Geologic Thermal Energy Storage (GeoTES) Using Shallow Subsurface Aquifers

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ABSTRACT

Long-duration energy storage can provide key economic, grid, and environmental benefits. Excess energy from variable renewable energy sources can be delivered to Geologic Thermal Energy Storage (GeoTES) systems utilizing permeable shallow reservoirs and associated vast formation storage capacities and heat storage efficiencies. GeoTES systems utilizing shallow aquifers are abundant in Europe. However, there is a general lack of awareness and knowledge of the viability of GeoTES in aquifers in the United States. Through this study, we identify a path forward for investigating many of these systems throughout the country to provide needed energy security and resiliency. GeoTES offers a means to shift power/heat generation from the summer to the winter and vice versa, as well as shorter durations (diurnal, weekly, etc.). In 2022, the U.S. DOE Geothermal Technologies Office (GTO) Data, Modeling, and Analysis (DMA) Program released a call for Geothermal Hybrid Power Analysis. This paper describes the initial stages of a project led by the National Renewable Energy Laboratory and supported by Idaho National Laboratory and Lawrence Berkeley National Laboratory which focuses on the technoeconomic analysis (TEA) and market potential of GeoTES using solar thermal and heat pumps as the thermal source. By investigating how shallow aquifers can be coupled with concentrating solar power (CSP) and renewable electricity using heat pumps, the understanding of these types of systems is growing and the possibilities they offer to the deployment of geothermal-type technologies in non-traditional regions are expanding. Because Texas and California are experiencing increasing energy demands, fluctuations, and crises, we focus on aquifers in those states for storing heat/cold energy.

In the initial stages of the project, we have performed preliminary characterization of subsurface formations and their associated thermo-hydrogeologic parameters to understand the suitability of storing excess energy in aquifers to provide building/industrial heating and cooling. Datasets from state, national, and private entities have been compiled into a shallow aquifer database for subsequent thermo-hydrologic (TH) and TEA modeling. Fifteen shallow non-potable (saline and/or brackish) aquifers in Texas and numerous in central California have been identified as potential locations for investigating GeoTES suitability in aquifers. Potable water sources are

being excluded from this study for regulatory and water availability concerns. Generated datasets including aquifer porosity, permeability, temperature, depths, chemistry, lithology, mineralogy, among others are being incorporated into reactive transport models to show long-term suitability of GeoTES operations linked to CSP and renewable energy generation systems.

1. Introduction

The world is experiencing energy challenges in many forms as we move to a decarbonized energy future. Variable renewable energy (VRE) generation technologies such as wind and solar provide ample amounts of electricity but only in certain geographic locations and when resources are present. This has led to the famous duck curve described by many authors (Denholm, et al., 2008, Denholm et al., 2015, CAISO, 2013) In order to bridge the gap and provide energy when and where it is needed, energy storage is not just essential but imperative. The U.S. Department of Energy (DOE) has established the Energy Storage Grand Challenge (US DOE, 2020) that defines a set of solutions guided by an overarching goal to develop and domestically manufacture energy storage technologies that can meet all U.S. market demands by 2030. In this challenge, the DOE identifies and is interested in advancing the market in areas such as electrochemical batteries, as well as magnetic, mechanical, and thermal energy storage. These options all vary in form, fit, and function and have wide ranges of storage duration, capacities, and costs.

One potential solution to providing long-duration, large-scale energy storage to the grid is GeoTES. Other names for this technology include Reservoir Thermal Energy Storage (RTES) and Aquifer Thermal Energy Storage (ATES) depending on the depths and formations involved. For the purposes of this study, we use GeoTES to include both shallow and deep reservoirs of subsurface fluids. Throughout recent years, a wealth of knowledge has been gained in understanding GeoTES challenges, benefits, successes, and failures of a variety of systems throughout Europe (McLing et al., 2022, Fleuchaus et al., 2020, Bloemendal et al., 2021, Wendt et al., 2019, Holstenkamp et al., 2017, Jin et al., 2022). The concept is relatively simple in that naturally occurring subsurface fluids are 1) produced from a suitable (porous and permeable) geologic formation, 2) passed through a heat exchange system at the surface utilizing either industrial waste heat or heat generated by renewable sources, and 3) reinjected into the subsurface for storage until it is needed (i.e., winter, diurnal, seasonal) (Figure 1). This heat is then used in either power generation or in a direct-use heating and cooling system. Essentially, a temporary and cyclic geothermal system is created and utilized for a variety of benefits including assisting with peak demand ramping, lessening grid transmission stress, and increasing grid stabilization and flexibility.

