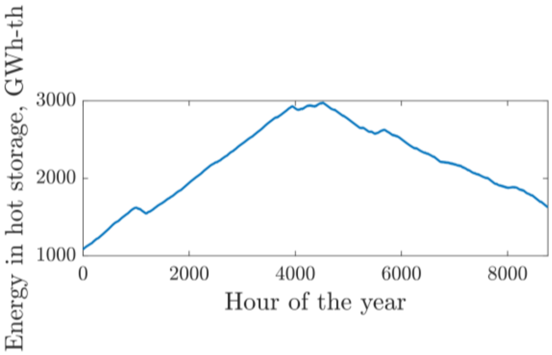


Figure 11: Energy capacity of the hot reservoir in a CB-GeoTES operating in California in 2021 and using electricity price signals to determine the dispatch.

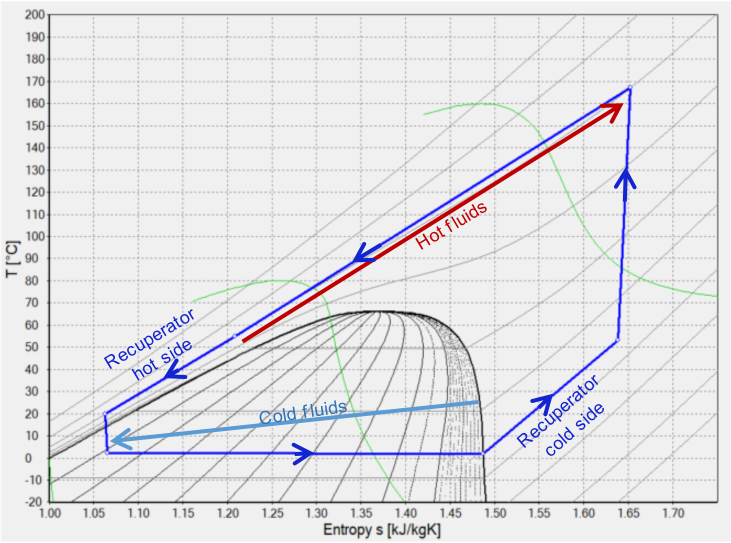


Figure 12: Temperature-entropy diagram of a recuperated heat pump using R125 working fluid. The heat pump heats one set of production fluids up to 162°C and another set of fluids are cooled to 5°C. The hot and cold fluid streams are then reinjected to separate regions of the GeoTES to create hot and cold storage.

While a large number of Carnot Battery concepts have been proposed (Olympios et al., 2021) and have started development (Novotny et al., 2022), new concepts have to be developed to manage the unique challenges of integrating with GeoTES. Two concepts are discussed in this paper. First, a recuperated transcritical heat pump cycle using R125 working fluid is proposed, and a temperature-entropy diagram is given in Figure 12. This heat pump creates both hot thermal storage and cold thermal storage. Cool fluids are drawn from a reservoir at 25°C and used as the heat source for the heat pump and are thus cooled as energy is extracted from them. The cold fluids are then reinjected to the reservoir at 5°C. Simultaneously, warm fluids are drawn from a reservoir at 50°C and used as the heat pump heat sink, thereby being heated to 162°C before being reinjected. A selection of techno-economic results is shown in

Table 3 for two locations with different electricity characteristics. It is notable that this system requires a relatively large number of cold wells compared to hot wells, and this is predominantly because the cold fluid goes through a small temperature change compared to the hot fluid. As a result, the addition of cold storage is likely to add significantly to project costs, complexity, and operations.

The second Carnot Battery concept therefore does not use cold storage. Instead, the environment is used as the heat source for the heat pump and the heat sink for the heat engine. This means the performance of the Carnot Battery is more susceptible to variations in ambient temperature, as the system uses an air-cooled condenser. A recuperated, transcritical R125 cycle is again used (as in Figure 12), although the heat pump evaporator is at a slightly higher temperature. The conventional wisdom for Carnot Battery design is that the round-trip efficiency can be increased by maximizing the temperature difference between the hot and cold storage. However, the results in

Table 3 show that the system with cold storage only has a small improvement in round-trip efficiency compared to the system without. This is essentially because the heat pump with no cold storage has an improved coefficient of performance (due to operating over a smaller temperature range) while the heat engine has a slightly worse heat engine efficiency. The performance of these two subsystems trade-off against one another such that the addition of cold storage (in this example) only provides small benefits. (Note, the temperature of the cold storage is limited due to the freezing point of water. Cold storage is essential in the design of other Carnot Battery variants).

