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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Development and Testing of Low-Cost Sulfur Thermal Energy Storage Integrated with Combined, Cooling, Heat, and Power

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Development and Testing of Low-Cost Sulfur Thermal Energy Storage Integrated with Combined, Cooling, Heat, and Power is the final report for the Small Combined Cooling, Heating, and Power Packaged System with Innovative Quick-Response, Compact, and High-Temperature Thermal Energy Storage project (PIR-16-009) conducted by Element 16 Technologies, Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

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 research team developed and validated the operation of a combined cooling, heating, and power plant integrated with novel sulfur thermal energy storage technology for adoption in commercial sectors. This technology uses low-cost molten sulfur as the storage fluid that can store and discharge heat efficiently. Element 16 adds flexibility to combined cooling, heating, and power plants by storing exhaust heat energy in sulfur thermal energy storage, and by allowing the production of electricity and steam to occur at different times. In areas of high renewable energy penetration, the thermal energy storage combined cooling, heating, and power system can be optimally designed and intelligently controlled to reduce peak demand charges and interact seamlessly with the grid to provide dispatchable power and essential services.

The pilot integrated sulfur thermal energy storage and combined cooling, heating, and power system was setup and commissioned at Element 16's facility in Arcadia, California. The measured average charge and discharge rates of the pilot sulfur thermal energy storage system were 12.6 kilowatts and 27.6 kilowatts respectively with a calculated thermal efficiency of 85.4 percent. A technoeconomic model was developed to determine the optimal sulfur thermal energy storage configuration for integration with combined cooling, heating, and power in a representative large commercial building located in Los Angeles with an average electricity and thermal energy requirement of 280 kilowatts and 206 kilowatts, respectively. An optimal sulfur thermal energy storage capacity ratio of 3.0 resulted in the minimum payback period of 8.7 years. The annual natural gas savings and emissions reductions for sulfur thermal energy storage capacity ratio ranging between 3.0 to 4.6 was estimated to be $7,320 to $9,015 and 34 tons to 42 tons of CO2 for the commercial building.

This report includes a review of the technical performance and the successful pilot demonstration of sulfur thermal energy storage and combined cooling heat, and power thermal energy storage systems, and technology-to-market activities of the technology realizing more than $6 million in sulfur thermal energy storage research and development and commercialization funding since the beginning of this project

Keywords: Combined Cooling, Heat, and Power (CCHP), Thermal Energy Storage (TES), Sulfur, Cogeneration, Net Present Value, Payback Period, Charge/Discharge Rates

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Executive Summary

Introduction

In California, approximately 30 percent of natural gas is used for residential and commercial applications which produce harmful emissions (EIA 2024a). Several areas in California, including Los Angeles, offer a unique opportunity to improve residential and commercial energy efficiency, and reduce the State's total greenhouse gas emissions. At least 30 percent of California's summer peak electricity demand is from residential and commercial air conditioning (Miller et al. 2008; CEC 2004). High peak electrical use for building cooling systems is costly to ratepayers, but often unavoidable due to the high summer temperatures.

One alternative to conventional electrical cooling are systems that generate combined cooling, heating, and power simultaneously. In a combined cooling, heating, and power facility (also known as tri-generation) electricity is generated by the turbines and the waste exhaust heat from electricity generation is used for heating (space heating, hot water generation) and cooling requirements of the facility. However, the economics of these systems at small scale are still often unfavorable. In addition, tightening emission regulations and variable renewable electricity generation mean that energy consumers and producers must add flexibility and efficiency including a way to store the waste exhaust heat or thermal energy storage. Integrating cost-effective thermal energy storage is critical for efficient and flexible operation of combined cooling, heating, and power systems, and for improved system economics.

In this project, comprehensive pilot testing of a novel, low-cost, high-temperature thermal energy storage technology integrated with combined cooling, heating, and power was conducted to quantify and validate the economic benefits, energy savings, and greenhouse gas emissions reductions. The results help reduce the uncertainty in the assessment of benefits resulting from the integration of thermal energy storage to a combined cooling, heating, and power system which include increasing the likelihood of meeting the state's greenhouse gas emissions reduction targets from natural gas sources through increased efficiency and operational flexibility.

Project Purpose

Element 16 explored improving the flexibility, efficiency, and economics of a high-temperature and low-cost sulfur thermal energy storage system integrated with a combined cooling, heating, and power unit. The team wanted to determine the capabilities of the system in a real-world environment, demonstrating its efficiency, flexibility, and energy cost savings.

The improved economics of small-scale combined cooling, heating, and power will translate to increased distributed generation, and increased adoption of trigeneration systems, in addition to the more common combined heat and power systems, which lead to many benefits for natural gas ratepayers. In California investor-owned utilities and many municipal utility districts, including the Los Angeles Department of Water & Power, time-of-use electricity rates have become increasingly common, even for residential ratepayers. Distributed generation allows the customer to generate electricity when most economically advantageous. By generating electricity during traditional off-peak times, independent of thermal need (a flexibility afforded by sulfur thermal energy storage), distributed commercial combined cooling, heating, and power could reduce the peak price of electricity. Recovering and storing the excess heat from the prime mover during periods of low thermal demand and using it when required will reduce customers' energy costs, increases overall combined cooling, heating, and power system efficiency, and reduce emissions.

The results of this research will be used by interested stakeholders in commercial or institutional facilities to make decisions about installing combined cooling, heating, and power with integrated thermal energy storage in their facility. Manufacturers of small power generation equipment, such as Capstone Green Energy, can use the results of this research to determine the performance and cost benefits of an integrated power generation (for example microturbine, engine) and sulfur thermal energy storage solution. Research organizations and government agencies could use the results to identify further research required to remove market barriers for combined cooling, heating, and power and sulfur thermal energy storage adoption.

Project Approach

The project was led by Element 16 Technologies, Inc. The pilot sulfur thermal energy storage project was designed by Element 16 engineers, and was fabricated by PCL Industrial Services, Inc., Bakersfield, California. Profusing, LLC., located in Azusa, California and Tube Bending Specialists and Machinery, LLC., in Hayward, California, provided other fabrication services such as welding and tube bending. Exponent, Inc. was chosen as the subcontractor to perform third-party performance measurement and verification of the pilot sulfur thermal energy storage operation.

The project involved testing and demonstrating a pilot sulfur thermal energy storage system integrated with a combined cooling, heating, and power system that includes absorption chiller, microturbine, and hot water generating heat exchanger at the Element 16's Arcadia, California site.

Multiple challenges were encountered during the project. Since this is the first installation of a large-scale sulfur thermal energy storage system, the impact of product design on the expected performance was unknown. Computational simulations were conducted to analyze the impact of various design iterations on the expected product performance. After multiple design reviews and iterations, sulfur thermal energy storage was designed based on the American Petroleum Industry standards established for the design, fabrication, and construction of welded steel storage tanks.

Another challenge was in specifying the material choice and corrosion allowance in terms of wall thickness for sulfur thermal energy storage fabrication. The team performed corrosion tests of various steel alloys in high temperature molten sulfur and spoke with corrosion experts to characterize the corrosion behavior. The testing results provided insights into material selection and corrosion allowance specification.

Using the performance metrics from measurement and verification, a technoeconomic model was developed to determine the optimal sulfur thermal energy storage configuration to integrate with a combined heating and power system in a representative large commercial building located in Los Angeles. The economic benefits resulting from integrating sulfur thermal energy storage in a combined cooling, heating, and power system was quantified as natural gas savings, payback period and lifetime value of sulfur thermal energy storage. Performance characteristics were measured according to standard practices in the thermal energy storage industries, and independently verified. Component and sulfur thermal energy storage costs were informed from vendor quotes and invoices from the fabrication service provider.

The technical advisory committee was created, composed of experts from various technical backgrounds including energy storage commercialization, energy efficiency, heat transfer, energy systems design, and combined cooling, heating, and power operations. The technical advisory committee reviewed the research and development progress during the critical project review meetings and provided feedback on the system design and testing activities.

Project Results

All the experimental testing tasks as planned for measurement and verification were completed. The numerical model predictions for the variation in sulfur temperature, heat rates, heat loss and pressure drop compared well against the testing results for various modes of operation. The experimental and numerical results confirm the high efficiency and the operational flexibility obtained from sulfur thermal energy storage. The overall dynamic performance of the pilot sulfur thermal energy storage was characterized in two critical parameters: power and energy. The experimentally measured performance metrics and the successful testing of various operation modes demonstrated the potential of Element 16's low-cost sulfur thermal energy storage to enable flexible and efficient operation of a combined cooling, heating, and power system.

The performance metrics of the 540-kilowatt-hour sulfur thermal energy storage were characterized in terms of average charge and discharge rates, and thermal efficiency. The measured average charge and discharge rates of the pilot sulfur thermal energy storage system were 12.6 kilowatts and 27.6 kilowatts, respectively, with a calculated thermal efficiency of more than 85 percent. The sulfur thermal energy storage achieved a minimum payback period of 8.7 years with an annual natural gas savings and emissions reductions of \$7,320 to \$9,015, and 34 tons to 42 tons of CO2, respectively.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Element 16 provided the results of this successful project to industry leaders and stakeholders by participating in expos, conferences, and site visits and panels, publications and intellectual property disclosures, and live demonstration of the operational combined cooling, heating, and power thermal energy storage unit to stakeholders.

Conferences and expos included the University of California, Davis Symposium on Industrial Energy Efficiency, ARPA-E Energy Innovation Summit, Northeast Power Producers Association Annual Conference, and Energy Storage North America. Members of the teams gave presentations and participated on panels in numerous meetings and conferences including the International Desalination Association's American-Made Challenges: Solar Desalination Prize Teaming Workshop, National Energy Technology Laboratory Advanced Energy Storage Initiative Program Project Review Meeting, and the Technical Advisory Committee for the Institute of the Environment and Sustainability at the University of California, Los Angeles.

Element 16 was a start-up company with multiple follow-on projects and demonstrated market interest in the sulfur thermal energy storage innovation. The technology developed in the grant has exceeded the project tasks and will continue development beyond the project's end date. Element 16 has already received a patent, with several applications pending.

Benefits to California

By storing thermal energy at high temperatures, sulfur thermal energy storage allows smaller systems to produce effective amounts of cooling at times of peak value. The improved economics of small-scale combined cooling, heating, and power will translate to increased distributed generation, and increased cogeneration systems that provide cooling, in addition to the standard heat and power systems, which leads to many benefits to natural gas ratepayers.

- *Environmental benefits:* By increasing the overall efficiency of natural gas and alternative fuel use, sulfur thermal energy storage is expected to decrease greenhouse gas emissions. This technology is extensible to a variety of distributed cogeneration systems from residential to industrial use and independent of the prime mover. With 25 percent of the market, the packaged system could reduce CO2 emissions generated from commercial/institutional buildings in California by 330,000 metric tons per year. This is comparable to removing 72,000 cars off roads for a year (the U.S. Environmental Protection Agency uses 4.6 metric tons as the annual average CO2 emissions of a typical passenger vehicle [EPA 2023]).
- *Improved economics:* By including cooling as an option, commercial and industrial ratepayers in California can use exhaust heat to cool facilities, which is of a higher value than heating, especially in summer months when electricity is most expensive. Additionally, due to the nature of high temperature storage, the heat can be used for heating and cooling, adding flexibility in use when compared with conventional chilled water or ice storage.

  The technoeconomic results conducted in this study showed that integrating sulfur thermal energy storage can result in an annual savings of $65,000 per megawatt-electric of installed combined heat and power capacity. Assuming 25 percent of the market in California, this can result in annual fuel savings of $71 million.
- *Greater reliability:* the sulfur thermal energy storage system's improved economics and flexibility will increase small, distributed generation. By increasing the cooling generated by natural gas and adding electricity generation at times of peak demand, the packaged

system helps to reduce load and increase generation when the grid is under its greatest stress. In Southern California, heat waves can often lead to outages that can be harmful to ratepayer safety and economic output.

