# Techno-Economic Analysis and Market Potential of Geological Thermal Energy Storage (GeoTES) Charged With Solar Thermal and Heat Pumps into Depleted Oil/Gas Reservoirs and Shallow Reservoirs: A Technology Overview

## Preprint


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*4 Premier Resource Management*
*5 EarthBridge Energy*



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# Techno-Economic Analysis and Market Potential of Geological Thermal Energy Storage (GeoTES) Charged With Solar Thermal And Heat Pumps Into Depleted Oil/Gas Reservoirs and Shallow Reservoirs: a Technology Overview

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**Abstract**

Depleted oil/gas reservoirs represent a waste of underground resource ad investments of drilling, and also a potential risk to the earth's environment. Geologic thermal energy storage (GeoTES) is proposed as a solution to convert depleted oil/gas reservoirs into long-term seasonal energy storage. GeoTES can be hybridized with other techniques for viable commercial deployment, such as 1) concentration solar power (CSP) collectors and 2) heat pumps with excess renewable energy. Here, a technology overview is given on two GeoTES technologies, which includes system overview, techno-economic models and case study. Both GeoTES are shown a great potential in economics of individual project deployment and applicability across the US.

## 1. Introduction

Energy storage is increasingly necessary as variable renewable energy (VRE) technologies replace fossil fuels for electricity generation, heating, and cooling. Many energy storage solutions are being developed to address short discharge durations, but there are significant seasonal variations in VRE generation and electricity consumption. Seasonal storage is a required solution for achieving 100% decarbonization of energy sectors in the US and around the world. Geological thermal energy storage (GeoTES) presents desirable attributes to seasonal energy dispatching. Here, two GeoTES technologies are presented: GeoTES hybridization with concentration solar power (CSP) collectors and GeoTES hybridization with heat pumps using excess renewable energy.

GeoTES with CSP hybridization utilizes solar collectors to produce high temperature pressurized water or steam and inject into the underground reservoirs, such as depleted oil/gas reservoirs. By using advanced power cycles, the stored heat can then be extracted for power generation when there is a demand. Economic of power production over a seasonal scale is shown to be particularly intriguing on a green field geological reservoir[1] and it would be further improved if applied to depleted oil/gas reservoirs.

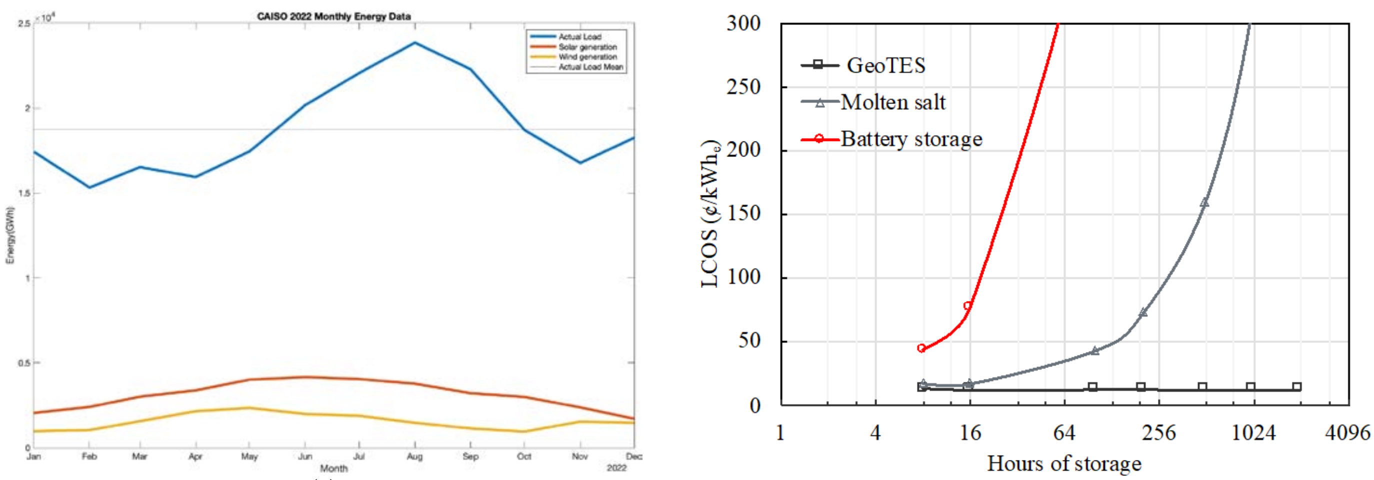
GeoTES with heat pump hybridization takes excess electricity from non-flexible renewable energy and create a hot source of pressurized water (>150°C) and a cold source of water(50°C) through a heat-pump cycle, which are pumped into a hot reservoir and a cold reservoir respectively. Suitable permeable reservoirs can be shallow aquifers which are widely distributed across the United States.