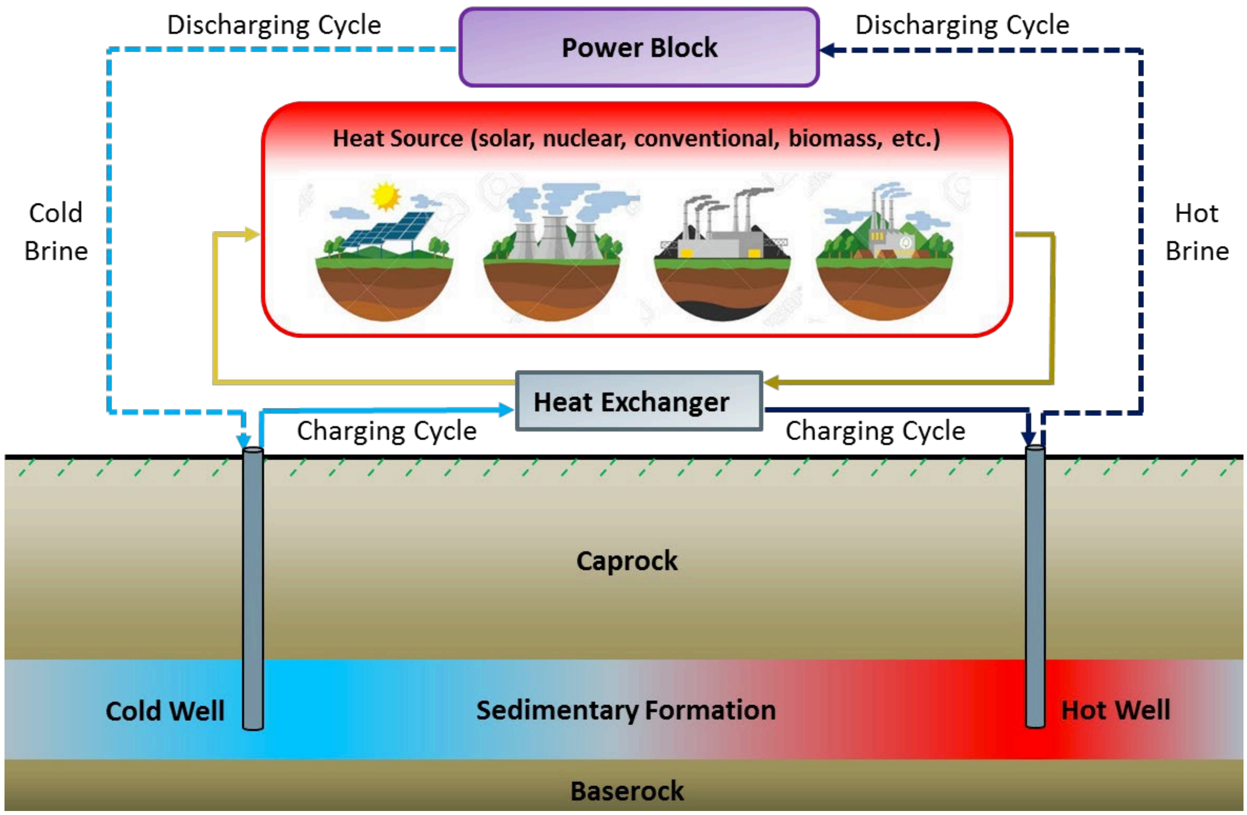

Figure 1: A conceptual model of a Geologic Thermal Energy Storage (GeoTES) system (US DOE, 2020).

Although thousands of these systems exist throughout Europe (Fleuchaus et al., 2018) as Aquifer Thermal Energy Storage (ATES), there are none in the U.S. and only a few exist that operate at high temperatures (>40 C). However, an active area of research among industry and the national labs is in deep, high-temperature formations (McLing et al., 2019, Wendt et al., 2020, McLing et al., 2022, Sheldon et al., 2021, Jin et al., 2022, Holstenkamp et al., 2017, Stricker et al., 2020, Koorneef et al., 2019, Bremer, 2022, Flechaus et al., 2020).