- *Economic development:* The sulfur thermal energy storage with combined cooling, heating, and power system, developed under this agreement, was completed in the Los Angeles Basin and all project funds were spent in California. The demonstration also funded salaries for Element 16 Technologies and its contractors, all of which are based in California.
- *Public health:* By improving natural gas efficiency, fewer natural gas reservoirs will be required.

CHAPTER 1: Introduction

Background

In a trigeneration plant, also referred to as a combined cooling, heat, and power (CCHP) plant, electricity is generated by the turbines, and the exhaust heat from electricity generation is used for heating (space heating, hot water generation) and cooling. However, the demand from the end user facility for power and heat produced by the combined cooling heat and power plants fluctuates during the day and seasonally. For example, a hotel in sunny Los Angeles, California might need a near constant amount of electricity day and night, but only requires large amounts of cooling in the early evening when guests return to their rooms, and then requires heating through the night.

CCHP plants are located within, or next to, the facility that requires the power, heating, and cooling from the plant, and are operated to either follow the electrical demand of the facility or follow the thermal demand of the facility. If the plant follows electrical needs, the mismatch between heat generation and heat need can lead to waste heat (and lost efficiency) or the need for additional auxiliary boilers and chillers that can be less efficient than CCHP plants. Stand-alone CCHP systems that are operated using a heat demand following strategy are also often unfavorable, as excess electricity will often be sold to the electric utility at a lower price than it costs to generate, or the end user must purchase additional electricity from the utility company at a higher price than they would be able to generate using their CCHP plant.

Without thermal energy storage (TES) separating the generation of electricity from the generation of heating and cooling, CCHP plants either incur reduced revenue or operate at low efficiency. The CCHP plant may generate large amounts of electricity during off-peak hours when electricity prices are low (because thermal loads are high), reducing revenues. It also means that during on-peak hours, when electricity prices are highest, CCHP units may either run at partial capacity (because of low thermal loads) or run at full capacity and waste the excess heat. If CCHP units are required to follow a changing thermal or electrical load, they will not always be operating in their most efficient operating region. In addition, the relatively high variability in grid conditions due to increased renewable amounts require CCHP operations to be flexible. Therefore, integrating cost-effective TES is critical for efficient and flexible operation of CCHP systems.

As is common in industry, this report will use the acronym CHP (combined heating and power) to include CCHP, because the addition of cooling capability is often considered a subset of CHP. This includes events that CHP equipment companies attended, as well as energy experts from industrial facilities (for example paper, food, chemicals, mining, and oil), universities, district energy utilities, hotels, and hospitals. Element 16 Technologies, Inc., (Element 16) conducted hundreds of interviews with relevant stakeholders through these events.

State of the Art and Challenges

Existing TES systems for industrial CCHP and university campuses rely on hot or chilled water as the storage medium. However, high temperature thermal energy storage media, such as salts or concrete or pebbles can provide significant advantages over water systems. Storing heat at temperatures near the exhaust temperature of the turbine (~572° Fahrenheit [°F] to 662°F, or 300° Celsius [°C] to 350°C) allows larger flexibility in applications. For instance, storing heat at such high temperatures allows for low-temperature (~194°F or 90°C) and high-temperature (~428°F or 220°C) absorption chillers operation, and enables efficient and economic operation of district heating (hot water and heating buildings) systems. It also provides high energy density, which allows for a more compact system.

State-of-the-art high temperature thermal energy storage uses high-cost solar salt (saltwater pond exposed to sunlight with evaporation leaving a more pure salt), at $800/ton to $1,200/ton as the storage media in an expensive two-tank configuration. Other TES options such as latent-based phase change materials, which are materials that can absorb and release thermal energy during phase change, and sensible-based solid-state thermal storage media (concrete, pebbles) are being investigated.

The salts used in phase change material storage are expensive and have low thermal conductivity values when they are in the solid state that limits the discharge rate during conduction dominated solidification. They also suffer from phase segregation and thermal cyclic stability concerns, and corrosion issues.

The main challenge associated with concrete-based TES systems is heat transfer. Heat transfer is problematic due to the conduction dominated thermal transport from a heat transfer fluid (HTF) to concrete, which has poor thermal conductivity. Investigators have either pursued chemically modifying concrete to improve its heat capacity or use expensive embedded structures such as thermosyphons or a large number of cast-in steel pipes to improve heat transfer between a heat transfer fluid and concrete. The number and complexity of pipes required for heat transfer makes the system expensive compared with comparable liquid thermal storage solutions. The challenges associated with rock-based TES systems are low thermal conductivity and thermal compatibility issues. Since the HTF is in direct contact with the storage media, thermal ratcheting (causing undesirable mechanical stress and potential tank failure), and high pressure drop associated with pumping through a porous bed of rocks, results in lower efficiency.

There is another option being explored – molten sulfur salt. Molten sulfur TES provides a low-cost bulk energy storage solution to store and deliver high quality thermal energy due to its low cost, high thermal stability (long lifetime), and high heat transfer rates.

This project was led by Element 16 Technologies, Inc. The pilot sulfur TES was designed by Element 16 engineers, and was fabricated by PCL Industrial Services, Inc., located in Bakersfield, California, Profusing, LLC., located in Azusa, California and Tube Bending Specialists & Machinery, LLC.

How the Sulfur TES Technology Overcomes the Challenges

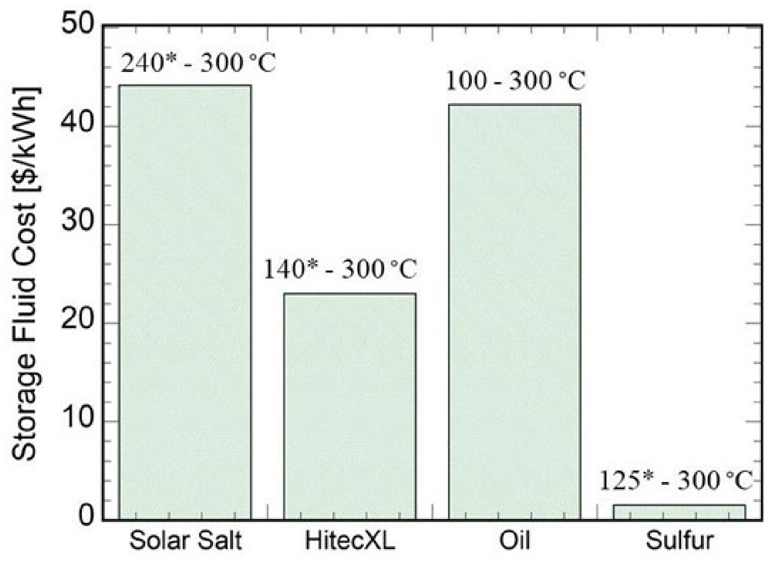
Sulfur is less than one-tenth the cost of molten salt at $40/ton to $80/ton, compared with $800/ton to $1200/ton for conventional salts, which commonly accounts for 70 to 80 percent of the storage system cost. Figure 1 shows the cost of the sulfur storage fluid in dollars per kilowatt-hour ($/kWh) operating between 302°F to 752°F (150°C to 400°C) and compares it with state-of-the-art solar salt. The storage fluid cost of Hitec XL molten salt with a low-freezing point, which enables operation in the same temperature range as sulfur TES, is also shown for comparison.

Sulfur has exceptional thermal stability in comparison to other fluids, and displays very little, if any, thermal degradation. This is a distinct advantage compared to molten salts that have phase segregation and thermal cyclic stability concerns. Due to its operation in the molten phase, the natural convection dynamics within sulfur promote high charge/discharge rate and the system does not require costly thermal enhancement structures.

Sulfur TES also provides a high volumetric energy density of over100 kWh/m^3 (kilowatt-hours per cubic meter) in the temperature range of interest (239°F to 572°F, or 115°C to 300°C) for compact storage, compared to about 6 kWh/m^3 provided by hot water or chilled water tanks (lower temperature excursion typically around 39.2°F, or 4°C).

By incorporating low-cost sulfur TES, Element 16's concept adds flexibility to these trigeneration plants allowing the production of electricity and heat to occur at different times and match the production and consumption profiles of the commercial and industrial facilities. This allows the CCHP plant to operate at high efficiency without wasting heat and power. Figure 2 shows the schematic of packaged and flexible CCHP system integrated with sulfur TES.

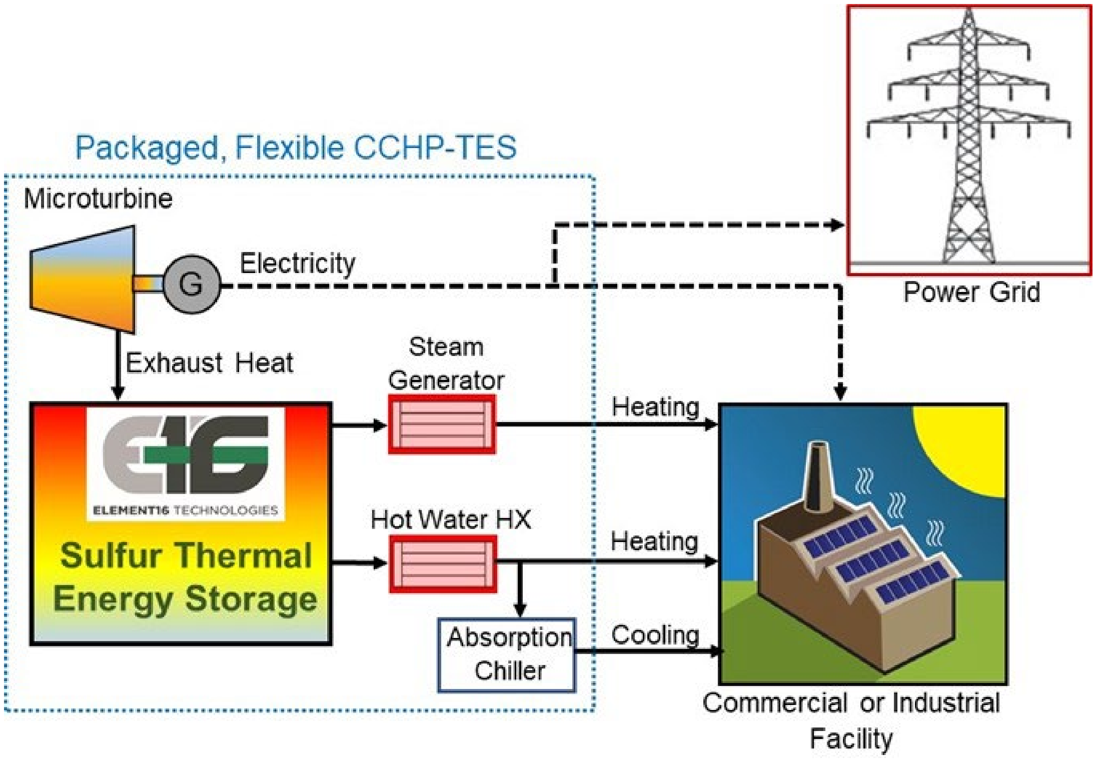
Figure 1: Comparison of Molten Sulfur Storage Fluid Cost Against Other Alternatives



***Bottoming temperature for molten salt and sulfur is chosen to be 20°C above their freezing point.**

Source: Element 16 Technologies

Figure 2: Schematic of Packaged and Flexible CCHP System Integrated With Sulfur TES



Source: Element 16 Technologies

Project Goal and Objectives

The overall goal was to increase the flexibility, efficiency, and economics of a Capstone microturbine-powered CCHP system through the development and testing of high temperature and low-cost sulfur TES, integrated with a CCHP unit. Systematic characterization and verification of the system performance for various operating modes were conducted to assess the overall benefits resulting from sulfur TES integration.