In this paper, the value of GeoTES for seasonable dispatching is first discussed; then, GeoTES with CSP hybridization and with heat pump hybridization are presented in details; initial works and future plans on subsurface economics, system economic analysis, reservoir suitability analysis and case studies are briefly discussed. The conclusion is given at last.

## 2. Value of GeoTES for seasonal dispatching

The 2022 monthly load profile is given by Figure 1a; it is an example demonstrating the substantial variation between seasons. While comparing with the solar and wind generation profile in the same plot, there would be a clear seasonal mismatch when the generation is scaling up. This indicates a need for seasonal storage/dispatching for achieving a 100% renewable energy grid in the future.

Figure 1b compares the levelized cost of storage (LCOS) for three thermal storage technologies: GeoTES, molten salt thermal energy storage and battery storage. It is shown that GeoTES has a minimal marginal cost with increasing hours of storage, particularly suitable for seasonal storage. The reason is that the cost of a larger reservoir is not scaling up with its size as it is naturally existing. In contrast, the cost of storage increases rapidly when molten salt and battery with increasing storage capacity requires large size (capitals) and are used less over a year. The value of GeoTES for seasonal storage is illustrated in this comparison.




(a) (b)

Figure 1: (a) Monthly load, solar generation and wind generation profile in 2022 reported by CAISO [2]; (b) Levelized cost of storage (LCOS) as a function of storage hours for various storage technologies [1].

## 3. GeoTES with CSP hybridization

A techno-economic analysis is to be carried out by adopting the methodology described in Figure 2. Multiple component models are adopted, which includes:

- SolTrace and SAM for CSP parabolic trough collectors [3,4]
- IPSEpro software for power cycle simulation and optimization[5]
- ToughREACT for reservoir storage system [6]
- Matlab model for economic analysis to calculate financial metrics and perform system sensitivity study.

The subsurface reservoir model, suitability study of identified reservoirs and case study sites are described in details below.

