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FINAL PROJECT REPORT

Large-Scale Sulfur Thermal Battery Demonstration for Enhanced Grid Flexibility and Increased Renewable Penetration

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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 emission 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

Element 16 Technologies, Inc., (Element 16) successfully developed and demonstrated a novel long-duration energy storage technology that uses sulfur in a single-tank configuration to economically and efficiently store and dispatch renewable energy electricity. The core innovation is the use of sulfur, an abundant waste byproduct from the oil and gas industries, to dramatically reduce the cost of Element 16's thermal energy storage. The team built and tested a pilot-scale, 1.5-Megawatt-hour sulfur thermal battery unit integrated with an electric heater designed to charge with variable excess electricity from renewable generation. The stored heat was converted to electricity using a small-scale, low-temperature power generation unit that can also be used directly for industrial process heat decarbonization.

A techno-economic model was developed to evaluate the levelized cost of storage of sulfur thermal batteries in grid-connected applications. The levelized cost of storage is the lifetime cost per unit of discharged electricity.

The sulfur thermal battery charges during periods when electricity demand and prices are low and there is surplus renewable generation, and discharges during peak demand periods when prices are higher. For example, connecting a sulfur thermal battery to a California Independent System Operator node where the electricity price is negative for more than 20 percent of the year, the levelized cost of storage of the sulfur thermal battery was estimated to be 0.08-0.12 $/kilowatt hour electric, which is favorable when compared with 0.15-0.18 $/kilowatt hour electric for Lithium-ion batteries. Adding a sulfur thermal battery to the grid also provides operational flexibility, allowing electric utilities to more effectively balance the electric grid, increase renewable energy penetration, and avoid the need for costly electric grid upgrades.

This report discusses the successful pilot demonstration of Element 16's sulfur thermal battery system and the technology-to-market activities of the sulfur thermal energy storage technology, which has secured over $6 million in research, development, and commercialization funding since award of this project.

Keywords: long duration energy storage (LDES), sulfur thermal battery, levelized cost of storage (LCOS)

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

California Senate Bill (SB) 100 (De León, Chapter 312, Statutes of 2018) established ambitious clean-energy and climate mandates for the state, including carbon neutrality and 100 percent renewable energy consumption by the year 2045. Senate Bill 350 (De León, Chapter 547, Statutes of 2015) complements SB 100 by addressing energy-efficiency and decarbonization goals across the state's economy. With increased penetration of highly variable renewable generation resources such as wind and solar, energy storage plays a key role in increasing both electric-grid reliability and flexibility. In this project, Element 16 Technologies, Inc., (Element 16) successfully developed and demonstrated a first-of-its-kind sulfur thermal battery system that stores and dispatches energy from renewable resources efficiently — and at lower cost — than available alternative technologies. This project aligns seamlessly with the following Electric Program Investment Charge (EPIC) strategic objectives, which focus on reaching the goals of SB 100 and SB 350, among other key California energy and climate-related mandates.

Two strategic objectives of this project were to:

Create a More Nimble Grid to Maintain Reliability as California Transitions to 100-Percent Clean Energy: By smoothing out the variability of renewable energy resources, sulfur-thermal battery technology ensures a more consistent and reliable energy supply, facilitating greater integration of renewable energy into the grid.

Improve the Customer Value of End-Use Efficiency and Electrification Technologies: Sulfur thermal batteries can be charged with renewable electricity during times of excess supply to dispatch firm, clean electricity and heat to industrial users, decreasing reliance on fossil fuels and accelerating industrial decarbonization.

This project is both timely and critical as California faces increasing energy demand, the urgent simultaneous need to combat climate change, and the growing challenge of renewable generation curtailments. By addressing the need for long-duration and cost-effective energy storage, this project plays an important role in realizing California's vision for a sustainable and resilient clean-energy future.

Project Purpose and Approach

Element 16, which developed and patented the use of molten sulfur for thermal energy storage, led this project. Its primary goal was to demonstrate the use of low-cost sulfur thermal battery technology as electricity storage and generation while achieving a technology readiness level of 8 (out of 9). A technical readiness level is a measurement system used to assess the maturity level of a particular technology. Advances from this project were designed to both accelerate the technology's path to commercial deployment and attract the interest of potential investors. Initial work focused on corrosion testing to determine the appropriate material selection and corrosion allowance specifications for molten sulfur storage. Element

16's engineering team then applied computational modeling tools to design a pilot-scale 1.5 Megawatt-hour sulfur thermal energy storage unit fabricated by PCL Industrial Services, Inc., located in Bakersfield, California. The sulfur thermal energy unit was integrated with an electric heater and power generation unit (collectively referred to as a sulfur thermal battery). The system was designed to charge with variable excess electricity from renewable resources. The discharged heat was converted to electricity using a small-scale, low-temperature organic Rankine cycle power-generation unit; organic Rankine cycle power generators use an organic fluid in a closed-loop thermodynamic cycle to convert heat to electricity. Alternatively, the stored heat can be used directly for industrial process heat. The system was installed and tested by Element 16 engineers at their facility in Duarte, California. Key performance metrics such as charge/discharge rates, round-trip efficiency, and the levelized cost of storage were thoroughly evaluated.

The results of this research will be used by interested stakeholders in both utilities and industries to help make informed decisions on the use of sulfur thermal batteries for both industrial process heat and electricity. Renewable energy project developers have also found the outcomes of this research beneficial and have used project insights to explore innovative ways to incorporate sulfur thermal battery technology into their renewable energy projects. Research organizations and government agencies will additionally use project results to identify and address further research required to overcome market barriers to broad sulfur thermal battery adoption.

Key Results

The pilot sulfur thermal battery, integrated with a small-scale, low-temperature organic Rankine cycle power generation unit, was set up and commissioned at Element 16's facility in Duarte, which is located in Los Angeles County, California. The unit was filled with 23 tons of sulfur, resulting in a capacity of 1,533 kilowatt hours for sulfur thermal energy storage cycling between 248°F (120°C) and 572°F (300°C). Comprehensive testing quantified the performance metrics of the sulfur thermal battery by charge/discharge rates and round-trip efficiency. The average thermal-to-thermal round-trip efficiency of the sulfur thermal battery was calculated to be 85 percent, and the overall thermal-to-electric round-trip efficiency was calculated to be 5 percent. By integrating with a high-temperature power generation unit, overall thermal-to-electric round-trip efficiency of between 15 percent and 16 percent is achievable.

Leveraging the project's measured performance data, a techno-economic model was developed to evaluate the feasibility of deploying sulfur thermal batteries in grid-integrated, front-of-the meter applications. The techno-economic benefits were quantified using annual revenues, payback periods, and the levelized cost of storage, which is the total lifetime cost of the battery divided by its cumulative delivered electricity. Due to low thermal-to-electric round-trip efficiency, low-cost sulfur thermal batteries for grid storage are best suited for installation at nodes where the electric price is either low or negative for a large part of the year (when compared with conventional Lithium-ion grid batteries), which benefit more from variances between periods of high and low electricity prices. As a result, the two energy-storage technologies are better suited for different grid applications. Element 16's sulfur thermal energy storage has better economic performance as a large grid-load in locations with significant renewable overgeneration since these locations have frequent periods of low-value electricity. The California Independent System Operator (ISO) Node DAIRYLND_N_013, which registers negative prices for more than 20 percent of the year (Berkeley Lab, 2023), was selected as the representative node to investigate the economics of adding sulfur thermal battery technology to the state's electric grid. This node is located in Madera County, in the California Central Valley, a region known for its strong agricultural base and home to several large-scale solar photovoltaic farms, including the 70-MW Lotus Solar Farm and the 20-MW Adera Solar project. The frequent occurrence of negative electricity prices at this node is largely attributed to high solar generation during midday hours, which often exceeds demand. When modeled for this node, the levelized cost of storage for a sulfur thermal battery was 0.08-0.12 $/kilowatt hours electric, compared with 0.15-0.18 $/kilowatt hours electric for Lithium-ion batteries. The results suggest that large-scale sulfur thermal batteries offer a sustainable and economically viable alternative to conventional electro-chemical batteries for long-duration electricity storage when deployed in areas with frequent low or negative electricity prices caused by renewable resource overgeneration.

Knowledge Transfer and Next Steps

Element 16's dedicated website (https://element16.com) provides information on sulfur thermal battery technology, the development team, and both project and company updates. Element 16 actively maintains a LinkedIn page, which regularly features updates on the company's progress and projects. The Element 16 team communicated project outcomes to both the public and key decision makers through various channels including speaking engagements; participation in expos, summits, and conferences; news releases; technical reports; test reports; and journal articles. Some notable public events where the Element 16 team presented on sulfur thermal energy storage technology included the VERGE sustainability conference in 2019; a 2019 annual conference hosted by the Association of Energy Engineers, SoCal Chapter; the Association for the Advancement of Artificial Intelligence in 2022; the RE+ event's United States Department of Energy's SETO awardee showcase in both 2022 and 2023; the San Francisco Bootcamp Startup Showcase; the High-Performance Computing for Energy Innovation workshop in Livermore, California, in 2023; and the 2023 American Nuclear Society's annual meeting. Additionally, through Element 16's research collaboration with the National Renewable Energy Laboratory, several interns presented on sulfur thermal energy storage at the 2022 Ignite Off! final national viewing event hosted by the Oak Ridge Institute for Science and Education. A peer-reviewed journal article on the technology was published in the American Society of Mechanical Engineers' *Journal of Energy Resources Technology*.

Element 16 received its first unsubsidized, paid purchase orders for front-end and detailed engineering for a sulfur thermal energy storage pilot project with a solar field that generates steam for process heat.

Future research efforts will focus on integration of sulfur thermal energy storage with renewable resources (such as solar photovoltaics) or tied to the electric grid, which is increasingly decarbonized with renewable generation for clean, dispatchable industrial-process heat. This approach aligns with the state's broader mandates for improving energy efficiency and accelerating industrial decarbonization. Building strong partnerships with key stakeholders in the renewable energy sector and collaborating on joint research initiatives like this one will be crucial to those efforts. Element 16 will also continue to work individually with customers to provide tailored solutions and comprehensive support for their unique energy requirements.

CHAPTER 1: Introduction

Energy storage plays an important role in California's electricity system; energy storage increases grid reliability and flexibility and is expected to grow as the grid evolves with greater penetration of highly variable renewable sources such as wind and solar. Pumped hydroelectric energy storage is one of the largest sources of stationary electricity storage on the state's grid today. However, installation of this technology is severely limited by geographic location (since it requires two bodies of water, one at a higher elevation than the other) and environmental impacts, which together limit its expansion in California. Electro-chemical batteries, especially Lithium-ion (Li-ion), are being researched and implemented for installation on the grid, but their high cost limits their viability in large-scale and long-duration applications. Lithium-ion technology also has safety issues such as thermal runaway (uncontrollable battery overheating), limits on the numbers and depths of daily cycles, adverse environmental impacts associated with Lithium extraction, and performance degradation over time (Agusdinata et al., 2018; Schmidt et al., 2019) .

Thermal energy storage presents an alternative option for competing with conventional pumped storage hydroelectric for long-duration energy storage (LDES) applications. However, challenges with thermal energy storage (TES) remain. The most common "hot TES" uses high-cost solar salts (between $1000-$1200/ton) in 2-tank configurations. Additionally, solar salts have high freezing points (around 430°F [221°C]), which require significant parasitic energy loss related to their extensive electric trace-pipe heating.

Element 16 invented sulfur TES to solve the two main challenges that prevent molten salt's use for LDES. The first is cost. Most of the cost of the molten salt heat storage system is the salt itself, which is generally about $1200 per ton. Sulfur is between $60 and $100 per ton, allowing sulfur TES to reduce the cost of TES on an order-of-magnitude scale when compared with existing TES technologies using solar salts. Second is the operational temperature range. Since molten nitrate salts solidify at around 430°F (221°C), they primarily operate only above 464°F (240°C), with extensive electrical heat tracing of tanks, equipment, and pipes that prevent solidification (or risk damage to the heat storage, heat exchanger equipment, pumps, piping and valves). The operational expenses associated with electrical heat tracing can cause a high levelized cost of storage. Sulfur solidifies below 230°F (110°C), meaning it does not generally approach solidification temperatures during normal operation. Element 16 also uses a single-tank design, which avoids sulfur pumping, so that sulfur can safely solidify (for example, during maintenance) without harming any heat-storage equipment.

Other TES options such as latent heat-based phase-change materials and solid-state sensitive heat storage media (concrete, rocks) are being investigated (for example by ENERGYNEST and Siemens Gamesa Renewable Energy) but suffer from inherent challenges related to poor thermal responsiveness, thermal cyclic stability, and large footprints. Element 16's TES uses liquid sulfur and can additionally use a variety of heat transfer fluids, so it combines the performance advantage of a liquid (molten salt) and the cost advantage of new solid-storage innovations.

The primary goal of this project was to develop and demonstrate a low-cost sulfur thermal battery technology for both electricity storage and generation. This project aligns with the following strategic objectives (Lew et al., 2023), which focus on reaching the goals of SB 100 (De León, Chapter 312, Statutes of 2018) and SB 350 (De León, Chapter 547, Statutes of 2015), among other key state energy- and climate-related mandates.

Create a More Nimble Grid to Maintain Reliability as California Transitions to 100-Percent Clean Energy: By smoothing out the variability of renewable energy generation, sulfur-thermal battery technology ensures a more consistent and reliable energy supply, which in turn facilitates greater integration of green energy into the state grid.

Improve the Customer Value Proposition of End-Use Efficiency and Electrification Technologies: Sulfur thermal batteries can be charged with renewable electricity during times of excess supply to dispatch firm, clean electricity and heat to industrial users, thereby decreasing reliance on fossil fuels and accelerating industrial decarbonization.

A first-of-its-kind 1.5 Megawatt-hours (MWh) sulfur thermal battery system was successfully built and qualified through comprehensive testing and demonstration. Key performance metrics such as charge and discharge rates, round-trip efficiency, and the levelized cost of storage were evaluated. This project is both timely and critical considering California’s increasing energy demands and the growing challenge of renewable generation curtailments. By addressing the critical need for long-duration and cost-effective energy storage, this sulfur thermal storage technology has the potential to play a role in realizing California's vision for a sustainable and resilient energy future.