The primary objectives of this project were:

- Demonstrate operation and performance of economically viable and compact high-temperature sulfur TES integrated with a CCHP system in a representative operating environment.
- Demonstrate the economic advantages of collecting, storing, and discharging high-temperature heat in commercial and residential buildings.

CHAPTER 2: Project Approach

Design and Fabrication of Sulfur TES

Element 16's pilot thermal storage vessel consists of an outer pressure vessel and an internal tube circuit that carries the thermal oil heat transfer fluid (Figure 3). The outer pressure vessel was constructed by PCL Construction of Bakersfield, California and designed to hold 5 tons of sulfur and operate between 250°F to 570°F (121.1°C to 298.9°C). The horizontal vessel is supported by two saddles symmetrically placed and designed based on American Society of Mechanical Engineers (ASME) standards. A finite element analysis tool was used to evaluate stresses and ensure safe design. The internal tube circuit along with the tube support structures shown in Figure 4 were fabricated by Tube Bending Specialists and Machinery of Fremont, California.

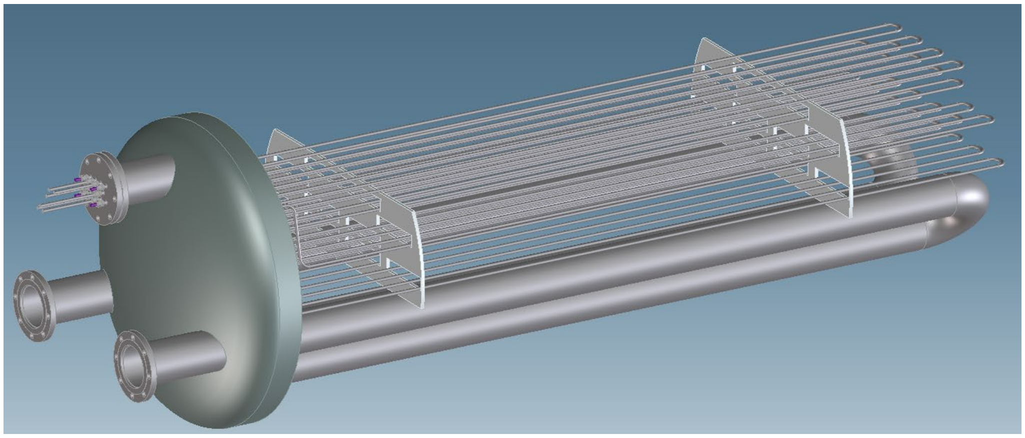
The internal heat exchanger circuitry involves three serpentine tubes located near the top of the vessel and a large pipe located near the bottom. The serpentine tubes will be used during discharge to circulate thermal oil and retrieve heat from molten sulfur. Provisions are made to connect the three serpentine tubes either in series or in parallel. The pipe at the tank bottom will be connected to the microturbine exhaust so that hot gas exhaust flows through the pipe and heats sulfur during the charge mode. The nozzles at the top of the tank provides access ports for filling sulfur, for installation of safety systems such as pressure relief valves and rupture discs, instrumentations such as thermocouples and pressure gauges.

Figure 3: Photograph of Pilot Sulfur TES

As fabricated by PCL Construction in Bakersfield, California

Source: Element 16 Technologies

Figure 4: Internal Heat Exchanger Tubing Configuration of Sulfur TES



Source: Element 16 Technologies

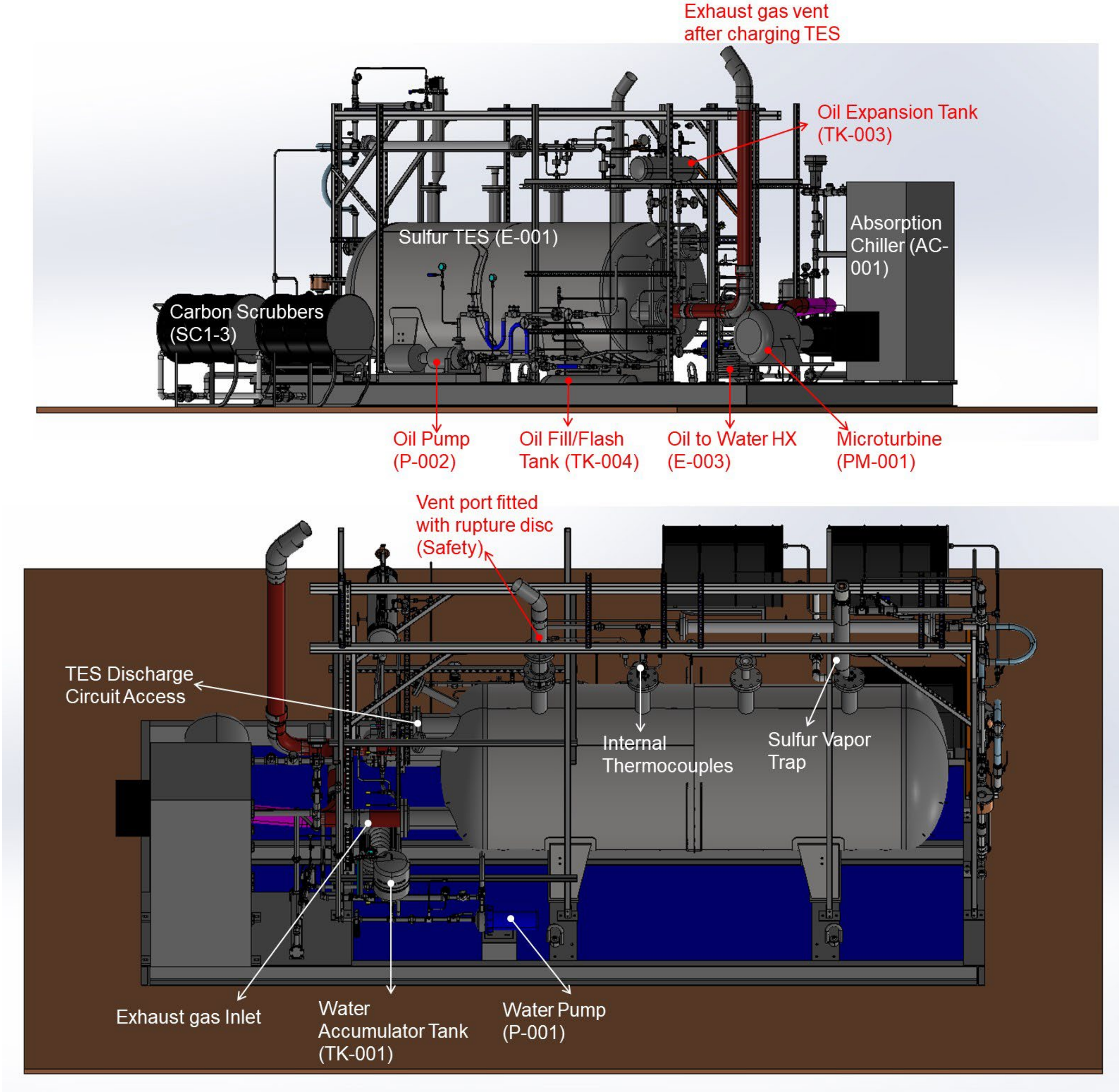
Integration of Sulfur TES With CCHP System

Figure 5 shows the computer-assisted drawing model of the sulfur TES system with the absorption chiller and capstone microturbine along with the thermal oil heat transfer fluid system and water loop. There are three main loops: (1) the exhaust gas loop that has the capstone microturbine equipment connected to the charging heat exchanger circuit of the sulfur TES; (2) the thermal oil heat transfer fluid loop that flows through the discharging heat exchanger circuit of the TES and connects to the oil to water heat exchanger; and (3) the water loop that collects heat from the thermal oil in heat exchanger and can be either used for hot water generation in, or used as a heat source for operating a water-fired 5-ton Yazaki absorption chiller to generate chilled water.

The generated hot water or chilled water from the absorption chiller is connected to the air handling unit. A cooling water loop is connected to the cooling tower to dissipate waste heat from the absorption chiller. During charge mode, the electricity generated by the microturbine is used to either charge the microturbine batteries — which supply electricity as needed and are used to start the system from a cold start — or dissipate as heat in an air-cooled resistor load bank. The exhaust heat from the microturbine is captured by the sulfur TES.

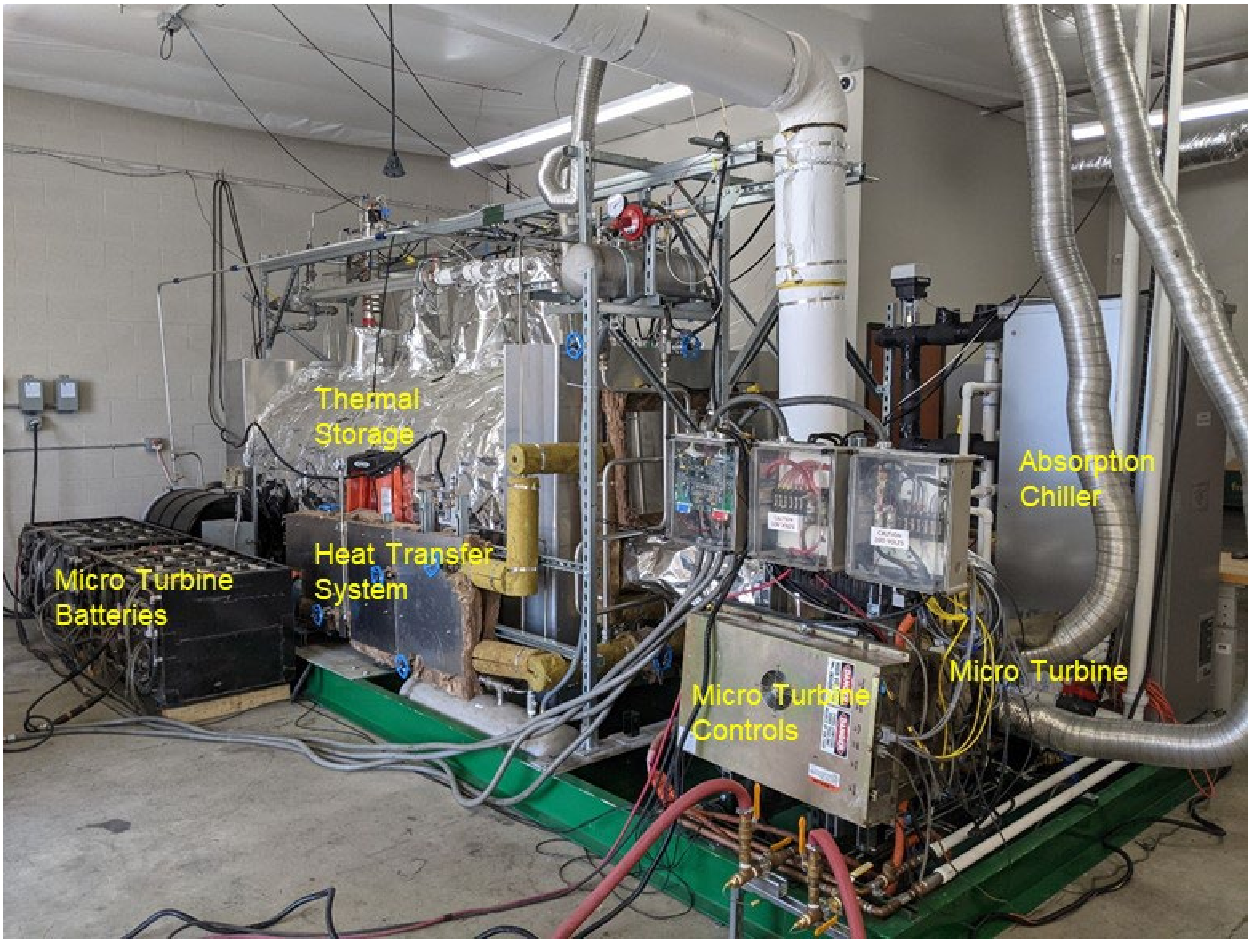
During discharge mode, thermal oil heat transfer fluid retrieves the heat stored in the sulfur TES that is used to heat the water in an oil to water heat exchanger. Independent of whether the microturbine is operating, the TES can send heat to the absorption chiller to generate chilled water or send heat to a water heat exchanger to generate hot water or both. By storing and discharging heat energy on demand, Element 16's sulfur TES improves the flexibility and efficiency of the overall CCHP system allowing the production of electricity and heat to occur at different times of day. It also provides heat demand peak shaving and reduces natural gas consumption. Figure 6 shows the photograph of the installed pilot system integrated into Element 16's facility at Arcadia, California.