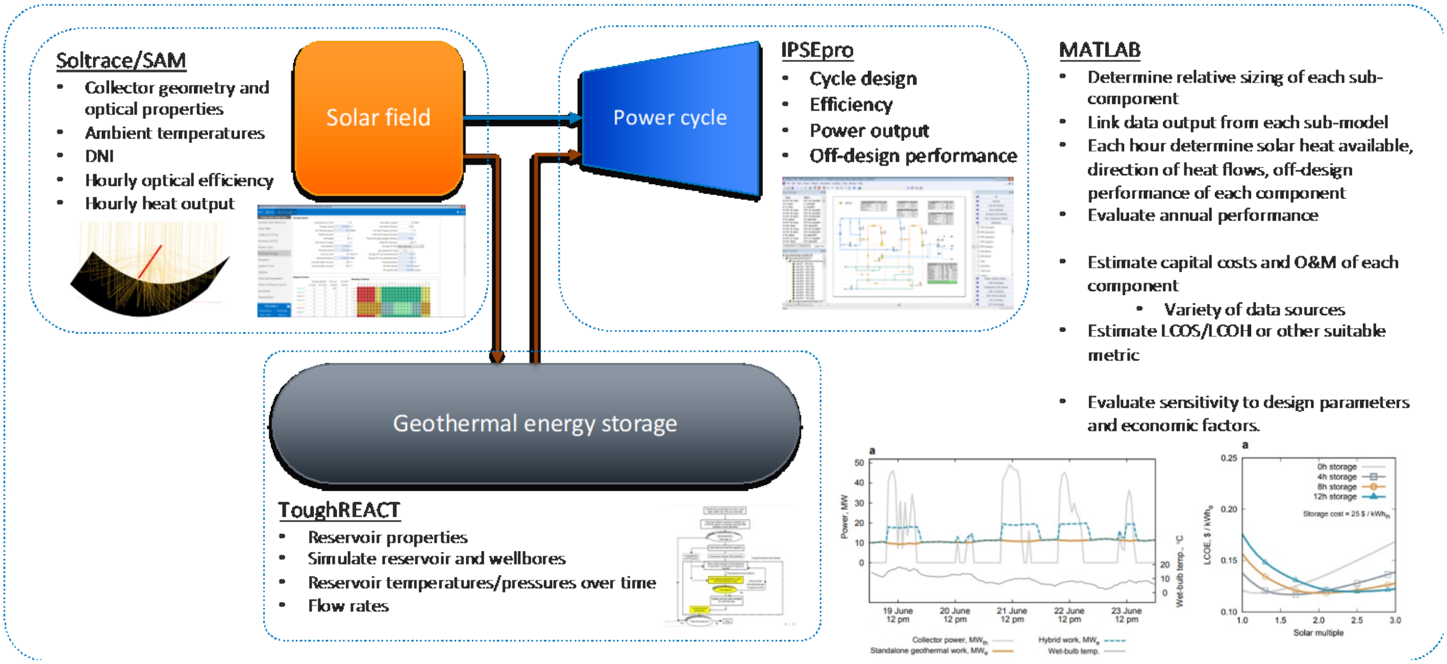



Figure 2: The techno-economic analysis (TEA) model for GeoTES with CSP hybridization.

### 3.1 Sub-surface techno-economic model

A subsurface techno-economic assessment model estimates the performance and cost of deploying a CSP-GeoTES system in a sedimentary basin. Formation types could be an uneconomic oil reservoir or a saline aquifer. Oil reservoir candidates for GeoTES are typically brownfields with varying pressure declines and greenfields with high water cut. To assesses the feasibility of coupling with a CSP system, a framework for reservoir capacity, thermal recovery, field operation, and well configuration is needed. This framework, shown in **Figure 2** consists of sub-models for (1) reservoir simulation, (2) wellbore simulation, (3) injection/production pumping calculations, (4) surface gathering line sizing, (5) capital cost estimation and (5) field operation and maintenance cost estimation.

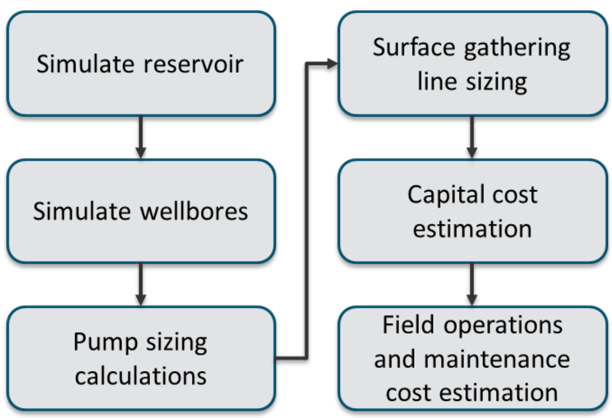



Figure 3: Framework for subsurface technoeconomic assessment

Past works on GeoTES have utilized simple rectangular reservoir grid models with the storage reservoir sandwiched between an overburden (caprock) and underburden (basal rock) [1,7,8]. This storage formation is characterized by suitable porosity, permeability, and thermal conductivity to allow for advective fluid flow and convective and conductive heat flow within the formation. The upper and lower layers are modeled as low permeable formations with much lower thermal conductivity compared to the storage formation. Overall, fine grid meshes are used in the storage formation compared to the caprock and basal rock layers. Also, finer meshes are used near source and sink (wellbore) regions. Single well and doublet well arrangements have been considered for CSP-GeoTES.

