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Geologic Thermal Energy Storage (GeoTES) - Technology Demonstration

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ABSTRACT

Concentrated Solar Thermal-Geologic Thermal Energy Storage (CST-GeoTES) works by producing brackish water from a geological formation using a production well. The water is heated by the solar thermal collectors to ~200° Celsius (C) then re-injected into the reservoir via an injection well. Later, the stored hot water is produced and either used directly in industrial processes or converted into electricity.

GeoTES can have extremely large energy capacities in surprisingly small subsurface volumes. For example, a cubic formation with a 275-meter side-length can store enough ~200°C water to drive a 100 MW_e (megawatt electric) power cycle for 1500 hours, or 150 GWh_e (gigawatt-hour electric). Furthermore, the cost of this storage is predicted to be very low – once the wells have been drilled, additional energy capacity is effectively "free". Premier Resource Management (PRM), the project developer, estimates a levelized cost of energy to be \$0.063/kWh_e (kilowatt-hour electric) at full development. Consequently, GeoTES can enable CST systems to manage daily and seasonal variations in energy supply and demand, as well as increasing system reliability by managing unexpected grid events. CST-GeoTES systems will play a critical role in decarbonizing fossil-dependent industries and decarbonizing power generation.

The National Renewable Energy Laboratory (NREL) has developed techno-economic analysis tools of CST-GeoTES designs and systems that hybridize CST and geothermal technologies. PRM has been awarded \$6 million through United States Department of Energy Solar Energy Technologies Office (DOE SETO) to demonstrate CST-GeoTES in Kern County, California. Since 2023, PRM has been engaged in a "geothermal partnership" with NREL, Lawrence Berkeley National Laboratory (LBNL), Idaho National Laboratory (INL), and DOE Geothermal Technologies Office (GTO). This paper will discuss the GeoTES demonstration plan, market for the technology, and state-wide community benefits of GeoTES development in California.

1. INTRODUCTION

Energy storage is increasingly necessary as variable renewable energy (VRE) technologies replace fossil fuels for electricity generation and heating. Recent studies have revealed an increase in curtailment of VRE with increasing VRE contribution, Frew, et al. (2021). This reduces the cost-competitiveness of VRE while contributing to power grid instabilities. Successfully balancing supply and demand across all time periods while maintaining grid reliability with high VRE contribution requires a combination of solutions that includes large-scale deployment of energy storage technologies, Denholm, et al. (2021).

California law requires all electricity sold in the state to come from renewable and zero-carbon sources by 2045, SB 100 (2018). Current renewable energy processes are limited by their ability to only provide electric power during daylight hours or when winds blow. Solar and wind power generating practices destabilize the power grid by overproducing power during the middle of the day and by forcing other base-load power plants off of the power grid. In 2023, solar and wind combined to provide 55,264 GWh (gigawatt-hour) of power to California, meeting 25.6% of demand, while nuclear and geothermal provided a combined 28,713 GWh of baseload power (13.2% of the power demand). With these circumstances, California depends heavily on natural gas power generation for demand response, with natural gas supplying 94,192 GWh to meet 44% of the state's demand, California Energy Commission (2023).

Furthermore, there are significant seasonal variations in renewable energy supply and electricity consumption; for example, wind, solar, and hydro generation are all reduced in the winter in California (see Figure 1). Delivering winter loads directly with VRE generators requires a significant overbuild, leading to curtailment in the summer. To displace fossil-fuel power generation, energy storage technologies need to be able to provide demand response over a range of time- scales – e.g. from hourly to seasonal. Lithium battery energy storage solutions under development address short discharge durations, 2-4 hours.

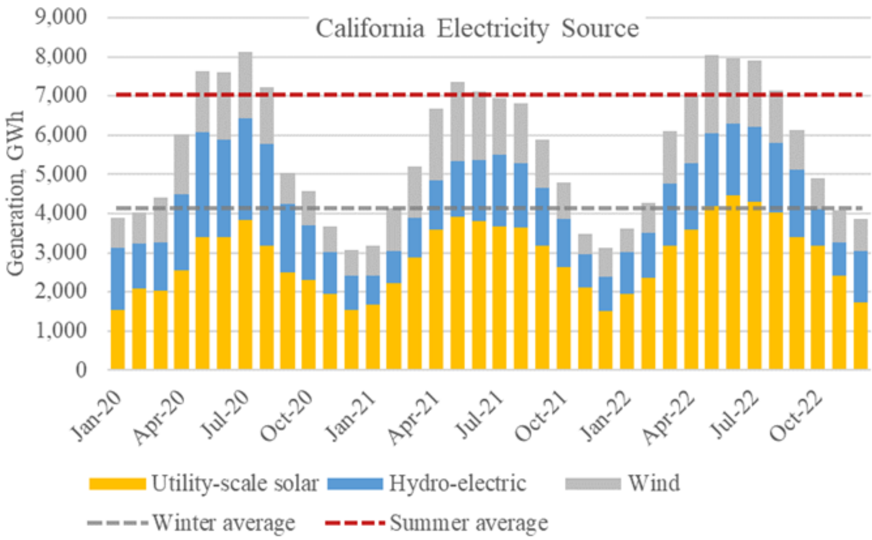

Figure 1: Variable renewable electricity generation in California demonstrates seasonal variations.

Lithium battery storage also must account for the environmental impacts associated with the exploration, mining, processing, and manufacturing of batteries. Not to mention, the largest lithium battery storage facility in the world located at Moss Landing in California has experienced no less than three major fires. The environmental fallout from the most recent fire at Moss Landing includes elevated heavy metals concentrations in neighboring protected marine ecosystems and agricultural farms, Cervantes Jr. et al. (2025). The Moss Landing lithium battery storage fire comes on the heels of a spree of three such fires at different facilities across Otay Mesa and Escondido in San Diego, California, Menezes (2024). As a result, concerned citizens are questioning environmental rules which favor application of lithium battery storage projects while apparently not seeking safer grid storage technologies, Harter (2025). Seasonal energy storage technologies must be safe for the environment, have extremely large energy capacities, and very low costs. This apparently is a challenging proposition for lithium battery storage.