Figure 5: CAD Model of the Sulfur TES Integrated Combined Cooling, Heat, and Power (CCHP) System



Source: Element 16 Technologies

Figure 6: Photograph of Sulfur TES Integrated CCHP System



Installed at Element 16's facility in Arcadia, CA

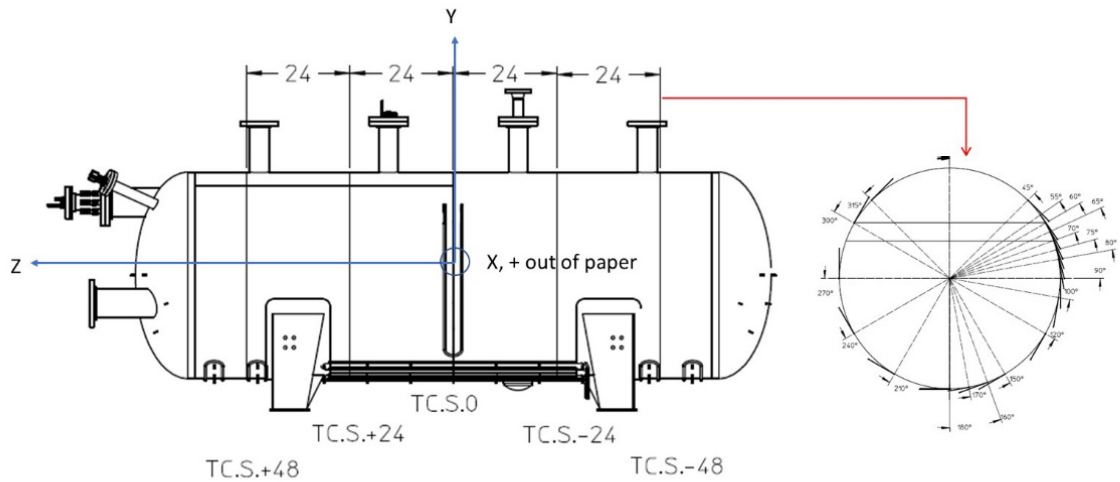
Source: Element 16 Technologies

Instrumentation and Controls

The sulfur TES is equipped with approximately 80 thermocouples on the exterior surface of the tank that are installed at various circumferential positions at five different axial locations: $z = \pm 24''$, $\pm 48''$, $0''$. The z-axis position is measured from the center of the tank as shown in Figure 7. The temperature measured by the external thermocouples was used to estimate the average tank shell temperature and energy stored in the tank shell. The sulfur TES is equipped with 31 internal thermocouples, 11 of which were installed through the front flanges when the tank's fabrication was in progress (Figure 8) and the rest were installed through the top flanges at the time of commissioning (Figure 9).

The internal thermocouples allow for monitoring of spatial and transient temperature distribution within the molten sulfur during charge, discharge, and dormant modes, and to calculate the heat transfer rate and energy stored within the sulfur. Figure 10 shows the heater control panels and the data acquisition modules. The temperature sensors that are installed near the steel jacketed heating elements are connected to the proportional-integral-derivative controller to regulate the heater operation (Figure 10). The induction current monitors installed in the control panel display the electric current consumption of the various heaters during operation. The electric current measurement provides information of the heat loss from the system especially at steady state conditions. The operation of the system is controlled by a programmable logic controller.

Figure 7: Surface Thermocouples Installed on Sulfur TES

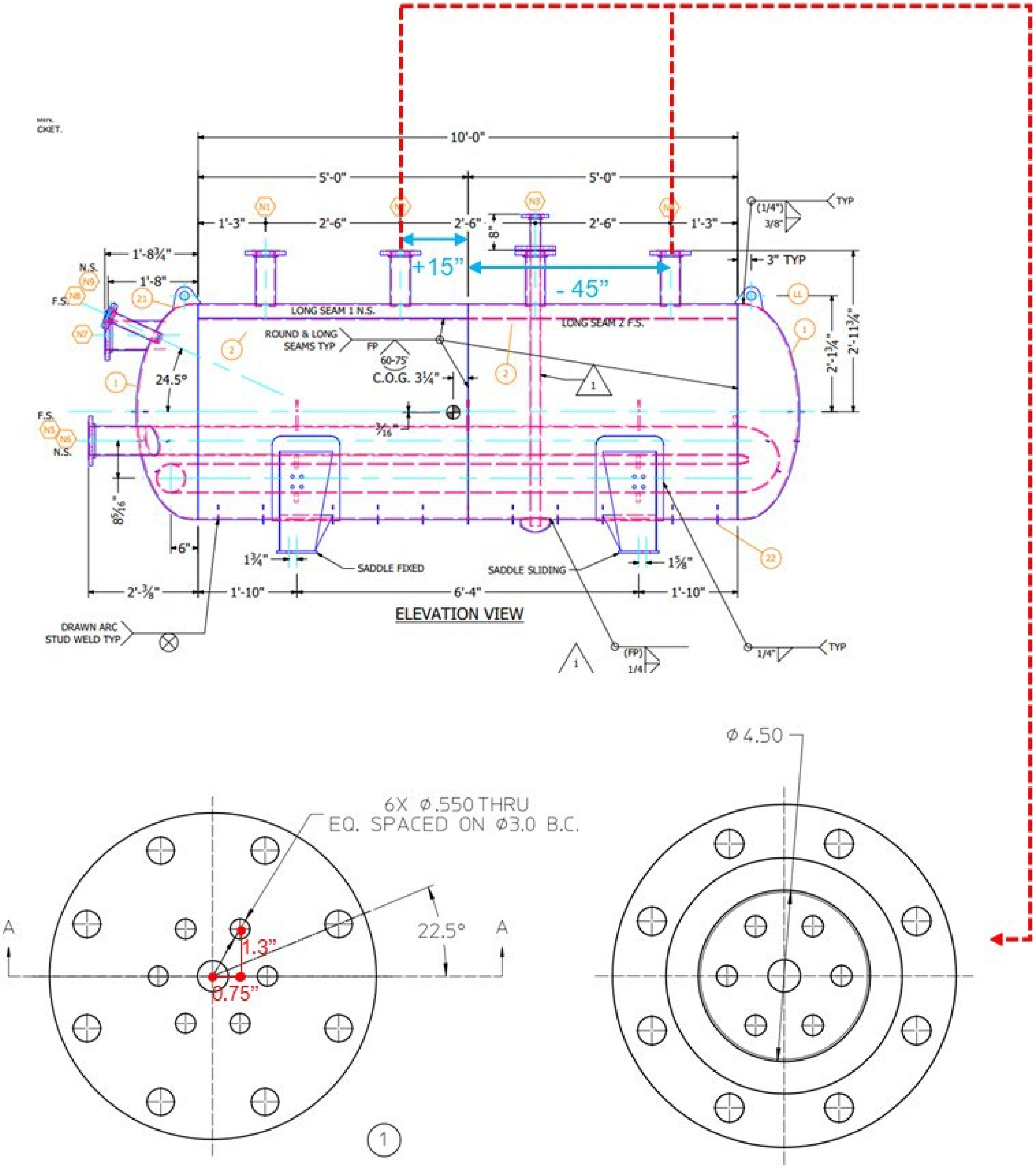


Source: Element 16 Technologies

Figure 8: Sulfur TES Internal Thermocouple Locations Installed through Front Flange

Source: Element 16 Technologies

Figure 9: Sulfur TES Internal Thermocouple Locations Installed through Access Port at the Top



Source: Element 16 Technologies

Figure 10: Photograph of Control System

Installed at Element 16's facility in Arcadia, CA

Source: Element 16 Technologies

CHAPTER 3: Project Results

Key Results

The performance of the system is summarized in Table 1 with the average results from all the runs. Across all trials, the average characteristics were:

- Storage rate: 12.6 kW
- Discharge rate: 27.6 kW
- Stored energy capacity in the interval from microturbine waste heat: 661 kWh
- Discharged energy capacity in the interval (two discharge cycles): 591 kWh
- Thermal Efficiency: 85.4 percent

It is noted that as the system size (tank diameter) increases, the surface area per unit volume decreases resulting in decreased heat losses per unit of storage capacity, and consequently, a higher round trip efficiency can be realized.

Table 1: Summary of Key Performance Characteristics Obtained from Cyclic Charge and Discharge Operation of Sulfur TES Integrated with CCHP System

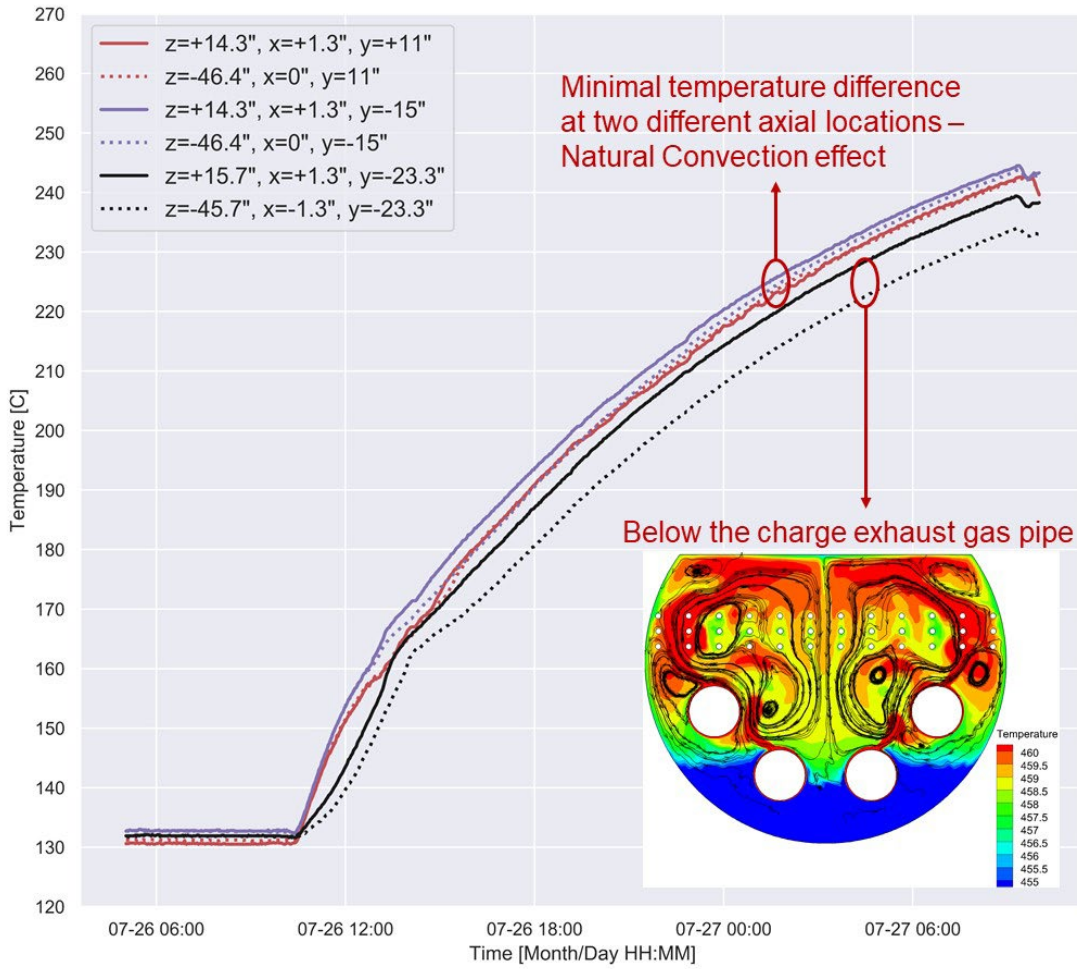
Trial Start Date	Output Mode	Avg. Storage Rate (kW)	Storage Capacity (kWh)	Avg. Discharge Rate (kW)	Discharge Capacity (kWh)	Electric Heat Input (kWh)	Thermal Efficiency (%)
Jul. 12	Cooling	11.5	619	28.5	537	7.4	85.7
Jul. 26	Heating	11.9	601	30.0	565	38.2	88.4
Aug. 2	Cooling	12.7	661	27.0	573	39.3	81.8
Aug. 16	Cooling	12.8	684	26.4	620	8.4	89.5
Aug. 23	Heating	13.3	697	25.4	598	53.7	79.7
Aug. 30	Heating	13.3	702	28.1	654	54.6	86.4