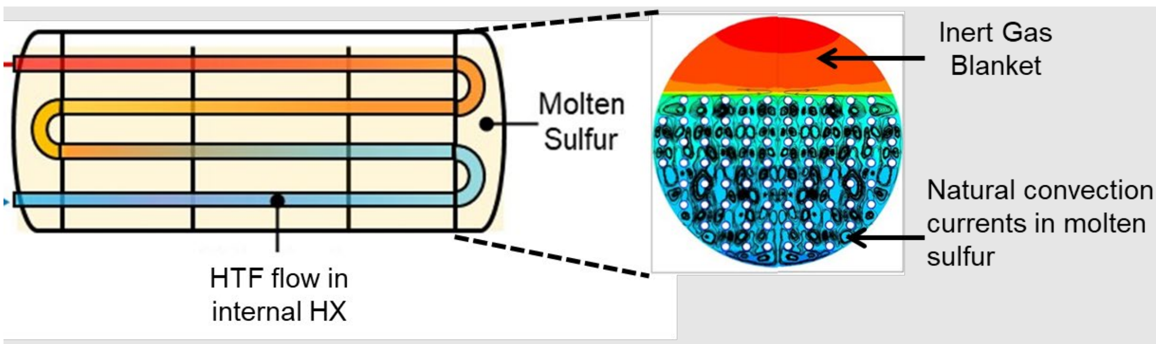
The results of this research will be used by interested stakeholders, including utilities and end users, to decide whether to install sulfur thermal batteries for industrial process heat and electricity. Renewable energy project developers will also find the outcomes of this research beneficial. Renewable energy project developers can use insights from this work to explore innovative ways to incorporate sulfur thermal battery technology into their respective renewable energy projects.

Industrial heat pump manufacturers can determine both the performance and economic benefits of integrating their technology with sulfur thermal batteries to provide load flexibility (including load shifting), peak shaving, and demand-side management, which additionally supports utilization of intermittent renewable generation. Research organizations and government agencies will be able to identify and address the research required to overcome market barriers to sulfur thermal battery adoption.

CHAPTER 2: Project Approach

Element 16 successfully developed and demonstrated a novel sulfur thermal battery to store and dispatch energy from renewable resources efficiently and inexpensively. Element 16's single-tank sulfur TES design configuration is shown in Figure 1 and has two major components: an internal heat exchanger assembly, referred to as "internal TES-HX" located within molten sulfur, and a vessel that houses molten sulfur.

Figure 1: Schematic Illustration of Sulfur Thermal Energy Storage

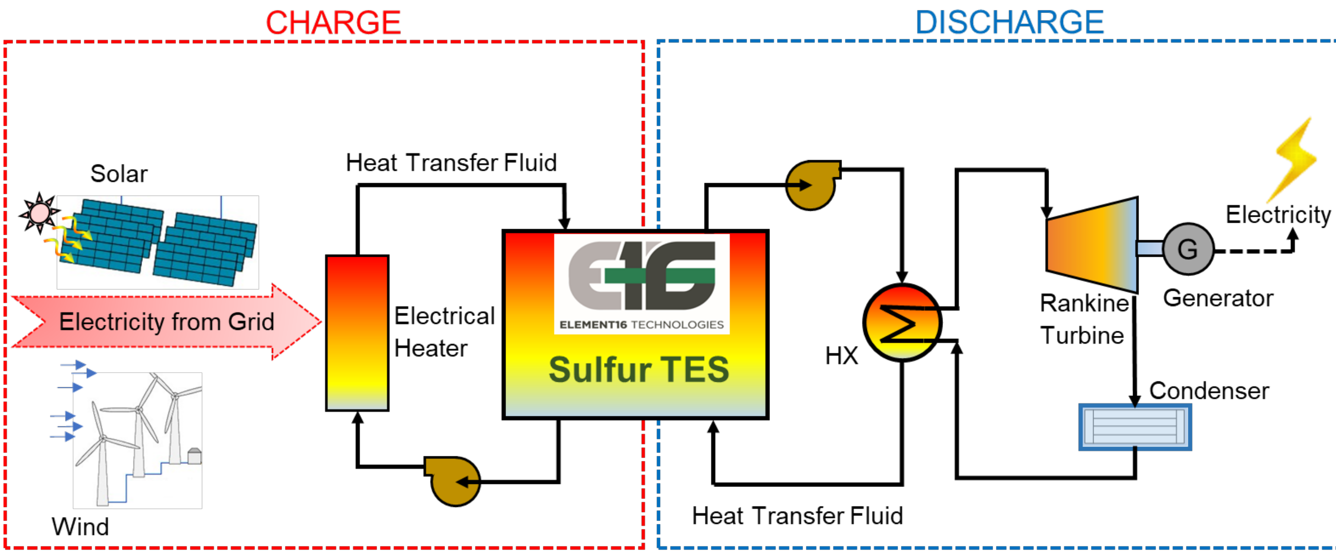


Sulfur is stored in the vessel and heat transfer fluid flows through the pipes. The inset plot shows representative temperature contours and natural convection current streamlines in molten sulfur.

Source: Element 16 Technologies, Inc.

Figure 2 shows the proposed sulfur thermal battery system configuration. During charge, the electric heater is powered by either the grid (when electricity prices are low) or by onsite renewable-energy installations when excess electricity is available to heat the heat-transfer fluid (typically thermal oil). Electric heater systems are similar to shell- and tube-heat exchangers where tubes are replaced with heating elements, commonly used in process industries. The hot heat transfer fluid enters the TES and stores heat in the molten sulfur. During discharge, cold heat transfer fluid (HTF) circulates through the internal TES-HX to retrieve that stored heat. The hot HTF from the sulfur TES exchanges heat with the power-block working fluid, which spins a turbine for predictable, on-demand electricity. The Element 16 engineering team used computational modeling tools to design a pilot-scale 1.5 MWh sulfur thermal energy storage unit fabricated by PCL Industrial Services, Inc. (PCL), located in Bakersfield, California. The sulfur thermal battery system was installed and tested by Element 16 engineers at the company's facility in Duarte, California. Key performance metrics such as charge/discharge rates, round-trip efficiency and the levelized cost of storage were evaluated. Waste Salt Technologies LLC, located in Anaheim, California, conducted an independent third-party review of the measurement and verification of the performance and techno-economic viability of the sulfur thermal battery system.

Figure 2: Schematic of Sulfur Thermal Battery Configuration for Electricity Storage and Generation



Source: Element 16 Technologies, Inc.

The project's technical advisory committee (TAC) was composed of experts from various technical backgrounds including heat transfer, systems engineering, techno-economics and power generation (Climeon and Enogia are developers of organic Rankine technology). The TAC reviewed research and development progress and critical project review meetings and provided feedback on system design and testing activities. The experts who served on the TAC included:

- Adrienne Lavine: Professor at UCLA, Mechanical and Aerospace Engineering
- Joachin Karthäuser: Co-founder, Chief Technology Officer, and Senior Advisor at Climeon
- Gael Leveque: Head of Research and Development at Enogia
- Ryan Bowers: Principal Technical Consultant, Project Manager, at Advisian (Worley Group)
- Alex Ricklefs: Program Manager at The Energy Coalition

System Performance and Cost Modeling

A system performance and cost model of the sulfur thermal battery system was developed to conduct a detailed parametric analysis of the key design and operating parameters on the system's techno-economics. The major components of the low-cost sulfur thermal battery system, as illustrated in Figure 2, include a sulfur TES module, a heat exchanger, a thermal-oil electric heater, pumps, and a power generation unit. The analysis highlighted the competing effects of various design and operating parameters on system performance metrics (namely system cost and round-trip efficiency), allowing the team to identify optimal system design and operating conditions for the planned demonstration unit. The pilot sulfur TES (with a capacity of 1500 kilowatt hours (kWh), designed to charge and discharge at a peak heat rate of 140 kW and integrated with a 100-kW electric heater and a 10-kilowatt-electric (kWe) organic Rankine cycle [ORC] unit), was determined to be the best configuration for the planned system demonstration. The predicted charge and discharge times of the system were 12 to 14 hours and 8 to 9 hours, respectively. The results indicated that the expected thermal-to-thermal round-trip efficiency of the system, with 6-inch fiberglass insulation on the pilot sulfur TES module and 2-inch fiberglass insulation on the piping circuit, was between 82 percent and 85 percent. The maximum and minimum temperatures of thermal oil HTF in the circuit during normal operations were 257°F (125°C) and 572°F (300°C), respectively. Table 1 shows the heat and mass balance for various operating scenarios.

Table 1: Heat and Mass Balance of Pilot Sulfur Thermal Battery System

Description	Sulfur TES Inlet	Sulfur TES Exit	Heat Exchanger Inlet	Heat Exchanger Exit/ Pump Suction	Pump Delivery/ Heat Exchanger Inlet	Heat Exchanger Exit/ORC Inlet	ORC Exit/Pump Suction
Medium	*Thermal Oil Multitherm-IG4*				*Pressurized Hot Water (15-20 psig)*		
A) CHARGE MODE							
Temperature [°F]	257 to 572				N/A		
Flow Rate [kg/s]	3.0				N/A		
B) DISCHARGE MODE							
Temperature [°F]	266	572 to 311	311	266	230	248	230
Flow Rate [kg/s]	0.3 to 2.5	0.3 to 2.5	2.5	2.5	3.3	3.3	3.3

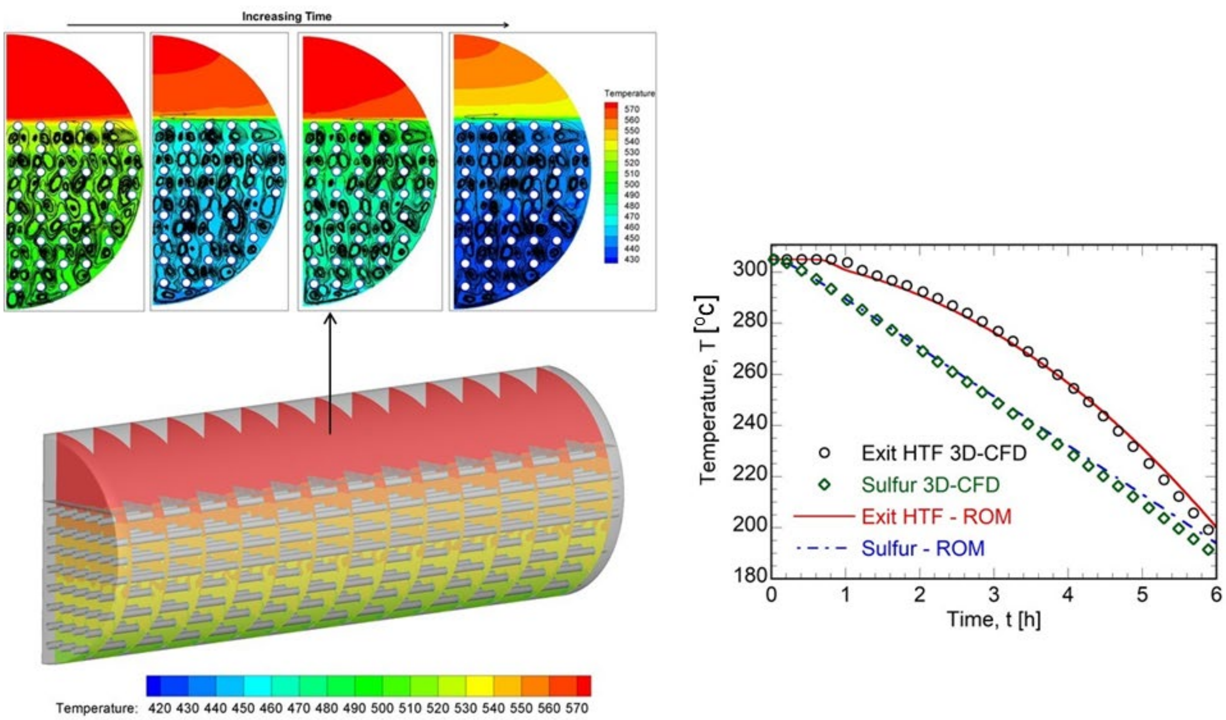
Source: Element 16 Technologies

Sulfur TES Design Optimization

A full-scale, high-fidelity computational model was developed to investigate important characteristics of the heat transfer behavior of sulfur and quantify the dynamic thermal performance of sulfur thermal battery in terms of heat rate, heat transfer coefficient, and Nusselt number. The effects of various design parameters, namely the internal TES-HX pipe diameter and spacing on system performance, were investigated. A correlation for transient Nusselt numbers governing natural convection dynamics in sulfur (as a function of the Rayleigh number and pitch) was derived. This validated correlation was used for the design of the sulfur thermal energy storage module, using a reduced order model (ROM). The ROM was based on the conservation of energy principle applied to the HTF flowing in the pipe, the pipe wall, and the sulfur in the tank. The thermal coupling between the HTF and sulfur was based on the forced convection heat transfer coefficient for HTF flow, which is well established in both the literature (Gnielinski, 1976) and the natural convection heat coefficient of sulfur. Appendix A has details of the numerical heat transfer reduced-order model.

Based on this analysis, the system size and design parameters required to meet the technical specifications of the 1500 kWh demonstration unit were determined. The HTF pipe diameter of 2”, with a pitch ratio of 2.5 to 4 located within 23 metric tons of molten sulfur bath stored in an 18 m³ vessel, provided favorable thermo-economic outcomes. A full-scale, high-fidelity, 3-dimensional simulation was conducted to verify the natural convection activities and the expected transient performance of the sulfur TES module. Figure 3 shows sulfur natural convection dynamics in a particular cross section for various times, and the temperature contours from full 3-dimensional computational fluid dynamics simulation involving the forced convection of HTF flow and the natural convection of sulfur, at a particular time. Little variation in the axial temperature distribution of sulfur was observed, which established the role of natural convection currents in uniform distribution of heat throughout. The numerical heat transfer ROM was also validated against results from high-fidelity computational fluid dynamics simulations for the 1500 kWh sulfur TES pilot-prototype design. Figure 3 shows the agreement between the transient prediction results of the numerical heat transfer ROM and the high fidelity computational fluid dynamics model for the HTF exit temperatures and bulk sulfur temperatures during discharge operations.