Successful demonstration of GeoTES will meet the aforementioned challenges. Thermal energy produced by a concentrating solar thermal (CST) system can be stored in permeable reservoirs such as aquifers, Zhu, et al. (2023), and depleted hydrocarbon reservoirs, Berger, et al. (2024). Hydrocarbon reservoirs offer distinct advantages to aquifers. Hydrocarbon reservoirs are defined by virtue of the fact that hydrocarbons have been trapped in a geologic formation. This ensures the presence of a "container" which can be heated without suffering potential leaking and heat loss. Discovered hydrocarbon reservoirs do not require exploration and associated costs which add risk, expense, and time delays to find usable aquifers. These systems can store vast quantities, thousands of terawatt-hours thermal (TWh_{th}) of thermal energy which can later be converted into electricity. Once the GeoTES system has been created, it can deliver power with great flexibility. For example, it can manage daily variations in power supply and demand (3-8 hours), as well as storing quantities of energy that are sufficient for seasonal storage (over 1,000 hours).

1.1 Historical Foundation for GeoTES

The historical foundation for GeoTES systems was developed by the thermal-enhanced oil recovery business, starting in the 1960's. That work, which defines the ability to store and recover heat from a reservoir, shows that heated rocks as reservoir sands will very effectively store that heat until it is called for. For example, reservoirs which were heated in steamfloods in California, where fluids were no longer being extracted, retained more than half of their elevated temperatures for more than a decade. This retention of heat verifies the effective insulative properties of surrounding sands of reservoirs which can be used for GeoTES purposes. We estimate that reservoir heat losses approximate 0.0014% per day once the reservoir has reached its planned temperature, making the repetitive delivery and recovery of heat to a reservoir an almost perfect heat storage process, Berger et al. (1991). Other losses associated with the PRM GeoTES demonstration project include losses of heat through insulated pipes used in carrying solar-heated heating fluids and produced reservoir fluids. These losses amount to about 4% of the entire thermal process in winter conditions (less in summer conditions).

1.2 The Case for Long Duration Energy Storage

Renewable energy is inherently intermittent. Solar power, for example, generates energy from the Sun for only 6–8 hours per day in winter and 12–14 hours per day in summer. Cloudy weather events can obscure sunlight for hours or days. Winter storms, particularly during El Niño or La Niña cycles, can produce extended periods of low solar generation, lasting days or even weeks. These interruptions highlight the importance of robust energy storage solutions to ensure grid reliability.

Current deployments of lithium batteries are limited to discharging energy over short durations, typically 2–4 hours. This is insufficient to address extended periods of low renewable generation. Long Duration Energy Storage (LDES) technologies are critical for future planning, as they can sustain energy output for days to weeks. As the share of renewable energy grows, the need for LDES becomes increasingly urgent. The Energy and Research Development Division of the California Energy Commission (CEC) explained "approximately 70 GW of 8-hour storage will be beneficial and may be cycled more than 300 times per year" under simulated emissions scenarios, California Energy Commission (2024). The CEC emissions scenarios find added benefit to 100-hour storage solutions throughout the year. GeoTES aligns with all categories from figure 2, save for wind, while providing safe, low-cost power that aligns with demand in all scenarios.

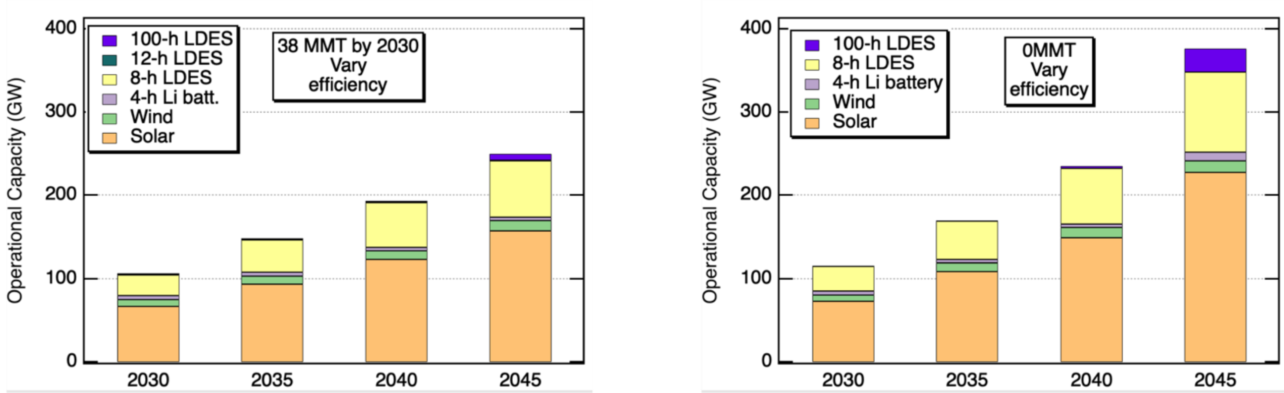

Figure 2: Capacity expansion for two emissions scenarios.

1.2.1 GeoTES Characteristics

GeoTES is designed to mitigate these challenges by operating for durations ranging from 5 to 1,000 hours, effectively covering most seasonal weather events. By providing long-term energy storage, GeoTES ensures grid stability and renewable energy integration even during prolonged periods of low generation. Key Features:

1. Duration: Supports energy supply for weeks, months, or longer, bridging gaps in renewable energy production caused by seasonal or weather-related disruptions.
2. Scalability: Enables integration with large-scale grids and industrial operations.
3. Versatility: Addresses applications such as grid balancing, renewable integration, backup power, and industrial energy demands. Also adding grid stabilizing rotating storage in the form of steam turbines/generators.
4. Efficiency: Minimizes energy losses over extended storage periods.

