CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

BHERM — Lithium Recovery Demonstration Final Project Report

August 2024 | CEC-500-2024-094

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ACKNOWLEDGEMENTS

BHER Minerals would like to thank the following for their contributions and support to make this research project possible:

1. Chuck Gentry, California Energy Commission Contract Agreement Manager
2. Build Momentum, Grant Agreement Management
3. Local Government Partners
    - Imperial Planning and Development Services
    - Imperial County Air Pollution Control District
    - Imperial County Fire Department
    - Imperial County Department of Public Health
    - Regional Water Quality Control Board
    - Department of Toxic Substances Control
4. Technical Advisory Committee Members:
    - Mike McKibben, Research Professor, Earth & Planetary Sciences, University of California, Riverside
    - Michael Moore, Geothermal Operations Expert and Trainer
    - George Furmanski, Metallurgical and Project Engineer
5. Technical Experts and Partners
    - Conductive Energy, Inc., Technology Provider
    - ZAP Engineering, Engineering, Procurement, & Construction
    - University of California, Riverside, Measurement and Verification
    - Lawrence Berkeley National Laboratory, Measurement and Verification

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The Lithium Recovery Demonstration project aimed to enhance California's geothermal resources by introducing advanced lithium recovery technology, potentially positioning California as a leader in global lithium production. The project, which was located in the Salton Sea Known Geothermal Resource Area, housing about 40 percent of the world's proven lithium reserves, addressed barriers hindering the utilization of this vast resource for achieving California's clean energy objectives. By co-producing lithium carbonate — a valuable commodity in the electric vehicle battery market — from geothermal brine, the project sought to improve the economic feasibility of geothermal power plants in California and thus facilitate the state's goals for a clean energy future.

Funded by the California Energy Commission, the project was executed by BHER Minerals, LLC, a wholly owned indirect subsidiary of Berkshire Hathaway Energy Renewables. The project's goal was to demonstrate a commercially viable lithium recovery process, and the demonstration system was designed, built, and tested. However, the project faced setbacks, leading to the termination of the technology provider's contract due to insufficient progress. This underscored the significance of brine pretreatment in lithium recovery, prompting a shift to alternative technologies focused on enhancing this process.

The project's ambitious goals encompassed not only advancing lithium recovery technologies at a fraction of commercial scale but also contributing to California's clean electricity targets and supporting the clean transportation revolution. Despite challenges, the project's insights into brine pretreatment and ongoing pilot tests continue to guide future endeavors in sustainable lithium recovery and geothermal energy utilization, maintaining the momentum towards achieving California's renewable energy and storage capacities by integrating lithium recovery with geothermal power production.

Keywords: geothermal energy, lithium recovery, lithium extraction, brine pretreatment

Please use the following citation for this report:

Fleming, Christina. 2024. *BHERM — Lithium Recovery Demonstration Final Project Report*. California Energy Commission. Publication Number: CEC-500-2024-094.

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Background

The Lithium Recovery Demonstration project sought to deploy and demonstrate advanced lithium recovery technology that would add significant value to California's geothermal resources and springboard the state of California into a leading global role for lithium production. The Salton Sea Known Geothermal Resource Area contains an estimated six million tons of recoverable lithium within presently available geothermal resources — an amount equal to roughly 40 percent of the world's proven reserves and approximately 11 percent of the total identified resources, according to the U.S. Geological Survey. Yet, significant barriers exist in accessing this abundant resource to achieve the state's statutory energy goals, such as those set forth in Senate Bill 100, The 100 Percent Clean Energy Act of 2018 (De León, Chapter 312, Statutes of 2018). The primary barrier to recovering the lithium is that the technology to recover lithium from high-temperature geothermal brine has not yet been proven commercially. This project sought to advance the process for lithium recovery from geothermal brine and overcome critical barriers that currently limit the value of geothermal resources to California's electricity system.

Although economically sustainable plants exist, the capital cost to build new geothermal power plants in California is generally too high to support significant development of new geothermal power production capacity — a critical barrier that limits the expansion of geothermal resources to California's electricity system. Advanced lithium recovery technology has the potential to positively shift the economics of geothermal power production in California by enabling reliable, low-cost production of a co-product — lithium carbonate (Li_2CO_3) — with immense commercial value in today's market. The increased adoption of electric vehicles (EVs) (which use lithium-ion batteries) has driven up demand for lithium. A domestic supply of lithium is an important step in growing the local battery supply chain and manufacturing, to strengthen energy security. The opportunity to share the cost of brine production with a lithium recovery business would open the doors to developing new geothermal power plants in the Salton Sea Known Geothermal Resource Area, directly supporting achievement of the state's energy goals.

Coupling geothermal power with lithium recovery represents a crucial opportunity for achieving California's clean energy targets, including reaching 100 percent clean electricity by 2045 and adding 25.5 gigawatts of supply-side renewable energy and 15 gigawatts of energy storage and demand response capacity by 2032. This approach would support the state's transition to renewable energy and secure lithium for EV batteries, essential for reducing transportation emissions.

Project Purpose and Approach

The purpose of the project was to prove the commercial viability of the lithium recovery technology by designing, constructing, and operating a demonstration that would consistently process 100 gallons per minute of geothermal brine and achieve a 90-percent recovery rate of the lithium contained in the lithium chloride (LiCl) solution. The core of the technology consisted of media that was a combination of the ion exchange material (sieve) lithium titanate and a polymer binder used to create a cluster. Pilot demonstration was conducted by BHER Minerals, LLC (BHERM), a wholly owned indirect subsidiary of Berkshire Hathaway Energy Renewables (BHER). A lithium-ion sieve (LIS) is a lithium-ion adsorbent with low toxicity, low cost, high chemical stability, and high lithium cation (Li^+) uptake capacity.