Figure 3: Temperature Contour (Scale in Kelvin) and Natural Convection Current Inside Sulfur TES



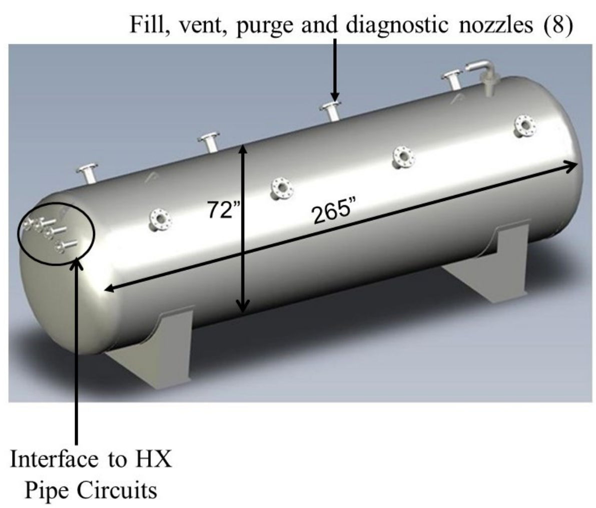
Source: Element 16 Technologies, Inc.

Construction of Sulfur Thermal Energy Storage Module

Thermal cyclic corrosion testing of metal coupons in hot molten sulfur was conducted to both determine the suitable material for construction and define the corrosion allowance specification for molten sulfur storage. Leveraging insights from these tests, along with findings from the sulfur TES design optimization initiative, Element 16 generated an engineering model of sulfur thermal energy storage (Figure 4). The TES vessel dimensions were 72″ diameter, 233″ tangent-to-tangent length, and ¼″ wall thickness with the American Society of Mechanical Engineers (ASME) 2:1 semi-elliptical head made of stainless steel 316.

The total volume of the vessel is 18 m³, which includes ullage for a nitrogen blanket. The internal TES-HX comprises 2-inch HTF pipes with a total surface area of approximately 100 m². The molten sulfur TES was designed according to ASME Section VIII Division 1 for the vessel and ASME B31.1 standards for internal heat-exchanger piping. The vessel was insulated using 6” fiber glass insulation with aluminum jacketing. Figure 5 shows the sulfur TES module, fabricated by PCL. The design went through multiple iterations between Element 16 and PCL’s engineering teams to ensure that the design of the sulfur TES is ASME code-compliant. Both the vessel and pipe circuit were pneumatically tested with nitrogen (as per code and ASME) after successful pressure testing. A helium-leak test with internal vacuum in the piping was done by Helium Leak Testing, Inc., for 30-minute dwell times, where both circuits showed no leak greater than 1×10-5 mBar-L/s (mBar liter per second).

Figure 4: Engineering Model of 1.5 MWh Sulfur Thermal Energy Storage Module



Source: Element 16 Technologies, Inc.

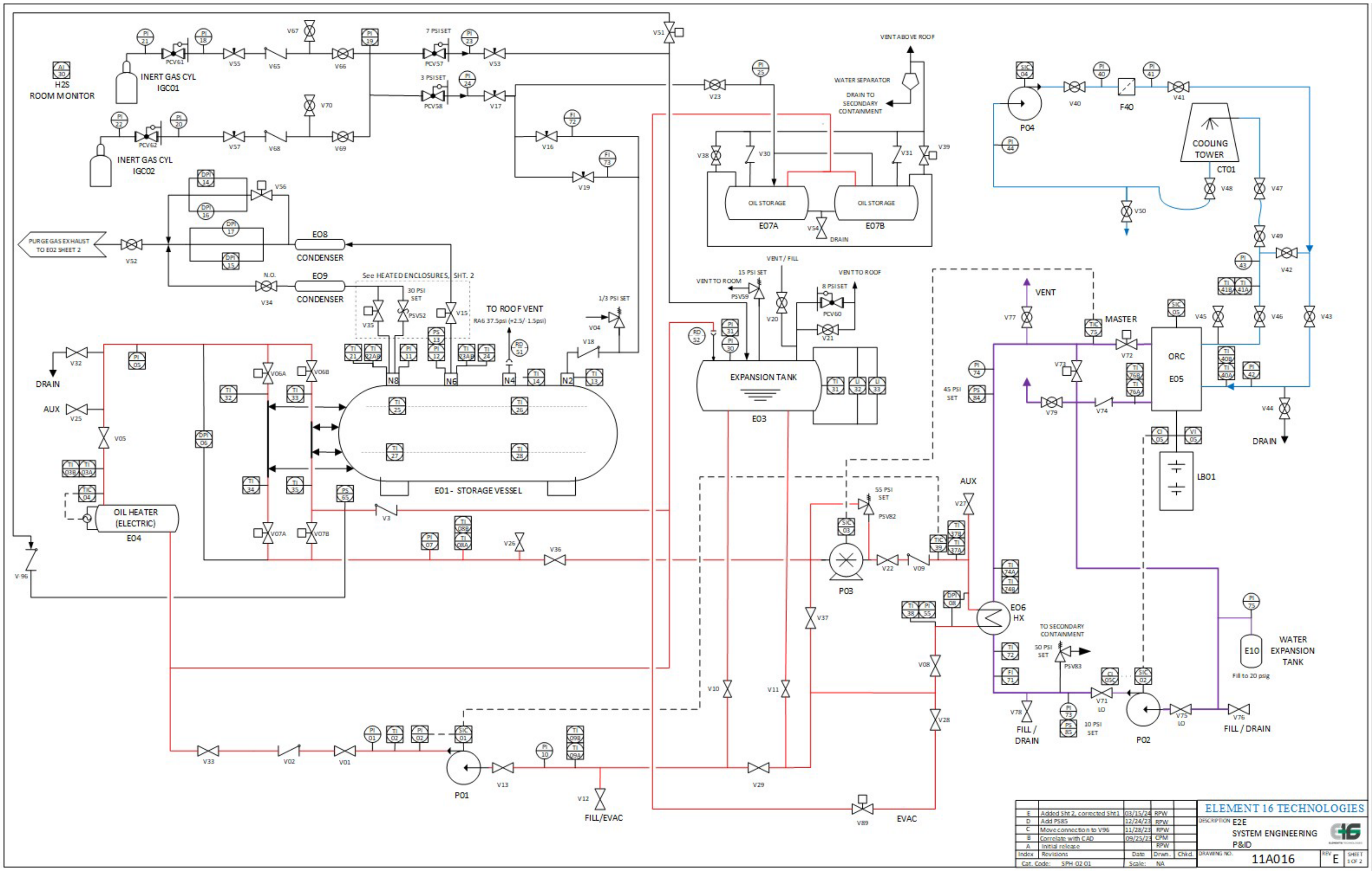
Figure 5: Fabricated Sulfur Thermal Energy Storage Module

Source: Element 16 Technologies, Inc.

System Integration

The sulfur TES module was integrated with an electric-oil heater, power-generation unit and other balance-of-system components and commissioned at Element 16’s facility in Duarte, California, for both system testing and demonstration. The process-flow diagram of the system, along with the instrumentation and sensors, is shown in Figure 6. The system has three main loops: a thermal oil loop (shown in red) heated by the electric oil heater (E04), which stores thermal energy in the sulfur heat-storage vessel (E01) during charge mode and retrieves heat from the sulfur heat-storage vessel during discharge mode; the pressurized hot-water loop (shown in purple), which is heated by the hot thermal oil in the discharge heat exchanger (E06) and used in the ORC power-generation unit (E05) for electricity generation during discharge mode; and the cooling water loop (shown in blue), which is connected to the cooling tower (CT01) and operates during the discharge mode for condensing the refrigerant in the ORC to close the power cycle. As illustrated in Figure 6, the system configuration includes temperature, pressure, and flow sensors for performance measurement and verification.

Figure 6: Piping and Instrumentation Diagram of Sulfur Thermal Battery System



Source: Element 16 Technologies, Inc.

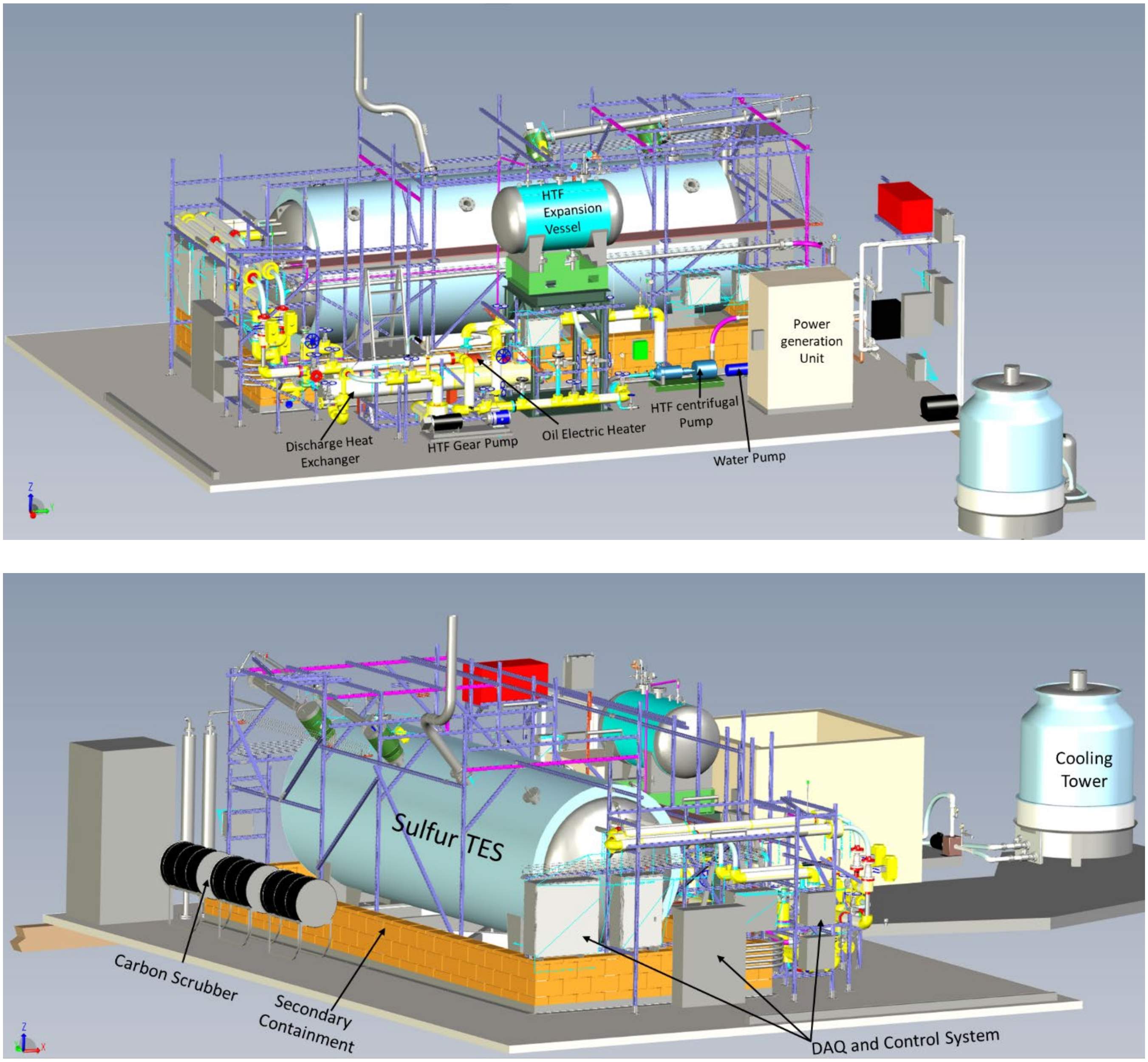
Figure 7 shows the detailed engineering drawing of the system layout, illustrating the sulfur TES integrated into the system balance in the thermal-oil loop. The system layout was carefully planned so that it could be located inside Element 16’s facility for commissioning and testing. The primary subsystems are sulfur TES, the HTF system, the process fluid system with the power-generation unit, the vapor-management system, and the electrical and controls system.

The HTF system includes the HTF-associated piping up to and from the sulfur TES, HTF circulation electric heater, HTF pumps, discharge heat exchanger, HTF expansion vessel, and filters. The expansion vessel allows thermal expansion of the heat transfer fluid during operation and assists in degassing the oil prior to and during operation. The expansion vessel is mounted so that the liquid level in the tank is at a higher elevation than the highest point in the piping system (including the internal TES-HX circuit). The expansion tank is supplied with inert gas at low pressure to minimize oxidation of the oil and prevent air intrusion. During the transient discharge operation, the temperature of the HTF exiting sulfur TES will decrease over time, a potential issue since industries need constant heat at constant temperatures. A combination of centrifugal and gear pumps was used to maintain constant inlet temperatures and flow rates of HTF into the discharge heat exchange. The filter installed at the discharge of the HTF pump was designed to remove particulate matter.

The process fluid system comprises the tie-ins between the process fluid stream, the power generation unit, and sulfur TES. The process fluid system includes a water pump, water expansion tank, discharge heat exchanger (where heat is transferred from hot oil exiting sulfur TES to the process water), and the ORC power generation unit. The vapor management system includes all scrubbers, pressure safety valves located on the sulfur TES and HTF expansion vessels, sulfur condensers, and nitrogen (inert gas) supplies. The inert gas (nitrogen) supply is used to flush out contaminants in the sulfur prior to operation. Inert gas is also used to maintain positive pressure in the vessel and as a cover gas to exclude air. Sulfur TES is protected from over-pressurization by redundant pressure-relief devices. Relief valves are attached to a nozzle near the top of the vessel and their output is routed through a sulfur vapor condenser, particulate filter, and, lastly, an activated carbon scrubber before release into the atmosphere. A rupture disc is fitted to a nozzle at the top of the vessel. The sulfur vapor condensers are natural convection, cooled to condense sulfur vapor prior to scrubbing.