2. THE TECHNOLOGY DEMONSTRATION PROJECT IN WEST KERN COUNTY, CALIFORNIA

The goal of this project is to demonstrate daily and long duration storage for CST-GeoTES. CST-GeoTES works by producing brackish water from a geological formation using production wells. The water is indirectly heated by the solar thermal collectors (to ~200°C, much like a pressurized water reactor nuclear power plant) and then re-injected into the reservoir via injection wells. Later, the stored hot water is produced and either used directly in industrial processes or converted into electricity.

GeoTES can have extremely large energy capacities in surprisingly small subsurface volumes. For example, a cubic formation with a 275m side-length can store enough ~200°C water to drive a 100 MW_e power cycle for 1500 hours (150 GWh_e). Furthermore, the cost of this storage is predicted to be very low – once the wells have been drilled, additional energy capacity is effectively "free." PRM estimates a levelized cost of energy to be \$0.063/kWh_e at full development. Consequently, GeoTES can enable CST systems to manage daily and seasonal variations in energy supply and demand, as well as increasing system reliability by managing unexpected grid events. CST-GeoTES systems will play a critical role in decarbonizing fossil-dependent industries and decarbonizing power generation.

2.1 Proposed Technology

A thermal energy storage (TES) system to facilitate daily and seasonal energy management for Concentrating Solar Thermal (CST) installations - Figure 3. The project comprises the following goals:

1. Install a >100 kWe demonstration power plant with >12 hours storage, using a concentrated solar thermal field.
2. Demonstrate the storage and recovery of solar heat in the GeoTES and deliver electrical power.
3. Create community benefits: local jobs and manufacturing to disadvantaged communities, clean and affordable power, reliable energy storage.
4. Conduct techno-economic analysis for a full-sized deployment of CST-GeoTES.

PRM's has available reservoirs for commercial CST-GeoTES development expansion up to ~400 MWe.

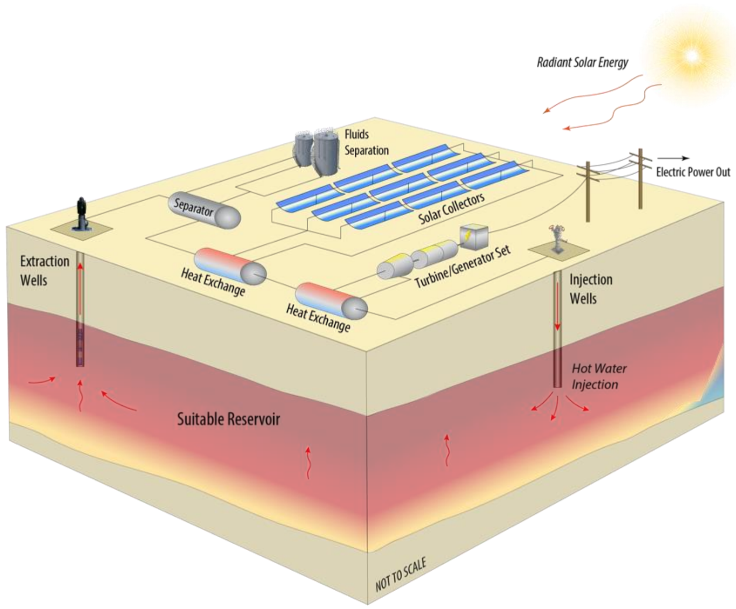

Figure 3: GeoTES layout.

2.1.1 Overview of CST-GeoTES demonstration site

- Location: PRM's 560-acre lease in Kern County, California.
- Production wells (2) and injection wells (6) will be drilled into Eocene Point of Rocks (POR) a porous and permeable sandstone, roughly 1,200-feet deep and target the upper 200-feet for the CST-GeoTES process, forming a 0.2-hectare fluids circulation geometry.
- Produced fluids will be processed to separate the various produced fluids.
- A 2 MWth parabolic trough collector system will heat a silicone heat transfer fluid (HTF) to 320-370°C.
- Heat will be transferred from the silicone heat transfer fluid to the produced fluids in a heat exchanger.
- The heated, pressurized water will be reinjected into the POR formation.
- The heated fluids produced from the GeoTES pattern will go through the fluid separation system to remove contaminates.
- Once the reservoir fluids are sufficiently heated the hot produced fluids will provide the heat input to a 100 kWe power cycle via a heat exchanger to provide electricity, prior to the produced fluids' reinjection into the POR formation.

2.2 Details of the Well Pattern(s)

- This demonstration system will have six injection wells and two production wells in a half-acre 7-spot configuration with an additional producing well for project reliability. Observation wells will be drilled as needed.
- The demonstration system encompasses an area of 3-5 acres on surface. The wells will be 'directional' meaning that the well heads can be located on a common drill site.
- The PRM GeoTES project scope will be increased in several expansion stages in the future to achieve power production of ~400MWe.
- The geological formation is an oil containing reservoir, and small concentrations of oil (at most, 50 barrels of oil per day is anticipated to be produced over the life of the first demonstration project) will be produced in the first 15 years of the project. The peak hydrocarbon production is not expected to exceed 2.6% of the circulating fluid flow rate.

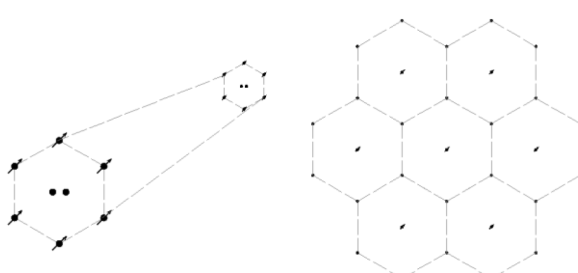

Figure 4: GeoTES demonstration project with ½ acre pattern (left) and commercial expansion with seven 2½ acre patterns (right) showing relative sizes.