In the first phase of the lithium recovery process, sodium hydroxide (already in use at the existing geothermal facility to adjust the pH of the brine) is used to condition the brine before the brine is routed to the lithium recovery process. The process then employs ion-exchange media to recover the lithium from the brine. The lithium recovery unit uses hydrochloric acid (currently used at the facility to adjust the pH of the brine), along with power and water utilities, to accomplish the recovery process. After lithium recovery from the brine, the post-recovery brine streams are returned to the current brine processing system, which results in the test being the minor treatment of a small side-stream of brine.

The project sought to demonstrate that the technology could support the economical production of lithium by producing a salable lithium carbonate product for under $4,000/metric ton. Additionally, by advancing this technology, the project would open the door to massive investment in the region by third-party developers seeking access to the lithium-rich geothermal brine currently being used to generate power by CalEnergy and others.

Relevant audiences interested in this project's results include the public, including the Imperial Valley community, geothermal power plant operators, EV manufacturers and other end users, electric utilities, and Imperial County.

The project’s goals included:

1. Developing and demonstrating all operational steps of the recovery of lithium from geothermal brine.
2. Developing and demonstrating a lithium recovery system that would improve the economic productivity and flexibility of existing geothermal facilities.
3. Demonstrating at 1/10 of commercial scale a lithium recovery technology that has already been demonstrated and proven at the pilot scale.
4. Fully processing recovered lithium to produce battery-grade Li_2CO_3.

Upon achievement of these goals, BHERM expected to move forward with the second phase of this initiative: to construct and operate a Lithium Carbonate Demonstration project, which could convert the LiCl from the lithium recovery demonstration project into battery-grade Li_2CO_3.

The metrics used to demonstrate the achievements of these goals included six primary metrics: 1) Brine throughput, 2) Spent brine reinjection volume, 3) Energy consumption, 4) Water consumption, 5) LiCl solution production rate, and 6) Li_2CO_3 purity. Environmental performance was intended to be tracked by monitoring four secondary metrics: 1) Direct greenhouse gas (GHG) emissions, 2) Indirect GHG emissions, 3) Criteria pollutant and other toxic emissions, and 4) Lithium recovery demonstration brine slurry discharge.

Key Results

This project designed and built a lithium recovery system to demonstrate lithium recovery on a 1/10 commercial scale. However, when the system was tested, it was unable to perform as expected, due to failure of the selected media to perform under field conditions.

The termination notice to the technology provider was issued and acknowledged on June 23, 2023, due to a lack of progress (see Chapter 3 for details of test results) and an indication that further testing would not lead to commercial-scale lithium recovery with the current design. Nevertheless, the project led to important lessons learned:

- Duplex stainless-steel alloys 2205 and 2507 are not compatible with very low pH (less than 1.0) fluid. New headers, laterals, and media screens with Inconel 625 material were installed in the three electrical contactors of the demonstration facility.
- On-site testing, using actual flowing brine, can produce a very different result than testing with synthetic or even actual brine in the lab.
- Brine pretreatment that will effectively remove other minerals, such as iron and silicon, is critical for the lithium recovery process.

Knowledge Transfer and Next Steps

Knowledge transfer activities, including the Technology/Knowledge Transfer Plan and the Technology/Knowledge Transfer Report, were canceled due to the technical challenges encountered in this project.

For next steps, BHER began a separate lithium recovery pilot test using a different technology, which was started on June 12, 2023. This effort, which does not use California Energy Commission grant funds, will have an additional focus on an improved brine pretreatment process. These research and development efforts will continue towards the goal of proving the commercial viability of the selected lithium recovery technology, using BHER’s funds.

CHAPTER 1: Introduction

Project Purpose

The Lithium Recovery Demonstration (LRD) project sought to design and develop a demonstration project on a 10,000-square-foot section of land south of the Unit-5 geothermal facility at 6922 Crummer Road, Calipatria, California, 92233. The project location, shown in Figure 1, is located southeast of the Region 1 clarifier.

BHER Minerals, LLC (BHERM), a wholly owned indirect subsidiary of Berkshire Hathaway Energy Renewables (BHER), was awarded California Energy Commission (CEC) grant funding for the design, construction, and operation of a lithium recovery system demonstration.

This project sought to:

- Prove the commercial viability of lithium recovery within the grant duration.
- Construct and operate, within the $12 million budget, a demonstration lithium recovery process that would process 100 gallons per minute (gpm) of geothermal brine and achieve over an 85-percent recovery rate of lithium contained in the lithium chloride (LiCl) solution.
- Demonstrate that the technology could support the economical production of salable lithium carbonate for under $4,000 per metric ton (mt).

The proposed demonstration project was set to open the door to billions of dollars of private investment in lithium recovery from geothermal brine in the Salton Sea region. When commercialized, BHER's LRD project would yield significant benefits to an area with one of the highest unemployment rates in the nation, including:

- Over $1.5 billion in construction activity
- Approximately $20 million in additional annual tax revenue for Imperial County
- Creation of hundreds of high-paying jobs with extensive workforce training targeted at residents of surrounding low-income and disadvantaged communities

The closed-loop demonstration was expected to be the world's most environmentally friendly lithium recovery plant and one of the most cost effective. The project could have led to the construction of a regional network of lithium recovery facilities that could produce as much as 300,000mt per year of high-quality, battery-grade lithium carbonate equivalent (LCE), making the Imperial Valley the foremost lithium production center in the world.

Figure 1: Aerial View of Demonstration Plant in Calipatria, CA

Ft=feet

Source: BHERM

Context and Relevant Background

Conventional lithium recovery from brine resources relies on inefficient and environmentally disastrous evaporation ponds. These evaporation pond systems make financial sense only for a few vast brine resources in South America with anomalously high lithium concentrations. The process involves placing the extracted salt brine into a large evaporation pond. This effectively removes water but can require up to two years to concentrate the brine to support lithium recovery sufficiently, ultimately supporting a lithium recovery rate of about 40 percent. Evaporation ponds are vulnerable to weather and have yet to be permitted in California. Other technologies offer reasonable lithium recovery rates but often at a high environmental cost.