The following research activities aim to understand the viability of utilizing this concept in shallower, low water quality aquifers of the United States focusing on areas with increasing energy demand, renewable energy curtailment and GeoTES potential. This project is in its initial stages and the presented material below is an approach to achieve the objectives mentioned above.

2. Methods

2.1 Aquifer Identification

To understand which aquifers could hold the greatest potential for GeoTES development, we conducted a high-level investigation of major U.S aquifers and reservoirs. The United States Geological Survey (USGS) has published literature regarding the many sedimentary basins and other reservoirs that exist across the country (Coleman and Cahan, 2012, Stanton et al., 2017, Miller et al., 2000). These reservoirs and aquifers could hold potential for increasing energy storage through GeoTES. Additionally, the National Energy Technology Laboratory maintains the National Carbon (NATCARB) Sequestration Database, a geographic information system that identifies suitable formations and areas for geologic sequestration of CO_2 (Gray 2015). Although the NATCARB maps are focused on carbon sequestration suitability, many of the same formations studied and identified could potentially be suitable for GeoTES under the right thermal-hydrogeological-chemical and operational parameters. More recently, and directly applicable to this study, the USGS has conducted preliminary investigations identifying the potential for RTES in major brackish groundwater regions across the U.S. (Figure 2, Pepin et al., 2021).

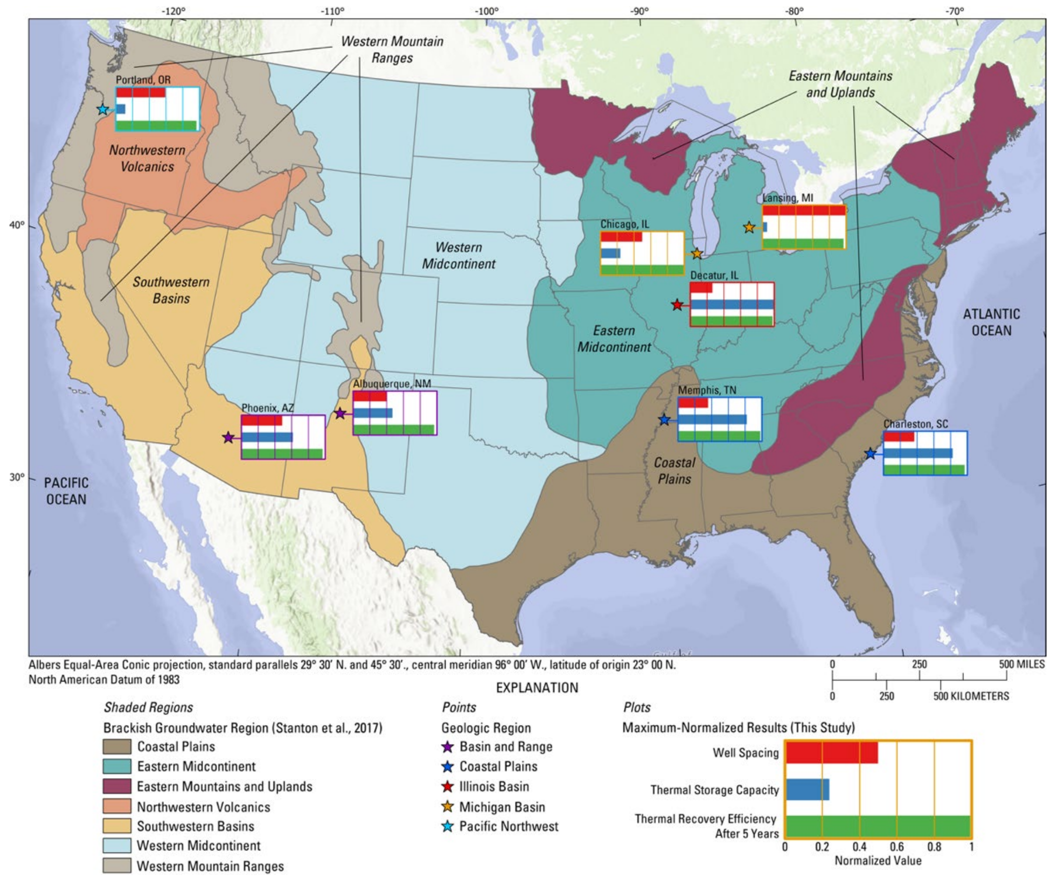

Figure 2: Map of the eight cities used in USGS analysis in seven brackish groundwater regions throughout the conterminous United States (Pepin et al., 2021).