The two cycles achieve a thermodynamic cycle round-trip efficiency of around 43%, which is typical of Carnot Batteries of this design (Mercangöz et al. 2012). However, the parasitic work in driving the production and injection pump—and also the air-cooled condenser fans are significant and reduce the round-trip efficiency to 33.7% for the cycle with cold storage and 30.4% for the cycle without cold storage.

As shown in economic results presented in

Table 3, the GeoTES capital cost per unit energy stored is again very low—for both hot and cold storage—due to the very large quantities of energy that are stored. (Large quantities of energy are stored predominantly during the summer when electricity prices tend to be higher). The capital cost of the CB-GeoTES with cold storage is about 70% higher than the system with no cold storage, and consequently has a higher LCOS—despite the CB-GeoTES with no cold storage having higher electricity costs due to parasitic loads and inefficiencies. Locating the CB-GeoTES in different regions leads to different patterns of charge and discharge, and as a result, the systems have slightly different characteristics and costs. In this example, the average price of charging was higher in California in 2021 than in Texas in 2021, and this is reflected in the LCOS. Further work is required to integrate different reservoir characteristics into the techno-economic model to compare the different storage performance in different regions in more detail.

Table 3: Techno-economic results for two CB-GeoTES concepts planned in California and Texas

		With cold storage		No cold storage	
Charge power input	MW$_e$	250		250	
Discharge power output	MW$_e$	100		100	
Hot reservoir	°C	162 → 50		153 → 50	
Cold reservoir	°C	5→25		-	
Depth	m	500		500	
Round-trip efficiency	%	43.4		42.8	
# Hot wells		55		70	
# Cold wells		190		0	
Heat pump energy in	GWh$_e$	1095		1095	
Charge pumps energy in	GWh$_e$	58		72*	
Heat engine energy out	GWh$_e$	438		438	
Discharge pumps energy in	GWh$_e$	50		84*	
Real round-trip efficiency	%	33.7		30.4	
Location		California	Texas	California	Texas
System capital cost	$\$/\text{kW}_e$	8,180	8,180	4,860	4,860
Hot GeoTES capital cost	$\$/\text{kWh}_{th}$	0.04	0.04	0.06	0.09
Cold GeoTES capital cost	$\$/\text{kWh}_{th}$	0.19	0.23	0	0
LCOS	$\$/\text{kWh}_e$	0.29	0.26	0.22	0.18
* These numbers include the parasitic fan consumption for air-cooled condensers.					

4. CASE STUDIES

We are working with industrial partners on two business case studies.

4.1 GeoTES System by PRM

PRM's project, located in the Antelope Hills on the west side of the San Joaquin Valley, will be configured to collect solar heat and store and retrieve that heat into and from a water-filled reservoir—naturally occurring, porous and permeable sandstone, possessing closure to ensure circulating fluids remain within the reservoir. This will be a zero-emissions power project that proves depleted oil reservoirs can be converted to GeoTES.

The GeoTES process will be configured into three interacting flow loops:

Reservoir Circulation: Multiple producing and injecting wells based on the size of the project (Table 4). The well pattern is designed for improved reservoir contact and increased lifting capacity where reduced, flow-related pressure drop in the reservoir is desired.

Solar Heat Collection: Solar heat will be collected using helio-dynamic, parabolic trough-style solar concentrators. Heat will be absorbed into a circulating working fluid, heated to roughly 370°C (700°F). As heat is collected, this loop will command the Reservoir Circulation loop to provide sufficient fluids to absorb the collected solar heat.

Power Generation: The Reservoir Circulation loop will provide heated fluids sufficient to boil and superheat a power-producing working fluid (demineralized water is planned as the working fluid), which will be circulated through a power turbine. When power is demanded by the power grid or industrial customer(s), this loop will command the Reservoir Circulation loop to deliver sufficient heat for power production purposes.