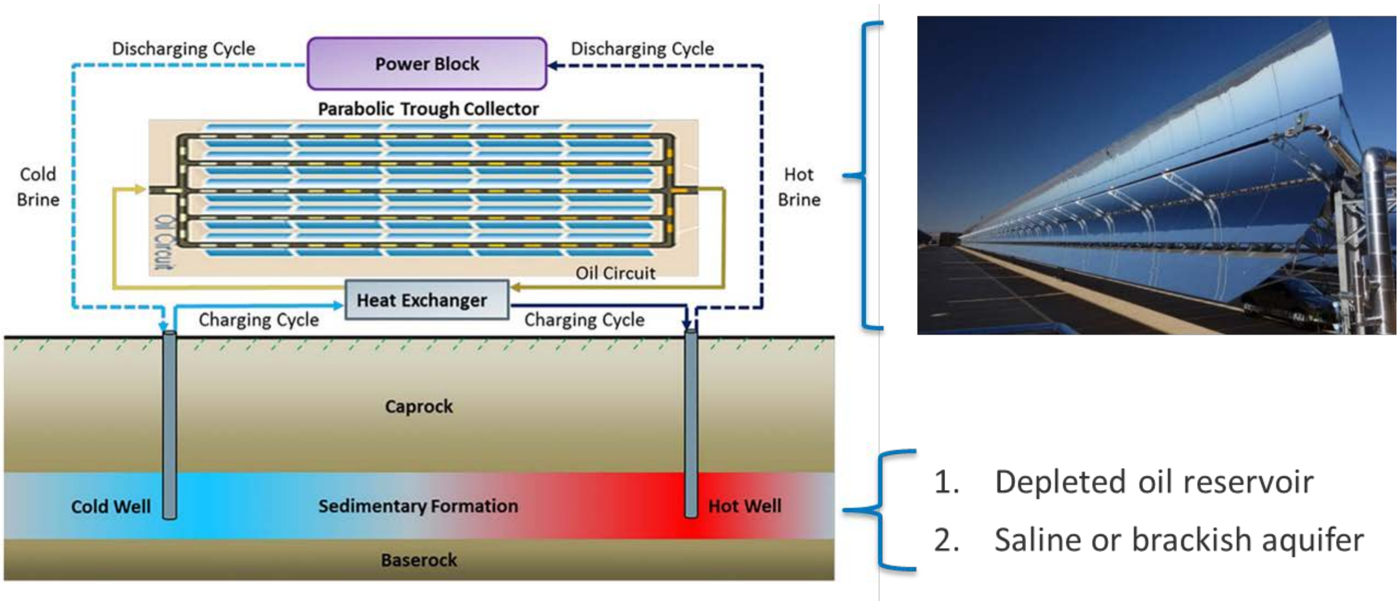



Figure 4: The single well configuration with a dedicated hot well and cold well.

The single-well approach mirrors the huff-and-puff mechanism that is used in cyclic steam floods for heavy oil recovery [1,7]. Under this well configuration (as shown in **Figure 3**), the reservoir is charged and discharged via a single hot well (or a set of hot wells). There are no dedicated production and injection wells. Cool wells operate in a reverse sequence to ensure continuous brine supply to the surface heat exchange unit and to mitigate formation damage due to severe pressurization during the charging cycle, and to receive the low-temperature fluid from the power outlet of the power cycle during the discharging cycle. The 5-spot (one hot and four cold) repeating well pattern is the most used. In the doublet well configuration, dedicated production and injection wells are used [1]. During the charging cycle, hot fluids are introduced into the reservoir via the injection well while cold fluids flow out of the production well into the heat exchange unit. During discharge, hot fluids are discharged from the producer while cold fluids from the power block are introduced back into the reservoir via the injector. One major disadvantage of the doublet well configuration is that the wells are exposed to a large variation in temperature with each charge and discharge sequence. This can induce severe thermal stress within the wellbore that could compromise well integrity and. Possible well arrangements include the 5-spot (one injector and four producers) and 7-spot (two-injectors and 5 producers) patterns.

Previous GeoTES studies have coupled thermal and hydrogeological properties of rocks and fluids and have simulated fluid and heat flow using existing software (e.g., CMG STARS and FALCON) [1,7,8]. Results from reservoir simulations include performance variables such as thermal recovery efficiency, reservoir thermal decline, net heat flow, and number of wells. For a fixed reservoir geometry and characteristics, these results vary based on initial charging duration, cycle rate (diurnally to seasonally) and injection/production rates (**Figure 4**).