The electrical and controls system includes all electrical equipment associated with the electric heaters including all system electrical load, the motor control center, variable frequency drives, programmable logic controllers, human machine interfaces, and instrumentation.

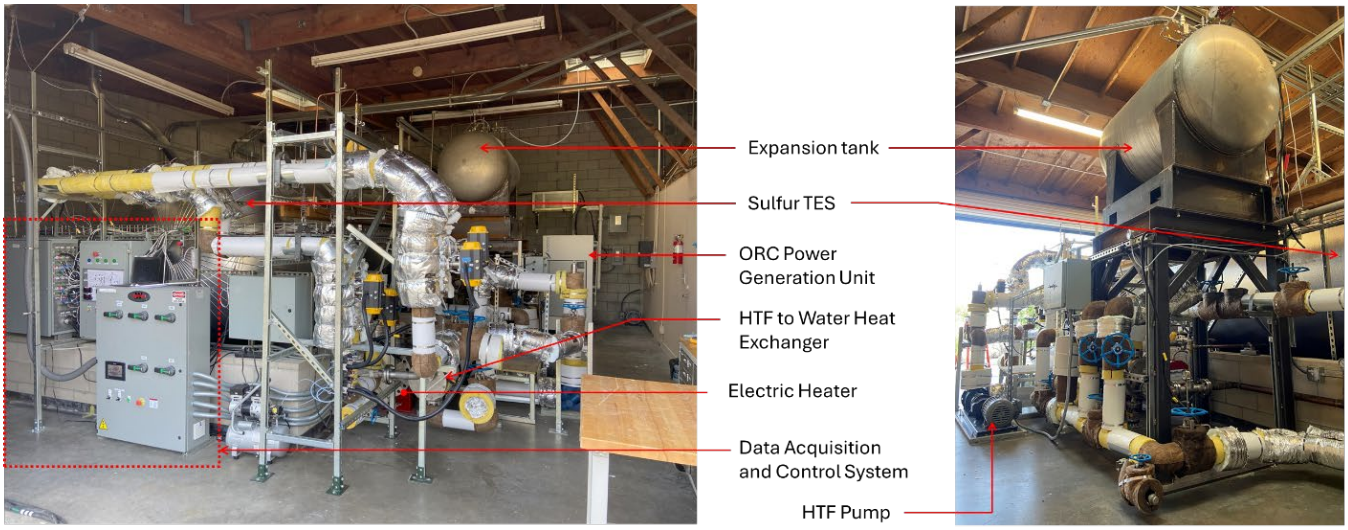
Figure 7: Sulfur Thermal Battery Demonstration System Layout



Source: Element 16 Technologies, Inc.

Figure 8 shows the installed sulfur thermal battery system at Element 16's facility. Figure 9 shows the sulfur TES module and the ORC power generation unit, procured from Enogia (Enogia, n.d.).

Figure 8: Installed Sulfur Thermal Battery System at Element 16 Facility in Duarte, California



Source: Element 16 Technologies, Inc.

Figure 9: (A) ORC Power Generation Unit, and (B) Sulfur Thermal Energy Storage

Source: Element 16 Technologies, Inc.

System Commissioning

Following system installation, the Element 16 team filled the TES vessel with sulfur pellets from Montana Sulfur Company through a hopper-feeder connected to one of the flanges atop the sulfur TES vessel (Figure 10).

Element 16’s sulfur TES design configuration has two primary components: an internal heat exchanger pipe assembly (referred to as “internal TES-HX”), located within molten sulfur, and a vessel that houses the molten sulfur itself. Based on the loaded 23-ton sulfur mass and the mass of the internal TES-HX and the mass of vessel, the sulfur TES capacity was calculated as follows:

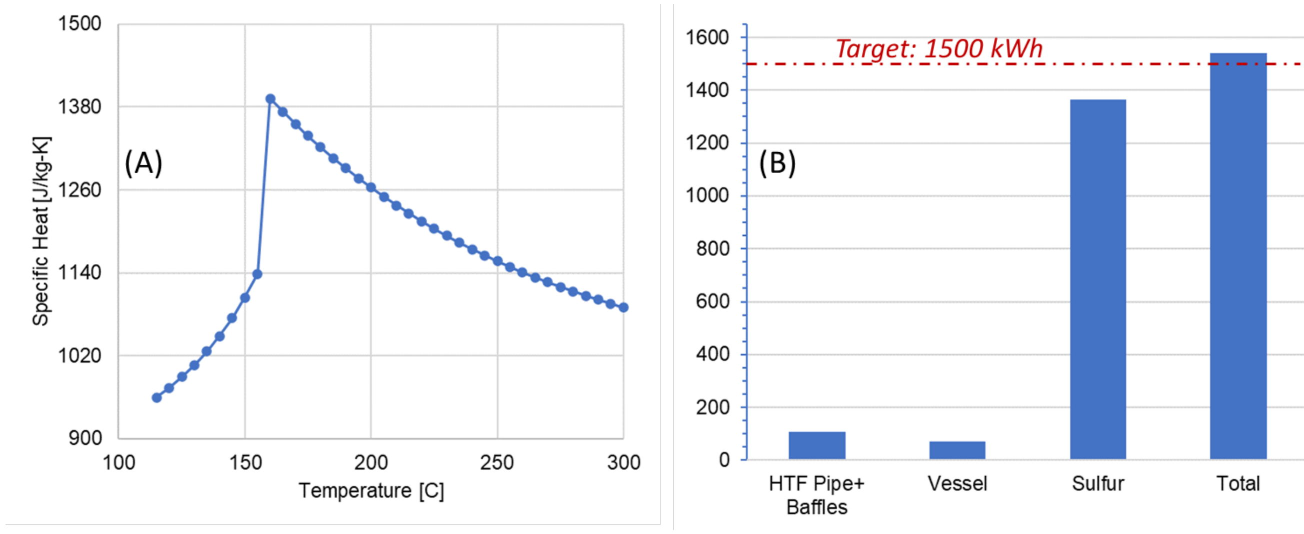
$$Q_{TES} = \{m_{sulfur}c_{sulfur} + m_{vessel}c_{wall} + m_{internal\ TES-HX}c_{wall}\}\Delta T \qquad \text{[Eq. 1]}$$

The mass of internal TES-HX and mass of vessel was obtained from the fabrication drawing provided by the manufacturing firm PCL. Since sulfur TES is thermally cycled between 248°F (120°C) and 572°F (300°C), ΔT is fixed at 324°F (180°C). The specific heat of sulfur was obtained from the National Institute of Standards and Technology database and plotted in Figure 11. The average specific heat of the sulfur for the temperature range of interest is 1,186 kilojoules per kilogram Kelvin (kJ/kg-K). The specific heat of internal TES-HX and vessel construction material was obtained from the literature (Kim, 1975). As shown in Figure 11, the calculated sulfur TES capacity is 1533.3 kWh, with sulfur contributing 89 percent of the total installed TES capacity. Figure 12 shows the sulfur thermal battery system, taken after the system was commissioned.

Figure 10: (A) Sulfur Pouring Onto a Conveyor Belt; (B) Element 16 Staff Positioning the Sulfur Bag for TES Vessel Filling; and (C) Sulfur Pouring Into a Funnel, Leading Into the TES

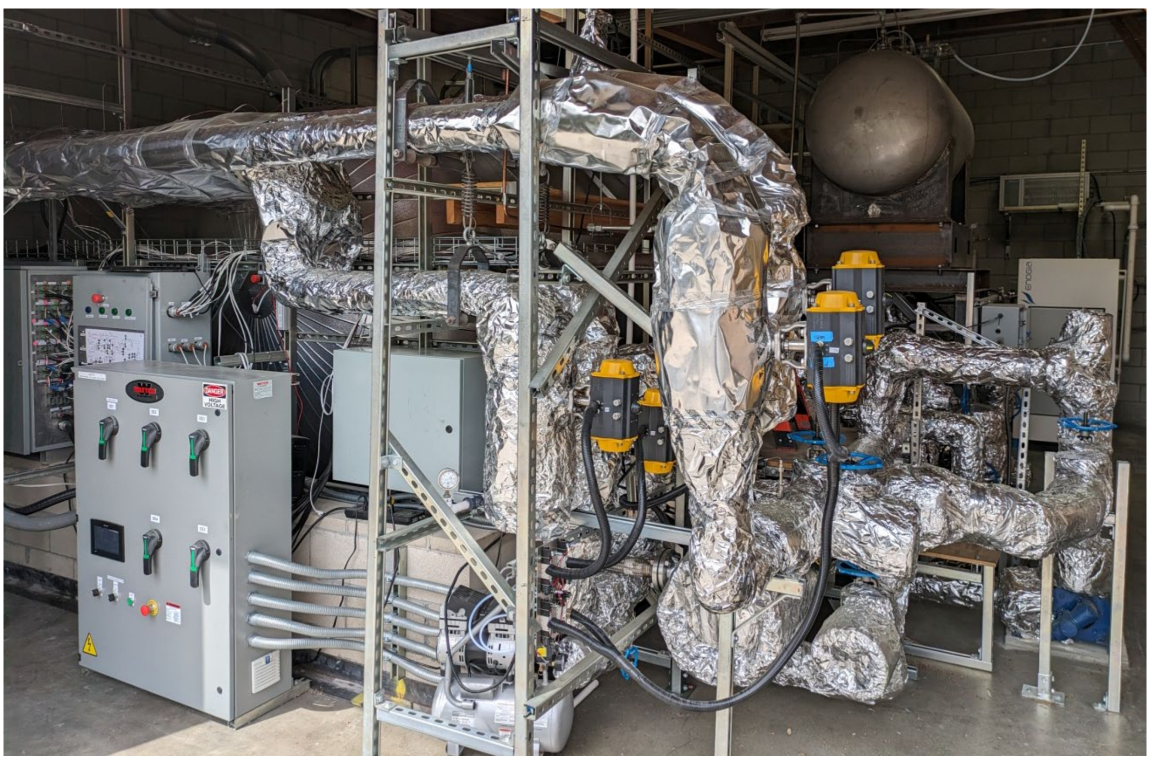
Source: Element 16 Technologies, Inc.

Figure 11: (A) Specific Heat of Sulfur as a Function of Temperature, (B) Storage Capacity of Sulfur TES and Distribution Across Various Components



Source: Element 16 Technologies, Inc.

Figure 12: Fully Insulated and Commissioned Sulfur Thermal Battery System



Source: Element 16 Technologies, Inc.

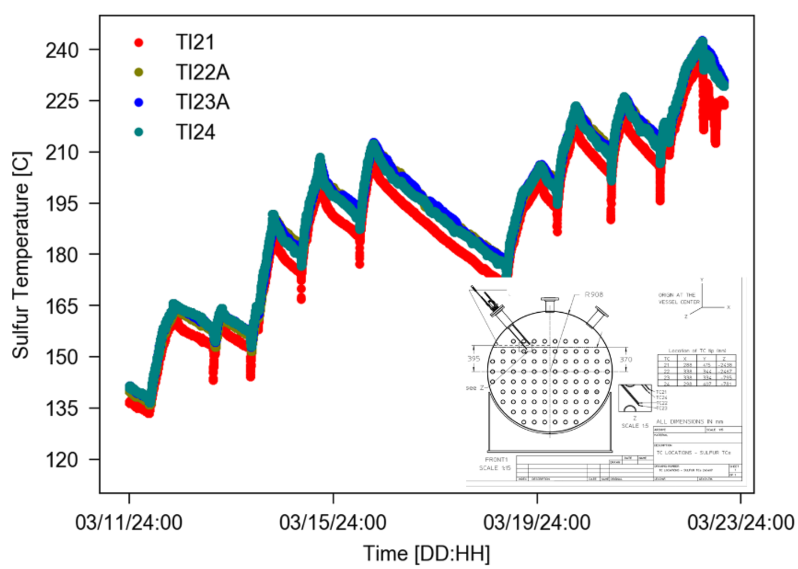
CHAPTER 3: Results

Performance Characterization

Experiments were conducted for multiple charge and discharge cycles to assess system performance and collect data to validate the computational model. Key performance metrics calculated included the charge rate, discharge rate, energy charged, energy discharged, and round-trip efficiency. The performance metrics are defined in Appendix B.

Figure 13 shows the transient temperatures recorded by thermocouples at various locations inside sulfur during the initial cyclic charge process. Figure 14 shows the transient temperature measured at various circumferential and axial locations on the vessel surface, which provided insight into surface temperature distribution. Since this was the system's first operational run, the electric-heater power was gradually increased, with careful monitoring. The calculated charge heat rate using the mass flow rate of the HTF, inlet and outlet temperature of HTF across the electric heater (E-04 in Figure 6) aligned well with the expected temperature rise within the sulfur TES, indicating effective heat transfer. Overall, the system operated without safety issues, and no leaks were detected during the tests. The drop in temperature during each thermal cycle corresponds to heat losses during nights and weekends when the charge process was paused. The heat loss calculated as a function of bulk sulfur temperature (using the measured temperature drop inside sulfur TES) is illustrated in Figure 15, which closely matched with estimated heat-loss values. These findings confirm the system's stability and thermal performance within the expected temperature range.