BHERM proposed to deploy and demonstrate an advanced environmentally friendly lithium recovery technology capable of recovering approximately 85 percent of the lithium in geothermal brine at less than $4,000/mt when integrated into a commercial-scale geothermal power plant. This would add significant value to California's geothermal resources and springboard the state into a leading global role for lithium production. The Salton Sea Known Geothermal Resource Area contains an estimated six million tons of recoverable lithium within presently available geothermal resources — an amount equal to roughly 40 percent of the world's proven reserves and approximately 11 percent of the total identified resources, according to the U.S. Geological Survey. Yet, significant barriers exist in accessing and using this abundant resource to achieve many of the state's statutory energy goals. The primary barrier to recovering the lithium is that the technology to recover lithium from high-temperature geothermal brine has not yet been proven commercially. Critical barriers currently limit the value of geothermal resources to California's electricity system. The capital cost to build new geothermal power plants in California is generally too high to support significant development of new geothermal power production capacity. The additional revenue stream of lithium recovery would help overcome this barrier.

Relevant Audience and Market

Lithium recovery technology has the potential to positively shift the economics of geothermal power production in California by enabling reliable, low-cost production of lithium carbonate (Li_2CO_3). The opportunity to share the cost of brine production with a lithium recovery business would open the doors to developing new geothermal power plants, supporting the achievement of the state's energy goals. Relevant audiences for the project include the public, including the Imperial Valley community, the geothermal energy sector, electric vehicle (EV) manufacturers and other end users, electric utilities, and Imperial County.

Project Goals and Metrics

The goals of the project were to:

1. Develop and demonstrate all operational steps of the recovery of lithium from geothermal brine.
2. Develop and demonstrate a lithium recovery system that would improve the economic productivity and flexibility of existing geothermal facilities.
3. Demonstrate at 1/10 of commercial scale a lithium recovery technology that has already been demonstrated and proven at the pilot scale.
4. Fully process recovered lithium to produce battery-grade Li_2CO_3.

The project sought to achieve these goals by:

a. Field-demonstrating LiCl recovery from Salton Sea geothermal brine at 100 gallons of brine per minute.

b. Demonstrating a process that would allow a commercial project at 10 times the scale (or less) to produce Li_2CO_3 with a cost of less than $4,000/mt of production.

c. Demonstrating potential payback of five years or less for a commercial-scale system.

d. Advancing the proposed lithium recovery technology to at least Technology Readiness Level (TRL) 8 (tested and ready for implementation).

e. Minimizing environmental impacts by avoiding the use of evaporation ponds.

f. Demonstrating lithium recoveries of greater than (>) 85 percent from raw brine to high-purity Li_2CO_3.

g. Demonstrating freshwater usage below 50,000 gallons per tonne of Li_2CO_3.

Table 1 summarizes project metrics and why they were included.

Table 1: Performance Metrics

Metric	Unit	Importance
Brine Throughput	gpm	Brine volume of 100 gallons per minutes (gpm) represents the 1/10 scale of the demonstration plant, since a commercially viable lithium recovery module could be 1,000 gpm. The brine with high lithium content is one of the major components in this lithium recovery system.
Spent Brine Reinjection Volume	gpm	The spent brine returned to the geothermal process shall not be allowed to cause any process upsets in the geothermal facility that would adversely impact the operation or cost of operation.
Energy Consumption	kWh	Energy consumption of the LRD facility during regular operation, defined in kilowatt-hours (kWh), is the sum of the electrical energy consumption, the geothermal steam consumed, and the fuel used by light-duty vehicles associated with the LRD operation.
Water Consumption	gpm	Water conservation measures adopted within the Region 1 geothermal facility limit water use to 1,000 acre-feet per year (acre-ft/yr) of fresh water from the Imperial Irrigation District (IID) canal system. This limits the total Region 1 and LRD dilution process water use to 620 gpm. Region 1 currently utilizes approximately (~) 530 gpm (856 acre-ft/yr), while the LRD project is expected to require an additional ~ 6 gpm (10 acre-ft/yr).
LiCl Solution Production Rate	gpm	The concentration and amount of lithium chloride solution recovered by the demonstration project will significantly measure the process's success.
Li_2CO_3 Purity	wt%	The purity of the lithium carbonate, measured by weight percentage (wt%), processed in the laboratory from the lithium chloride solution samples will be a crucial determinant of the process's success.
Direct GHG Emissions	kg CO_2/kWh	The only point where greenhouse gas (GHG) emissions are possible during normal operations is the steam vent controlling steam blanket pressure on the process vessels. The kilogram (kg) CO_2/kWh unit is a measurement of the carbon dioxide (CO_2) emission intensity per kilowatt-hour of electricity.

Metric	Unit	Importance
Indirect GHG, Criteria Pollutant, and Other Toxic Emissions	kg CO_2e /kWh	Periodic GHG emission calculations will use mobile equipment emissions and emissions from fossil fuel consumption for internal-combustion-engine-based vehicles utilized for the LRD project. Emissions factors are established by the CEC (electricity: 0.331 kg carbon dioxide equivalent [CO_2e]/kWh).

Source: BHERM

CHAPTER 2: Project Approach

Technology and Research Approach

The project sought to achieve technological and scientific advancements and innovations that would overcome critical barriers that currently limit the value of geothermal resources to California's electricity system. These geothermal facilities pump super-heated brine (>450°F [232°C]) under high pressure (>350 pounds per square inch absolute, or psia) from subsurface depths exceeding 4,000 feet into five power plants, where steam flashed from the brine is used to generate electricity via steam turbines. After flashing the steam, the system removes any precipitated suspended solids from the spent brine and returns it to the geothermal reservoir — along with many valuable minerals, including zinc, manganese, potassium, and lithium. Every day, these plants bring 1.8 million barrels (approximately 50,000 gpm) of super-heated brine to the surface and return 1.4 million barrels (approximately 40,000 gpm) of spent brine. The project sought to demonstrate that the technology could support the economical production of lithium by producing a salable lithium carbonate product for under $4,000/mt.