Source: Element 16 Technologies

Discussion (Experimental)

Figure 11 shows the transient and spatial variation in bulk sulfur temperature at two different axial positions (z = 14.3″ and z = -46.4″) measured by the thermocouples installed through the top flanges. Figure 11 shows that there is negligible variation in the spatial variation of molten sulfur during the transient charge and discharge process. This trend suggests the strong activity of natural convection currents within the molten sulfur that plays a key role in enabling high heat transfer rates. The temperature measured by the thermocouples below the charge exhaust gas pipe is lower than the temperature measured by other thermocouples despite it being closer to the hot wall. This is also representative of the fluid movement associated with buoyancy-driven natural convection physics that results in hot, lighter molten sulfur rising and cold, denser molten sulfur descending. A temperature contour plot along with natural convection streamlines obtained from a simple two-dimensional computational model shown in the inset corroborates the theory.

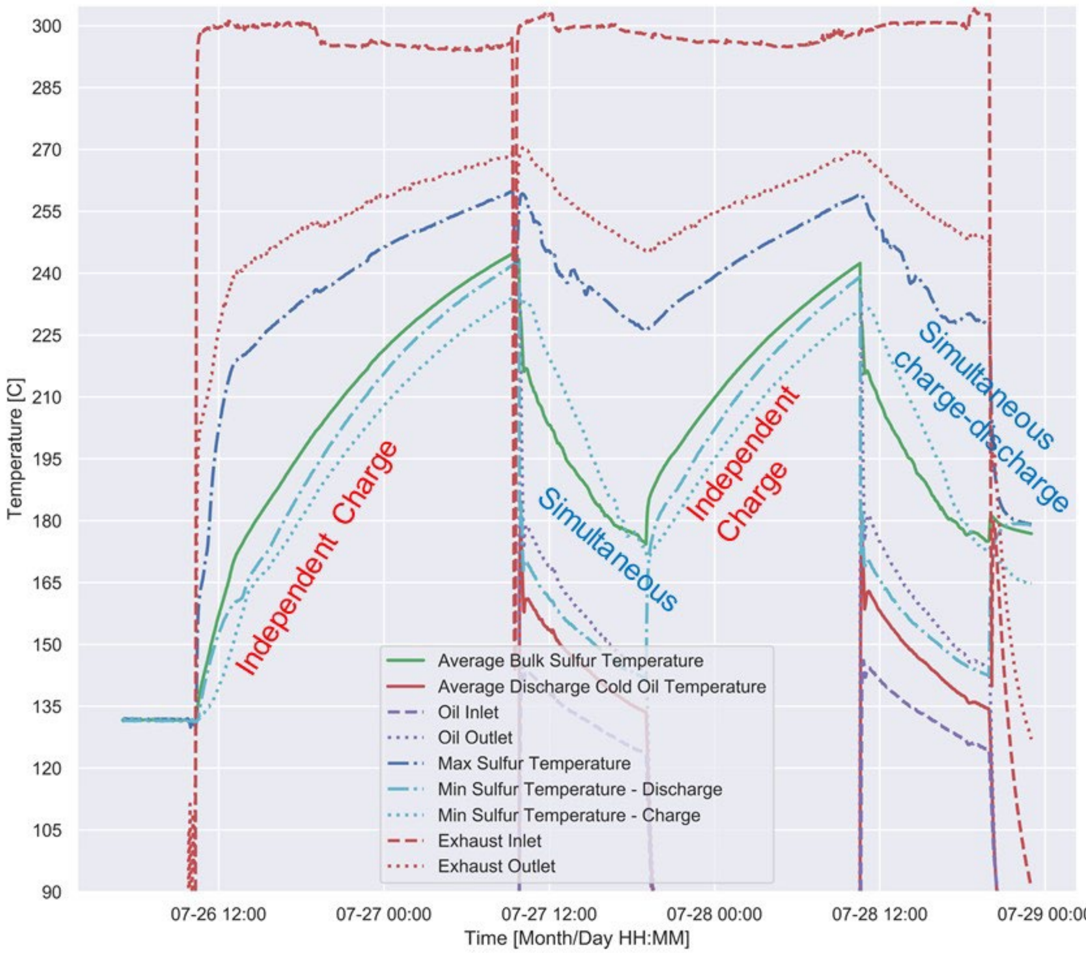
Figure 11: Transient and Spatial Variation in Sulfur Temperature



Source: Element 16 Technologies

Figure 12 shows the maximum and minimum sulfur temperature, average bulk sulfur temperature, exhaust gas inlet and outlet temperature during charge process, and thermal oil inlet and outlet temperature during the discharge process. The data corresponds to when the system was operated in 'simultaneous mode.' The average temperature of all the internal thermocouples excluding one that measures the ullage temperature (z = -44.3″, x = +1.3″, y = 22″) was used to determine the bulk molten sulfur temperature. As shown in Figure 12, due to the minimal spatial variation in sulfur temperature, the error associated with methodology used to obtain the average bulk temperature is likely negligible.

Figure 12: Temperature Variations

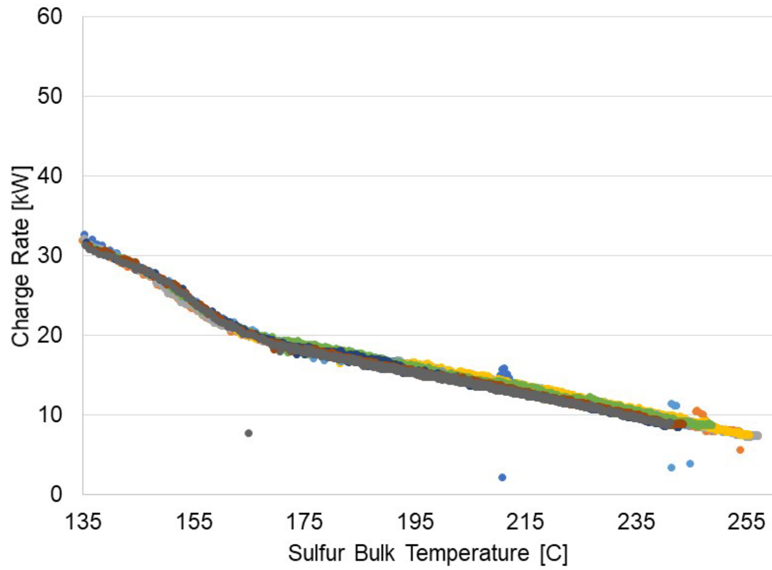


Temperature variations during cyclic 'independent charge' and 'simultaneous discharge-charge mode' operation.

Source: Element 16 Technologies

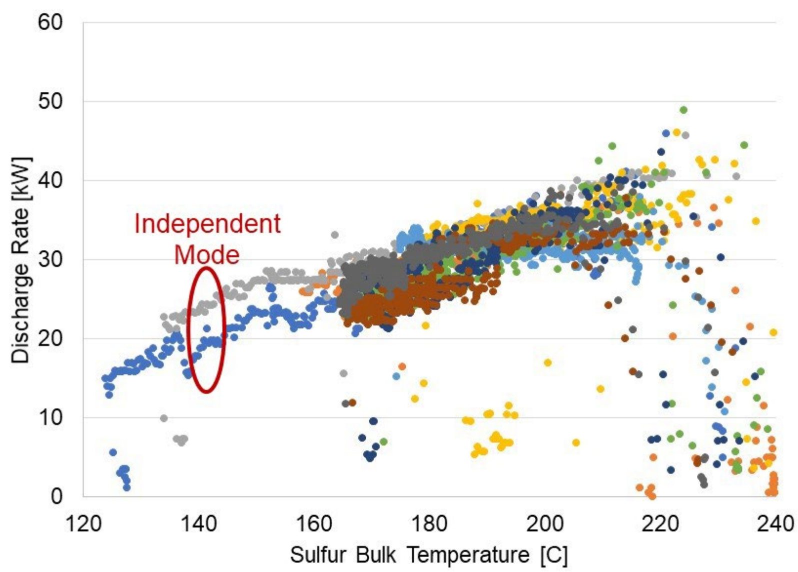
Figures 13 and 14 show the measured transient charge rate and discharge rate, respectively obtained from the different experimental runs plotted as a function of bulk sulfur temperature. The charge rate is calculated using the exhaust gas flow rate, inlet and outlet temperature (Equation 1), while the discharge rate is calculated from mass flow rate, inlet temperature and exit temperature of the water from the oil to water heat exchange (Equation 3). The results from all the experiments are very close to each other that verifies repeatable system performance. It is observed that the discharge rate is higher than the charge rate because of higher convective thermal resistance of exhaust gas flow compared to liquid-based thermal oil flow.

Figure 13: Transient Charge Rate from Experiments Plotted as a Function of Bulk Sulfur Temperature



Source: Element 16 Technologies

Figure 14: Transient Discharge Rate from Experiments Plotted as a Function of Bulk Sulfur Temperature