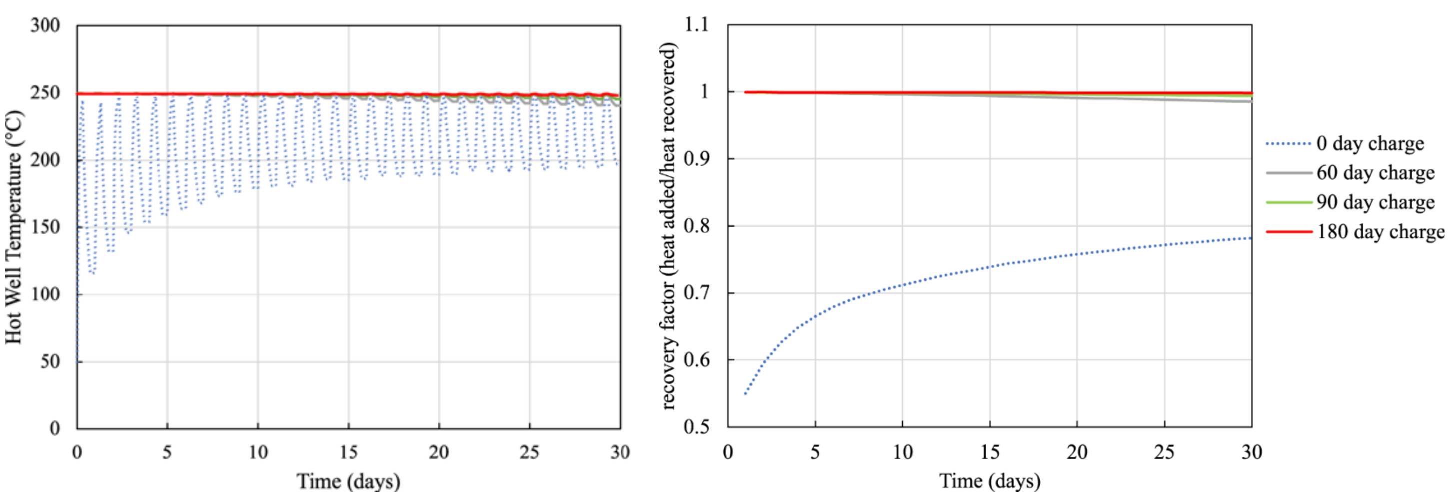



Figure 5: Typical results from subsurface simulations. The production temperature and heat recovery vary based on the initial charging duration (Sharan et al., 2021).

The subsurface capital costs include costs for drilling and completing the wells, pump purchase and installation cost, surface gathering line costs, and costs for surface processing equipment such as water treatment units, three phase separator (in the case of oil reservoir), and storage tanks. The field operations and maintenance cost include labor, pump maintenance and replacement, and make-up water.

### 3.2 Suitability of depleted/sub-economic oil/gas reservoir

The factors/parameters to access the suitability of depleted/sub-economic oil/gas reservoirs are as follows:

- Reservoir temperature: Efficiency of power cycle increases with temperature. Temperature of the production fluid in excess of 195 °F (91 °C) is minimum temperature required for small-scale binary power systems (Pratt and Whitney design of "Pure Cycle Power System 280"). Reservoir at higher temperature are more efficient for High Temperature thermal energy storage. For example, a reservoir at 300 ºC cooled to 25 °C yields 48% efficiency versus 20% efficiency for reservoir at 100 ºC cooled to 25 °C (Glassey W.E., 2014).
- Pressure of the depleted reservoir: Reservoir pressure decreases in course of oil and gas production. In order to produce fluid from depressurized reservoir, excess energy will be required to increase the reservoir pressure above hydrostatic pressure which should be accounted for techno-economic analysis. Geopressured reservoirs are favored for geothermal energy production due to gravitational potential of the fluid to flow up by adding kinetic energy component. Ideally, geopressured reservoirs are identified when measured pressure exceeds the hydrostatic trend in a region. Screening of reservoirs based on the pressure is the key criteria to repurpose the depleted oil and gas reservoirs for geothermal storage.
- Porosity and permeability of the formation: Porosity and permeability of natural systems can vary considerably and requires mathematical approximations to model porosity-permeability correlation and fluid flow in heterogeneous formations. The variables that control flow in the porous medium are the extent to which the individual pores are interconnected, tortuosity and surface area affecting flow. For fractures, the primary variables are the aperture and number of fractures per rock volume. In both instances, the pressure gradient is an additional influence that affects flow rate. Hydrologic modeling can predict flow path/vectors and thermal short circuiting in the high permeability regions (fractures). However, the accuracy of modeling results depends on the availability of high-quality data for in situ rock properties (Glassey W.E., 2014).
- Potential scaling and clogging: Scaling can reduce the flow rate in injection and production wells which reduces the geothermal energy production. The composition of scales depends on parameters such as pH, formation water composition, pressure, temperature, mineralogy, and injection rates (Tonkul et al., 2021; Bozau et al., 2015). Presence of salt in a high amount in sedimentary formations leads to chemical clogging. Changes in pressure and temperature during the geothermal energy production cycle may cause solubility reduction in minerals, corrosion of metal surfaces, and emission of gasses (Song et al., 2020).
- Permeability of caprock/seal: Low permeability seals/caprocks act as a barrier for heat and mass flow and also stops inflow and outflow of gasses such as methane, $CO_2$, and sulphur oxides.
- Presence of small amount of remaining oil- Initial injection and production of fluid during energy production can have added benefits of Enhanced Oil Recovery (EOR) which can further add to revenue during the operation.
- Depth of the formation- Although reservoir temperature increases with depth which leads to improved power cycle efficiency, it may require additional wells which can significantly increase the capital cost of the project. It is necessary to evaluate life cycle analysis of the project to evaluate the Return on Investment (ROI).
- Formation damage induced during geothermal energy extraction: Changes in reservoir temperature during the operation may lead to changes in geomechanics of the formation (Yuan and Wood, 2018). High flow rates and variability in temperature may lead to plugging of well injectivity due to permeability reduction induced by plugging of clay particles (You et al., 2015). Temperature dependent rock properties also affects the heat recovery, changes in rock stability, seismic properties and fracture propagation during the cyclic operations (Jaya et al., 2010; Kristinsdóttir et al., 2010).
- Steeply slope in the formation can also cause the updip movement of hot water away from the production wells due to buoyancy.