The following tasks were designed to achieve timely completion of the project.

- Task 1 — General Project Tasks: BHERM, BHER, and Momentum were to complete all required grant administration, management, accounting, and coordination activities.
- Task 2 — Demonstration of Lithium Recovery System:
  - Task 2.1 — Lithium Recovery System: The team was to design and engineer the lithium recovery system and the geothermal brine pretreatment system; procure all necessary hardware, equipment, and construction contracts; fabricate the skid-mounted lithium recovery module and deliver it to the project site; and install and integrate the systems.
  - Task 2.2 — System Commissioning: The team was to commission the integrated system.
  - Task 2.3 — Operations: The team was to operate the 1/10-scale integrated system for three months, send weekly samples for quality verification, and purify LiCl to Li_2CO_3.
  - Task 2.4 — Measurement, Verification, and Analysis: The team was to collect and analyze operational data and produce a variety of key deliverables, including a Mass Balance Analysis and a Techno-Economic Analysis.[1]
- Task 3 — Evaluation of Project Benefits

[1] This task was cancelled due to technical challenges with the project.

- Task 4 — Technology Transfer/Knowledge Transfer Activities[2]
- Task 5 — Production Readiness Plan[2]

Technology Approach

The demonstration system was sited on a 100ft x 100ft section of land at the Region 1 geothermal power production facility at 6922 Crummer Road in Calipatria, California. This facility produces up to 167 megawatts (MW) of renewable electricity from approximately 18,000 gpm (post-flash) of super-heated geothermal brine. BHERM planned to build on the identified technology provider's pilot projects and bench testing of the Region 1 brine to demonstrate the viability of a more extensive integrated 1/10 commercial-scale system. To do so, the project team planned to operate the demonstration system continuously for 90 days, optimizing process conditions to demonstrate the cycle life of the ion exchange lithium recovery system while maintaining a lithium capture rate at or > 85 percent.

The lithium recovery process employs ion-exchange media to recover the lithium from the brine. The process involves the use of sodium hydroxide, hydrochloric acid, power, and water utilities. After lithium recovery from the brine, the post-recovery brine streams are returned to the current brine processing system, which results in the test being the minor treatment of a small side-stream of brine. The lithium recovery process comprises several unit operations (UOs). The UOs required for the lithium recovery include:

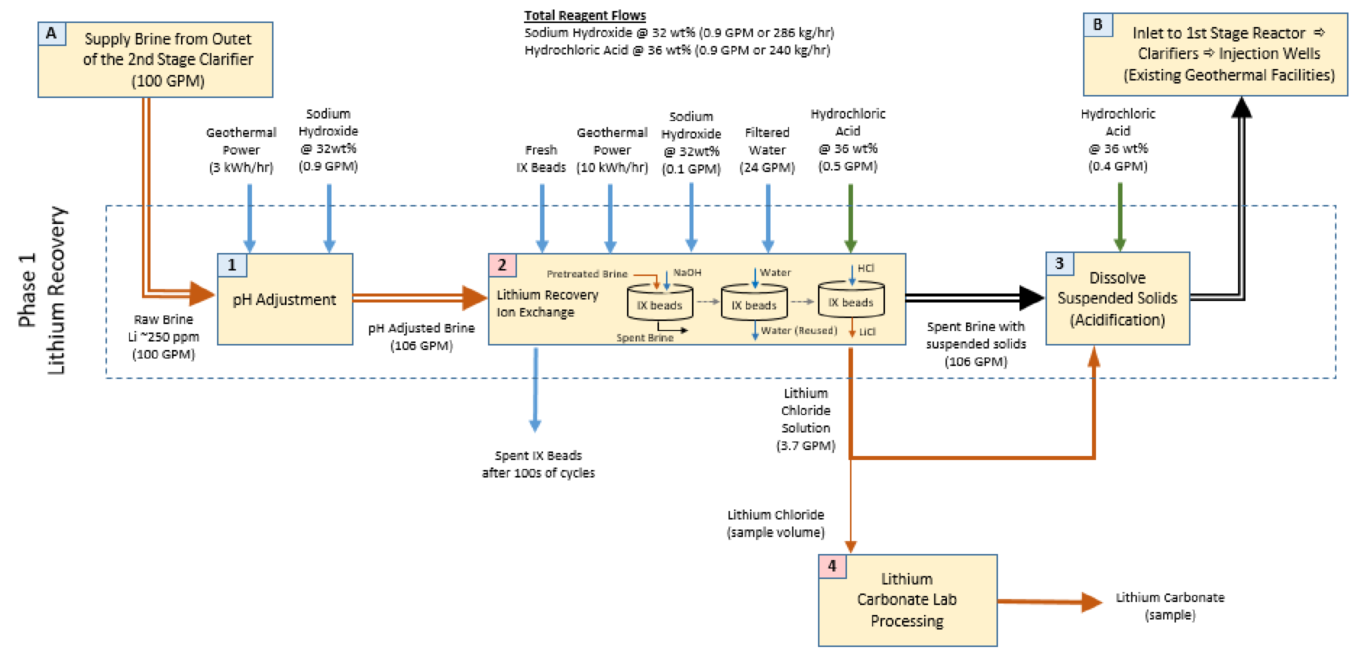
1. The pH elevation UO, where the pH of the brine is increased from 4.7 to 7.5. Sodium hydroxide (already in use at the existing geothermal facility to adjust the pH of the brine) is used to condition brine from the Unit 5 secondary clarifier.
2. An adsorption UO, where the lithium ions in the geothermal brine are exchanged with protons in the protonated media.
3. A brine wash cycle, where solids are removed from the lithium-loaded (lithiated) media.
4. A water rinse cycle, where brine residue left behind from the brine wash is diluted and washed off the lithiated media and contactor surfaces.
5. An elution UO, where the lithium ions from the lithiated media are exchanged with protons via the addition of hydrochloric acid (currently used at the facility to adjust the pH of the brine).
6. A post-elution water rinse cycle, where lithium-rich eluate residue left behind after the elution fluid is drained from the contactor is diluted and washed off the protonated media and contactor surfaces. This rinse water is used as make-up water in the elution tank (TK-1900).
7. A lithium-depleted geothermal brine (depleted brine) acidification UO, where a percentage of the precipitated solids from the pH elevation UO is dissolved back into solution.

