Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis

Preprint

Joshua D. McTigue,[1] Guangdong Zhu,[1] Dayo Akindipe,[1] and Daniel Wendt[2]

1 National Renewable Energy Laboratory
2 Idaho National Laboratory

Presented at the 2023 Geothermal Rising Conference
Reno, Nevada
October 1-4, 2023

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5700-87000
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Suggested Citation

McTigue, Joshua D., Guangdong Zhu, Dayo Akindipe, and Daniel Wendt. 2023. *Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-87000 https://www.nrel.gov/docs/fy24osti/87000.pdf.

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis

Joshua D. McTigue[1], Guangdong Zhu[1], Dayo Akindipe[1], Daniel Wendt[2]

[1]National Renewable Energy Laboratory

[2]Idaho National Laboratory

Keywords

Thermal energy storage; Solar thermal; Carnot Battery; Reservoir thermal energy storage

ABSTRACT

Energy storage is increasingly necessary as variable renewable energy technologies are deployed. Seasonal energy storage can shift energy generation from the summer to the winter, but these technologies must have extremely large energy capacities and low costs. Geological thermal energy storage (GeoTES) is proposed as a solution for long-term energy storage. Excess thermal energy can be stored in permeable reservoirs such as aquifers and depleted hydrocarbon reservoirs for several months.

In this article, we describe a techno-economic model that has been developed to evaluate GeoTES systems. The models are developed by combining the output of specialist models, which enables the performance and cost of both the subsurface and surface systems to be captured. Off-design models are developed so that the performance can be evaluated at each hour of the year.

GeoTES can be charged with two different energy sources: (1) concentrating solar thermal and (2) renewable electricity using heat pumps (henceforth known as a “Carnot Battery”). The stored thermal energy can be used to generate electricity and, uniquely, also directly produce heat that can be used by industrial processes. Furthermore, Carnot Battery GeoTES can also be used to form a cold storage reservoir.

Preliminary results that quantify the technical and economic performance of these two GeoTES systems are presented.

1. Introduction

Energy storage is increasingly necessary as variable renewable energy technologies are deployed. Seasonal energy storage can shift energy generation from the summer to the winter, but these technologies must have extremely large energy capacities and very low costs. Geological thermal energy storage (GeoTES) is proposed as a solution for long-term energy storage. Excess thermal energy can be stored in permeable reservoirs such as aquifers and depleted hydrocarbon reservoirs for several months. Previous work analyzed a GeoTES charged with solar thermal energy and calculated it to have a levelized cost of storage (LCOS) of 0.12 $/kWh$_e$ for 700 hours of capacity.

This value was low compared to other comparable technologies at the same scale, such as hydrogen (0.5 \$/kWh$_e$), compressed air energy storage (2.8 \$/kWh$_e$), and pumped hydro-electric storage (1.6 \$/kWh$_e$) (Sharan et al., 2020). These low costs derive from the fact that – unlike other storage systems – the GeoTES storage volume has little-to-no cost. Wells provide access to the reservoir and determine the rate that energy can be extracted (and therefore the cost of power), but the marginal cost of adding energy capacity is effectively zero as long as the reservoir volume is large enough.

These results suggest that GeoTES is suitable for storing large capacities of energy. Large energy stores can be used to dispatch power over short and long durations. Therefore, GeoTES could potentially provide a range of energy storage services, including load-shifting, arbitrage, grid reliability, energy capacity, and seasonal storage. There are many different GeoTES configurations depending on the energy source, reservoir characteristics, and local energy market. For example, previous work considered storing solar thermal energy generated by a parabolic trough collector which would be suitable in regions of high solar irradiance (Sharan et al., 2020). It is also conceivable that excess electricity could be converted to heat using an electrical heater or a heat pump. Other suitable sources of energy include waste heat from industrial processes.

In this research paper, two methods of charging a GeoTES are examined: (1) The GeoTES is charged with heat generated by concentrating solar thermal (CST), and (2) the GeoTES is charged with heat generated by a heat pump powered by renewable electricity, a system known as a Carnot Battery.

1.1. GeoTES With Concentrating Solar Thermal

CST uses mirrors to concentrate sunlight onto a line or point to heat at relatively low costs and over a wide range of temperatures. One example of how GeoTES can be charged with CST is shown in Figure 1 (Sharan et al., 2020). In this example, surface components comprise a parabolic trough collector (PTC) system connected to a heat exchanger and a power block for generating electricity. The PTC is designed to collect the radiative solar energy from parabolic mirrors into a pipe network that uses mineral oil as a working fluid. The subsurface system consists of a sedimentary formation connected to the surface via a doublet (injection and production) well arrangement. During the charging cycle, the reservoir fluids are continuously produced from the "cold" production well and passed into the countercurrent heat exchanger (with the PTC heated oil as the working fluid) and then injected into the reservoir through the "hot" injection well for storage.