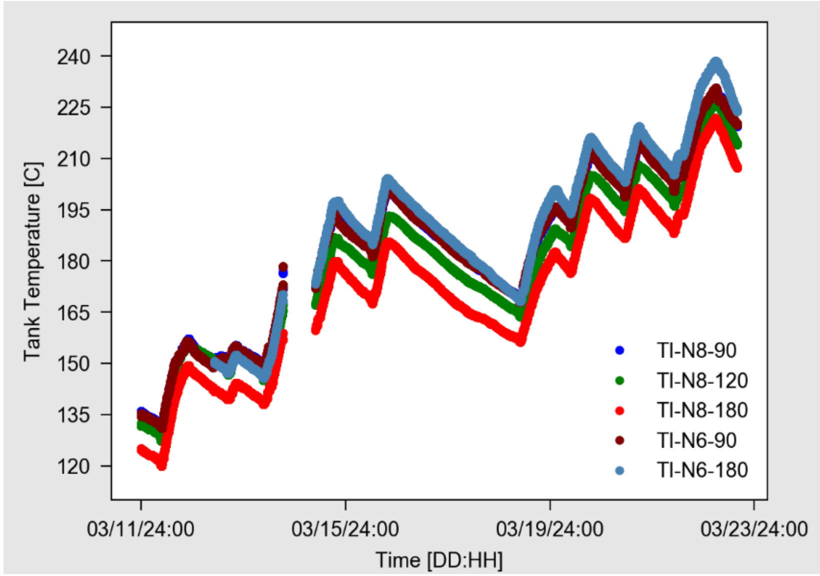
Figure 13: Temperatures Measured by Various Thermocouples Inside Sulfur



The inset plot shows the location of thermocouples located near the first and second row of the internal HX tube circuit.

Source: Element 16 Technologies, Inc.

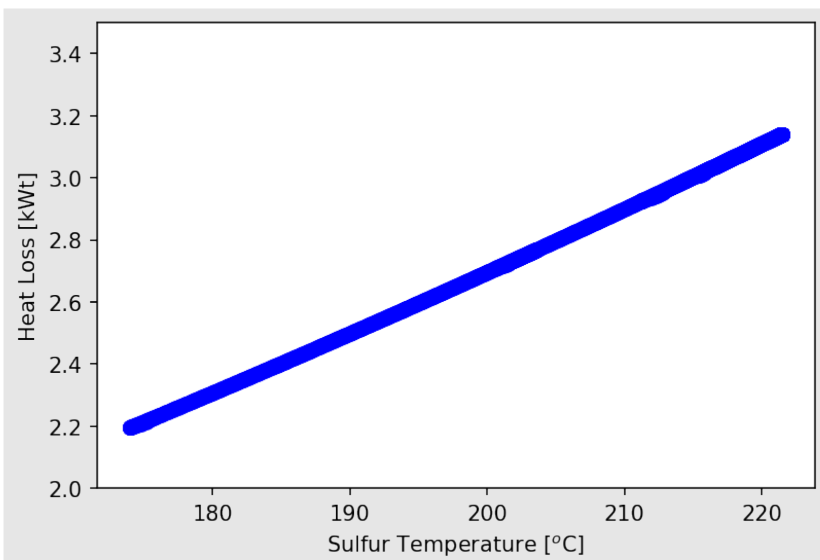
Figure 14: Temperatures Measured by Thermocouples on the Surface of the Sulfur TES Vessel at Various Circumferential and Axial Locations



90 refers to the thermocouple located 90° from the top of the vessel, and 180 refers to the thermocouple at the bottom of the vessel.

Source: Element 16 Technologies, Inc.

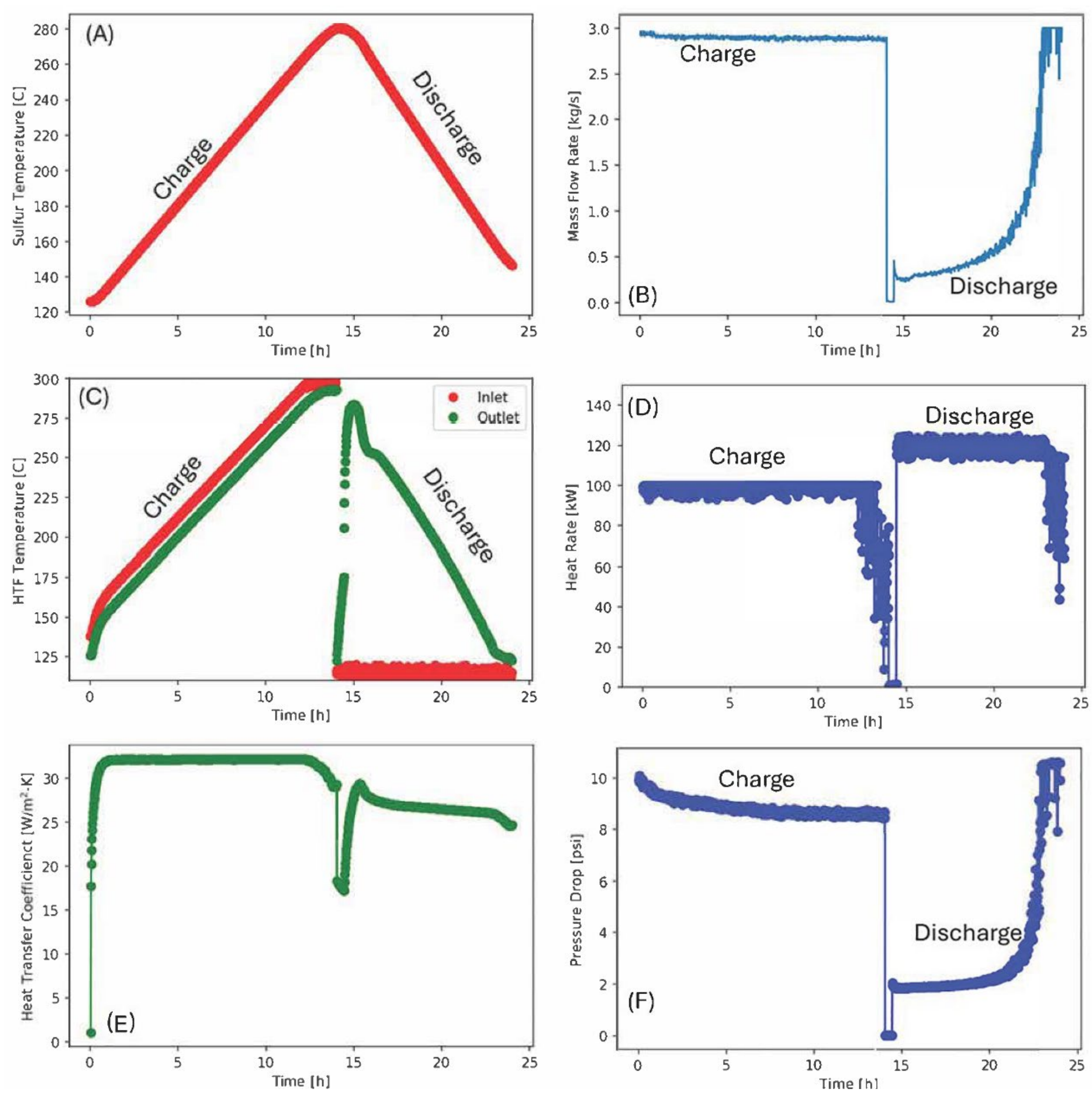
Figure 15: Calculated Heat Loss as a Function of Sulfur Temperature



Source: Element 16 Technologies, Inc.

Figure 16 shows the measurement of sulfur temperature, HTF temperature at the inlet and outlet of TES (TI-03A and TI-08), mass flow rate of HTF, calculated thermal charge and discharge rates, heat transfer coefficient and pressure drop of HTF flow across TES (calculated using PI-05 and PI-07 in Figure 6) during a charge/discharge cycle. During the charge process, the mass flow rate of the HTF was held steady (Figure 16B). The system was able to charge at the peak electric heater power output of 100 kW until the bulk sulfur temperature reached a temperature of approximately 500°F (260°C), as shown in Figure 16A. Beyond this point, the achievable charge rate gradually decreased due to the reduced temperature differential between the inlet HTF temperature of 572°F (300°C) and the bulk sulfur temperature (Figure 16A and C). During discharge, the HTF exit temperature from the TES decreased over time (Figure 16C). To maintain a constant heat rate across the discharge heat exchanger (E-06 in Figure 6) for steady ORC operation, the HTF pump regulated the flow rate dynamically. Figure 16B illustrates the variation in HTF flow rate during the discharge process and Figure 16D shows that a constant heat rate was maintained throughout most of the discharge process. This data demonstrated the system's ability to charge efficiently up to a bulk sulfur temperature of 500°F-510°F (260°C-265°C) at the peak charge rate and regulate flow for stable heat output during discharge, which is essential for reliable ORC performance.

Figure 16: Transient Variation of (A) Sulfur Bulk Temperature, (B) HTF Flow Rate Variation, (C) HTF Temperature at the Inlet and Exit of TES, (D) Heat Transfer Rates, (E) Heat Transfer Coefficient, and (F) Pressure Drop Across Sulfur TES During a Charge/Discharge Cycle



Source: Element 16 Technologies, Inc.

Table 2 shows the performance metrics in terms of energy charged, energy discharged, thermal-to-thermal round trip efficiency (RTE), electricity generated, and the overall thermal to electric RTE, calculated using the methodology described in Appendix B.

Table 2: Key Performance Characteristics Obtained From the Cyclic Charge and Discharge Operation of the Sulfur Thermal Battery

Energy Charged [kWh]	Energy Discharged [kWh]	Thermal to Thermal RTE [%]	Electricity Generated by ORC [kWh]	Thermal to Electric RTE [%]
1336.1	1137.3	85.1	70.5	5.1

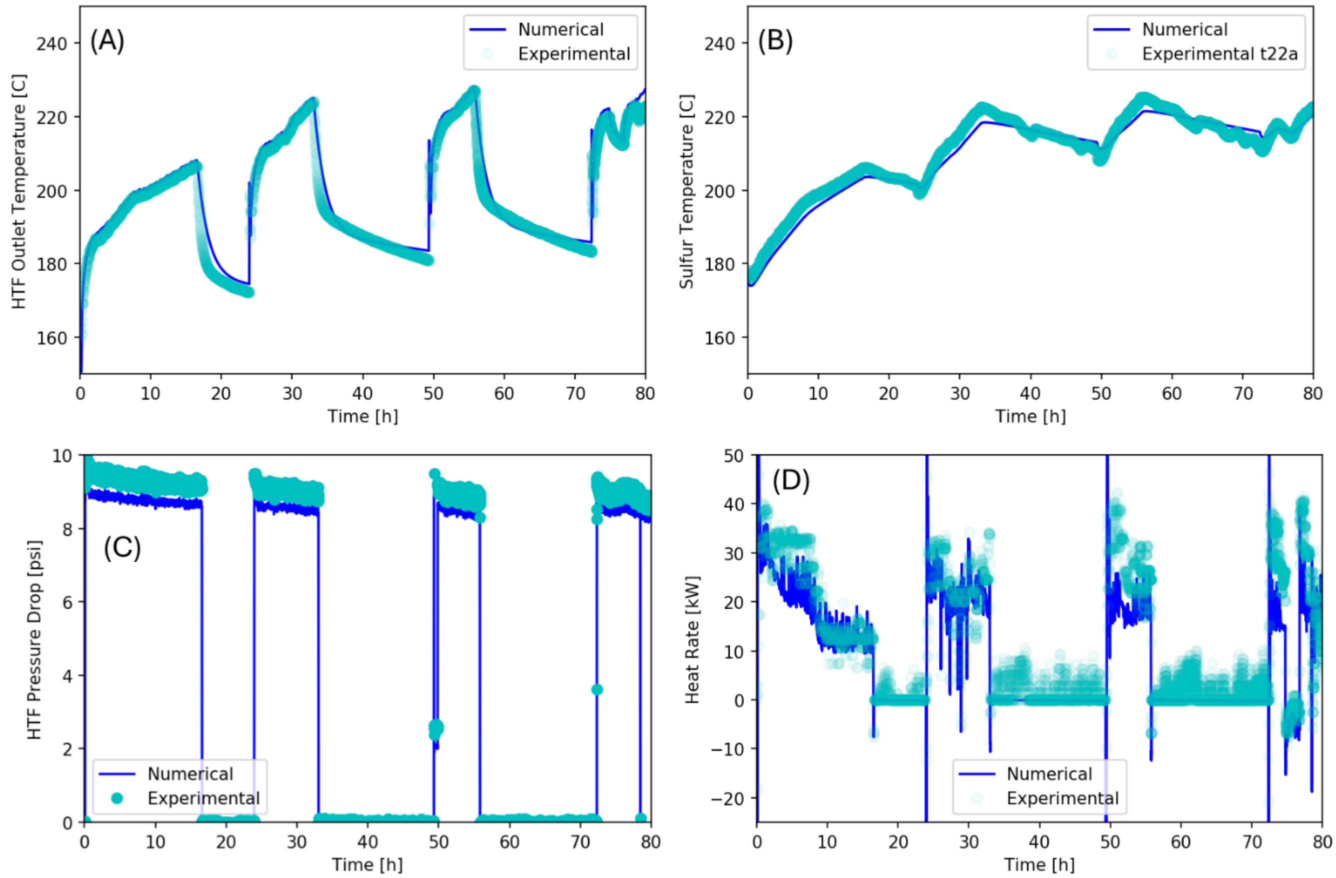
Source: Element 16 Technologies, Inc.

System Model Validation

A conjugate heat transfer reduced order model (ROM) of the sulfur TES was developed to predict the transient system performance during charge and discharge mode operations. Appendix A includes details of the numerical heat transfer ROM. The model inputs are thermo-physical properties of HTF, the pipe wall material, and sulfur; design parameters such as pipe radius, pipe wall thickness, pipe length, tank shell radius, tank length, and filled sulfur mass; and initial system temperature and inlet conditions of the HTF. The model predicts the spatial and temporal evolution of the temperature profile in the tank during charge, discharge, and the transient variation in outlet HTF temperature, and evaluated key performance metrics such as charge and discharge rates. From the experimental testing data, the inputs to the model were the initial temperature (average temperature measured by the thermocouples TI-21, TI-22A, TI-23A and TI-24 located inside sulfur), inlet HTF temperature (TI-03A in Figure 6), and inlet HTF mass flow rate.

Figure 17 compares the transient prediction results between the numerical model and experimental measurements for the HTF temperature at the outlet of sulfur TES (TI-08A in Figure 6), sulfur temperature (TI-22A in Figure 6), HTF pressure drop across TES (PI-05 and PI-07 in Figure 6) and heat rate (Eq. B1 in Appendix B). The model prediction agrees with experimental results, with an average difference of less than 1.2 percent across all variables.