[2] This task was cancelled due to technical challenges with the project.

8. A depleted brine filtration UO, prior to brine reinjection back into the geothermal reservoir.

Figure 2 shows the simplified process flow diagram for the lithium recovery demonstration.

Figure 2: LRD Plant Process Flow Diagram



Li=lithium; GPM=gallons per minute; pH=potential of hydrogen; kg/hr=kilogram per hour

Source: BHERM

Technical Specifications

A wide variety of technical specifications apply to the demonstration system. The applicable standards and specifications for the system include the International Building Code and the California Building Code; National and California Electrical Codes; American Society of Mechanical Engineers (ASME) B 31.1, Power Piping; ASME B 31.2, Fuel Gas Piping; ASME B 31.3, Process Piping; American Society for Testing and Materials (ASTM) standards for HDPE pipe; American National Standards Institute (ANSI) standards for valves and fittings; and Occupational Safety and Health Administration (OSHA) Process Safety Management requirements due to the potential presence of acid(s) at threshold quantities. More specifically, through BHER's 40 years in geothermal brine processing and ZAP Engineering's years in design, construction, and operations, the team internally developed best practices for managing the challenges of working with hot brine.

Project Partners

Table 2 summarizes the partners' roles and tasks within the grant scope.

Table 2: Project Partners

Partner	Grant Role	Project Task
BHERM	Prime	Project developer/manager
CalEnergy Operating Corporation	Site host	Site host
Conductive Energy (AquaMin Lithium and Water Recovery, LLC)	Subcontractor	Technology developer
ZAP Engineering & Construction	Subcontractor	Construction work
Lawrence Berkeley National Laboratory	Subcontractor	Measurement & verification
University of California Riverside	Subcontractor	Measurement & verification
Momentum	Subcontractor	Project assistance

Source: BHERM

BHER is a wholly owned Berkshire Hathaway Energy Company subsidiary and an independent power producer for both the wholesale market and customers under long-term power purchase agreements. BHERM is indirectly wholly owned by BHE Geothermal, LLC, which BHER wholly owns.

BHER's operating affiliate, CalEnergy Operating Corporation (CalEnergy), is based in Calipatria, California. The company owns 10 geothermal facilities in California's Imperial Valley that can produce up to 350 MW of renewable electricity. Its assets include 23 production wells that pump approximately 50,000 gpm of super-heated geothermal brine for approximately 1.8 million barrels per day. CalEnergy also operates 22 injection wells that return approximately 40,000 gpm of brine to subsurface depths for 1.4 million barrels per day.

The LRD project team selected Conductive Energy, Inc. (AquaMin Lithium & Water Recovery, LLC) as the LRD recovery technology provider to oversee the development and optimization of the material (media) for the lithium recovery process.

The project team entered into an engineering, procurement and construction agreement with ZAP Engineering & Construction Services, Inc., (ZAP). Under this agreement, ZAP would design and engineer the project as well as manage the procurement, construction, testing, and commissioning of the demonstration project on a turnkey, fixed-price basis. ZAP is a private company providing engineering and fabrication solutions with $31.8 million in assets as of 2019.

BHE Renewables created an advisory committee for the project. The Technical Advisory Committee (TAC) was composed of diverse professionals: Mike McKibben, Research Professor, Earth & Planetary Sciences, University of California, Riverside; Michael Moore, Geothermal Operations Expert and Trainer; and George Furmanski, Metallurgical and Project Engineer. BHE Renewables and the CEC contract agreement manager met with the TAC every six months. The purpose of the TAC was to provide guidance on the direction of the project, review project updates, and provide recommendations for project adjustments, refinements, enhancements, and strategies.

The University of California, Riverside is a public research university with a history of 60-plus years and three colleges, including the Marlan and Rosemary Bourns College of Engineering and the College of Natural and Agricultural Sciences.

Lawrence Berkeley National Laboratory (LBNL) is a multiprogram science lab in the national lab system, supported by the U.S. Department of Energy through its Office of Science. It is managed by the University of California and charged with conducting unclassified research across various scientific disciplines.

Momentum inspires, manages, and executes campaigns for organizations around the globe. Since 2005, Momentum has helped more than 300 high-profile public and private clients plan, develop, and finance $5 billion in advanced technology projects. Currently, Momentum provides grant administration and project management on projects valued at more than $250 million.

Project Milestones

On August 3, 2020, BHERM was awarded a CEC grant for $6 million to deploy and demonstrate lithium recovery from geothermal brines. At the time, it was believed that the media provided by the technology partner would not experience a performance drop caused by the metals and dissolved solids contained in the Salton Sea brine at operating temperatures in the range of 195°F (91°C) to 215°F (102°C). This would eliminate the need for brine impurity removal and lead to an estimated operating cost of $3,576 per ton of lithium carbonate equivalent. Media refers to combining the lithium titanate sieve and a polymer binder used in a nominal 50 percent mass ratio to create a cluster. Figure 3 shows the media before (left) and after exposure to very high dissolved iron in continuous elution (right). The media on the left is on a two-millimeter mesh screen.