In the discharge cycle, the hot reservoir fluid is produced from the hot well and directly piped to the power block. Previous research by the project team investigated several different power cycles—such as steam flash plants and recuperated binary plants—and found that a two-stage flash cycle provided the highest efficiency (Sharan et al., 2020). This work was conducted for a reservoir temperature of 250°C. In this study, lower reservoir temperatures (200°C) are considered.

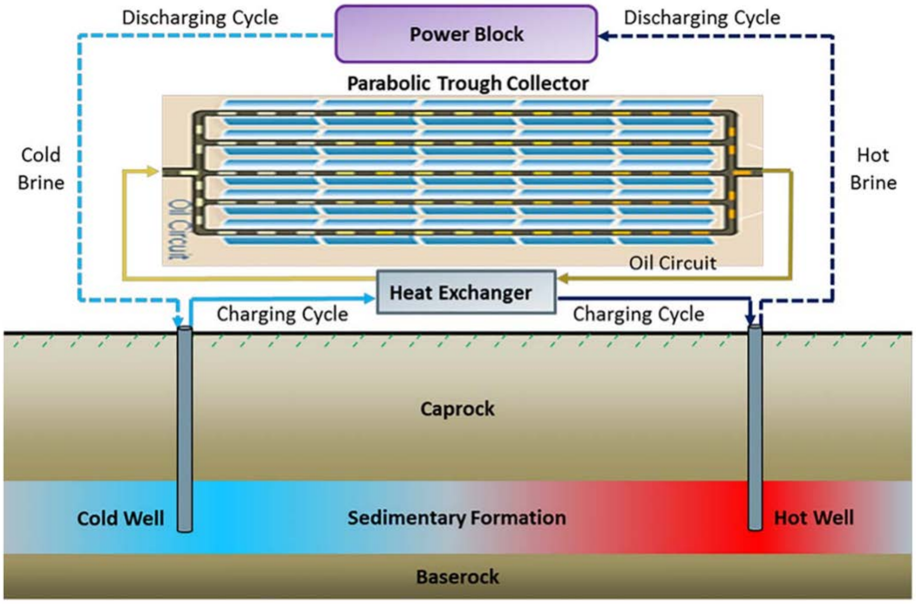

Figure 1: Schematic of a GeoTES integrated with concentrating solar thermal (Sharan et al. 2020)

1.2. GeoTES With Carnot Batteries

Carnot Batteries are electricity storage systems: A heat pump converts electricity into thermal energy, which is stored. Special heat pump cycles are developed, which create hot and cold thermal storage. Later, the cycle is reversed, and thus acts as a heat engine that generates electricity from the thermal potential between the two stores. A wide variety of power cycles, thermal storage materials, and system configurations have been explored (Olympios et al., 2021) and are typically being developed by various organizations for long-duration storage (>10 hours) (Novotny et al., 2022).

Carnot Batteries typically use a contained thermal storage on the surface, such as tanks of water (Morandin et al., 2013), molten salt (Laughlin, 2017), packed beds of rocks (McTigue et al., 2015), or fluidized particles (Joshua D. McTigue and Ma, 2022). In this research paper, GeoTES is proposed as the storage system with the objective of achieving lower marginal costs of energy capacity due to the low cost of the reservoir volume. This will enable Carnot Batteries to provide seasonal storage as well as manage daily variations in energy demand in a similar way to other Carnot Batteries. These systems have the potential to deliver hot and cold thermal energy in addition to electricity, thereby enhancing the flexibility and value of the system.

1.3. Scope of This Research Paper

The objective of this research paper is to introduce concepts relating to GeoTES charged with CST and Carnot Batteries. Illustrative system configurations are described, and techno-economic models are developed. The configurations are shown here to illustrate the operating principles, and performance will be improved by optimizing the layout and operating parameters. The techno-economic models evaluate the hourly performance over the course of a year using I dispatch methods and simple economic models that will be improved in future work.

2. Modeling Methods

Specialist tools are used to model each subsystem and are combined into a single techno-economic analysis tool that enables the annual performance and cost of GeoTES systems to be evaluated. Concentrating solar thermal is modeled using the System Advisor Model (SAM) (National Renewable Energy Laboratory (NREL), 2022). This program is used to define the geometry and optical properties of PTCs. The sun position, and therefore sunlight incidence angles, depend on the time of year and location, and mean that the optical efficiency of the collectors varies throughout the year. SAM is used to calculate the thermal power generated for each hour of the year.

The solar field may be oversized relative to the power output of the thermal power cycle. A solar field that generates the design thermal input to the power cycle on a day with nominal irradiance (1,000 W/m^2) at normal incidence angles (maximum optical efficiency) has a solar multiple of one. Increasing the solar field area relative to this size increases the proportion of the year where the solar field can produce the design power. Thus, a system with a solar multiple of two will have double the area, and at the design solar irradiance will generate double the thermal energy. The excess energy is stored and later dispatched when solar irradiance decreases below the design levels. This enables the CST subsystem to deliver the design thermal input for a greater proportion of the year.