The majority of this planned demonstration will take place on a pad location, which already conforms to California Environmental Quality Act requirements through the Kern Planning and Natural Resources Department.

Table 4: Project Development in the San Joaquin Valley

Phase	Surface Footprint	Producer Wells	Injector Wells	Monitoring Wells
One-Pattern Demonstration	3-5 Acres	2	6	1
Seven-Pattern Commercial Project	50-60 Acres	24	7	3

4.2 GeoTES System by EarthBridge

In collaboration with EarthBridge Energy, a geothermal energy storage company, we are examining a specific site for GeoTES potential north of Houston, Texas. Here, EarthBridge and their partners are planning a MW-scale, commercial demonstration of their GeoTES technology referred to as the GeoBattery^{TM}. The site is well-characterized due to the >60 test wells drilled to-date. Target storage reservoirs of the Yegua Formation and Jackson Group at the site exist at moderate depths of 2,000–3,000 ft. (~600–1000 m) and temperatures ~50–60°C. These widespread quartz-rich sandstone reservoirs were deposited in a fluvio-deltaic environment of the Texas Gulf Coast during the Middle to Upper Eocene. Individual reservoir flow units range in thickness from 250–350 ft (75–110 m) and exhibit high porosity and permeability (>30% and >1000 mD, respectively). In situ fluids have high dissolved solids content and are unsuitable for drinking water or agricultural use in the local area. Also importantly, no hydrocarbons have been discovered in any previous well drilled at the site to at least 11,000 ft depth (3,350 m).

The planned GeoTES system will provide energy storage to the site using a combination of on-site solar and grid electricity to charge the system. Existing site infrastructure will accelerate grid-interconnection and project timelines to meet the renewable energy demands of the facility. EarthBridge will leverage operational and performance learnings from this smaller-scale demonstration to optimize their larger-scale GeoBattery systems planned for deployments in west and central Texas. Researchers at national labs are working closely with EarthBridge to evaluate site data, develop various models, and evaluate different operational scenarios to understand the techno-economic feasibility for GeoTES in this part of Texas.

5. CHALLENGES

Prior high-temperature aquifer thermal energy storage (HT-ATES) projects (e.g., Fleuchaus et al., 2020; McLing et al., 2022; Dobson et al., 2023) provide useful examples of a number of challenges associated with these systems. It is critical to have detailed characterization of the GeoTES reservoir to accurately predict important attributes such as the storage volume, fluid transmissivity within the reservoir, the thermal conductivity of the reservoir rocks, the nature of the lateral and upper and lower boundaries of the reservoir (fluid and thermal trapping), and the heterogeneity of the reservoir rocks. It is also important to know if hydrocarbons (both oil and gas phase) are present—these could be seen as a benefit (providing additional revenue via enhanced oil recovery of these resources during the early stages of the GeoTES project) or seen as a complicating factor.

Geochemical issues represent another important aspect of the GeoTES system to consider. One key challenge is mineral scaling, which can occur in wells, surface heat exchangers, and within the reservoir. Many subsurface reservoir fluids consist of brines that are saturated with respect to carbonate and/or sulfate mineral phases. Because these minerals have retrograde solubility, they will become supersaturated with heating of the brine. It is important to evaluate the potential for scaling using geochemical modeling, as it depends on the fluid composition, the initial reservoir temperature, and the mineralogy of the reservoir (e.g., Spycher et al., 2021; Dijkstra et al., 2020). Another geochemical issue of note is corrosion, which can result from introducing oxygenated fluids into a reducing reservoir environment, causing changes in the subsurface microbial community and increasing the potential for corrosion of pumps and casing (e.g., Würdemann et al.

2014). In attempting to mitigate the impacts of these geochemical processes, it is important to ensure that the mitigation measures do not result in other problems. This was the case for the Utrecht HT-ATES system, where an ion exchange system was used to treat the formation fluid to reduce the potential for scaling, but resulted in clay swelling that greatly reduced transmissivity in the reservoir (e.g., Willemsen 1992; Drijver 2011).