Data on oil/gas reservoirs in California will be collected and analyzed carefully for the suitability assessment.

### 3.3 Case study

Premier Resource Management, LLC is a clean energy developer focused on the conversion of traditional oilfields to reservoir thermal energy storage. Premier's first thermal project - developed over the next 10 years - will support a 400MW clean, dispatchable geothermal power plant on the West Side of the San Joaquin Valley in Kern County, California. The company is led by a team of engineers with over 200 years of experience managing thermal reservoirs in California and throughout the world. PRM's mission is to help California meet its clean energy goals of 100% zero-carbon electricity by 2045.

PRM's project 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 and to ensure that fluids outside the reservoir do not enter into the project system). The process will be configured into three interacting flow loops:

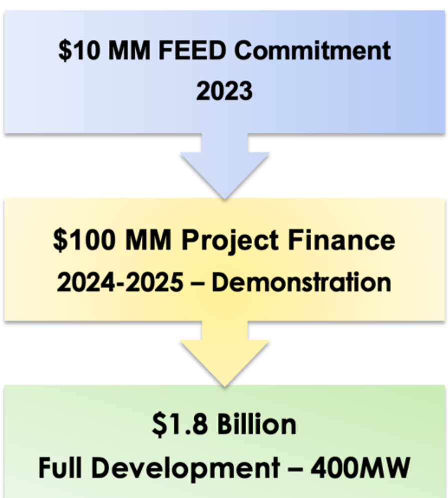
- Reservoir circulation
- Solar heat collection
- Power Generation

Reservoir Circulation: The project will be equipped with multiple producing and injecting wells in a "seven-spot" arrangement. Seven spots typically possess improved reservoir contact and increased lifting capacity where reduced, flow-related pressure drop in the reservoir is desired, when compared to five-spot geometry. The reservoir circulation loop will operate with varying circulation rates depending on demands made by the two other, interacting loops.

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, it being heated to roughly 700F. 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, which will be circulated through a power turbine. When power is demanded by the power grid this loop will command the Reservoir Circulation loop to deliver sufficient heat for power production purposes.

The pilot project will consist of seven, 2½ acre seven spot pattens. Roughly 40 acres of solar collectors will be installed to support the process heating requirement and a 10MW peaking turbine/generator will be installed to generate pilot project sales-power.




| YEAR | ACTIVITY |
|---|---|
| 2022 | GeoTES Simulation & Optimization |
| 2023-24 | Environmental Surveys & Mitigation Planning, Stakeholder Engagement |
| 2023 -24 | Secure Aquifer Exemption (AE) & Underground Injection Control (UIC) |
| 2024-25 | Drill 37 geothermal wells – Phase I |
| 2024-25 | Install 40 Acre Solar Array – Phase I |
| 2026+ | Produce Power, Develop Phase II |

Figure 6. PRM project plan for GeoTES demonstration on the West Side of San Joaquin Valley in Kern County, California.

Challenges in future deployment include and are not limited to:

- State and Federal Agency Communication: interagency memorandums of understanding to provide clear permit pathways and regulatory cooperation.
- Land and location: widespread adoption will require ample surface availability for solar fields.
- Labor: finding available workers and paying prevailing wages.