2.3 Details of CST System

The solar collector manufacturer, Gossamer Space Frames, will deliver a 2 MW_{th} array of the QUASAR Large Aperture Trough (LAT). A 2 MW_{th} array has four rows of solar collectors, and each row is known as a Solar Collector Assembly (SCA). Each SCA has 12 elements called solar collector elements (SCE), and each SCE comprises 12 reflectors – requiring a total of 1356 reflectors (including spares). This design has several expected benefits over the state-of-the-art. Gossamer has deployed successful designs of each trough size Gossamer RP-2 and RP-3 trough designs populate the solar fields of six utility-scale power plants. Gossamer has constructed four demonstration loops for the LAT 7.3 that have validated the innovation pathway. The new QUASAR will build on this success. Gossamer's systems are made in the United States of America.

2.4 Reservoir Heating

The demonstration project is configured, as described, above, to achieve rapid heating of a small portion of the reservoir rock, to allow rapid application of the technology upon demonstration of success.

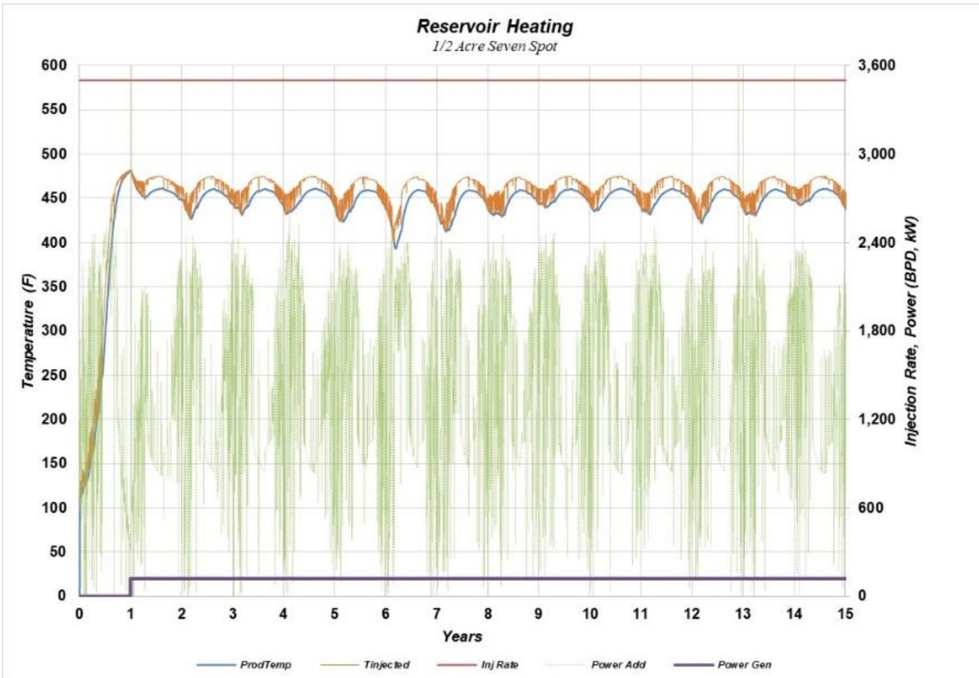

Figure 5: Demonstration project anticipated performance.

The demonstration plan uses historical NREL solar irradiance data which demonstrates the impact of solar variability on the process at the planned development site. The initial plan is to achieve heating of the formation to usable temperatures within roughly nine months, as shown in Figure 5. True project performance should demonstrate this expected heating timeline, modified for actual project circulation and heating performances (i.e., reservoir circulation rates, circulating pressure drops, actual irradiances, etc.). It will be important in this process that fluids flowing in the reservoir remain in the "diffusion" flow domain. Fracturing the reservoir will ensure that the process will fail, so close monitoring and managing of the circulating reservoir fluids so as to avoid fracturing will be one of the key commitments for success. Heating rate will also demonstrate the effectiveness of the rock heating process; poor contact of the rock will result in faster heating, and will result in reduced heat storage.

3. LOCATION AND SITING CONSIDERATIONS

For CST-GeoTES to be viable, suitable geology must exist in regions of high solar irradiance. California provides an excellent intersection of solar irradiance and sedimentary formations (which are suitable for GeoTES based on its depth, thickness, porosity, permeability, and lower cost of drilling). PRM's location has solar irradiance of 2,614 kWh/m^2 (kilowatt-hours per square meter). An abundance of data is available from the large number of oil and gas wells drilled in these areas which helps to reduce exploration costs. Moreover, these formations are prevalent across the USA. Results indicate there are a large number of suitable reservoirs at shallow depths that could provide a significant portion of peak California demand. The project engineers calculate as much as 100GW_e could be generated from California's legacy oil fields if converted to GeoTES.

The exploration costs for finding suitable formations can be reduced by using data from depleted or under-developed oil fields which tend to have suitable characteristics for GeoTES. Such fields will produce small quantities of oil (relative to their peak) in the early stages of operation, although any oil produced will have a lower carbon intensity than that produced by conventional means. GeoTES conversion of extant oilfields offers environmental benefits through decarbonization and redevelopment of disturbed oil field land (and idle wells) for a zero-emission power production process.

3.1 GeoTES Technology Demonstration Site

PRM's GeoTES technology demonstration will be developed on the west side of the southern San Joaquin Valley in Kern County, California. Located approximately three miles west of Highway 33 "Petroleum Highway," this region is known for expansive oil field operations that have been developed for nearly 130 years. The GeoTES technology demonstration will convert land that is already disturbed by oil field operations, resulting in no environmental impact.