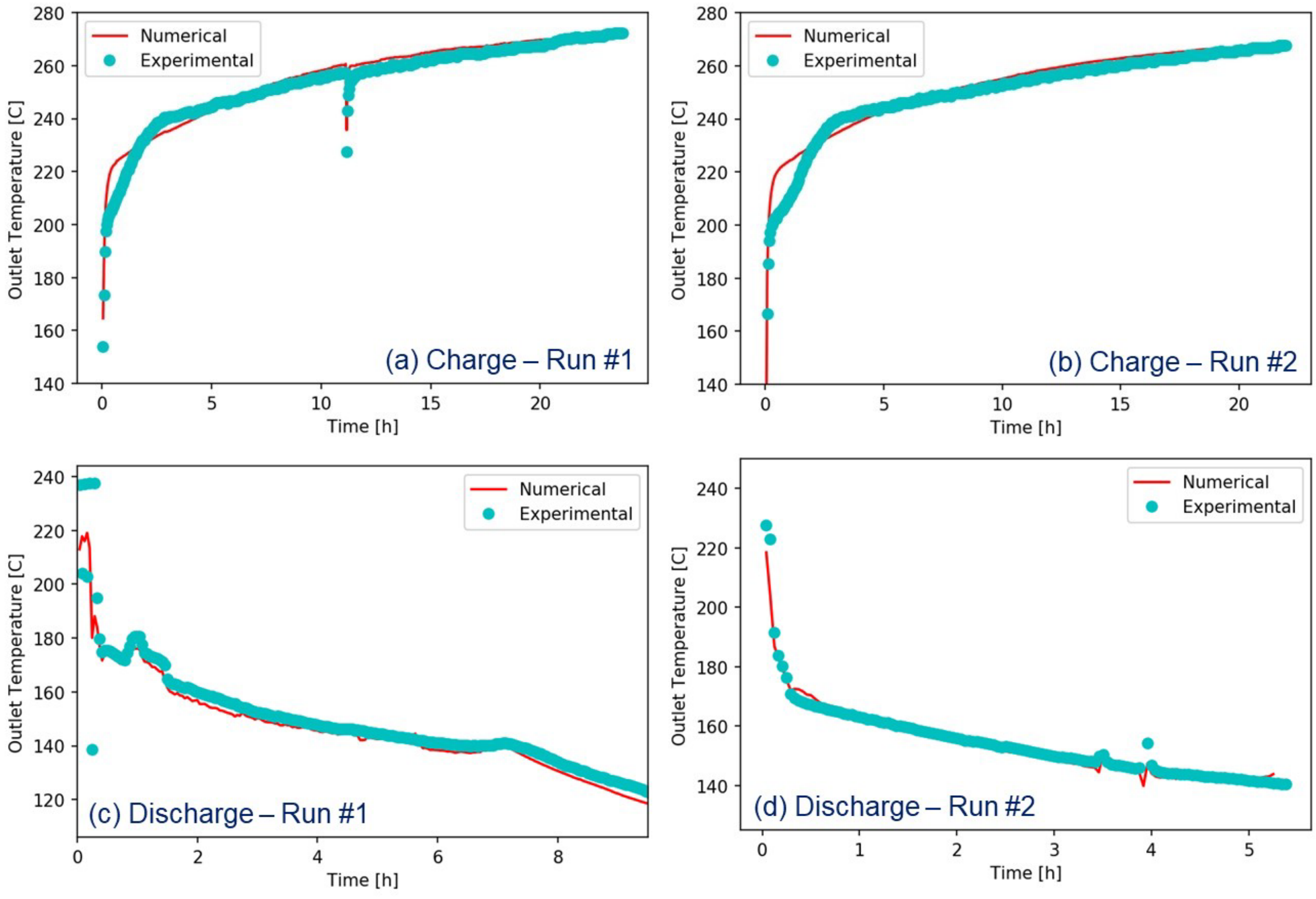


Source: Element 16 Technologies

Discussion (Numerical)

Figure 15 compares the predictions from the numerical model for two different charge experimental runs and two different discharge experimental runs. As noted, the inputs to the model are the initial temperature, inlet HTF temperature and inlet HTF mass flow rate. The plots in Figure 15 compare the numerically predicted outlet HTF temperature against the recorder experimental temperature measurements. The average errors (with standard deviation in parenthesis) between the numerical model predictions and experimental data for the results shown in Figures 15a-d are 1.2 percent (1.2), 1.2 percent (1.6), 2.3 percent (2.5) and 1.4 percent (5.6). Overall, the numerical model results agree closely with the experimental data and can be used for making design decisions with high level of confidence.

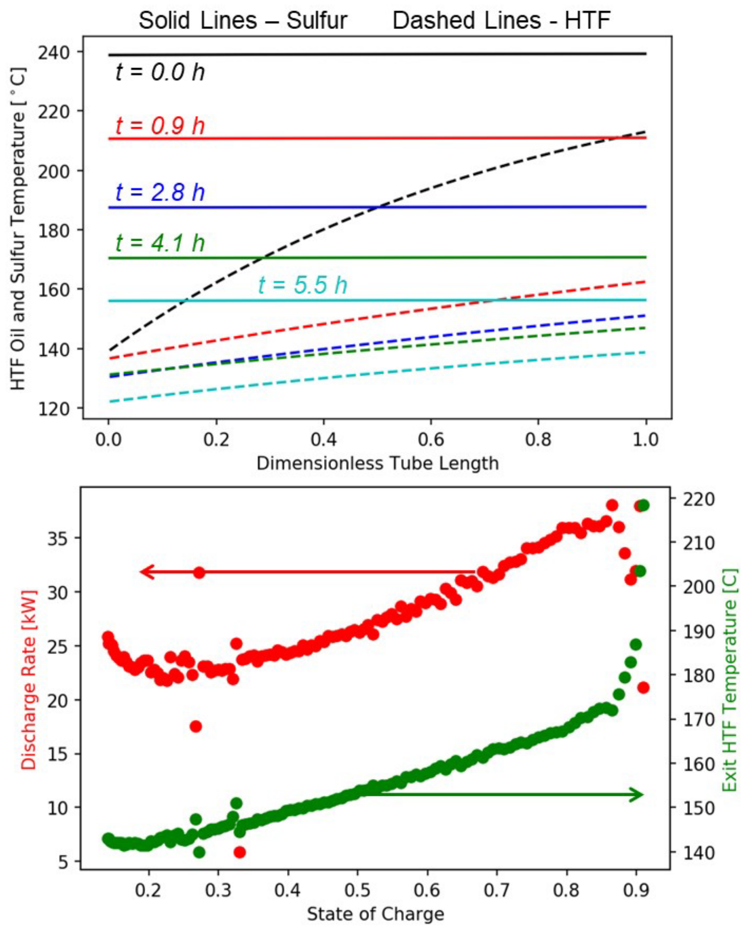
Figure 15: Comparison between the Experimental Data and Numerical Predictions Obtained for Different Charge and Discharge Runs



Source: Element 16 Technologies

Figure 16 shows the predictions from the numerical model for the spatial and temporal variation in HTF and sulfur temperature during the discharge process corresponding to one of the runs. It is observed that the sulfur temperature at any given instant of time is nearly constant throughout the tank. This is not surprising, and it agrees with the previous experimental result, further corroborating the activity of natural convection currents within molten sulfur. The bottom plot shows the thermal power and exit HTF temperature versus state of charge. This characterizes the overall transient performance of the pilot sulfur TES in terms of two critical parameters: power and energy (state of charge). It is observed that the discharge rate gradually decreases with decrease in state of charge. This is due to the decrease in temperature difference between the sulfur temperature — that decreases as stored energy content is depleted during discharge — and the HTF temperature. Below a state of charge of ~ 0.2, the discharge rate rises because of the increase in the Rayleigh number with decrease in sulfur viscosity (the viscosity of molten sulfur has a non-linear relationship with temperature as it increases from 374°F to 464°F (190°C to 240°C), depending on the concentration of impurities, and decreases with further increase in temperature).

Figure 16: Numerical Model Results



(top) Variation in HTF and sulfur temperature as a function of time and position in the TES, (bottom) discharge rate and exit HTF temperature as a function of state of charge (Ragone relations)

Source: Element 16 Technologies

Method for Technoeconomic Assessment

An integrated technical assessment tool was developed by combining the technical performance metrics of the pilot sulfur TES system with the technical performance model of the microturbine prime mover and the natural gas boiler. Using realistic hourly electrical and heat usage data of a representative large commercial building located in Los Angeles, along with energy pricing and installed system costs, the natural gas savings and emissions reductions associated with integration of sulfur TES to combined heat and power system are quantified.

The value of adding TES to CCHP system are quantified in terms of the payback period, and lifetime value. The commercial building model used in the analysis is a representative prototype building located in the Los Angeles region (Deru et al. 2011). The hourly electricity and natural gas consumption — for heating, cooling, ventilation, lighting, and plug and process loads — of the commercial building located in the Los Angeles region for the year was simulated using the EnergyPlus software (DOE 2010).[1] The capacity of CCHP microturbine prime movers (PM_{cap}) for commercial applications was selected based on the electrical demand of the facility. An appropriate capacity for the prime mover is 0.5 of the average electrical demand (Smith et al. 2013 and Derrow et al. 2015). Natural gas fuel for the prime mover, $F_{NG,PM}$ was calculated using:

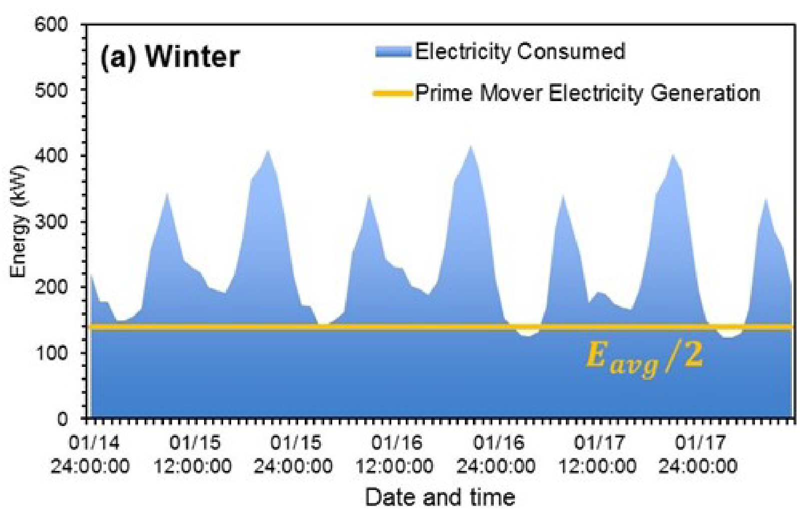
$$F_{NG,PM} = {}^{0.5 \times E_{avg}}/_{\eta_e}$$

where η_e denotes the capstone microturbine prime mover higher heating value efficiency and is taken to be 0.26 (Derrow et al. 2015). The thermal efficiency of the CCHP unit (η_{CHP}) is 0.41 (Derrow et al. 2015). The exhaust heat from the CCHP prime mover, after accounting for the thermal efficiency of the TES(η_{TES}), provides the heat available to the building (Q_{CCHP}) as shown in Equation 6a. When natural gas is directly used for heating the building in a boiler, heating efficiency (η_h) is used to calculate the natural gas fuel required as shown in Equation 6b. η_{TES} and η_h are 0.854 and 0.8 (Kurup and Turchi 2015), respectively.

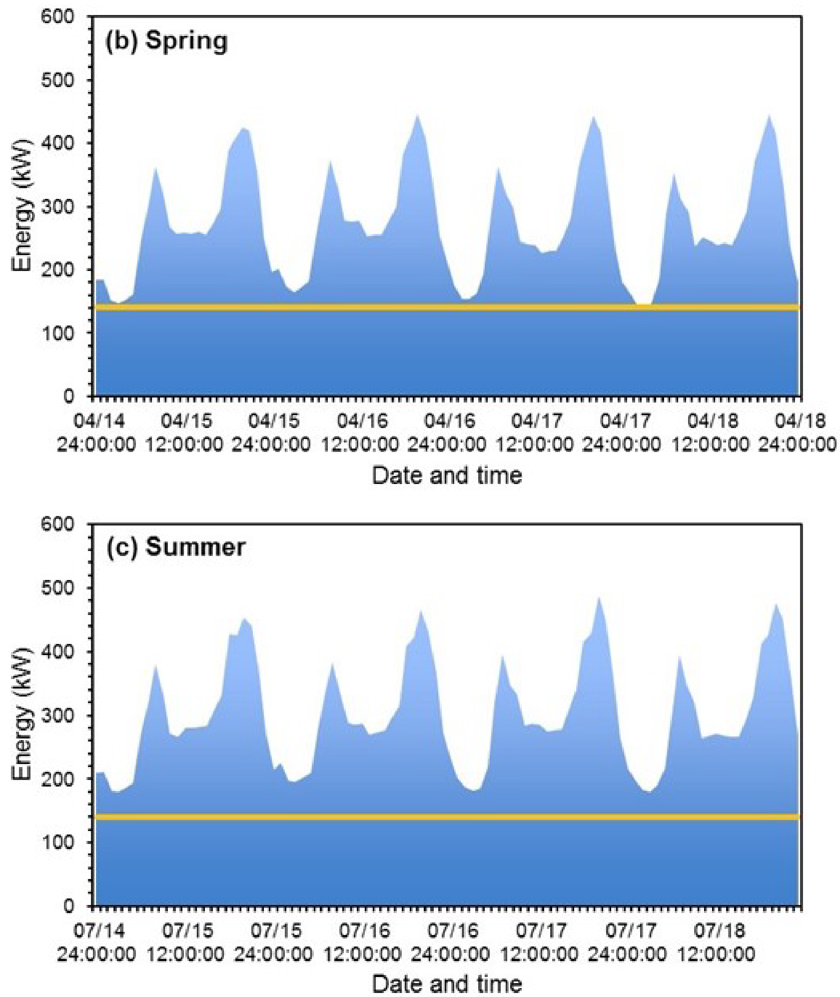
$$Q_{CHP} = F_{NG,PM} \times \eta_{TES} \times \eta_{CHP} \qquad [6a]$$
$$Q_{CHP} = F_{NG,h} \times \eta_h \qquad [6b]$$

The base case of CCHP without TES is obtained using the electricity and natural gas demand from EnergyPlus models and assuming baseload operation of the CCHP unit. Figure 17 and Figure 18 show the electricity and natural gas demand of the representative commercial building located in Los Angeles that has an average electricity and thermal energy requirement of 280 kW and 206 kW, respectively.