Thermal cycles, such as heat pumps and heat engines, are modeled using SimTech IPSEpro flow-sheet software (SimTech, 2022). Components such as pumps, compressors, turbines, motors, generators, and heat exchangers are modeled in terms of key design parameters, such as efficiencies and approach temperatures. The governing energy equations are solved, and this is particularly important in the heat exchangers where fluids may exhibit real fluid behavior, and therefore care must be taken to ensure temperature cross-over does not occur. The off-design performance of each component is also specified using either data tables or correlations (for example, the turbine efficiency may be specified for several specific loads while heat exchanger heat transfer coefficients depend on the Nusselt number). This enables the off-design performance of the full system to be evaluated as a function of key variables, such as solar heat input, load, and ambient temperature (which affects the effectiveness of heat rejection). Off-design maps are generated for a range of these parameters, and this data table is then interpolated to find the thermal cycle performance under any particular condition.

The Geothermal Electricity Technology Evaluation Model (GETEM) was used 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. This model is available within SAM. A key assumption in this work is that wells can be used for production and injection of fluids to the reservoir in an effort to minimize costs. This also means that fluid is produced/injected at the same location in the reservoir so that the storage operates in a “push/pull” fashion.

The outputs of the individual models are combined in MATLAB, and the performance and cost of the full system are subsequently calculated. For CST-GeoTES, the electrical power output and solar multiple 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 PTC design. The thermal energy is then known for each hour of the year. 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. A similar approach is used for CB-GeoTES, although SAM is not required in that case.

At the start of simulation, the GeoTES is assumed to be at its initial temperature, i.e., at a fully discharged state. Several years are therefore simulated so that the results reflect steady-state operation: Typically, at the start of the calendar year, the GeoTES will have some energy remaining in it, which is then discharged in the remaining winter months.

Once steady-state operation is achieved, the annual energy production is evaluated, and economic metrics are calculated. Solar field and power cycle costs are estimated using simple per unit values (e.g., dollars per unit area and dollars per electrical power output) based on our previous analysis and discussion with industry representatives. Annual operations and maintenance (O&M) costs are evaluated as a percentage of the total capital cost. Subsurface capital costs and O&M are calculated using GETEM methods.

Having estimated the total energy output and cost, the levelized cost is evaluated using the Fixed Charge Rate (FCR) method (Short and Packey, 1995). The FCR requires assumptions about the project lifetime, debt fraction and interest rate, inflation rate, tax rate, and depreciation.

$$\mathrm{LCOE} = \frac{\mathrm{FCR} \cdot \mathrm{Capital\ cost} + \mathrm{O\&M} + \mathrm{Fuel\ cost}}{\mathrm{Energy\ output}} \tag{1}$$

Here, $\mathrm{Fuel\ cost}$ accounts for any electricity that is bought to drive the Carnot Battery. The $\mathrm{Energy\ output}$ may be the total electricity output or total thermal energy output. For CST-GeoTES, the system is being used for energy generation; therefore, either the levelized cost of electricity (LCOE) or levelized cost of heat (LCOH) are calculated, depending on whether the system delivers electricity or thermal energy as the output. For CB-GeoTES, the system provides electricity storage, so the appropriate term is levelized cost of storage (LCOS), although the denominator of the LCOS equation is the annual electricity output.

The analysis does not include any subsidies the system may receive, such as investment tax credits or production tax credits, although these are likely to have a significant impact on the system cost.

3. Performance of CST-GeoTES

The CST-GeoTES system comprises a concentrating solar field that concentrates sunlight to generate heat using PTCs at 200°C. The heat is either converted directly into electricity using an air-cooled organic Rankine cycle (ORC) or stored in the GeoTES, as illustrated in Figure 1. A simple dispatch approach is implemented: Whenever there is excess solar heat that cannot be absorbed by the ORC, the GeoTES is charged. The GeoTES is discharged whenever solar heat is less than the design heat input to the ORC.

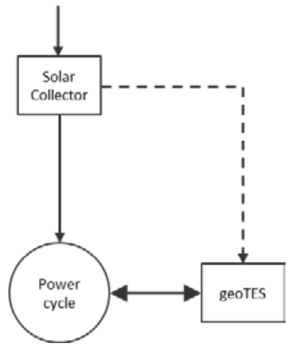

Figure 2: Diagram illustrating the energy flows between components in a CST-GeoTES system

Results are generated for a system with a 10-MW_e power cycle located in the Imperial Valley in California, a region with high solar irradiance (>7.5 $kWh/m^2/day$) which makes it very suitable for CST applications. The solar field is sized such that the power plant runs at its design power output continuously throughout the year. Figure 3 illustrates how the GeoTES is charged and discharged over the course of several days in January and August. The GeoTES is discharged each night when there is no solar availability. However, during the summer months, the heat added to the GeoTES each day exceeds the nightly requirement. Therefore, the excess heat is stored until the winter, which ensures that the power plant can deliver continuous power during the shorter, less sunny winter days. Figure 4 shows the quantity of energy stored in the GeoTES throughout the year, which demonstrates that sufficient energy is stored to last through the winter months. The unique feature of the GeoTES is that its unlimited capacity means that no solar energy has to be curtailed and that the storage can manage both daily and seasonal variations in solar irradiance.