Figure 17: Comparison Between the Experimental Data and Numerical Predictions of the (A) HTF Outlet Temperature, (B) Sulfur Temperature, (C) HTF Pressure Drop Across TES, and (D) Calculated Heat Rates

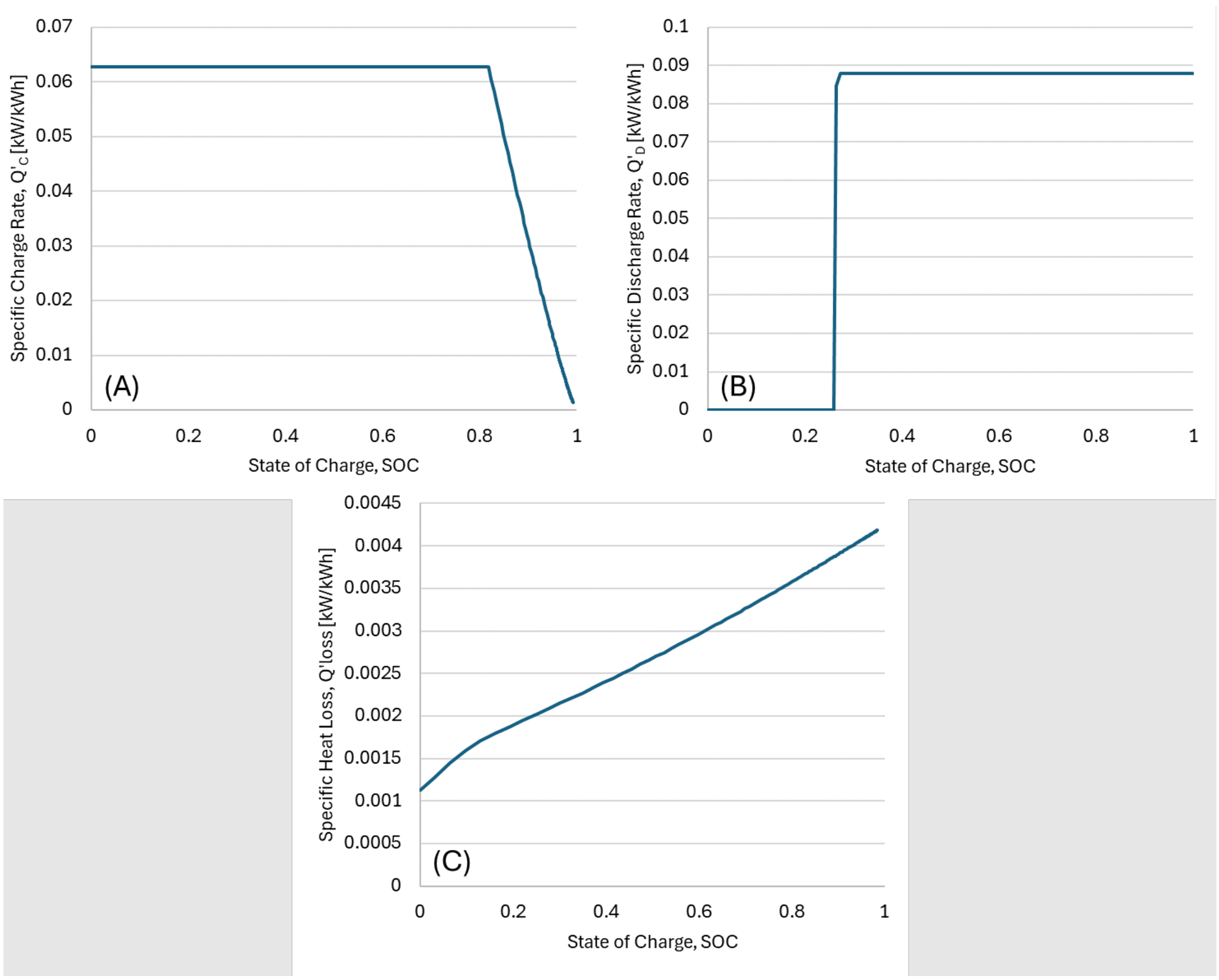


Source: Element 16 Technologies, Inc.

Using the validated numerical ROM, the performance curves of the sulfur thermal battery's specific charge rate (Q'_C), the specific discharge rate (Q'_D), and the specific heat loss (Q'_{loss}) as a function of system state of charge, were generated and are illustrated in Figure 18. The performance metrics are characterized by the storage capacity so they could be readily scaled to large-scale systems. The state of charge (SOC) for the sensible sulfur TES was defined as: $= \frac{T_{sulfur} - T_{cold}}{T_{hot} - T_{cold}}$; where T_{sulfur} is the bulk temperature of sulfur, T_{cold} is the minimum inlet temperature of HTF entering TES during discharge (266°F [130°C], which is 18°F [10°C] above the CLIMEON ORC hot-water inlet temperature requirement of 248°F [120°C]) (Climeon, n.d.) and T_{hot} is the maximum inlet temperature of HTF entering TES during charge (590°F [310°C]). Since part-load operation of the ORC power generation unit was not considered in this analysis, the specific discharge rate plot in Figure 18 shows that full-load operation cannot be sustained below a cut-off state-of-charge, $SOC_{cut-off} = 0.27$. Using the validated numerical model, the performance of sulfur thermal battery cycling between 410°F (210°C) and 590°F (310°C) was also characterized. This thermal cyclic temperature range is suitable for integration with the ORC power turbine from ORMAT technologies that uses n-pentane as the working fluid and requires a turbine inlet temperature of 392°F (200°C) (Canada et al., 2004).

Since the performance metrics of the pilot system are normalized to energy capacity in Figure 18, the predicted performance of large-scale systems with similar design configurations (for example, internal pipe diameter and spacing) can be linearly extrapolated to systems of different capacities. It's important to note that as the system size (tank diameter) increases, the surface area per unit volume decreases, leading to reduced heat losses per unit of storage capacity. Linearly extrapolating the performance of large-scale systems from pilot system performance is therefore a conservative estimate. In reality, the performance, especially thermal round-trip efficiency, is expected to improve with increased scale.

Figure 18: (A) Specific Charge Rate, (B) Specific Discharge Rate and (C) Specific Heat Loss as a Function of Sulfur Thermal Battery State-of-Charge for Sulfur TES Thermally Cycling Between 266°F (130°C) and 590°F (310°C)



Source: Element 16 Technologies, Inc.

Techno-Economic Assessment

The validated numerical thermal performance model was used to calculate annual energy savings, payback periods, and the levelized cost of storage for sulfur thermal batteries. An integrated techno-economic assessment tool was developed by combining the technical performance metrics of the sulfur thermal battery with the battery schedule optimizer. The major inputs to the model are the hourly locational marginal price data for a specific California Independent System Operator (ISO) node, and sulfur thermal battery performance as a function of state-of-charge. The objective function to be maximized is the annual revenue, expressed as:

- $$C_{revenue} = \sum_{t=0\,h}^{t=8760\,h} C_{elec}(t) \times \left\{ \dot{Q}_d(t) \times \eta_{ORC} - \frac{\dot{Q}_c(t)}{\eta_{Charge}} \right\} \quad \text{[Eq. 2]}$$

$C_{elec}(t)$ is the hourly locational marginal price, $\dot{Q}_d(t)$ is the thermal energy discharge rate of the sulfur thermal battery, η_{ORC} is the efficiency of the ORC prime mover and $\dot{Q}_c(t)$ is the charge rate of the sulfur thermal battery. The decision variables are the hourly TES charging rate ($\dot{Q}_c(t)$) and discharge rate ($\dot{Q}_d(t)$). η_{ORC} is the net efficiency of the ORC power generation unit after accounting for pump and cooling tower parasitic power consumption. η_{Charge} is the electric to thermal efficiency of the charge operation after accounting for HTF pump parasitic power consumption. Optimization is subject to the following practical constraints on overall system operation.

a. The internal heat exchanger design and heat transfer physics of the molten sulfur TES limits the achievable charge and discharge rates that are a function of SOC of TES and characterized using the validated performance model described in the previous section. The constraints for the charge and discharge rate can be expressed as:

   - $$\dot{Q}_c(t) \le Q'_C(SOC) \times Q_{TB} \quad \text{[Eq. 3a]}$$
   - $$\dot{Q}_D(t) = \left\{ \begin{matrix} Q'_D \times Q_{TB},\ SOC \ge SOC_{cut-off} \\ 0,\ SOC < SOC_{cut-off} \end{matrix} \right\} \quad \text{[Eq. 3b]}$$

b. The TES energy balance constraint that maintains the energy balance between state-of-charge and the charge-discharge cycle when considering the associated heat loss from the sulfur thermal battery.

   - $$SOC(t) = SOC(t-1) + \frac{1}{Q_{TB}} \left\{ \dot{Q}_c(t) - \dot{Q}_d - \dot{Q}_{loss} \right\} \times \Delta t \quad \text{[Eq. 4]}$$

The levelized cost of storage (LCOS) was calculated from:

$$LCOS = \frac{CRF \times (C_{direct} + C_{indirect}) + C_{Fixed,om} + \sum_{t=0}^{8760} C_{elec}(t) \times \dot{Q}_c(t)\}}{\sum_{t=0}^{8760} \dot{Q}_d(t) \times \eta_{ORC}} \quad \text{[Eq. 5]}$$

CRF is the capital recovery factor that is dependent upon both the discount rate and system lifetime. A discount rate of 3 percent and a system lifetime of 30 years were used in this analysis. C_{direct} is the capital cost of sulfur thermal battery system including sulfur TES, heat exchanger, ORC power generation unit, electric heater, and balancers of the system such as pumps and cooling towers. $C_{indirect}$ are the indirect expenses, and $C_{Fixed,om}$ is the annual fixed operation and maintenance cost. The simple payback period was calculated from:

$$Payback = \left(C_{direct} + C_{indirect} + C_{Fixed,om} \right) / C_{revenue} \quad \text{[Eq. 6]}$$

In this analysis, the ORC power capacity was fixed at P_{ORC} =500 kWe and the storage capacity was fixed at:

$$Q_{TB} = \frac{P_{ORC}}{Q'_{D(SOC=1)} \times \eta_{ORC}} \quad \text{[Eq. 7]}$$

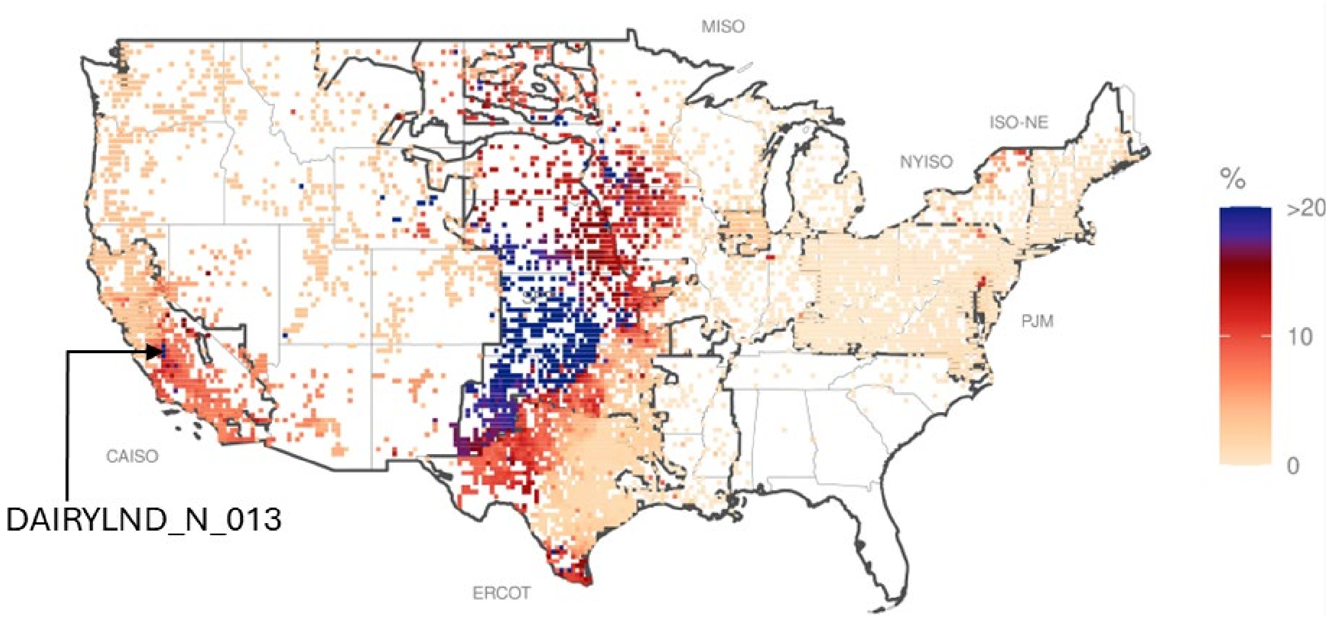
The net efficiency of the ORC power generation unit (η_{ORC}), as well as associated costs, were sourced directly from vendor data and technical specifications data sheets (Enogia, n.d.; Climeon, n.d.; Canada et al, 2004; Tartière & Astolfi, 2017). Like most of the industrial equipment, the sulfur thermal energy storage cost at various capacities was estimated using "the rule of six-tenths" (Guthrie, 1969):

$$C_{TES} = C_{o,TES} \left\{ \frac{Q_{TB}}{Q_{o,TB}} \right\}^{0.6} \quad \text{[Eq. 8]}$$

$C_{o,TES}$ is the capital cost of the recently quoted 250-ton sulfur TES system, corresponding to the storage capacity $Q_{o,TB}$ = 17 MWh for sulfur TES cycling between 266°F (130° C) and 590°F (310°C). The installed cost of sulfur TES measured in $/kWh decreases with increases in storage capacity because of decreases in tank surface area required per unit volume, with increases in radius and economies of scale. The cost of the thermal oil electric heater at scale, based on vendor data, was 200 $/kW. The cost of the pump and cooling tower for the pilot system, sourced from vendor data, was scaled to a large-scale system using "the rule of seven-tenths" (Guthrie, 1969), based on heat rate.