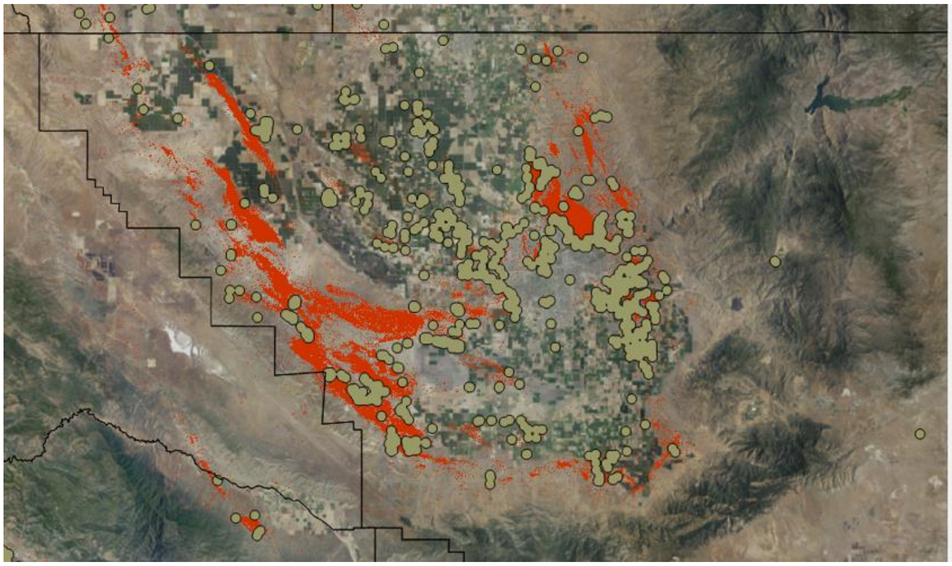

Figure 6: Oil and gas wells (red) in the southwest San Joaquin Valley with health protection zones (green/black outline).

3.2 No Environmental Impact

PRM's GeoTES technology demonstration is far removed from communities and health protection zones which were recently defined by Senate Bill 1137 in California. Situated among existing oilfields and thousands of existing oil wells, PRM's GeoTES project offers a roadmap to decarbonize the oil industry. As a responsible operator, PRM has abandoned idle wells that were orphaned by prior operators. While most oilfield operations in this region require natural gas as a feedstock for steam generators, GeoTES is a zero-emission synthetic geothermal process that can be applied across the legacy oilfields. This offers a true transition of legacy fossil processes. Additionally, GeoTES will only use and reuse brackish water from depleted oil reservoirs that is not suitable for agriculture or human consumption.

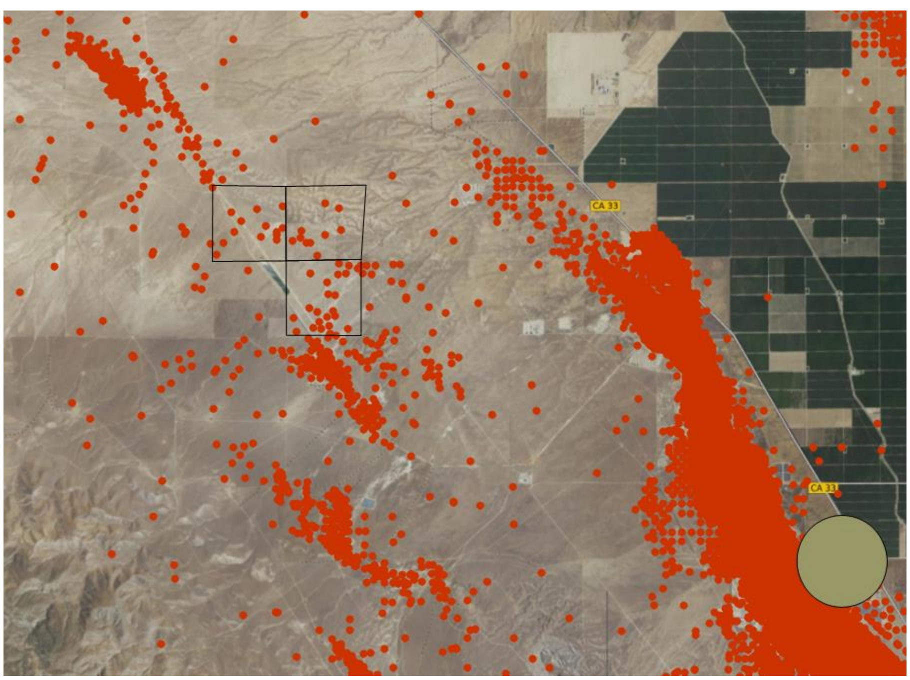

Figure 7: PRM's lease in Antelope Hills within the area outlined in black, with oil and gas wells (red) and the nearest health protection zone approximately 6 miles away (green with black outline).

4. ECONOMIC IMPACTS

The capital cost of the thermal storage component comprises two parts: (1) a cost of power capacity by kilowatt-thermal ($\$/kW_{th}$) and (2) a cost of energy capacity ($\$/kWh_{th}$). Like most long-duration energy storage systems, GeoTES is characterized by a high-power capacity cost and a low energy capacity cost. The number of wells and their allowable flow rate limits the rate at which thermal energy can be injected and produced from the GeoTES system. Therefore, the power capacity cost depends on the number and depth of the wells, the wells' capacity, and their pumping requirements. NREL's calculations in Figure 8 indicate that these costs can be substantial – especially for deeper geological formations, although these costs are amortized over the long-life of the storage system – up to 100 years, Akindipe, et al. (2024). Power capacity costs can potentially be reduced by re-purposing idle oil and gas wells. PRM intends to use a formation that is roughly 1,200 feet deep, which our analysis shows correspond to a power capacity cost of ~$350/kW_{th}$, or when used to produce electric power, ~$1,700/kW_e$ (for comparison, the most recently construct USA constructed nuclear power plants, completed in 2023 and 2024, have a capital cost of ~$15,000/kWh_e$). Moreover, drilling into sedimentary basins greatly reduces drilling costs compared to traditional geothermal systems.