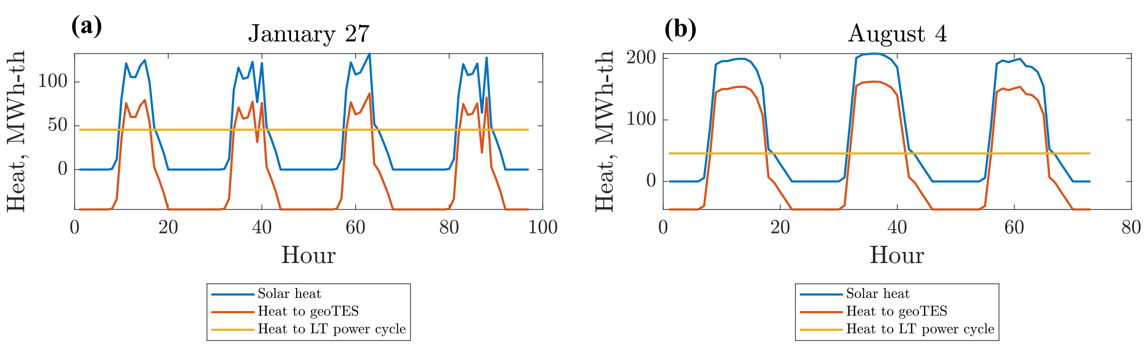

Figure 3: Example results for a CST-GeoTES system (a) energy flows in January, (b) energy flows in August

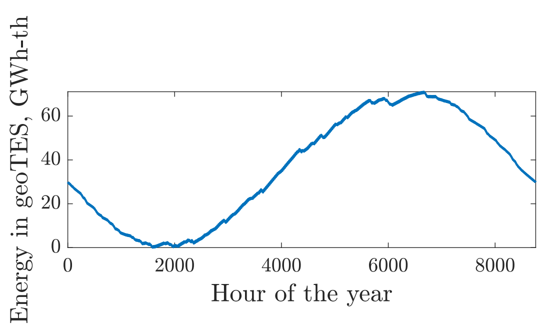

Figure 4: Energy stored in the CST-GeoTES reservoir over the course of one year

Table 1: Results for a CST-GeoTES System

Parameter		Value
Solar multiple	-	5
Maximum temperature	°C	200
Power rating	MW_e	10
Heat engine efficiency	%	22
Number of charging production wells		5
Number of discharging production wells		2
Solar thermal energy generated	GWh_{th}	438.9
Electricity output	GWh_e	89.8
Energy into GeoTES	GWh_{th}	268.5
Maximum thermal energy in GeoTES	GWh_{th}	71
Volume of subsurface required	Million m^3	1.4
Solar field cost	M$	73.5
Power cycle cost	M$	21.4
Drilling, wells, pumps	M$	39.5
Total capital cost	M$	134
Total yearly O&M	M$	5.83
LCOE	$/kWh_e$	0.152
LCOH	$/kWh_{th}$	0.028

Additional results, including economic estimates, are provided in Table 1. Two significant design factors are the number of wells and the size of the solar field, which both contribute significantly to the capital cost. More wells are required during charge than in discharge because the charging thermal power input to the GeoTES is considerably larger than the discharging power output: large quantities of solar energy must be stored in short time frames but are then extracted over longer periods of time. Therefore, the flowrates of geofluids during charge exceed those during discharge, leading to more charging wells than discharging wells. Providing the design power continuously requires a very large solar multiple (5) compared to conventional CST installations (~2). This large solar field therefore takes up a large proportion of the capital cost. Furthermore, the relatively low temperature (200°C) limits the conversion efficiency, effectively meaning that more mirror area is required to generate the required power, therefore further increasing costs.

As a result, this implementation of CST-GeoTES has a very high capital cost and LCOE. However, these numbers are not directly comparable to other renewables, such as wind, solar PV, or conventional CST, which have considerably lower capacity factors and may not include integrated energy storage. While the cost of the subsurface equipment is high, it enables a low cost of energy storage. For example, the maximum energy stored in the reservoir is 71 GWh_{th}, meaning that the equivalent cost of the thermal energy storage is 0.6 $/kWh_{th}$, compared to conventional molten salt costs of 20–33 $/kWh_{th}$ (for 8.1 GWh_{th}) (Mehos et al., 2017). This energy capacity is also sufficient for the system to deliver 10 MW_e continuously for 1,578 hours: In comparison, batteries are typically sized for 4–8 hours and CST molten salt storage is sized for 10–20 hours.