## 4. GeoTES with heat pump technique hybridization

A techno-economic analysis for CSP with heat pump hybridization is to be carried out by adopting the methodology described in Figure 7. Multiple component models are adopted, which includes:

- IPSEpro software for power cycle simulation and optimization[5]
- ToughREACT/GeoPHIRES for reservoir storage system [6,9]
- Matlab model for economic analysis to calculate financial metrics and perform system sensitivity study.

The suitability study of identified reservoirs and case study sites are described in details below, as the subsurface techno-economic model is same to the one used above for GeoTES with CSP hybridization.

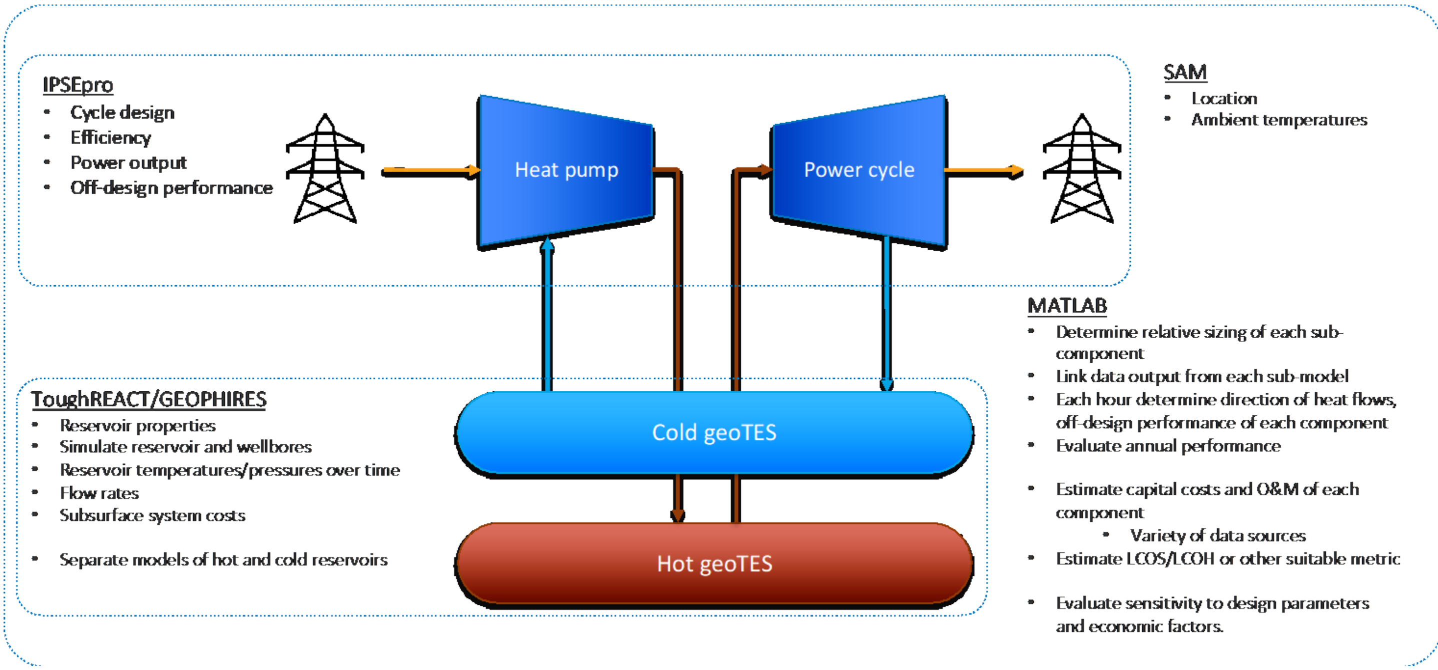



Figure 7: The techno-economic analysis (TEA) model for GeoTES with heat pump hybridization.

### 4.1 Suitability of shallow reservoir

Shallow reservoir data is being gathered on various formations, aquifers, and reservoirs to be used comparatively to evaluate different parameters against each other for the purposes of high-grading 1-2 reservoirs. Parameters of interest include: formation lithology, depth, thickness, temperature, porosity, permeability or hydraulic conductivity, pressure, subsurface area, sulfate content, salinity, TDS, etc.

Focus areas in Texas include all brackish aquifers (15) identified by the Texas Water Development Board in their Brackish Resources Aquifer Characterization System, as shown in Figure 8. Data is being gathered from previous studies, reports, and the BRACS database. Information is also being gathered from Earthbridge Energy on their project locations near El Paso, Houston, and West Texas in order to better characterize them. Other shallow locations include areas that have been investigating or operating Aquifer Storage and Recovery systems where injection of fluids is already understood to be feasible and operational data exists. Such locations include El Paso, San Antonio, and Kerrville, TX.