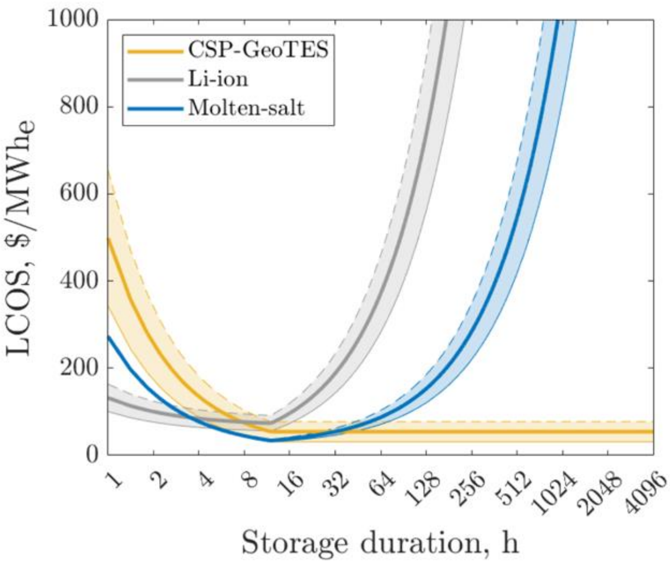

Figure 8: NREL's Calculation of LCOS

The remaining further demand for power, in the desert conditions found at PRM's site, will be an additional steam turbine discharge surface condenser power load of another 1MW, demonstrating a parasitic power load of ~15% of plant output, consistent with similar power plants using comparable power production methods.

It is important to emphasize that CST-GeoTES power is not merely a storage application but a firm, zero-emission renewable power source capable of providing additional power for grid stabilization when other renewables are offline. While CST-GeoTES integrates reservoirs for storing solar-gathered heat to enable process time-shifting, this characteristic is inherent to its design rather than a secondary feature. Its function is more akin to conventional power plants storing fuel onsite—whether coal piles, liquid fuel tanks, or fissile fuel rods—rather than a dedicated energy storage system.

Unlike lithium-ion battery storage, which primarily shifts renewable generation capacity to peak demand periods, CST-GeoTES provides firm, dispatchable power directly. This allows it to complement intermittent sources like solar photovoltaics and wind, ensuring continuous power delivery without requiring fossil fuel backup.

Moreover, integrating CST-GeoTES with existing thermal power infrastructure facilitates a seamless transition from fossil-based generation to renewable thermal energy. This approach leverages existing turbine technology and grid connections, enhancing both scalability and economic feasibility, particularly in industrialized regions such as California's Kern County.

By positioning CST-GeoTES as a renewable baseload alternative, the system supports the broader energy transition goals of reducing greenhouse gas emissions, enhancing grid reliability, and repurposing existing oilfield infrastructure for clean energy applications.

4.1 GeoTES Process Longevity

Enhanced recovery processes have been employed by the oil industry for decades (nearing 100 years), with few process-induced failures. Oilfields stop yielding profits which ultimately results in the termination of said processes. Nonetheless, given the stable operation of reservoirs planned for GeoTES service, we anticipate that GeoTES reservoirs can be continuously employed in this service for at least 100 years without process or reservoir integrity deterioration.

4.2 Levelized Performance Metrics

Questions arise regarding the levelized performance metrics of the CST-GeoTES power systems. These values are calculated to be ~\$0.06/kWh$_e$ and ~\$0.01kWh$_{th}$ for the commercial project. However, it is important to recognize several caveats regarding levelized cost calculation assumptions:

- These determinations are made for investment decisions.
- Any such investment is independent from the system into which the investment is made.
- For electric power systems the power produced or energy stored is fungible.
- Costs are being evaluated as being equivalent to investments, as in discounted cash flow return on investment determinations.

These assumptions fall short in evaluating electric power projects. Starting with the independence of the investment decision, as demonstrated by the California power grid, investment in solar photovoltaic systems has resulted in an econometric shift in the stability of the power grid. This forces export of power onto neighboring states' grids and local dispatch of power generation. Thus, decisions to invest in powerplants cannot be made using any assumption of installed system independence from grid limitations and the associated econometrics. This point is further amplified through the realization that California photovoltaic and wind power has destabilized the grid, grossly modifying the value of that power, clearly showing that time of day power production is one factor in demonstrating the non-fungibility of electric power generating projects.

Application of levelized cost metrics in public policy decisions assume the independence and fungibility are operative. Yet, it is essential that system output durability in various forms (e.g., time of day stability, impacts to the power distribution grid, seasonal impacts of weather in meeting voter expectations for a stable grid) be key to effective grid management. Erroneously using the concepts of independence and fungibility has led to many base-loaded systems being crowded out of the power grid by photovoltaic and wind power, creating serious grid stability management problems.

5. COMMUNITY BENEFITS

The demonstration system, and subsequent development of CST-GeoTES technologies will provide high-quality, high-paying jobs that require similar skills to transitioning oil and gas workers. The oil and gas workforce in Kern County, CA has been severely impacted by industry-wide layoffs as local oil production is phased out. CST-GeoTES will be a transition lifeline to a fossil-dependent community in need of clean energy developments and job growth. PRM will support community-based organizations, local contractors, employer outreach organizations, and workforce development boards. PRM's GeoTES development will have a significant positive impact on local disadvantaged communities considered to be underserved by Justice40 metrics. The majority of Kern County is designated as 'disadvantaged community', PRM views CST-GeoTES as an opportunity to renew prosperity in the community through high paying jobs that exceed \$85,000 per year in annual salary with an oil and gas work force that is over 51% Hispanic, Oviatt, et al. (2021). PRM is committed to strengthen this community.

5.2 Workforce Characteristics

PRM has a history of contracting with independent contractors in Kern County that are often woman-owned, minority-owned, veteran-owned, and disabled-owned businesses (or combination of). Nearly all of PRM's vendors are headquartered in the region. PRM has support from West Kern Environmental, an environmental service provider that has completed biological studies at this location. West Kern is a small family business that is Hispanic and woman-owned. PRM also contracts with General Production Service, which is woman-owned and employs approximately 600 people that include over 70% Hispanic work force and second chance individuals. Companies like GPS and West Kern are fossil dependent and need technologies like GeoTES to maintain work in legacy oil fields. These two companies, along with a myriad of other service providers, will work on this PRM demonstration project which will generate well over 200 jobs for the local community while the project is being developed.