This system is intended for electricity generation but could also be used to deliver industrial process heat, a significant proportion of which requires temperatures less than 200°C (Kurup and Turchi, 2015; Mcmillan et al., 2021). Here, the LCOH is calculated by considering the total thermal energy deployed by the system and not counting the power cycle capital cost. The LCOH of 0.028

$/kWh$_{th}$ is competitive with the average industrial price of natural gas in California in 2022 (0.047 $/kWh$_{th}$) (U.S. Energy Information Administration, 2023). A particular strength of this technology is that it could deliver heat continuously throughout the year. The prospect of using this system to deliver both electricity and industrial process heat should be considered further.

The cost and performance of this CST-GeoTES system could be improved in numerous ways. Design optimization would improve the performance of individual components, while a comprehensive analysis of the relative sizes of the CST and GeoTES could improve the cost. Furthermore, results are shown for the extreme case where the system has a 100% capacity factor. Reducing the size of the solar field and the number of charging wells would significantly reduce the capital cost, but the system could still feasibly provide daily and seasonal storage capabilities. Therefore, the value of such services should be estimated rather than considering only the cost.

Results can also be improved by using alternative designs. As noted above, the low temperature of heat limits the efficiency and requires a larger solar field. However, CST systems can generate temperatures up to 600°C, therefore alternative systems that use a high-temperature topping cycle with high-temperature thermal energy storage (such as molten salts) should also be considered. Such systems could use a high-temperature power cycle for daily cycling, while storing excess solar heat in a GeoTES for seasonal storage. Dispatch analysis is required to optimize the relative sizes of the power cycles, solar field, and thermal storage, and to ensure that energy is dispatched at the most valuable times. This system would have features than enable it to target peak power prices as well as providing baseload characteristics.

4. Performance of CB-GeoTES

Carnot Batteries use a heat pump to convert electricity into thermal energy, which is stored and later converted back into electricity using a heat engine. Heat pumps extract thermal energy from a low-temperature heat source (conventionally the air or ground). This thermal energy is upgraded to higher temperatures by adding work (electricity) to the system and finally delivering the higher temperature energy to a heat sink. In a conventional vapor compression heat pump, compressing a gas generates high temperatures and heat is transferred to an external reservoir. The cooled fluid is then expanded and must be evaporated to return to its original state: Evaporating the fluid absorbs energy from an external reservoir that is therefore cooled. By this principle, the heat pump can create a hot storage and a cold storage. In a Carnot Battery, a heat engine later operates between these two reservoirs to generate electricity, converting the thermal potential into work. Conventionally, the environment (i.e., air) is used as the heat source of a heat pump and the heat sink of the heat engine. However, Carnot Batteries typically use a contained volume for the cold reservoir. This enables cold storage at temperatures lower than the environment (which improves efficiency and energy density) and also reduces the impact of ambient temperature variations. Previous work has demonstrated that by using thermal energy storage media, Carnot Batteries can achieve low marginal costs of electricity storage capacity, especially for longer duration storage (McTigue et al., 2022). However, very large durations of storage (e.g., weekly to seasonal storage) would require impracticably large containment volumes. One solution is to create thermal reservoirs in the subsurface, i.e., GeoTES, to achieve low-cost, long-duration storage.

One method of integrating Carnot batteries with GeoTES is illustrated in Figure 5. Fluid is produced from one reservoir (point 1g. on Figure 5) and used as both the heat source and sink for the heat pump: The production fluids are split, and one fraction is heated up by the hot side of the heat pump before being reinjected into another formation that will become the hot reservoir (2g.). The other fraction of production fluids is cooled in the heat pump evaporator and then reinjected into a separate formation, which becomes the cold storage (3g.).