Due to a variety of issues related to state and local regulations, the lack of laws governing heat storage and recovery, the potential for potable groundwater mixing, and unanswered water rights questions (Fleuchaus, 2018, Fleuchaus, 2020, Bloemendal et al., 2014, Bloemendal et al., 2021) we have focused our efforts on low-quality groundwater reservoirs that underlie and are isolated from more utilized aquifers. The hosting formations contain brackish to saline fluids and are not currently being utilized for drinking water purposes. This does not, however, mean that major aquifers will be excluded in the analysis because oftentimes brackish or more saline zones exist within the same formations as the freshwater but occur at greater depths. But the deeper formations are often widespread and have potentially suitable temperatures and hydrologic parameters (porosity and permeability) for the storage and extraction of fluids. The main focus of this research is currently on Texas and California.

2.2 Parameter Selection

When determining the suitability of an aquifer or reservoir for GeoTES, it is common to gather important hydrogeologic parameters such as:

1. Lithology
2. Mineralogy
3. Temperature of aquifer fluids
4. Formation depth and thickness
5. Porosity
6. Permeability or hydraulic conductivity
7. Fluid geochemistry (sulfate, salinity, TDS, etc.)

These parameters were chosen to understand how certain formations might receive, store, and later produce fluids for power or heat production. Additionally, these parameters help to understand potential thermochemical reactions that might take place upon heating and cooling of native fluids. The parameters listed above will serve as a baseline to compare various aquifers and eventually down select to more specific areas for case studies. Further geomechanical and geochemical parameters will be investigated in future phases of this work. Subsequent thermo-hydrogeological-mechanical-chemical modeling and TEA work will depend on the data collected from the data sources discussed below. It is important to note here that although certain areas may overlap with oil and gas fields, we are avoiding any reservoirs that contain hydrocarbons to simplify the reactive transport modeling and TEA work.

2.3 Data Sources

By interrogating databases from federal, state, and local entities, we gathered important information regarding each aquifer under question. Major subsurface data sources include Federal, State, and local agencies and organizations listed below:

1. USGS-Produced Water Database (Blondes et al., 2018) - https://www.sciencebase.gov/catalog/item/59d25d63e4b05fe04cc235f9
2. USGS National Water Information System (NWIS) - https://waterdata.usgs.gov/nwis
3. Texas Water Development Board-Brackish Resources Aquifer Characterization System (BRACS) - https://www.twdb.texas.gov/groundwater/bracs/index.asp
4. Texas Commission on Environmental Quality (https://www.tceq.texas.gov/)
5. Railroad Commission of Texas - https://www.rrc.texas.gov/
6. WellDatabase - https://welldatabase.com/
7. California Water Board Groundwater Ambient Monitoring and Assessment Program - https://www.waterboards.ca.gov/gama/
8. California Department of Water Resources - https://water.ca.gov/
9. Geotracker - https://geotracker.waterboards.ca.gov/
10. California Department of Conservation Geologic Energy Management - https://www.conservation.ca.gov/calgem

Other public reports published by federal and state agencies as well as industry have been utilized to gather the necessary data included in this work. Oftentimes, data has been collected for alternative purposes rendering data collection and interpretation time consuming. Care has been taken to organize and source data appropriately for the purposes of this study. Industry partners for this project also have provided key information on the specific sites undertaken to understand the subsurface.

3. Results

California and Texas are two of the largest states in the U.S. and are home to many groundwater basins that supply fresh groundwater to residents (Figure 3). This freshwater is highly protected and regulated due to increasing demand and water use in these states. In addition to those reasons mentioned above, we have focused our efforts on the identification of low water quality aquifers (brackish and saline) that can be utilized for heat storage and recovery. Some major aquifers within these regions containing potable groundwater were added to our analysis due to a portion of them having suitable characteristics at depth. These unconfined aquifers can be problematic though in that the potential for mixing between fresh and brackish water will likely hold great implications for developing regulations around these types of projects. The following two sections will provide background on the various aquifers in Texas and California that are under investigation as well as preliminary results on the various hydrogeologic parameters of the aquifer and formations.