Figure 17: Hourly Variation in Electricity Demand of a Representative Commercial Facility in the Los Angeles Region



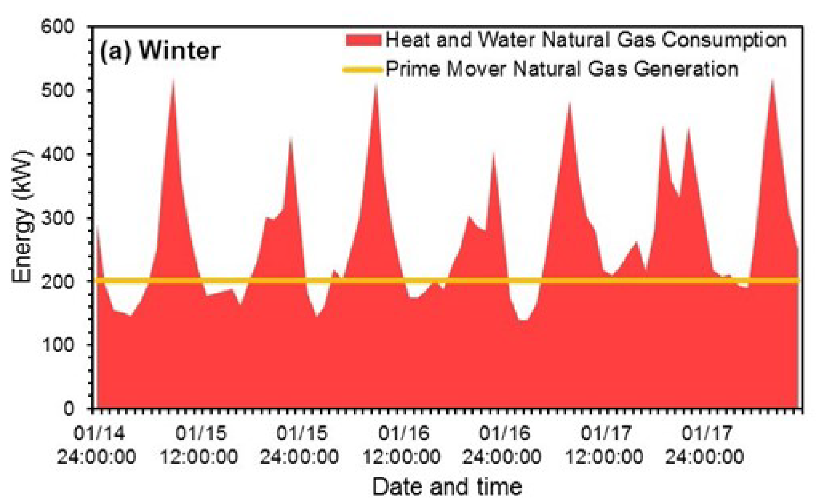
[1] The Energy Plus software, Version 6.0 is available at the Department of Energy link in the References section.

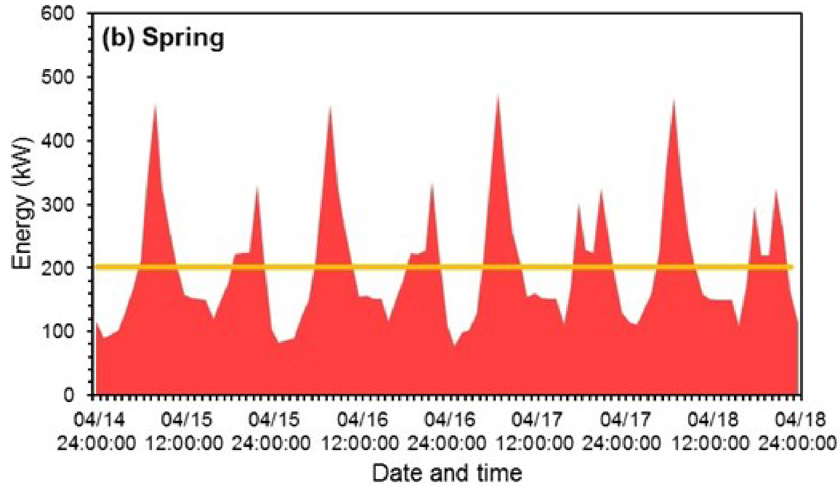


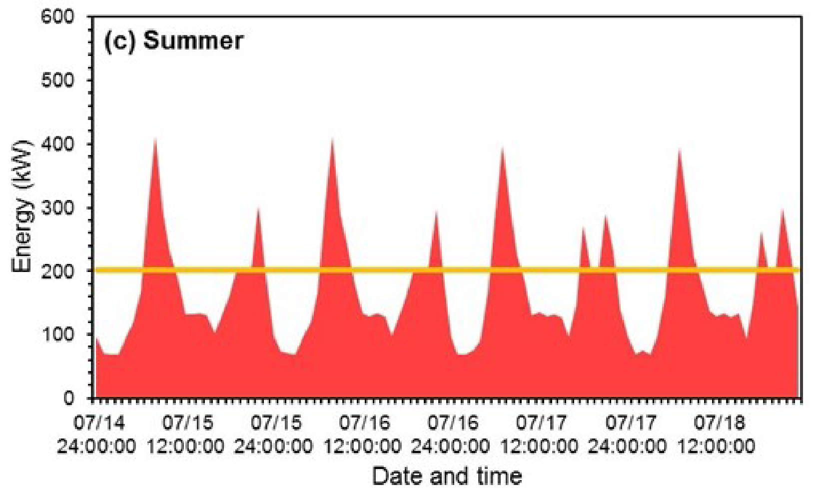
Electricity demand and production 4 days in (a) winter, (b) spring, and (c) summer obtained from EnergyPlus.

Source: Element 16 Technologies

Figure 18: Hourly Variation in Thermal Demand of a Representative Commercial Facility in the Los Angeles Region







Heat demand and production 4 days in (a) winter, (b) spring, and (c) summer obtained from EnergyPlus.

Source: Element 16 Technologies

With integration of sulfur TES, excess heat is stored and discharged in place of additional natural gas purchases. When the CCHP unit produces more heat than the building requirement and the TES is not fully charged, the TES stores excess thermal energy as shown in Figure 19a. If the TES unit is fully charged (hot), heat is exhausted. When the CCHP unit provides less thermal energy than the building requirement, energy is discharged from the TES as shown in Figure 19b. Once the TES is completely discharged (cool), additional natural gas is purchased and sent through a boiler to provide the additional required thermal energy, as shown in Figure19c. The transient variation in charge and discharge rates that can be achieved by the sulfur TES are informed by the pilot system performance results. The maximum (average) charge and discharge rates were determined to be 0.14 (0.05) kW/kWh and 0.2 (0.11) kW/kWh, respectively. Figure 20 shows the general logic tree, which is computed for each hourly time step. It is assumed that the TES is completely discharged, or cool, at the beginning of the year.

For the economic analysis, the annual avoided cost of purchasing supplemental natural gas (ΔC_{NG}), is compared with the one-time installed cost of the TES (C_{TES}). ΔC_{NG} is calculated from:

$$\Delta C_{NG} = \sum_{t\,=\,0\,h}^{t\,=\,8760\,h} (F_{NG,h} + F_{NG,PM}) \times C_{NG} \qquad [7]$$

The California price of natural gas sold to commercial consumers, C_{NG} is obtained from the Energy Information Agency (EIA 2024b). The average price for the year 2021 is \$11.30/MMBtu (million British thermal units). Like most of the industrial equipment, the sulfur TES cost at various capacities is estimated using the rule of six-tenths (Whitesides 2005):

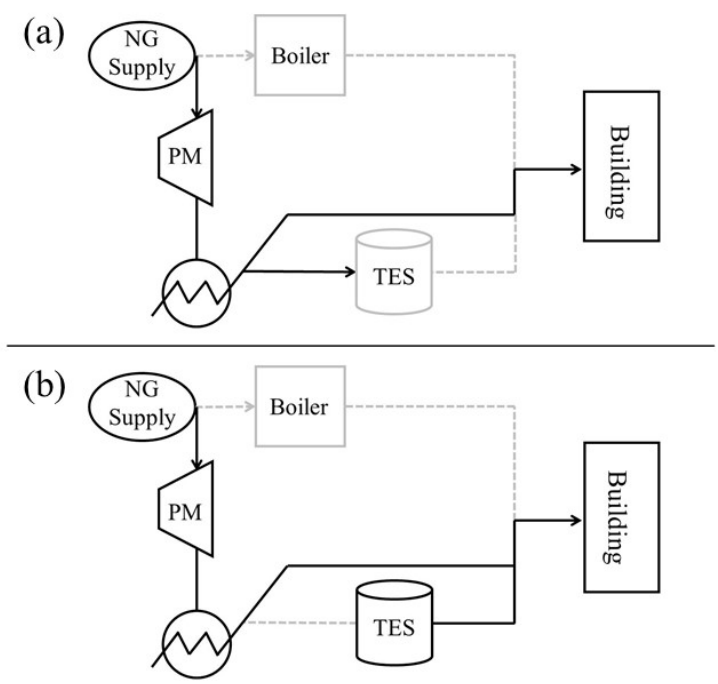
$$C_{TES} = C_{o,TES} \left\{ \frac{Q_{TES}}{Q_{o,TES}} \right\}^{0.6} \qquad [8]$$

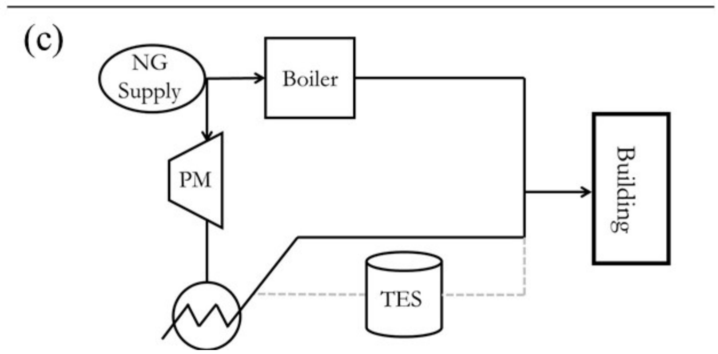
$C_{o,TES}$ is the capital cost of the pilot TES system corresponding to the storage capacity $Q_{o,TES}$. The installed cost of sulfur TES measured in \$/kWh decreases with increase in storage capacity because of decrease in tank surface area required per unit volume with increase in radius and economies of scale. The payback period of a TES retrofit, PP_{TES}, is calculated using Equation 9, and the total value of the TES to the end-user for a 25-year lifetime is calculated from Equation 10.

$$PP_{TES} = {C_{TES}}/{\Delta C_{NG}} \qquad [9]$$

$$LV_{TES} = 25\ years \times \Delta C_{NG} - C_{TES} \qquad [10]$$

Figure 19: Operating Schematics of TES Integrated to a Combined, Heat, and Power System

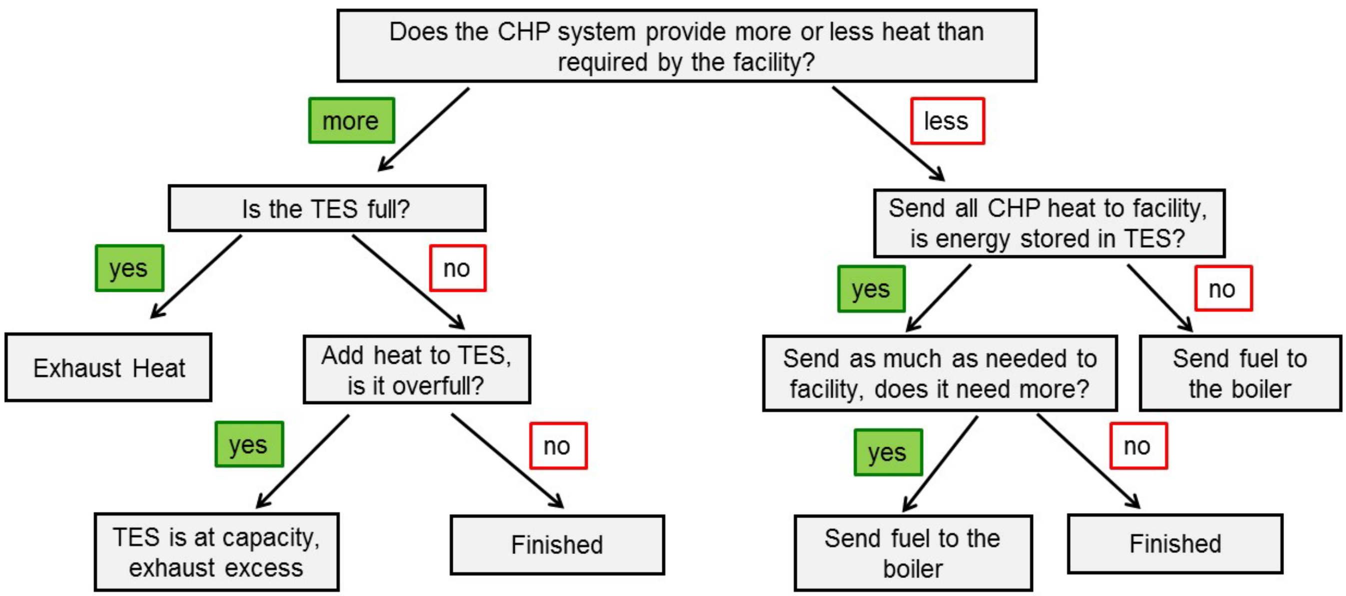




Building heat requirement less than CCHP supply and TES is charged; (b) Building heat requirement greater than CCHP supply and TES is discharged; (c) Building heat requirement greater than CCHP supply + TES supply and additional natural gas is burned