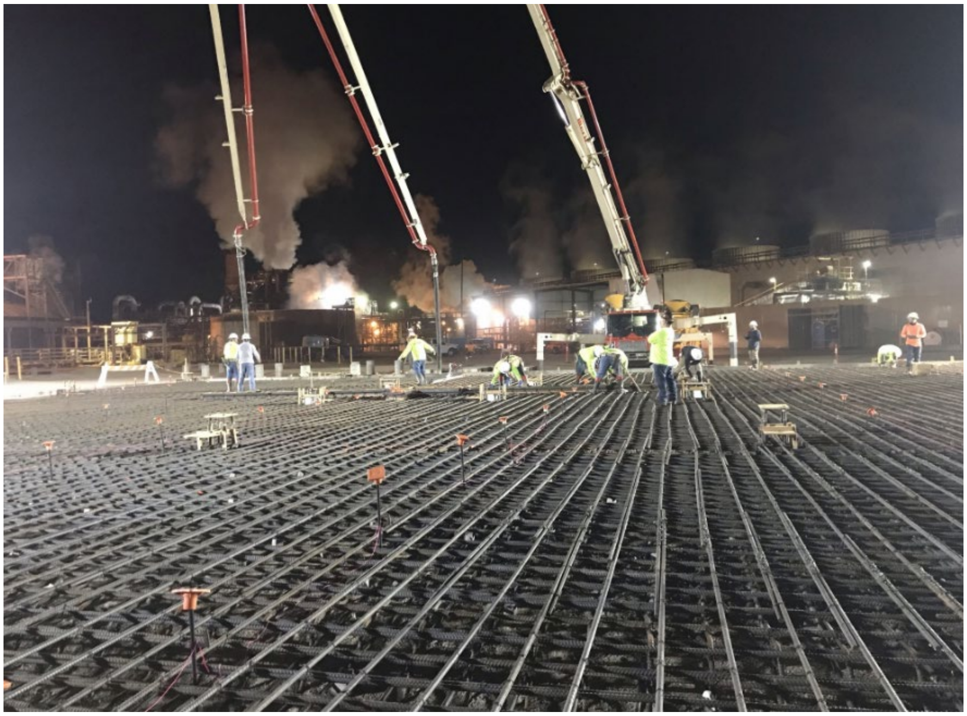
Figure 3: Lithium Recovery Media

Source: BHERM

Construction

Construction of the demonstration facility began in June 2021 and was completed in April 2022. Figure 4, Figure 5, Figure 6, and Figure 7 show different phases of construction.

Figure 4: Foundation Setting at the LRD Facility



Source: BHERM

Figure 5: Four Reactor Tanks Set at the LRD Facility

Source: BHERM

Figure 6: Nine Vessels Installed at the LRD Facility

Source: BHERM

Figure 7: LRD Facility Building Envelope

Source: BHERM

Testing

With the cooperation of the technology provider, the test milestones summarized in Table 3 were achieved.

Table 3: Test Milestones and Timelines

Milestone	Timeline
Media bench testing (in laboratory, prior to construction of demonstration plant)	From August 24, 2020, to January 12, 2021
LRD unit commissioning	June 5, 2022
Production of over one metric ton of media	June 5–8, 2022
LRD unit media testing	December 19–31, 2022
Pilot trials with improved media	February 23–25, 2023 March 1–8, 2023 April 19–25, 2023 May 16–22, 2023

Source: BHERM

Measurement and Verification

Pre-Installation Measurement and Verification Findings

Existing Measurements

Measurement and verification (M&V) activities in the pre-installation phase included analyzing the following metrics:

- Geothermal brine constituents (post-power generation)
- Canal water constituents
- Steam constituents

Table 4, Table 5, and Table 6 summarize the analysis results of these metrics. Measurements are in parts per million (ppm).

Table 4: Geothermal Brine Analysis

Metals (ppm)							
Arsenic	15		Iron	1001		Nickel	0.0039
Barium	223		Lead	82.3		Potassium	15599
Cadmium	1.99		Lithium	222		Silver	0.12
Calcium	31365		Magnesium	69.2		Sodium	66916
Chromium	0.43		Manganese	1077		Strontium	532
Copper	4.15					Zinc	356

Anions (ppm)	
Chloride	181019
Fluoride	25
Sulfate	111

pH	**4.82**
Silica (ppm)	161
TDS (ppm)	305453
TSS (ppm)	418

Note: These are average values from CalEnergy laboratory analysis.

Source: BHERM

Table 5: Canal Water Analysis (September 13, 2021)

Concentrations				
Calcium (ppm)	0.42		Manganese (ppm)	0.001
Chlorides (ppm)	1.83		Potassium (ppm)	0.05
Iron (ppm)	0.01		Sodium (ppm)	0.47
Magnesium (ppm)	0.12		pH	6.96

Note: These are average values from CalEnergy laboratory analysis.

Source: BHERM

Table 6: Steam Analysis

Metals (ppm)				
Barium	0.035		Manganese	0.031
Calcium	68.1		Potassium	4.77
Iron	1.04		Sodium	108
Magnesium	29.4			

Anions (ppm)	
Chloride	113
Fluoride	0.319
Sulfate	247

Not Detected in Analysis
Antimony, Arsenic, Berylium, Cadmium, Cobalt, Copper, Lead, Molybdenum, Nickel, Nitrates, Selenium, Silver and Thalium

Note: These are average values from CalEnergy laboratory analysis.

Source: BHERM

LRD Process Measurements

The energy consumption by the LRD facility during regular operation was defined by the electrical energy consumption, the geothermal steam consumed, and the fuel used by light-duty vehicles associated with the LRD operation. Since the LRD facility was a new installation, energy consumption at the pre-installation was zero.

GHG emissions from the LRD facility at pre-installation were zero since the facility was a new installation. The only point where GHG emissions were possible during normal operations was the steam vent controlling steam blanket pressure on the process vessels. The steam vent was monitored for carbon dioxide emissions and underwent the same testing protocol used by the geothermal plant for its steam vent applications.

Indirect GHG emissions were calculated from the energy consumption, using emission factors established by the CEC (electricity: 0.331 kg CO_2e/kWh) during the operation of the LRD. Other emissions included mobile equipment; the fossil fuel consumption for internal-combustion-engine-based vehicles utilized for the LRD project were logged.

As a new installation, the mass and energy return to the geothermal plant, measured at sample port, SP-0320, LRD brine slurry discharge at pre-installation, was zero. Lab testing and continuous measurements have analyzed this stream as prescribed in Table 7.