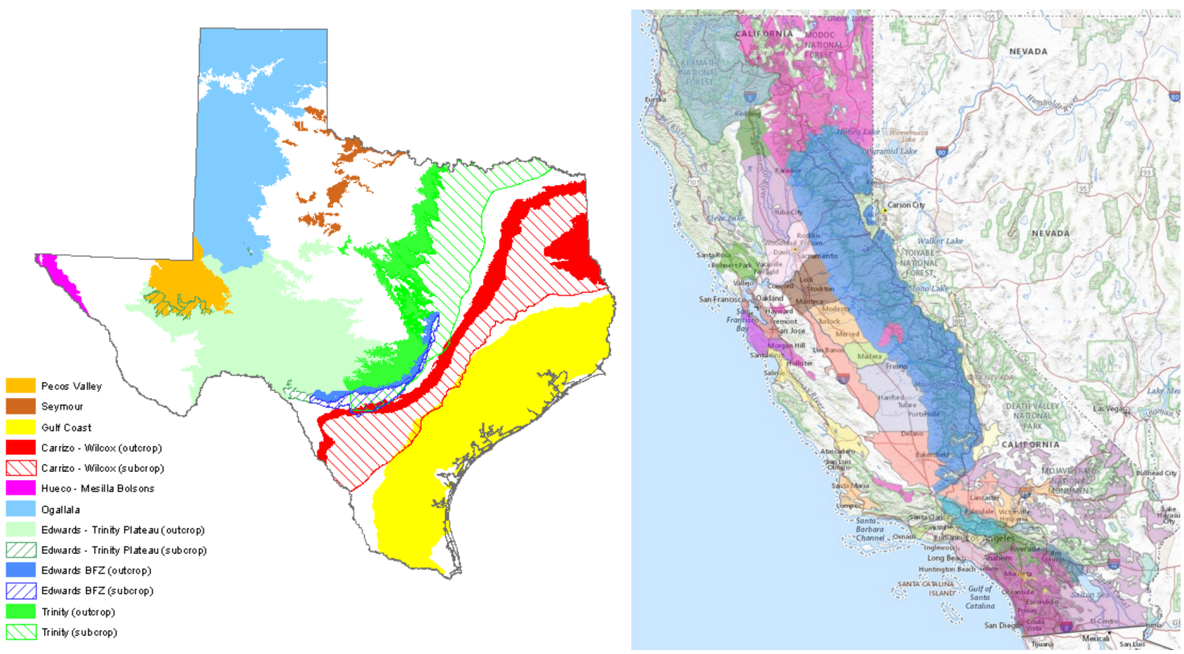

Figure 3: Left - Major aquifers in Texas (Texas Water Development Board) and principal aquifers in California (USGS, Reilly 2008). Right - California deep aquifer groundwater study units (CA Water Board GAMA Program).

3.1 Texas Brackish Aquifers

In 2009, the Texas Water Development Board (TWDB) implemented and has continued to operate the Brackish Resources Aquifer Characterization System (BRACS) program to study various aquifers throughout the state to estimate potential volumes and to provide a more thorough characterization of these aquifers that could potentially have a beneficial use. The goals of the program are to "map and characterize the brackish aquifers of the state in greater detail using existing water well reports, geophysical well logs and available aquifer data and 2) to build datasets that can be used for groundwater exploration and replicable numerical groundwater flow models to estimate aquifer productivity." To date, there have been 19 studies either completed or ongoing (Figure 4). As a part of this program, a database was generated and is maintained by the BRACS staff. We refer the reader to the BRACS website (https://www.twdb.texas.gov/groundwater/bracs/index.asp) for specific data sources and reports. Note that due to the size of the datasets many of these numbers are either averaged (*) or are provided as ranges. Data given without an * represent values gathered and directly published in BRACS reports.