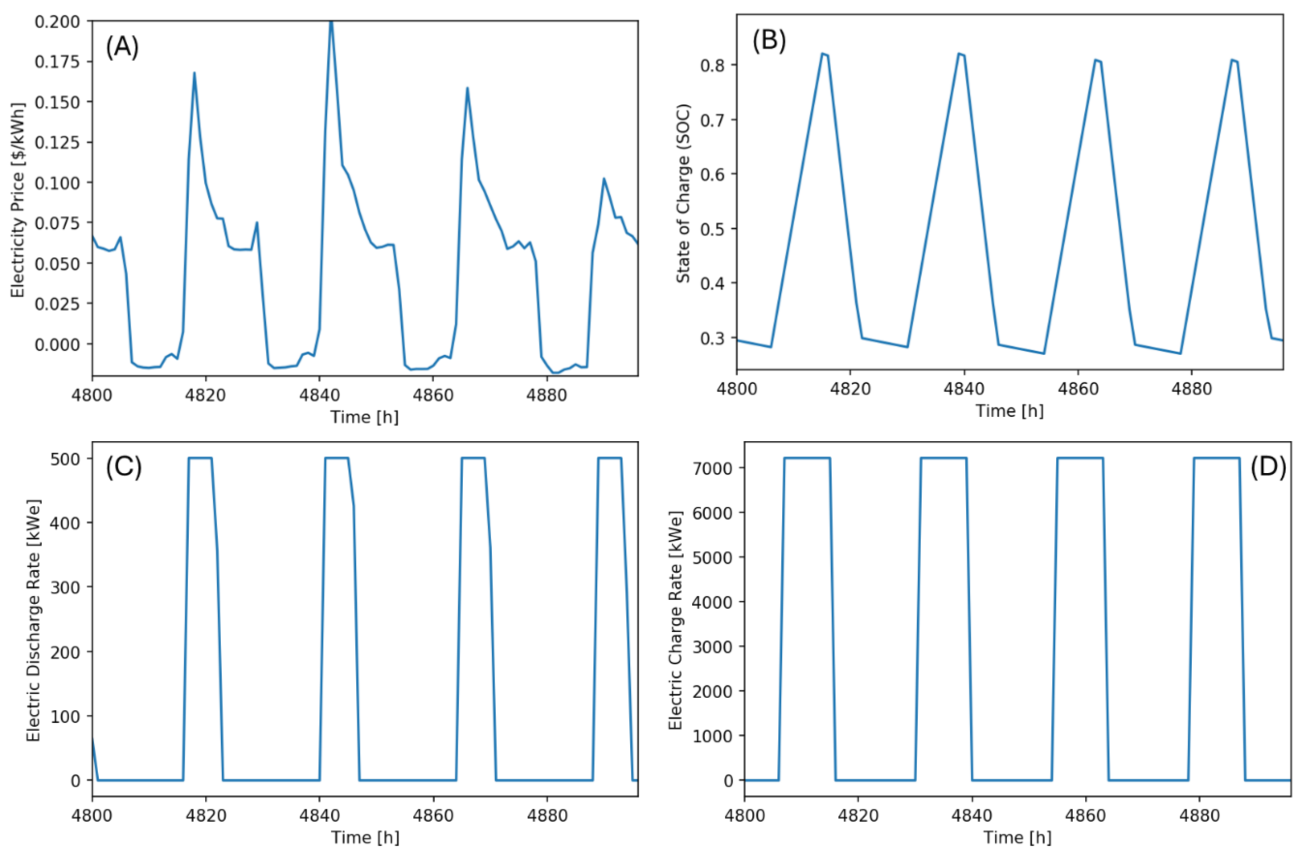
In order to delineate the techno-economic benefits associated with this configuration, the hourly electric prices at the ISO Node DAIRYLND_N_013, obtained from the 2023 ISO website, were selected (ISO, 2023). This node was chosen because the electricity price is negative for nearly 25 percent of the year (Berkeley Lab, 2023), as shown in Figure 19, creating a compelling incentive to utilize thermal batteries for revenue generation. By charging during periods of negative pricing and discharging when positive prices return, a thermal battery can effectively earn double from a single negative-pricing event. Figure 20 shows the model output for four representative days in the month of July 2023. It is readily observed from Figure 20 that sulfur thermal-battery charges when grid electricity prices are low and dispatches electricity when grid-electricity prices are high to maximize savings.

Figure 19: Negative Electric Price Frequency in 2023



Source: Berkeley Lab, 2023

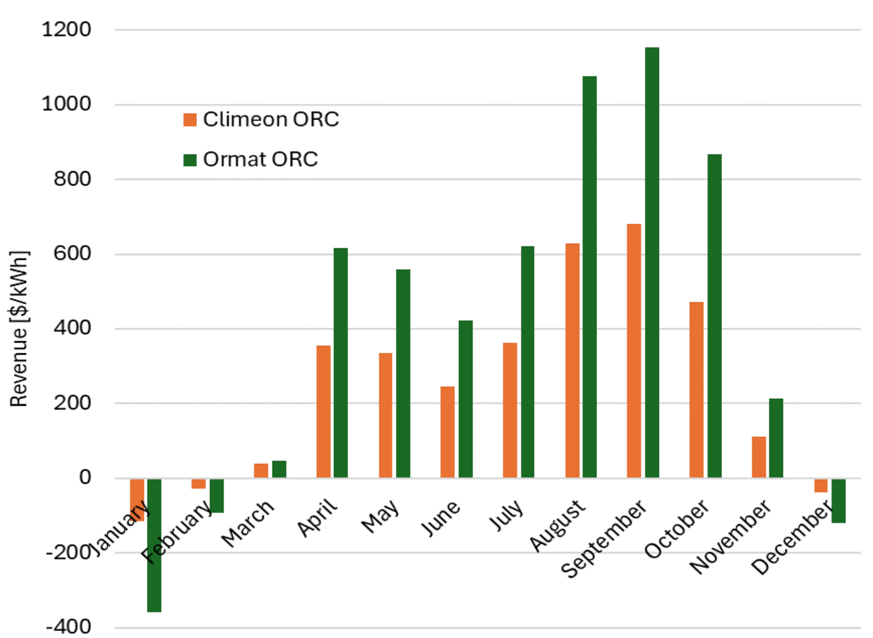
Figure 20: A) Hourly Electric Prices at ISO Node DAIRYLND_N_013, and Hourly Variations in (B) State-of-Charge, (C) Electric Discharge Rate and (D) Electric Charge Rate of Sulfur Thermal Battery for Four Representative Days in July 2023



Source: Element 16 Technologies, Inc.

Figure 21 shows the monthly revenue normalized to the storage capacity of the grid-integrated sulfur thermal battery. Positive values indicate profit, while negative values indicate loss. The results are shown for sulfur thermal energy storage integrated with different ORC technologies, each with a 500 kWe net power capacity, sourced from CLIMEON and ORMAT (Climeon, n.d.; Canada et al., 2004; Tartière & Astolfi, 2017). The seasonal variability in revenue, with lower or even negative values in the winter months (January, February, and December), is likely influenced by the fluctuations in solar generation. During winter, solar output is lower, reducing electricity overgeneration and thereby lowering opportunities for storing energy at cheap or negative prices. Although the negative revenue could be avoided during these months, it occurs due to the electricity required to compensate for heat losses in the system. Conversely, in the late summer months (August to October), higher renewable generation relative to demand leads to more frequent periods of excess electricity, creating potentially profitable conditions.

Figure 21: Monthly Revenue of Sulfur Thermal Battery Integrated With Different ORC Technologies Based on the Hourly Electric Prices at ISO Node DAIRYLND_N_013



Source: Element 16 Technologies, Inc.

Table 3 provides a comprehensive breakdown of the annual revenue, simple payback period, and levelized cost of storage for sulfur thermal battery integrated with the three different ORC technologies. Among these, the ORC technology employed by ORMAT stands out due to its utilization of higher temperature n-pentane (operating at 392°F [200°C]) as the internal working fluid (Canada et al., 2004), resulting in notably enhanced thermal-to-electric conversion efficiency. The direct and indirect costs of the sulfur thermal battery system were normalized for storage capacity, as shown in Table 3.

Notably, annual revenue increases with increases in efficiency of the ORC, leading to reduced payback periods and lower LCOS. With the present configuration integrating the sulfur thermal battery with low temperature ORC, the resulting LCOS is 0.12 $/kWh. However, upon integration with the high-temperature ORMAT ORC, the levelized cost of storage reduces to 0.08 $/kWh (shown in Table 3).

Table 3: Techno-Economics of Sulfur Thermal Battery Integrated With Different ORC Technologies, Each With a 500 kWe Net Power Capacity Based on the Hourly Electric Prices at ISO Node DAIRYLND_N_013

	Climeon	Ormat
Required ORC Inlet Working Temperature	248°F (120°C)	392°F (200°C)
Net ORC Efficiency [%]	10.3	19.0
Storage Capacity [MWht]	85	45
Sulfur Cycling Temperature Range	266°F - 590°F (130°C - 310°C)	410°F - 590°F (210°C - 310°C)
Direct and Indirect Cost [$/kWh]	67	119
Annual Revenue [$/kWh]	3.1	5.0
Payback Period [years]	22.0	23.8
Levelized Cost of Storage [$/kWhe]	0.12	0.08

Source: Element 16 Technologies, Inc.; Climeon, n.d.; Canada et al., 2004
MWht = megawatt hour thermal

Technology/Knowledge Transfer

Technology and knowledge transfers to various stakeholders and decision makers were completed through multiple channels during the project. This effort had four main components: engaging with industry leaders and stakeholders through events, site visits, and meetings; networking with the related business community via clean tech and energy programs; disclosing intellectual property and technology descriptions; and hosting visitors to showcase the sulfur thermal battery technology firsthand.

Major Successes and Strategic Engagements

Element 16 was successful in its technology and knowledge transfer efforts. During this project, Element 16 was paid approximately $500k by a large industrial chemical processor to design the sulfur thermal energy storage system. Because this was an unsubsidized contract, this stimulated appreciable interest in the new technology. Element 16 hopes that this early success will lead to the first commercial pilot system sale upon completion of this project. Element 16 has also received a new grant from the CEC to install a sulfur thermal battery pilot at a large industrial facility in a cogeneration power plant owned by Searles Valley Minerals in Trona, California. These two major milestones in bringing this technology to the market were accomplished through numerous events, business programs, site visits, in-person meetings, technology information documents, and more that took place not only in California but as far away as Switzerland and Oman, on the Arabian Peninsula.

Industry and Business Engagement

Engaging with industry leaders and stakeholders took place through attendance and presentations at various events such as competitions, summits, expos, and conferences. Notable engagements included the Energy Storage North America Expo, RE+ events, and the University of California, Davis, Industrial Decarbonization Symposium. These events allowed Element 16 to connect with representatives from government agencies, investors, and other clean-tech innovators. Site visits to related energy facilities and one-on-one meetings further strengthened these relationships. Element 16 also built a network within the related business community by participating in programs like MassChallenge, Creative Destruction Lab, and SparkLabs Energy, which facilitated interactions with venture firms, angel investor groups, and public clean-tech-focused organizations.

Intellectual Property and Knowledge Sharing

Element 16 disclosed and shared knowledge about the technology through various written mediums including patent applications, project proposals, and detailed technical documents. The company now holds multiple patents related to thermal energy storage, which are accessible both to the public and to potential partners. Written documents were shared with clients and partners to provide in-depth information about the sulfur thermal battery technology, often leading to further technical and financial discussions. This approach ensured that Element 16 could protect its intellectual property while fostering collaboration and interest from potential stakeholders.

Technology Showcase

Hosting visitors at Element 16's facility in Duarte, California, played a crucial role in demonstrating the progress and potential of sulfur thermal battery technology. In-person visits allowed stakeholders to witness the scale, design, materials, and safety features of the system firsthand. These visits were instrumental in describing aspects of technology that are difficult to capture in either written documents or virtual meetings. Notable visitors included executives from leading solar thermal technology developers, potential industrial clients, engineering firms, and international technology partners. These interactions not only validated the high level of interest in Element 16's technology, but also helped build strong relationships with key stakeholders.

CHAPTER 4: Conclusions and Recommendations

The Element 16 team successfully set up, commissioned, and demonstrated a pilot sulfur thermal battery system at its facility in Duarte, California. The numerical model predictions of system performance compared well against testing results from various modes of operation. The performance metrics of the 1.5 MWh sulfur thermal battery were described in terms of average charge and discharge rates, thermal efficiency, and the levelized cost of storage.

The average thermal-to-thermal round-trip efficiency of the sulfur thermal battery was calculated to be 85 percent, and the overall thermal-to-electric round-trip efficiency was calculated to be 5.1 percent. As the system size (tank diameter) increases, the surface area per unit volume decreases, resulting in reduced heat losses per unit of storage capacity. Consequently, higher thermal-to-thermal round-trip efficiency can be achieved as the technology moves from pilot to full-scale project installations. By integrating with a high-temperature organic Rankine power generation unit that uses n-pentane as the working fluid (ORMAT ORC), an overall thermal-to-electric round-trip efficiency of between 15 and 16 percent can be achieved. The numerical model predictions for transient variations in sulfur temperature, heat rates, heat loss, and pressure drop compared well with the testing results in different modes of operation. The validated sulfur thermal battery performance model was combined with a battery scheduling optimization tool that can be used to assess the techno-economic benefits of sulfur TES integrated across different ISO nodes and diverse geographic locations. Due to the low cost of sulfur TES and its low thermal-to-electric round trip efficiency, sulfur thermal batteries for grid storage are best suited for installation at nodes where the electric price is typically low or negative for a large share of the year. For instance, when integrated at the ISO Node DAIRYLND_N_013, which registers negative prices for more than 20 percent of the year (Berkeley Lab, 2023), the LCOS of sulfur thermal battery was estimated to be between 0.08 and 0.12 $/kWhe compared with 0.15-0.18 $/kWhe for Lithium-ion batteries. Overall, the results indicate that large-scale sulfur thermal batteries offer a sustainable and economically viable alternative to conventional electro-chemical batteries for long-duration electricity storage when deployed in areas with frequent low or negative electricity prices caused by renewable overgeneration.