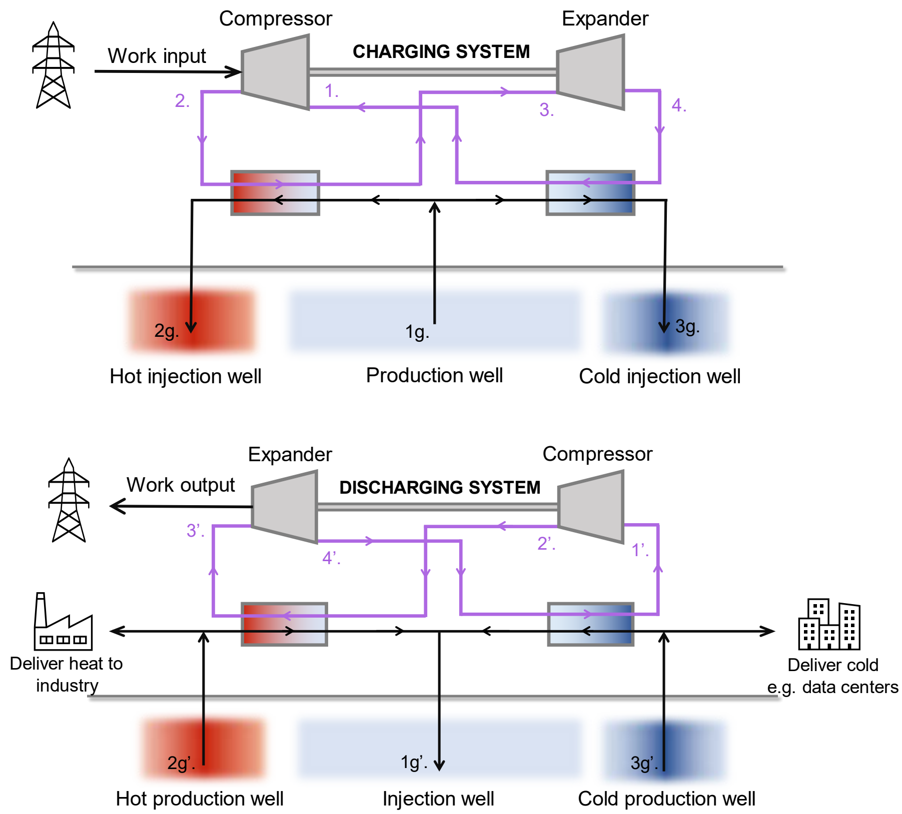

Figure 5: Schematic of a Carnot Battery with geological thermal storage during charge (top) and discharge (bottom)

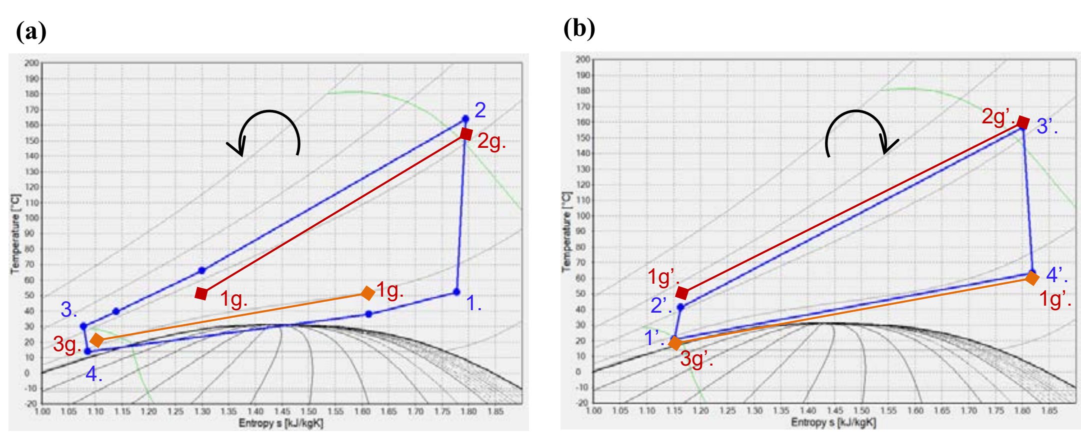

Figure 6: Temperature-entropy diagrams of the CB-GeoTES. Blue lines indicate the temperature and entropy of the heat pump/engine working fluid. Red lines indicate the temperature change of the hot geofluid. Orange lines indicate the temperature change of the cold geofluid. Numbering corresponds to Figure 5. (a) The charge heat pump using a recuperated supercritical CO_2 cycle. (b) The discharge heat engine using a supercritical CO_2 cycle.

To discharge the system, the flow direction of each process is reversed. Hot fluid is produced from the hot geothermal reservoir (2g'.) and used as the heat source in a heat engine. Heat engines conventionally reject heat to the environment, but in this case, cold fluid produced from the cold reservoir (3g'.) is used. Because the cold reservoir is at temperatures below the average ambient temperature, the heat engine should achieve higher efficiencies than a conventional heat engine operating between the hot reservoir and the environment.

Continued steady-state operation of the Carnot Battery imposes several constraints on the system design. First, fluid must be returned to its original temperature at the end of discharge—i.e., hot fluid must be cooled to its original temperature, and cold fluid must be heated to its original temperature by the heat engine before it is reinjected to the original reservoir. This ensures that the temperature of the reservoirs do not change over time (which could compromise system performance). Secondly, the hot and cold reservoirs should be discharged at the same rate. If one reservoir is discharged more quickly than the other, then the full energy potential of the system cannot be exploited.

These constraints can be simplified by using the atmosphere as the cold reservoir instead of a geological formation. Then, only the hot fluid would be subject to temperature constraints, and there would be more flexibility in the system design. The cost of the cold wells and pumps must be balanced against the cost of moving large volumes of air instead. Furthermore, cold storage will provide some efficiency advantages and decouple the plant power output from ambient temperature variations. Such comparisons will be made in future work, while this work concentrates on introducing a system that uses a cold GeoTES.