California Labor Market's data shows Kern County's unemployment rate has jumped from 6.4% in November of 2022 to 7.8% in November of 2023. This figure includes recent job losses of over 200 in the mining sector and is double the national average unemployment rate of 3.7% reported in December of 2023 by the U.S. Bureau of Labor Statistics. Workers in California's oil and gas sector are facing an abrupt halt to permitting and work associated with new development, despite the oil and gas industry accounting for over \$9 billion per year in economic impact to Kern County, Oviatt, et al. (2021). Over 24,000 direct energy jobs are at risk in Kern County; we need CST-GeoTES job creation. Future commercial application of this technology will likely require ~5,000 full-time workers dedicated to the construction of plants around the San Joaquin Valley and require ~1,000 full-time operating personnel for distributed plant operations, sourced from disadvantaged communities.

5.3 Accessibility & Energy Equity

The project team believes accessibility and energy equity will be the cornerstones of this demonstration. CST-GeoTES systems will directly compete with fossil-fired power generation by reducing reliance on natural gas peaking power plants. PRM's demonstration will also reveal attributes of accessibility and affordability. PRM will conduct a site-specific environmental impact report through Kern Planning as dictated by the project's future expansion. PRM's CST-GeoTES will not encroach on farm lands, community lands, or disturb any surface that is not offset by a land banking procedure. PRM's remote location within existing oil fields offers a transition project that is responsibly sited. As part of the TEA modelling, case studies will be defined with the objective of evaluating the benefit that CST-GeoTES can provide to underserved communities by job creation and reduced pollution. Results will be published in open-access journals.

5.4 Workforce Development

The PRM team will work with both unions and independent service companies to supplement their existing training programs with additional information and training needed to enable workers to make the transition to this promising career path. Ultimately, the objective is to add clean energy jobs and offer prevailing wages to the local community that is disadvantaged and low-income. Recruitment and educational materials will be made available in multiple languages to ensure we reach all community members.

PRM is also engaged with Taft Oil Tech Academy at Taft Union High School, Taft College, California State University at Bakersfield, and University of California at Berkeley to educate students on CST-GeoTES as a growth opportunity for careers in clean energy. PRM has guest lectured at these institutions and participated in workforce development seminars in preparation for the demonstration project and future expansion of the technology.

6. NREL TECHNO-ECONOMIC ANALYSIS

NREL has developed techno-economic analysis tools of CST-GeoTES designs, McTigue, et al. (2023), Sharan, et al. (2023), Zhu, et al. (2023) and systems that hybridize CST and geothermal technologies, McTigue, et al. (2018, 2020). Software records have been submitted for these tools and numerous journal articles and conference proceedings published. These tools will provide clarity and guidance in the future for considering application of CST-GeoTES, and NREL will continue their development, as well.

7. TRANSITIONING LEGACY OIL FIELDS TO GEOTES PRODUCTION TO REDUCE GREENHOUSE GAS EMISSIONS

California's clean energy policies, such as The Global Warming Solutions Act of 2006 (AB 32) and SB 100 (100% Clean Energy Act), aim to reduce greenhouse gas (GHG) emissions and transition the state to renewable energy sources. GeoTES embodies these goals by hybridizing CST technology and reservoir thermal energy storage within legacy oilfields. This innovative approach reduces GHG emissions while utilizing existing oilfield infrastructure, making it a sustainable and transitional solution for the energy sector.

7.1 GHG Accounting from GeoTES versus Foreign Oil Imports to California

While oil recovery is not the true goal of GeoTES, oil is a byproduct by virtue of using legacy oil reserrvoirs as thermal storage containers. The application of CST-GeoTES in oilfields, especially those fields which are nearing end of life, will result in further economic recovery of residual oils due to the protracted operation of the CST-GeoTES process. Importantly, the use of CST-GeoTES in oil recovery, will produce oils having some of the lowest carbon intensity scores known.

GHG emissions from crude oil depend on various lifecycle factors:

1. **Extraction** – The energy and emissions involved in removing oil from the ground.
2. **Flaring by foreign producers** – The release of volatile gases during production.
3. **Transportation** – Emissions from shipping crude over long distances.
4. **Refining** – The energy-intensive process of converting crude into usable products.

Currently, California imports 84% of its crude oil, primarily from countries like Iraq, Saudi Arabia, and Ecuador. This shift away from domestic production contributes significantly to GHG emissions due to the lifecycle impacts of imported oil. In contrast, California crude historically has some of the lowest Carbon Intensity (CI) scores globally due to stricter environmental regulations and cleaner extraction methods.

7.2 Carbon Intensity: Comparing Antelope Hills (CA) Crude to Imported Crude from Iraq

We compare crude oil produced at PRM's Antelope Hills field versus California's largest source of foreign crude, Iraq, California Energy Commission (2023).

Table 1: Carbon Intensity (CI) Comparison of Antelope Hills (CA) and Iraqi Crude in (gCO_2e/MJ)

Emission Item	Antelope Hills (CA)	Iraq (with flaring)
Upstream Extraction*	2.84	82.6
Transportation**	8.5×10^{-9}	2.41
Refining**	7.5	8.5
Total Lifecycle CI	**10.34**	**93.51**

*Antelope Hills data from California Air Resources Board, Low Carbon Fuel Standard (2022). Iraq data from World Bank (2024), Organization of Petroleum Exporting Countries (2023), Oil and Gas Climate Initiative (2023), CEIC (2021), California Energy Commission (2023). Iraq flaring accounts for released gases such as methane, ethane, propane, butane, sulphur.

**Transportation and refining data from California Air Resources Board Greenhouse Gas Inventory (2023).

California's local crude, such as from PRM's Antelope Hills oilfield in Kern County, has a significantly lower lifecycle CI compared to imported crude oil. The use of CST in the GeoTES process further reduces emissions by replacing natural gas used for process heating with renewable solar energy, as well as transitioning away from traditional Steamflood methods.