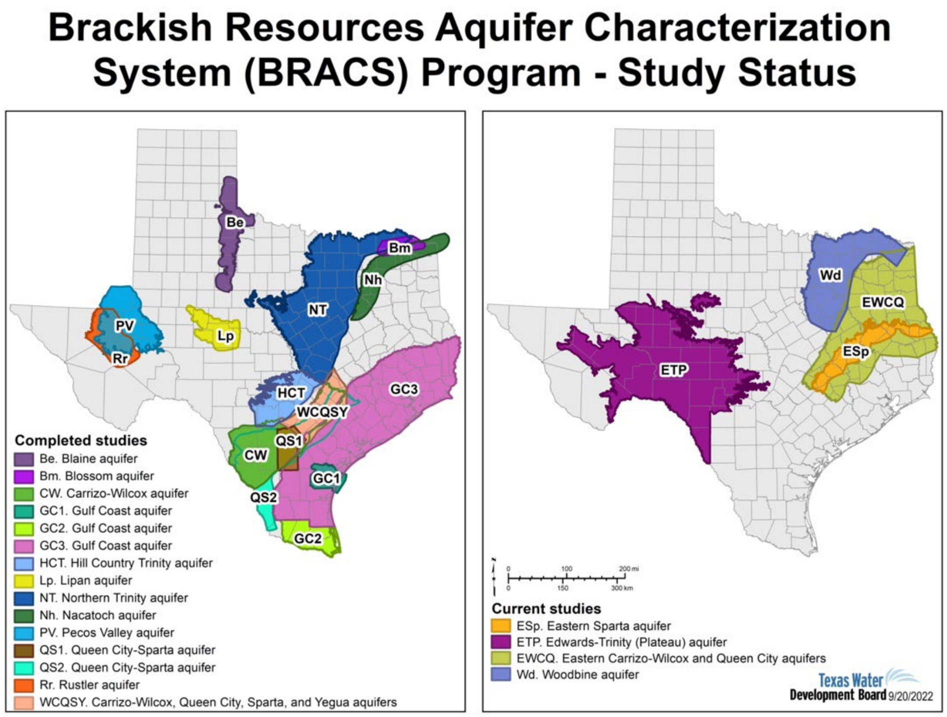

Figure 4: The TWDB Brackish Resources Aquifer Characterization System (BRACS) Program study areas and status as of September 2022.

Formations studied as part of the BRACS program range from marine alluvial sediments including various rock types including those found in coastal and marine depositional environments such as sandstone, siltstone, shale, gravel, mudstone, dolomite, limestone, gypsum, conglomerate, etc. These all vary in terms of compaction, cementation, alteration, induration, and other hydrogeologic parameters. The data presented below in Table 1 show 15 of the brackish aquifers identified as well as the data that was gathered from the BRACS database to include in our future analyses.

Table 1: BRACS aquifers and selected datasets used to evaluate GeoTES feasibility. Averages and ranges taken from the BRACS database and other values taken from BRACS reports.

BRACS Aquifer	Depth to top (ft bgs)*	Average Thickness (ft)	Formation Temperature (°F)	Average Porosity (%)	Hydraulic Conductivity (ft/day)	Total Dissolved Solids (mg/L)
Blaine	136	225*		35**	101	385-7356
Blossum	863	256	46-116	37	10.8	881
Carrizo-Wilcox	2448	528*	26-254	37.5	251	925-C 836-W
Gulf Coast-Chicot	401	239*	68-114	35	94	1337
Gulf Coast-Evangeline	1439	411*	69-172	35	18	1659
Lipan	1147	257*	68-132	35**	4	1252
Nacatoch	935	338*	64-110	34	4.98	1009
Pecos Valley	319	319*	65-74	35**	8.6	2757
Queen City	1706	509*	57-176	34		1342
Sparta	1859	197	42-178	36		1355
Rustler	1068	450	64-98	35**		2765
Dockum	482	713*	70-72	35**		2758
Edwards-Trinity Plateau	30	307*	66-332	24**	10	
Trinity	272	206*	66-332	35**		
Yegua Jackson	3297	749*	64-154	31	1200 (mD)	926

***Indicates an average was taken from the BRACS Database. **Indicates an average porosity between the rest of all aquifers presented due to lack of data available.**

3.2 California Shallow Aquifers

Numerous shallow aquifers in California have potential to be considered for GeoTES development. This study includes three major aquifers (Figure 5): California Coastal Basin, Basin & Range basin-fill, and Central Valley aquifers. A large percentage of saline groundwater (oil field brines and irrigation waters) and sea water intrusions are present in California Coastal Basin aquifers. Several researchers (Clark 1924, Poland et al., 1959, Durham 1974) reported geology, groundwater characteristics in the Santa Clara Valley, Torrance-Santa Monica area, and southern Salinas Valley area of the California Coastal Basin aquifers. Basin & Range basin-fill aquifers have shallow brackish groundwater in closed basins/playas above the confining units, or near streams (Anderson 1995, and Anning et al., 2007).