Table 7: Overall Mass and Energy Balance Sample Points

Sample Port	Stream	Lab Measurement	Instrumentation Continuous Data
SP-0100	Geothermal Brin (IN)	Daily: TSS Weekly: pH, ICP (full), pH, TDS, TSS, CL, ORP, BS, T, Li	PIT, F (1)
SP-0320	LRD Brine Slurry Discharge	Daily/As needed: TSS Weekly: pH, ICP (full), TDS, TSS, CL, ORP, BS, T, Li, Solids ICP (full)	PI, F (1)
SP-9000	Canal Water (IN)	As need: ICP (full), ICP (spot), T	F (1)
SP-9800	Steam (IN)	Weekly: ICP (full), T	PIT, TIT, F/T (3)

CL=Chlorine; F=Flowmeter; F/T=Vortex Flowmeter/Temperature Meter; ICP=Inductively Coupled Plasma; Li=Lithium; ORP=Oxidation Reduction Potential; PI=Pressure Indicator; PIT=Pressure Transmitter; PS=Particle Size; T=Temperature; TDS=Total Dissolved Solids; TIT=Temperature Transmitter; TSS=Total Suspended Solids

Source: BHERM

CHAPTER 3: Results

Project Findings

At the time of project awarding, it was believed that the media provided by the technology partner would not experience a performance drop caused by the metals and dissolved solids contained in the Salton Sea brine at operating temperatures in the range of 195°F (91°C) to 215°F (102°C). This would eliminate the need for brine impurity removal and lead to an estimated operating cost of $3,576 per ton of lithium carbonate equivalent. Media refers to combining the lithium titanate sieve and a polymer binder used in a nominal 50-percent mass ratio to create a cluster.

Testing Summary

The ion exchange media was tested in six different scenarios during the LRD project.

Media Test #1: June 5–8, 2022

On May 31, 2022, 1.3 tons of media was transferred to the LRD unit contactors for initial fill and performance evaluation. Laboratory acceptance testing showed that the media adsorbed lithium at a level > 90 percent and eluted lithium at a level > 160 percent due to the residual lithium left in the system during media manufacturing. Both values met the acceptance-level targets, and the media was approved for demonstration-scale testing. Unfortunately, due to the high level of dissolved solids found in geothermal brine, these solids precipitated out of the solution, clogging adsorption tank inlet valves and contaminating the media. Consequently, the test had to be stopped to clean the LRD unit and remove the contaminated media. This result prompted the acquisition of a weir tank to remove solids before they entered the lithium recovery reaction units.

Media Test #2: December 19–31, 2022

On December 13, 2022, approximately one ton of media was transferred to the LRD unit contactors for evaluation. This time, the process worked without issue, and testing could be carried out as planned. Unfortunately, the media adsorption performance started at less than 50 percent. Then it seemed to rise slightly over the successive seven cycles, after which it dropped continuously to a very low level and finally stopped at cycle 44. The media was washed with dilute acid to refresh the surface and remove impurities that might cause fouling. However, as it did not return to the starting adsorption levels, the test was stopped to investigate the root cause of the low performance. X-ray diffraction analysis found that the functional structure in the lithium titanate was no longer present and had been degraded to unfunctional anatase titanium dioxide structures. The reduction of active lithium titanate in the media reduced the media’s ability to capture lithium and was believed to be a root cause for the overall decrease in performance.

Media Test #3: February 23–25, 2023

After the first two demonstration-scale tests, it was decided to move the next set of tests to a smaller pilot-scale unit to employ a more agile approach to testing and evaluating the media performance. The media used in this trial was prepared on a kg scale and contained 54-percent lithium titanate and 46-percent polymer binder by dry weight. The titanium dioxide used to produce the titanate ion exchange material was at 97-percent purity. This test aimed to investigate the performance of a medium made with the highest quality material available to reduce the adverse effects impurities could cause. The test was done in the pilot-scale facility with six kg of conditioned media. Although the media initially showed promising performance, it quickly degraded after cycle five and did not recover. The planned 30-cycle test was stopped at cycle 21.

Media Test #4: March 1–8, 2023

Since the media used in the LRD unit in December 2022 had not previously been tested on a pilot scale, it was decided to run a trial while waiting to produce a modified media formulation from the technology provider. The media contained 40 percent lithium titanate and 60 percent polymer by dry weight and was made from a standard purity (92 percent) titanium dioxide feedstock. From the start of the run, the media adsorbed lithium at around the 50-percent level and steadily dropped over 30 cycles. In media test #3, the testing had been stopped at cycle 21, so it was decided to continue to cycle 30 to see if the performance drop was an anomaly. The steady decline showed that this was not the case.

Media Test #5: April 19–25, 2023

As a result of the x-ray diffraction studies that indicated that the core structure of the lithium titanate had been destroyed, the technology provider produced a new media that contained magnesium as a doping agent. There are examples in the literature that show that magnesium doping can strengthen the crystal lattice of the lithium titanate structure, and it was hypothesized that this modification would improve the adsorption characteristics of the media. For this test, media that contained about 50 percent lithium titanate, doped with about 6 percent magnesium, was produced. High-purity-grade (97 percent) titanium dioxide made the lithium titanate. As seen in previous runs, the media adsorbed less than 90 percent of the lithium in the brine and slowly degraded in performance over 30 cycles. In this test, the variation in adsorption performance between cycles was more dramatic than in previous tests. It also appeared that the overall performance drop (10 percent) was less than in earlier tests, going from about 60 percent adsorption to 50 percent. This could be due to the addition of magnesium, but the overall performance was below the target of 90 percent or greater.