7.3 The Potential Impact of Prioritizing Local Crude Production

If California were to increase local crude production and displace 100% of foreign Iraqi crude, the state could eliminate 53 million metric tons of CO_2e annually, California Energy Commission and California Air Resources Board (2023). This represents a major opportunity for GHG reduction while maintaining energy independence and reducing reliance on high-carbon-intense and methane-intense imports. California oil production moved by oil pipelines emits very little GHGs while imported crude oil arrives on pollutant-spewing tanker ships. "The twin ports of Los Angeles and Long Beach are the largest in the nation as well as the single largest fixed source of air pollution in Southern California. Collectively, sources at the port are responsible for more than 100 tons per day of smog- and particulate-forming nitrogen oxides – more than the daily emissions from all 6 million cars in the region," South Coast Air Quality Management District (2024).

7.3.1 Flared Gas Regulations in California Versus Foreign Imported Crude

California has historic precedence dating back to 1939 that restricts flaring and venting of natural gas implicitly, "all persons, firms, corporations, and associations are prohibited from willfully permitting natural gas wastefully to escape into the atmosphere," U.S. Department of Energy (2017). Meanwhile, Iraq routinely flares nearly 18 billion cubic meters of methane, ethane, propane, butane, and sulphur in poorly combusted flared gas protocols, enough gas to power ~20 million homes annually in Europe, OGCI, Pinwell, et al. (2023). According to World Bank data, the Rumaila oil field in Iraq has the highest documented levels of flaring in the world (2023). "Iraqi Environment Minister Jassem al-Falahi has acknowledged that pollution from oil production is the main reason for increases in local cancer rates," Stallard (2022). California's regulatory agencies should immediately act to reduce foreign oil imports.

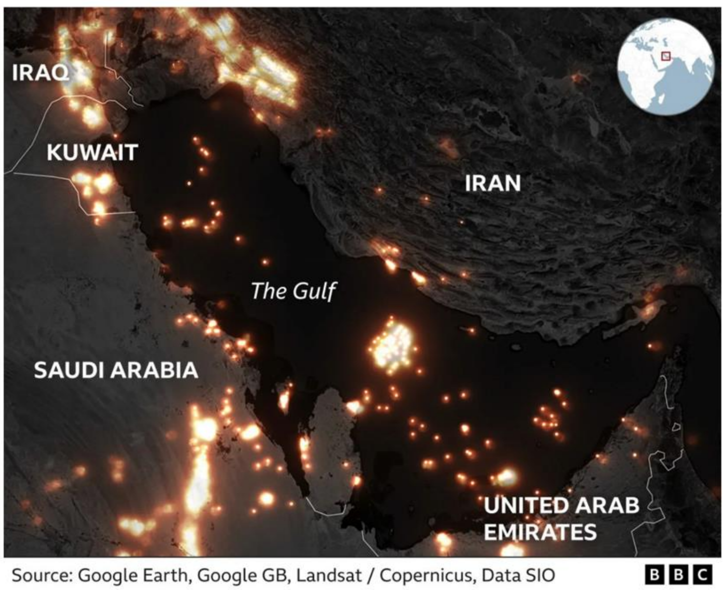

Figure 9: Gas flaring across the Gulf region from oil drilling and gas capture sites. California imported 120 million barrels of oil from Iraq and Saudi Arabia, top two sources accounted for ~38% of California's imported oil (CEC, 2023)

7.4 Broader Implications of the Decline in California Oil Production

- **Environmental Impact**: While California's policies aim to reduce GHG emissions, the heavy reliance on imported crude offsets much of these gains due to the higher carbon intensity of foreign oil.
- **Economic and Energy Security**: The decline in local production has economic repercussions, including job losses and increased vulnerability to global oil price fluctuations. Solar GeoTES addresses these challenges by providing renewable energy jobs and stabilizing local energy supplies.
- **Policy Alignment**: Solar GeoTES aligns with AB 32 and SB 100 by providing clean, renewable energy while repurposing existing infrastructure to minimize environmental disruption.

California Air Resources Board published the *2022 Scoping Plan for Achieving Carbon Neutrality* which states "a complete phase out of oil and gas extraction and refining is not possible by 2045" due to continued demand for aviation fuel, gasoline, and diesel. California also exports finished products to surrounding states, providing Nevada with 85% of its liquid fuels and Arizona with 40% of its supply. The Scoping Plan further explains, "any crude oil demand by California refineries not met by California crude oil will be met by marine imports of Alaskan and foreign crude." This will result in a two- to five-fold increase in the number of tankers delivering product to marine terminals, previously mentioned as the largest source of pollution in the region, California Air Resources Board (2022).

8. CONCLUSIONS

- The CST-GeoTES technology demonstration is a combination of known technologies, integrated in a novel process.
- CST-GeoTES is not a "true" energy storage process, but more akin to a renewable power generation process with a large "fuel tank", well suited to peaking, dispatchability and seasonal power demands, as is being required for complete transition to renewable electric power production.
- CST-GeoTES aligns with AB32, SB100, and clean energy goals.
- Application of this technology supports local jobs and disadvantaged communities
- Application of this technology supports local manufacturing and reduces reliance on foreign oil, mineral supply chains, and foreign-made batteries
- The use of "levelized" metrics are of marginal value as currently employed, and are not appropriate to use in public policy. Current policies and associated metrics are creating and exposing a fragile grid while impacting all ratepayers with ever-increasing utility costs.
- Clean, affordable, reliable energy can be achieved with GeoTES, with integral long duration energy storage potential (1,000 hours).
- Transitioning oil fields in Kern County to CST-GeoTES offers the potential for 100GW of electric power in both dispatchable and seasonal support services, to supply all of California's electrical needs, with a power/emissions production performance equivalent to nuclear power plants, but in much shorter time periods and lower costs.
- Any crude oil produced as a byproduct of CST-GeoTES in Kern County will be among the lowest carbon intensity products in the world, providing a pathway towards decarbonization that aligns with the California Environmental Quality Act.

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