Another important challenge is to make sure that the GeoTES systems are designed in a robust manner, so that they can adapt to changes over time. In some cases, thermal breakthrough between the hot and cold wells have been observed for some systems (e.g., Schmidt and Müller-Steinhagen 2004; Bloemendal et al. 2019), so it may be necessary to modify the well scheme to ensure that storage performance is not negatively affected. For many of the early HT-ATES systems, they used a doublet system, so if a downhole pump failed, operation of the entire system was suspended until a repair could be conducted (e.g.,Kabus et al. 2009). Finally, the availability of hot fluids needed to recharge the GeoTES system may vary due to market conditions, potentially impacting the ability to provide thermal energy when needed.

6. CONCLUSIONS AND FUTURE WORK

This paper presented two GeoTES concepts – one (CST-GeoTES) using solar thermal energy stored in oil and gas reservoirs to power a binary Rankine power cycle, and the other (CB-GeoTES) using excess grid electricity to charge a Carnot Battery system coupled to a shallow (<500 m) aquifer. The analysis used existing tools and data to do a high-level analysis of energy flows, annual generation potential, and system costs. The analysis assumed idealized reservoir behavior. The estimated LCOS for the CST-GeoTES ranged from 0.11-0.13 cents/kWh and for CB-GeoTES from 0.18-0.29 cents/kWh, although it should be noted that these preliminary estimates depend greatly on the assumptions.

Compared to alternatives such as concentrating solar power towers with TES or battery energy storage systems, the GeoTES concepts are more expensive. However, the GeoTES concepts are capable of providing storage on a seasonal basis, which conventional storage technologies cannot do. The value of this GeoTES attribute to the grid needs further assessment.

In the future, our efforts will be focused on validating the techno-economic analysis model on two types of GeoTES technologies and assessing the economic potential of two case studies with real-world data from the industrial partners.

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REFERENCES

Bloemendal, M., Beernink, S., Hartog, N., and van Meurs, B.: Transforming ATES to HT-ATES, Insights from Dutch Pilot Project. European Geothermal Congress 2019, Den Haag, The Netherlands (2019).

Burns, E.R., Bershaw, J., Williams, C.F., Wells, R., Uddenberg, M., Scanlon, D., Cladouhos, T., and van Houten, B.: Using saline or brackish aquifers as reservoirs for thermal energy storage, with example calculations for direct-use heating in the Portland Basin, Oregon, USA, Geothermics, 88, (2020), 101877.

California Department of Conservation, Division of Oil, Gas, and Geothermal Resources: California Oil & Gas Fields Volume 1 - Central California, 4th Edition, California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, Sacramento, California, (1998).

Daniilidis, A., Mindel, J.E., De Oliveira Filho, F., and Guglielmetti, L.: Techno-economic assessment and operational CO_2 emissions of high-temperature aquifer thermal energy storage (HT-ATES) using demand-driven and subsurface-constrained dimensioning. Energy, 249, (2022), 123682.

Denholm, P., Wesley C., Frazier, W., Podkaminer, K., and Blair, N.: The Challenge of Defining Long-Duration Energy Storage. NREL/TP-6A40-80583. Storage Futures Study. National Renewable Energy Laboratory (NREL), Golden, CO (United States) (2021).

Dijkstra, H., de Boer, C., Griffioen, J., and Koenen, M.: Workflow to Evaluate the Risk of Mineral Scaling in a HT-ATES System and Application to a Potential Site in Middenmeer, The Netherlands. Utrecht, The Netherlands.: Netherlands Institute for Applied Geosciences (2020). https://www.heatstore.eu/documents/TNO%20report%202020%20R10437_HEATSTORE_Final_2020.04.16.pdf.

Dobson, P.F., Atkinson, T.A., Jin, W., Acharya, M., Akindipe, D., Li, B., McLing, T., and Kumar, R.: Hybrid Uses of High-Temperature Reservoir Thermal Energy Storage: Lessons Learned from Previous Projects. SPE Energy Transition Symposium, Houston, Texas, SPE-215750-MS, (2023).

Drijver, B.: High Temperature Aquifer Thermal Energy Storage (HT-ATES): Water Treatment in Practice. 1e Nationaal Congres Bodemenergie, Utrecht, Nederland, (2011).

Fleuchaus, P., Schüppler, S., Bloemendal, M., Guglielmetti, L, Opel, O., and Blum, P.: Risk Analysis of High-Temperature Aquifer Thermal Energy Storage (HT-ATES). Renewable and Sustainable Energy Reviews, 133 (2020), 110153.