An example of a heat pump/heat engine arrangement that meets these constraints at temperatures suitable for CB-GeoTES is illustrated via temperature-entropy diagrams in Figure 6. This system uses supercritical carbon dioxide as a working fluid: this fluid is chosen because it enables effective heat transfer between the power cycle and the geothermal fluids, and has also been developed for use in the CSP industry (Mehos et al., 2017) and for Carnot Battery applications (Morandin et al., 2011; McTigue et al., 2020). In this example, it is assumed that the native reservoir temperature is 50°C. During charge, warm, supercritical CO_2 is compressed from T_1 = ~50°C to T_2 >160°C (numbers correspond to points on Figure 5 and Figure 6). Fluid is produced from a well at T_{g1} = 50°C and heat is transferred from the CO_2 to these fluids, which are therefore heated to T_{g2} = ~160°C and injected into the hot reservoir. The CO_2 temperature is further reduced in a recuperator and then in a small heat rejection unit before being expanded to low temperatures T_4 = ~10°C. This cold (still supercritical) fluid is then used to cool the production fluids to T_{g3} = ~15°C, which are injected into the cold reservoir. The CO_2 is then returned to the compressor inlet temperature by the recuperator. Thus, the recuperated, supercritical CO_2 heat pump converts 50°C production fluids into thermal energy that is stored in a 160°C hot reservoir and 15°C cold reservoir. This particular cycle has a coefficient of performance ($COP = Q_{hot} / W_{in}$) of 3.7, indicating that for each unit of electrical work, 3.7 units of hot thermal energy are stored.

To generate power, fluid is produced from the hot and cold reservoirs and used to drive a supercritical CO_2 heat engine, as shown in Figure 6b. Hot produced fluids (point 2g'.) heat supercritical CO_2 to high temperatures (3'.), and in the process are returned to their original temperature of 50°C (3g'.) before being reinjected to the original reservoir. The CO_2 is expanded (4'.) to produce work and is then cooled (1'.) using fluid from the cold reservoir (3g'.), which itself is reheated to 50°C (1g'.) and reinjected to the original reservoir. This cycle has an efficiency of

11%, which appears somewhat low given the fluid temperatures but is a result of the requirement to reheat the cold fluid to 50°C. Supercritical cycles are used in this case to facilitate a good temperature match between the geofluids and the CO_2 in the heat exchangers. Systems that use a cooler initial reservoir (<50°C) could be considered to ease the constraint on the cold fluid, but it should be noted that reducing the temperature change of the cold fluid will increase the number of production/injection wells and a cost-efficiency trade-off should be explored.

As an example, this CB-GeoTES design is simulated over the course of one year, and results are shown in Figure 7, Figure 8, and Table 2. Electricity prices obtained from the California Independent System Operator (CAISO) are used to determine whether to charge or discharge the GeoTES. The heat pump runs when prices are below the median value and thus charges the hot and cold GeoTES. The heat engine runs when the electricity price is greater than the median value thereby discharging the GeoTES and generating electricity that is sold on the grid. More sophisticated dispatch schedules can be developed and are likely to depend on technology performance and the local market signals and will therefore be implemented later in the project.

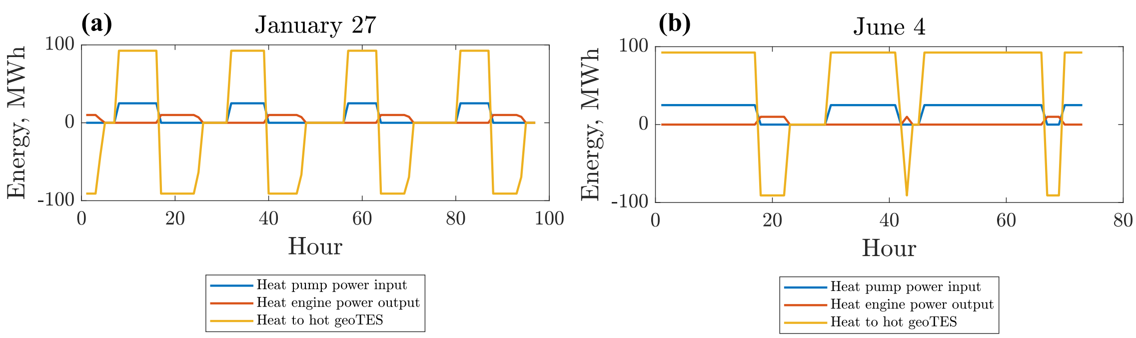

Figure 7: Energy flows in a CB-GeoTES in (a) January, (b) June

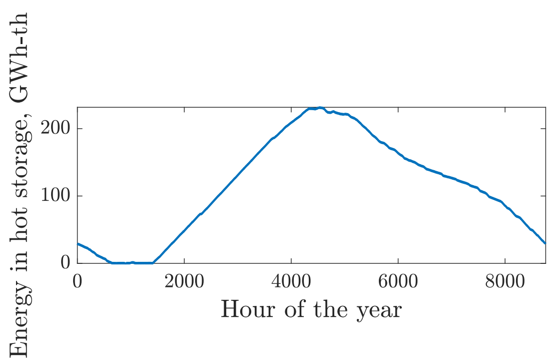

Figure 8: Energy stored in the CB-GeoTES hot reservoir over the course of one year