Media Test #6: May 16–23, 2023

The unexpected variation in adsorption levels between cycles observed in media test number five led to the decision to increase the doping level of the media from 6 percent to 15 percent. The hypothesis was that the magnesium was not fully incorporated into the titanium oxide crystal lattice. Increasing the level of magnesium used during doping was expected to improve the performance stability by forcing more magnesium into the crystal lattice. The media contained a starting concentration of about 49 percent lithium titanate and about 49 percent polymer binder, to which about 2 percent of magnesium was added as a doping agent to stabilize the crystal lattice. The lithium titanate was produced with high-purity (97 percent) titanium dioxide. In this test, the media started at a higher absorption level (80 percent) than seen in the previous run, but it also dropped in performance at a higher rate. When the testing was stopped at cycle 30, the adsorption was at 25 percent, indicating a 55-percent drop in overall performance. This was one of the worst performance declines, and it was decided that testing should be discontinued, and a new approach should be recommended.

Evaluation of Project Benefits

From the previously conducted demonstration test, it was identified that duplex stainless-steel alloys 2205 and 2507 are not compatible with very low pH (less than 1.0) fluid. New headers, laterals, and media screens with Inconel 625 material were installed in the three contactors of the demonstration facility.

The results of the testing showed that brine pretreatment that will effectively remove other minerals, such as iron and silicon, is a significant unit of operation for the lithium recovery process. BHE Renewables has an ongoing lithium recovery pilot test using a different technology, which was started on June 12, 2023, with an added focus on an improved brine pretreatment process.

Technology and Knowledge Transfer Activities

During the project, BHERM planned to work closely with the University of California, Riverside and LBNL to develop and execute a Technology/Knowledge Transfer Plan to assess and advance the commercial viability of the technology by making the knowledge gained, experimental results, and lessons learned available to the public and key decision-makers. Specifically, the plan would have described how the knowledge would be shared with the public, targeted market sectors, end users, utilities, regulatory agencies, and others; described the intended use(s) for end users; and included published documents, fact sheets, journal articles, conference presentations, and other documents.

Knowledge transfer activities, including the Technology/Knowledge Transfer Plan and the Technology/Knowledge Transfer Report, were canceled due to the technical challenges observed in this project.

For next steps, BHER began a separate lithium recovery pilot test using a different technology, which was started on June 12, 2023. This effort does not use CEC grant funds. This test will have an additional focus on an improved brine pretreatment process. These research and development efforts will continue towards the goal of proving the commercial viability of the selected lithium recovery technology, using BHER’s funds.

CHAPTER 4: Conclusion

Project Outcomes

The annual world demand for lithium is currently 620,000mt of LCE, but it is expected to grow as much as fourfold by 2030. The demand started to outpace supply in 2021 and is expected to remain strong.

BHE Renewables owns and operates 10 geothermal plants that could produce approximately 90,000mt of LCE per year, representing approximately 15 percent of 2022's global demand for lithium. The primary barrier to advancing this opportunity is that the technology to recover lithium from high-temperature geothermal brine has not yet been proven commercially; thus, the lithium recovery technology demonstration project is needed.

This project did not result in a successful demonstration of lithium recovery from geothermal brine on a 1/10 commercial scale, due to the failure of the selected media to perform under field conditions. However, the demonstration led to critical lessons learned.

Lessons Learned and Recommendations

During the project, it was identified that duplex stainless-steel alloys 2205 and 2507 are not compatible with very low pH (less than 1.0) fluid. New headers, laterals, and media screens with Inconel 625 material were installed in the three contactors of the demonstration facility.

The termination notice to the technology provider was issued and acknowledged on June 23, 2023, due to a lack of progress and an indication that further testing would not lead to the realization of commercial-scale lithium recovery using the current design. An important lesson learned is that testing onsite, using actual flowing brine, can produce a very different result than testing in the lab.

Brine pretreatment that will effectively remove other minerals, such as iron and silicon, is critical for the lithium recovery process. BHE Renewables has an ongoing lithium recovery pilot test using a different technology, which was started on June 12, 2023, and is not using CEC grant funds. This test will have an additional focus on an improved brine pretreatment process. These research and development efforts will continue towards the goal of proving the commercial viability of the selected lithium recovery technology, using BHER's funds.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
~	approximately
°C	degree Celsius
°F	degree Fahrenheit
>	greater than
Acre-ft/yr	acre-feet per year
ANSI	American National Standards Institute
ASME	American Society Of Mechanical Engineers
ASTM	American Society for Testing and Materials
BHE	Berkshire Hathaway Energy
BHER	Berkshire Hathaway Energy Renewables
BHERM	BHER Minerals, LLC
$Ca(OH)_2$	calcium hydroxide
CEC	California Energy Commission
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
Contactor	An electromechanical switch used for controlling an electrical circuit
EPCM	Engineering, procurement and construction management
EV	electric vehicle
GHG	greenhouse gas
gpm (GPM)	gallons per minute
ICP	Inductively Coupled Plasma
IID	Imperial Irrigation District
kg	kilogram
kg/hr	kilograms per hour
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCE	lithium carbonate equivalent
Li	lithium
Li+	lithium cation
Li_2CO_3	lithium carbonate
LiCl	lithium chloride

Term	Definition
LIOH	lithium hydroxide
LIS	lithium-ion sieve
Lithiated	A solution or material that has been treated with lithium or one of its compounds
LRD	Lithium Recovery Demonstration
M&V	measurement and verification
mt	metric ton
MW	megawatt
NaOH	sodium hydroxide
ORP	oxidation reduction potential
OSHA	Occupational Safety and Health Administration
pH	A measure of how acidic or basic a substance or solution is by measuring the potential of hydrogen
ppm	parts per million
psia	pounds per square inch absolute
sieve	ion exchange material
TAC	Technical Advisory Committee
TDS	Total Dissolved Solids
TRL	Technology Readiness Level
TSS	Total Suspended Solids
UO	unit operation
wt%	weight percentage
ZAP	ZAP Engineering & Construction Services, Inc.

Project Deliverables

Below is a list of key deliverables BHERM has submitted. Project deliverables are available upon request, by submitting an email to pubs@energy.ca.gov.

- System Procurement Plan
- System Execution Plan
- Cold Testing and Commissioning Plan
- M&V Protocol
- Measurement and Verification Plan
- Pre-Installation M&V Findings Report
- Initial Fact Sheet