Rigorous analysis on shallow reservoir suitability will be carried out in a near future.

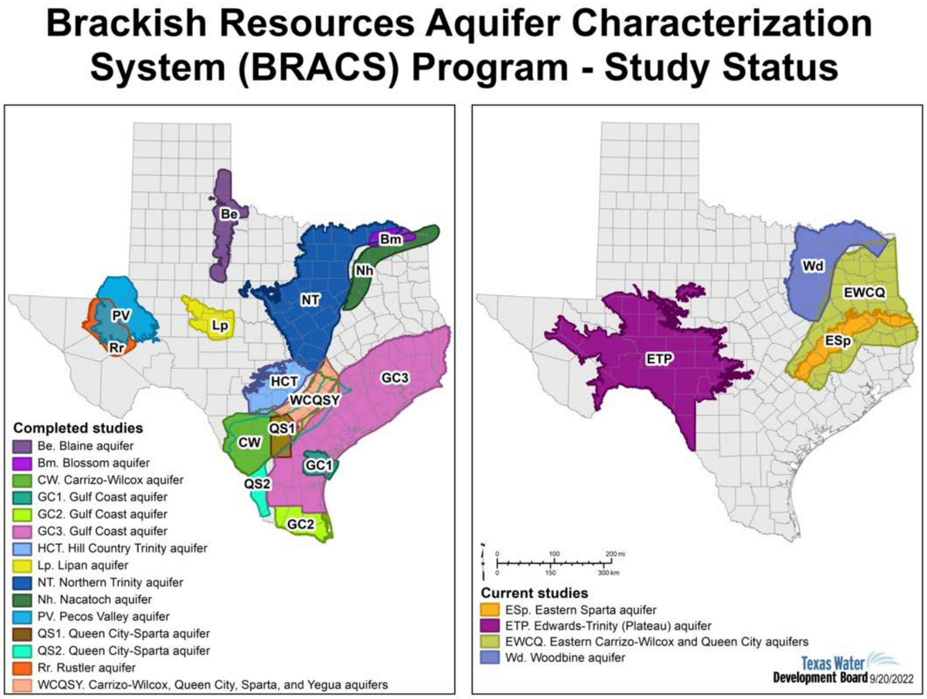



Figure 8. Brackish aquifers (15) identified by the Texas Water Development Board in their Brackish Resources Aquifer Characterization System.

### 4.2 Case study

EarthBridge Energy, a Texas-based geothermal company, is enabling a smooth transition to renewable energy by developing a grid-scale energy storage technology. The GeoBatteryTM uses a subsurface reservoir to safely store waste electricity from wind, solar, or the grid for when power is needed most. Development of this long duration storage technology furthers EarthBridge Energy's mission of achieving a 100% renewable energy future.

The system to be developed works by withdrawing non-potable water (brine) from a subsurface reservoir using a production well. The brine is simultaneously heated and cooled at the surface using an electric heat pump and then injected into a different zone of the same reservoir via hot and cold storage wells. When energy is needed, the flow direction is reversed and the stored brine is returned to the surface where the thermal energy (both hot and cold) is reused to generate power. The brine is never exposed to the surface environment and remains in a closed, air-tight, piping loop at all times. Storage durations ranging from 12 hours to 12 weeks allow the GeoBattery to be paired with solar, wind, or as stand-alone grid-connected storage.

A Commercial Demonstration is planned at our drilling technology partner's well-characterized site, North of Houston, Texas. The MW-scale system will provide storage to the Site using a combination of on-site solar and grid electricity to charge. Existing site infrastructure will accelerate grid-interconnection and project timelines to meet the renewable energy demands of the facility. This demonstration will lay the foundation for large-scale GeoBattery systems planned in West and Central Texas.

Key challenges include adequate subsurface characterization to ensure sufficient brine production rates at each site, sourcing turbomachinery and maintaining a steady supply chain for long-lead items, given current market conditions.

## 5. Conclusions

GeoTES has a substantial potential to provide valuable seasonal dispatching the future renewable dominated energy sector needs. Its hybridization with CSP and heat pump are two technologies to be developed through demonstration projects at pre-identified sites. If successful, it would greatly promote their greater deployment across the US and the world.

**Acknowledgements**

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