The major aquifer with significant GeoTES potential is the Central Valley aquifer. This major aquifer system covers approximately 20,278 square miles located in the Central Valley in California and is three miles deep in San Joaquin Valley and six miles deep in Sacramento Valley. The formations are composed mainly of late cretaceous to quaternary marine and alluvial sediments. The aquifer system is both unconfined and confined depending on location and depth. At depths less than 500 ft represent the upper parts of the unconfined system, whereas below 500 to 3000 ft is a saline connate water in marine sediments. Bertoldi et al., (1991) provided a summary report for the ground water in the central valley of California. Similarly, Faunt (2009) provided a detailed assessment of groundwater availability of the Central Valley aquifer. Burow and others (2004) hydrologically characterized the Modesto Area, San Joaquin Valley. Scheirer (2007), Schierer and Magoon (2007) developed the petroleum systems and geologic assessments along with age, distribution, and stratigraphic relationship of rock units of the San Joaquin basin province in California. This current study will focus on three prime regions of the Central Valley (San Joaquin Basin, Tulare Basin, and Delta). Some of the important parameters identified from San Joaquin basins are reported in Table 2.

Figure 5: Major Aquifers of California (Stanton and others, 2017).

Table 2: San Joaquin Basin (Data taken from WESTCARB Topical Report)

Parameters	Notes	
Location	Southern half of Great Valley province	
Geologic Age	Marine Cretaceous and Cenozoic clastic sedimentary rocks	
Thickness (San Joaquin Formation)	680 m (2232 ft)	Largely brackish water sandstone and mudstone derived from Sierran arc, the Coast Ranges, and the Gabilan Range
Average Porosity	(14-16%) to 20%	Gatchell sandstone
	20-38%	Point of Rocks sandstone
	28-34%	Shallow sands
Permeability	(6.4×10^{-14} m^2 - 7.4×10^{-14} m^2) to 4.2×10^{-13} m^2	Gatchell sandstone
	3.9×10^{-14} m^2 - 4.9×10^{-12} m^2	Point of Rocks sandstone
	4.2×10^{-13} m^2	Shallow sands

4. Texas Case Study - Yegua Jackson Aquifer

In collaboration with EarthBridge Energy, a geothermal energy storage company, we are examining a specific site for GeoTES potential north of Houston, Texas. Here, EarthBridge and their partners are planning a MW-scale, commercial demonstration of their GeoTES technology referred to as the GeoBattery™. The site is well-characterized due to the >60 test wells drilled to date. Target storage reservoirs of the Yegua Formation and Jackson Group at the site exist at moderate depths of 2,000-3,000 ft. (~600-1000 m) and temperatures ~50-60 C. These widespread quartz-rich sandstone reservoirs were deposited in a fluvio-deltaic environment of the Texas Gulf Coast during the Middle to Upper Eocene. Individual reservoir flow units range in thickness from 250-350 ft (75-110m) and exhibit high porosity and permeability (>30% and >1000 mD, respectively). In situ fluids have high dissolved solids content and are unsuitable for drinking water or agricultural use in the local area. Also importantly, no hydrocarbons have been discovered in any previous well drilled at the site to at least 11,000 ft depth (3350 m).

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

5. Conclusion and Next Steps

The work to date on this portion of the project has focused on the subsurface technical feasibility and the subsurface component of the TEA. We have focused our work on understanding what aquifers exist geospatially and what characterization has been done. Data from Texas and

California indicate that many aquifers may be suitable for GeoTES development with favorable porosity and permeability at fairly shallow depths. Brackish aquifers and depleted oil and gas reservoirs throughout these states provide ample opportunity to investigate how GeoTES may be coupled with renewable energy sources. Next steps for this project include performing a screening of the various aquifers to only include the most favorable for further analyses. Another next step is to deliver key data to the TEA team to understand the costs and technical feasibility of installing an GeoTES system under a variety of conditions and operational scenarios. Oftentimes these commercial considerations, (offtake analyses, grid interconnection, electricity pricing, power purchase agreements, etc.) require a significant amount of effort and will be performed by the joint NREL-LBNL-INL team. For this portion of the project, major product of this study will be a complete database of aquifers throughout Texas and California that could be investigated further for GeoTES development. Additionally, a few specific case studies will be generated to provide a basis for how to start such investigation.

Acknowledgements

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