Glassley, W.E., Brown, E., Asquith, A., Lance, T., and Perez, G.: Geothermal Energy Potential from Oil Fields in the Los Angeles Basin and Co-Located Renewable Resources. Geothermal Resources Council Transactions, 37, (2013), 715–720.

"IPSEpro: Process Simulation and Heat Balance Software." n.d. SimTech. https://www.simtechnology.com/cms/.

Kabus, F., Wolfgramm, M., Seibt, A., Richlak, U., and Beuster, H.: Aquifer Thermal Energy Storage in Neubrandenburg - Monitoring throughout Three Years of Regular Operation. EFFSTOCK 2009, (2009).

McLing, T.L., Dobson, P., Jin, W., Spycher, N., Doughty, C., Neupane, G.H., Smith, R.W., and Atkinson, T.A.: Dynamic Earth Energy Storage: Terawatt-Year, Grid-Scale Energy Storage Using Planet Earth as a Thermal Battery (GeoTES): Phase I Project (Final Report). INL/RPT-22-66762-Rev001. Idaho National Laboratory (INL), Idaho Falls, ID (United States), (2022).

McTigue, J.D., Zhu, G., Akindipe, D., and Wendt, D.: Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis. GRC Transactions, 47, (2023), 2649–2663.

Mercangöz, M., Hemrle, J., Kaufmann, L., Z'Graggen, A., and Ohler, C.: Electrothermal Energy Storage with Transcritical CO_2 Cycles. Energy, 45 (1), (2012), 407–415.

Meyer, J.E.; Brackish Resources Aquifer Characterization System Database Data Dictionary. Texas Water Development Board Open File Report 12-02, Fifth Edition, (2020).

Novotny, V., Basta, V., Smola, P., and Spale, J.: Review of Carnot Battery Technology Commercial Development. Energies 15 (2), (2022), 647.

Olympios, A., McTigue, J., Farres-Antunez, P., Tafone, A., Romagnoli, A., Li, Y., Ding, Y., et al.: Progress and Prospects of Thermo-Mechanical Energy Storage—a Critical Review. Progress in Energy, 3 (2), (2021), 022001.

Pepin, J.D., Burns, E.R., Dickenson, J.E., Duncan, L.L., Kuniansky, E.L., and Reeves, H.W.: National-scale Reservoir Thermal Energy Storage Pre-Assessment for the United States. Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University (2021).

Railroad Commission of Texas: Oil and Gas Division District Boundaries, (2020), https://www.rrc.texas.gov/media/3bkhbut0/districts_color_8x11.pdf

Schmidt, T., and Müller-Steinhagen, H.: The Central Solar Heating Plant with Aquifer Thermal Energy Store in Rostock - Results after Four Years of Operation. EuroSun 2004, 5th ISES Europe Solar Conference, (2004).

Sharan, P., Kitz, K., Wendt, D., McTigue, J., and Zhu, G.: Using Concentrating Solar Power to Create a Geological Thermal Energy Reservoir for Seasonal Storage and Flexible Power Plant Operation. Journal of Energy Resources Technology, 143 (1), (2021), 010906.

Spycher, N., Doughty, C., Dobson, P., Neupane, G., Smith, R., Jin, W., Atkinson, T., and McLing, T.: Evaluation of Mineral Scaling during High-Temperature Thermal Energy Storage in Deep Saline Aquifers. GRC Transactions, 45, (2021), 1201–2015.

"System Advisor Model (SAM)." National Renewable Energy Laboratory. (2022) sam.nrel.gov.

Willemsen, A.: PHREEQM-2D: A Computer Model to Calculate Geochemical Reactions during Transport of Groundwater; Model Description and Application to the Utrecht University ATES. 1992 Intersociety Energy Conversion Engineering Conference, San Diego, CA., (1992).

Würdemann, H., Westphal, A., Lerm, S., Kleyböcker, A., Teitz, S., Kasina, M., Miethling-Graff, R., Seibt, A., and Wolfgramm, M.: Influence of Microbial Processes on the Operational Reliability in a Geothermal Heat Store – Results of Long-Term Monitoring at a Full Scale Plant and First Studies in a Bypass System. Energy Procedia, 59, (2014), 412–417.