Table 2: Results for a CB-GeoTES

Parameter		Value
Cold reservoir initial temperature		50
Cold reservoir depth	m	1,000
Hot reservoir initial temperature		50
Hot reservoir depth	m	1,000
Heat pump cycle		Recuperated, supercritical
Heat engine cycle		Supercritical
Maximum temperature	C	159
Minimum temperature	C	5
COP		3.7
η_{HE}	%	11.0
η_{rt}	%	40.0
Number of hot production wells		4
Number of cold production wells		7
Heat pump power rating	MW_e	25
Heat engine power rating	MW_e	10
Annual electricity input	GWh_e	105.8
Annual electricity output	GWh_e	40.9
Energy into hot reservoir	GWh_{th}	391.5
Maximum energy stored in hot reservoir	GWh_{th}	231.7
Volume of subsurface required	Million m^3	7.0
Cost of subsurface equipment	M$	46
Heat pump cost	M$	25
Heat engine cost	M$	10
Capital cost	M$	81
LCOS	$/kWh$_e$	0.24

In this example, the heat pump has a higher power rating (25-MW_e input) than the heat engine (10 MW_e); this enables the GeoTES to be "over-charged" during the spring and summer months when low prices occur more frequently. (This arrangement is also convenient as it uses the same number of wells during charge as discharge). The GeoTES is then fully discharged during the winter months, as shown in Figure 8. Therefore, this system also provides both daily and seasonal electricity storage that is facilitated by the GeoTES. The ratio of heat pump to heat engine power ratings is an important design consideration that will require optimization for each unique deployment location. Furthermore, different locations will have different energy mixes and electricity price patterns, which will affect the system sizing and optimal dispatch scheme.

Table 2 includes some economic estimates that illustrate that CB-GeoTES has a high upfront capital cost and LCOS. These values are high compared to other implementations of CBs (2,000–4,000 $/kW$_e$ and 0.1–0.25 $/kWh$_e$ (McTigue et al., 2022)), which are typically designed for shorter duration storage (4–12 hours). In this example, the maximum energy stored in the hot reservoir is around 230 GWh_{th}: Given that the heat engine requires 90 MW_{th} to discharge at its design rate of 10 MW_e, the GeoTES stores ~2,000 hours' worth of electricity and can therefore provide services that other storage technologies cannot. Another unique attribute of this system is the high COP, which indicates large quantities of hot and cold thermal energy are also stored per unit work input. Therefore, the potential value of delivering electricity, heat, and cold energy should also be evaluated.

5. Conclusions

In this research paper, two systems that create thermal energy storage within the geological subsurface are introduced. These GeoTES systems are evaluated using techno-economic models.

CST concentrates sunlight to generate heat, which can be stored in the GeoTES. Later, the heat is extracted and used to generate electricity via an ORC. The system is sized so that it can generate power continuously throughout the year, and the GeoTES therefore provides both daily and seasonal energy storage. The LCOE is high (0.15 $\$/kWh_e$) compared to other renewable energy systems, although those systems have lower capacity factors. It is also noted that there are numerous ways to improve the system efficiency (such as by using a solar topping cycle), cost (by optimizing the sizes of the subsystems), and value (by using more sophisticated dispatch methods). Alternatively, this system could be used to deliver industrial process heat, in which case the LCOH is competitive (0.03 $\$/kWh_{th}$) with current natural gas prices in California.

Carnot Batteries are a type of electricity storage system that uses a heat pump to convert electricity into hot and cold thermal energy that is stored and later converted to electricity using a heat engine. Many Carnot Battery systems have been proposed, but here GeoTES is proposed as the storage system, which enables Carnot Batteries to provide daily and seasonal energy storage. A heat pump and heat engine cycle using supercritical CO_2 is introduced, and various operational constraints are discussed. Under operating conditions suitable for GeoTES, this cycle has a round-trip efficiency of 40%, and annual calculations estimate an LCOS of 0.24 $\$/kWh_e$, which is high compared to other storage technologies, although those technologies do not provide seasonal storage. Further system optimization is required to improve efficiency and reduce costs while also analyzing electricity markets to understand the optimal dispatch of stored energy.

Acknowledgment

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U. S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the United States Department of Energy through contract DEAC07-05ID14517. Funding was provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Geothermal Technologies Office (GTO). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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