The development of this low-cost sulfur thermal battery technology will increase grid resiliency, support transmission and distribution infrastructure, and provide low-cost, long-duration electric storage capacity to the California grid. Electrically charging the low-cost sulfur thermal battery provides system flexibility to coupling different types of intermittent renewable sources that significantly lower the cost of achieving SB 100 environmental mandates. Specifically, it addresses the following strategic objectives in the CEC's EPIC investment plans to increase the value proposition of distributed energy resources to both customers and the grid, improve the customer value proposition of end-use efficiency and electrification technologies, and increase successful clean-energy entrepreneurship in California.

Support from the CEC through this project was critical in advancing the product from technology readiness level (TRL) 6 to TRL 8 through comprehensive testing and demonstrations. The success of this project directly led to multiple grant-funded projects from both the United States Department of Energy and the California Energy Commission, an awarded patent, and the first unsubsidized, paid purchase orders from an industrial customer of the Front End Engineering Design Study and Detailed Engineering of a sulfur thermal energy storage pilot project, integrated with photovoltaic solar.

Although the focus of this project was on electricity generation as the output, sulfur TES promises a low-cost energy storage solution for electrifying and firming heat (McKinsey and Co., 2022). Decarbonizing the heat sector is crucial for realizing a net-zero energy system by the 2045 state mandate. Process heating accounts for most of the industrial manufacturing sector's energy consumption (~85 percent in California), which is primarily supplied by the combustion of natural gas and other greenhouse gas-emitting fossil fuels. Electrifying industrial process heat through leveraging advancements in low-carbon electricity from both the grid and onsite renewable generation is critical for both industrial decarbonization and lower fossil-fuel dependency. The key challenge with adoption of renewables (such as solar photovoltaic) for industrial process heat is intermittency since most industrial processing facilities (such as chemicals, foods, plastics, materials, and cement) operate 24 hours a day, requiring continuous energy supplies. To provide value to these end-user industrial facilities, renewable heat must be available 24 hours, in the temperature range required by those facilities, at a cost that is competitive with natural gas. Without TES, expensive natural gas boilers are required to operate at off-peak efficiency, increasing their dependence on solar availability (dependent on clouds, weather, and time of day). Low-cost sulfur thermal energy storage can be connected to renewable energy installations to store excess off-peak renewable electricity and provide heat on demand when renewables are not available, eliminating the need for new ramping natural gas boilers and fully transitioning facilities to renewable energy. This approach aligns with the objectives of California's SB 350 mandate to both improve energy efficiency and accelerate industrial decarbonization.

One of the recent grant projects selected for funding by the California Energy Commission involves the testing and demonstration of a 1.5 MWht sulfur heat storage system at the Westend facility of Searles Valley Minerals in Trona, California. Sulfur TES can increase overall system resiliency to provide an on-demand/flexible heat supply that meets individual requirements of the industrial process, achieves a lower levelized cost of energy (increasing the share of renewable energy and reducing the carbon dioxide footprint of industrial processes), and enables industries to become independent of rising fossil fuel and carbon dioxide prices. Future efforts should focus on larger-scale pilot projects at operating industrial facilities where sulfur energy storage can replace thermal loads, not just electricity loads. Completing large projects in an operating industrial facility will allow Element 16 to prove the expected benefits from economies-of-scale and work through the physics and engineering challenges of designing sulfur TES systems at a sufficient scale to meaningfully support California's electric grid.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ASME	American Society of Mechanical Engineers
CEC	California Energy Commission
CFD	Computational Fluid Dynamics
EPIC	Electric Program Investment Charge
E16	Element 16 Technologies
HTF	Heat Transfer Fluid
internal TES-HX	internal heat exchanger pipe assembly
ISO	California Independent System Operator
kJ/kg-K	kilojoules per kilogram Kelvin
kWe	Kilowatt-electric
kWh	kilowatt hours
LCOS	Levelized Cost of Storage
LDES	Long duration energy storage
Li-ion	Lithium-ion
mBar-L/s	mBar liter per second
MWh	Megawatt hours
MWht	Megawatt hour thermal
ORC	Organic Rankine Cycle
ORIS	Oak Ridge Institute for Science and Education
PCL	PCL Industrial Services
PLC	Programmable Logic Controller
ROM	Reduced Order Model
RTE	Round Trip Efficiency
SB	Senate Bill
SOC	State of Charge
TAC	Technical advisory committee
TES	Thermal Energy Storage
TRL	technology readiness level

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Project Deliverables

- Design/Cost Modeling Report
- Facility Characterization Report
- HCS Fabrication Report
- HCS Test Plan
- HCS Fabrication Report
- Demonstration Test Plan
- Demonstration System Performance Report
- CPR Report
- Optimized HCS Fabrication Report
- Final Demonstration Test Plan
- Final Demonstration System Performance Report
- Measurement and Verification Report
- Potential Market Impact Report
- Kick-off Meeting Benefits Questionnaire
- Mid-Term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet
- Final Project Fact Sheet
- Technology/Knowledge Transfer Plan
- Technology/Knowledge Transfer Report
- Production Readiness Plan

The project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

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APPENDIX A: Sulfur TES Numerical Heat Transfer Reduced Order Model

January 2025 | CEC-500-2025-006

Appendix A: Sulfur TES Numerical Heat Transfer Reduced Order Model

A physics-informed numerical heat transfer model that can predict the spatial and transient temperature distribution of sulfur and HTF inside sulfur TES was developed. The sulfur TES design configuration involves heat transfer fluid (HTF) tubes located within sulfur bath. The performance of sulfur thermal storage system is dependent on the thermal resistances of the natural convection heat transfer dynamics of sulfur stored in the tank shell, conduction in the tube wall, forced convection heat transfer dynamics of HTF flow in the tubes, and heat loss to the ambient through the insulation surrounding sulfur vessel. The coupled set of governing equations solved using an iterative finite volume framework for sulfur TES performance characterization are:

HTF: $$(\rho c)_{htf}\frac{\partial T_{htf}}{\partial t}+(\rho c)_{htf}v_{htf}\frac{\partial T_{htf}}{\partial x}=k_{htf}\frac{\partial^2 T_{htf}}{\partial x^2}-\frac{(T_{htf}-T_{wall})}{V_{tube,\Delta x}\{\mathcal{R}_{i,wall}+\mathcal{R}_{htf}\}} \qquad [A1]$$

Tube Wall: $$(\rho c)_{wall}\frac{\partial T_{wall}}{\partial t}=k_{wall}\frac{\partial^2 T_{wall}}{\partial x^2}+\frac{1}{V_{wall,\Delta x}}\left\{\frac{(T_{htf}-T_{wall})}{\{\mathcal{R}_{i,wall}+\mathcal{R}_{htf}\}}-\frac{(T_{wall}-T_{su})}{\{\mathcal{R}_{o,wall}+\mathcal{R}_{su}\}}\right\} \qquad [A2]$$

Sulfur: $$(\rho c)_{su}\frac{\partial T_{su}}{\partial t}=\frac{1}{V_{su,\Delta x}}\left\{\frac{(T_{wall}-T_{su})}{\{\mathcal{R}_{o,wall}+\mathcal{R}_{su}\}}-\frac{(T_{su}-T_{amb})}{\{\mathcal{R}_{tank}+\mathcal{R}_{ins}+\mathcal{R}_{eff,amb}\}}\right\} \qquad [A3]$$

In the equations above ρ is the density, c is the specific heat, k is the thermal conductivity, T is the temperature, v is the HTF velocity, and R is the thermal resistance. The subscripts *htf*, *wall*, *su*, *tank*, *ins* and *amb* denote heat transfer fluid, tube wall, sulfur, tank wall, insulation and ambient, respectively. The model inputs are thermo-physical properties of HTF, tube wall material and sulfur; design parameters such as tube radius, tube wall thickness, tube length, tank shell radius, tank length and filled sulfur mass; initial temperature of the system and inlet conditions of the HTF. The mass flow rate and inlet temperature of the HTF are fed as inputs into the model. The model predicts the spatial and temporal evolution of temperature profile in the tank during charge and discharge process, the transient variation in outlet HTF temperature and evaluate key performance metrics such as charge and discharge rates. The heat transfer coefficient on the HTF side (h_{htf}) which appears in the HTF convective thermal resistance term ($\mathcal{R}_{htf}={}^{1}/_{h_{htf}\pi d_{t,i}}$) was based on the Gnilenski correlation for single phase heat transfer fluid obtained from literature (Gnielinski, 1976). The heat transfer coefficient on the sulfur side (h_{sulfur}) which appears in the sulfur natural convection thermal resistance term ($\mathcal{R}_{su}={}^{1}/_{h_{sulfur}\pi d_{t,o}}$) was informed by the 2D single-tube unit cell computational analysis for various design and operating parameters namely, spacing between the HTF tubes (tube pitch) and Rayleigh number discussed in Task 3 report. $d_{t,o}$ and $d_{t,i}$ are the outer and inner diameter of the internal heat exchanger tube circuit. The thermal resistance terms due to heat conduction across the tube wall is given by: $\mathcal{R}_{i,wall}=\ln\left[\frac{d_{t,i}+0.5b_t}{d_{t,i}}\right]\Big/2\pi L_{tank}k_{wall}$ and $\mathcal{R}_{o,wall}=\ln\left[\frac{d_{t,o}}{d_{t,i}+0.5b_t}\right]\Big/2\pi L_{tank}k_{wall}$ where b_t is the tube wall thickness and L_{tank} is the vessel length. The conduction thermal resistance across the tank wall and insulation is given by: $\mathcal{R}_{tank} = ln\left({d_{tank,o}}/{d_{tank,i}} \right)/2\pi L_{tank}k_{wall}$ and $\mathcal{R}_{ins} = ln\left({[d_{tank,o} + b_{ins}]}/{d_{tank,o}} \right)/2\pi L_{tank}k_{ins}$, where $d_{tank,o}$, $d_{tank,i}$ and b_{ins} are the outer vessel diameter, inner vessel diameter and insulation thicknesses, respectively. $\mathcal{R}_{eff,amb} = \frac{1}{h_{eff,air}\pi(d_{tank,o}\times b_{ins})}$ is the thermal resistance for heat transfer between the outer insulation and ambient that accounts for both convective and radiative heat loss to the surroundings.

The three main sources of error in computational simulations are round-off error, iterative convergence error and discretization error. All simulations are performed using double point floating point precision. At each time step during the iteration the residuals are converged to the order of $1e^{-6}$. Hence, their contribution to the overall numerical error is small ~0.0001. The discretization error was quantified by performing simulations on systematically refined mesh and time step sizes. The numerical simulation modeled charge process of the 1500 kWh pilot sulfur TES prototype with a constant HTF flow rate of 3 kg/s, HTF inlet temperature of 590°F (310°C) and initial temperature of 275°F (135°C). The HTF exit temperature and heat rate at the time instant of 3 hours and 6 hours were analyzed to determine the observed numerical order of accuracy and the corresponding discretization error using Richardson's error estimation method (Roy, 2005). The observed order of accuracy is ~1.0 which matched with the formal order of accuracy of 1.0, indicating that the solution is within the asymptotic range of interest for mesh sizes less than 1.25 m and time step sizes less than 1 minute and it is also noted that the solution is in the asymptotic range of interest for the mesh size < 1.25 m and time step size < 1 minute. Consequently, for the computational simulations, a mesh size of 0.4125 m and a time step size of 1 minute were selected. With a factor of safety 3, the calculated numerical discretization error based on the results of the next finest mesh and time step size is 0.067 % (±0.4°F for a temperature of 572°F).

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APPENDIX B: Sulfur TES Pilot Prototype Performance Metrics

January 2025 | CEC-500-2025-006

Appendix B: Sulfur TES Pilot Prototype Performance Metrics

The charge and discharge rates were calculated from:

$$\dot{Q}_{c(d)} = \dot{m}_{HTF} c_{HTF} (T_{in} - T_{out}) \quad \text{[Eq. B1]}$$

$\dot{m}_{HTF}$ is the flow rate of HTF calculated using the differential pressure measured across the sulfur TES (DPI-06 in Figure 6). c_{HTF} is the specific heat of HTF. For charge, T_{in} is the temperature of the HTF measured at the inlet of electric heater using the thermocouple TI-02 in Figure 6 and T_{out} is the temperature of the HTF measured at the exit of electric heater using the thermocouple TI-03A in Figure 6. For discharge, T_{in} is the temperature of the HTF measured at the inlet of heat exchanger E06 HX using the thermocouple TI-37A in Figure 6 and T_{out} is the temperature of the HTF measured at the exit of the heat exchanger using the thermocouple TI-38 in Figure 6. The energy charged (Q_{charge}) and discharged ($Q_{discharge}$) during a thermal cycle is calculated by integrating Eq. (B1) over the charge and discharge duration, respectively. The thermal-to-thermal round-trip efficiency (RTE) of sulfur thermal battery (thermal-to-thermal) was then calculated from: $\eta_{thermal} = \frac{Q_{discharge}}{Q_{charge}}$.

The electrical power generated by the ORC (E05 in **Figure 6**) during discharge was determined from the turbine current (I) and voltage measurements (V) using CI05 and VI05, respectively that are shown in **Figure 6**. Subsequently, the dispatched electric storage capacity was computed from:

$$\xi_{discharge}\,[kWh] = \int_{t_{i,d}}^{t_{f,d}} (V \times I).\,dt \quad \text{[Eq. B2]}$$

The net electric thermal energy generated was calculated by subtracting the electricity consumption of the pumps (HTF, process water, and cooling tower water) and the cooling tower from the electric energy generated by the ORC for the calculation of overall thermal to electric RTE:

$$\eta_{elec} = \left(\xi_{discharge} - \xi_{pumps} - \xi_{cooling-tower}\right) \Big/ Q_{charge} \quad \text{[Eq. B3]}$$