Source: Element 16 Technologies

Figure 20: Hourly Logic Tree for TES Integrated CHP System



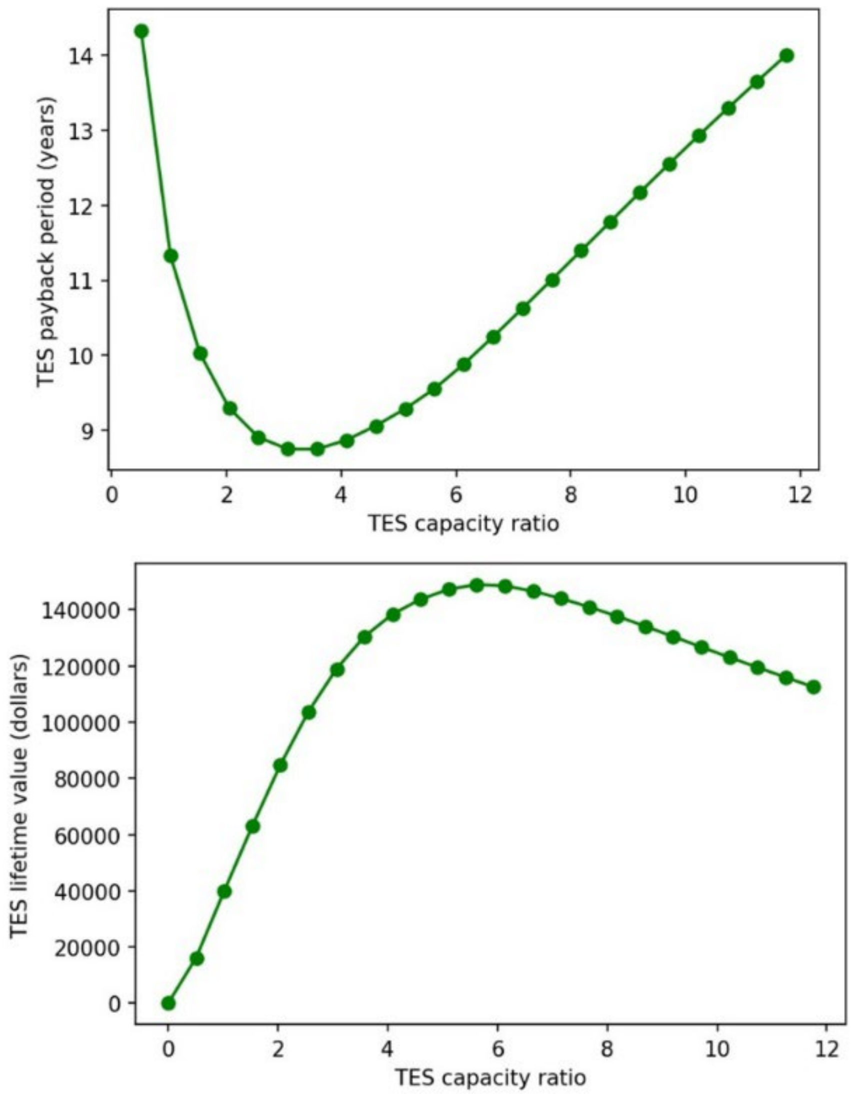
Source: Element 16 Technologies

Discussions (Techno-economics)

Figure 21 shows the payback period and lifetime of the sulfur TES retrofit as a function of capacity ratio, which is the capacity of the TES system normalized with the average heat usage of the building. It is noted that the minimum payback period of less than nine years is obtained for optimal capacity ratio of 3.0 while from a maximum lifetime value perspective, the optimal capacity ratio is obtained to be 4.6 for a system lifetime of 25 years. It should be noted that this analysis does not take incentive programs into account, and therefore the real economics could be significantly more advantageous than shown here.

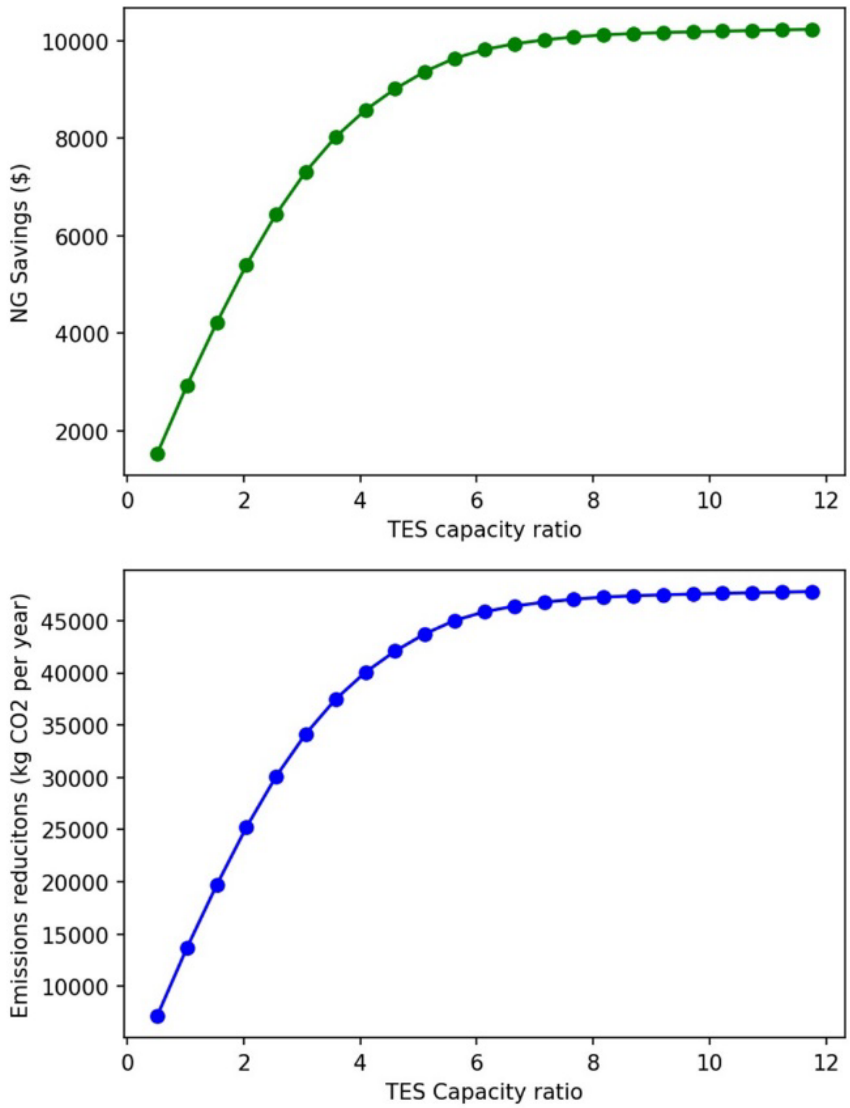
Figure 22 shows the annual natural gas savings as a function of sulfur TES capacity ratio. Based on the carbon dioxide emissions coefficient obtained from the Carbon Dioxide Emissions Coefficients by Fuel (EIA 2024c), the emissions reduction achieved from natural gas savings due to sulfur TES retrofit is also plotted in Figure 22. The reduction in carbon dioxide emissions is estimated to be 34 tons to 42 tons when retrofitted with sulfur TES of capacity ratio between 3.0 to 4.6. The annual natural gas savings and emissions reductions for capacity ranging between 3.0 to 4.6 was estimated to be $7,320 to $9,015. With this framework built using validated sulfur TES performance metrics, Element 16 team can assess the techno-economic benefits of sulfur TES integrated to CCHP system for buildings of various types and at different locations.

Figure 21: Payback Period and Lifetime Value of TES Retrofit as a Function of Capacity Ratio



Source: Element 16 Technologies

Figure 22: Natural Gas Energy Savings and Emissions Reduction as a Function of TES Capacity Ratio



Source: Element 16 Technologies

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Knowledge Transfer to Industry Leaders and Stakeholders

The key drivers of knowledge transfer to industry are awareness of the new technology and a clear definition of how the technology can solve a problem that industry leaders are facing. Element 16 set out a three-part plan to: (1) increase awareness, (2) learn the nuanced requirements and needs of future customers, and (3) craft a clear message that explains how the technology solves industry challenges. Different types of industry leaders and stakeholder engagement were required to accomplish the plan:

a. Contacts and network developed through events, such as competitions, summits, expos, and conferences

b. Site visits to related industry facilities and one-on-one meetings

c. Event speeches, panel participation, and/or advisory positions in related fields

Part A: Developing Contacts and Networks

At the beginning of this grant project, sensible sulfur TES had only been investigated at research institutions. Because industry awareness of the technology in industry was effectively non-existent, and the technology is unique (popular thermal energy storage research was focused on salts, concrete, rocks, and phase change materials), Element 16 had to establish its own credibility and reputation without expecting invitations to present or speak at industry events. With limited company funds allocated for stakeholder engagement, Element 16 sought invitations and free/discounted/sponsored tickets and travel to attend events that would attract industry experts that develop, fabricate, install, and/or use CHP units.

CHP Workshop: Assessment of Small-CHP Technical and Market Potential in California

In 2017 and 2018, the California Energy Commission (CEC) funded an event to promote market potential of small-CHP by ICF Inc., SoCalGas, and DE Solutions. As part of this effort, the team held in-person workshops with key equipment manufacturers and other stakeholders. Element 16 attended this event, which was instrumental in Element 16’s development. While there, Element 16 met a Searles Valley Minerals energy manager, which led to a subsequent CEC project together that saves Searles Valley Minerals hundreds of thousands of dollars in natural gas costs and water efficiency savings. The energy manager also introduced Element 16 at the company’s Techstars Demo Day, which is a presentation in front of hundreds of investors, media, and start-up ecosystem partners.

University of California, Davis Symposium on Industrial Energy Efficiency

University of California, Davis hosted an on-campus symposium about Industrial Energy Efficiency that brought together food processing and oil industry energy experts to discuss best practices and recent technological advances. Both industry sectors are reliant on heat for production, and often operate CHP/CCHP plants. The event was attended by decision makers at companies like E&J Gallo Winery, Shell, and Pacific Coast Producers.

ARPA-E Energy Innovation Summit

In 2019, Element 16 attended the Advanced Research Projects Agency – Energy: Energy Innovation Summit, which features the latest developments in energy. Among researchers and government, executives from large industrial and energy corporations attend to meet innovators developing the next generation of energy equipment. At this event, Element 16 met with more than a dozen potential collaborators, customers, and investors, including multiple representatives that are potential funders and industry advisors to Element 16 today.

AEE GLOBALCON

Element 16 attended the Association of Energy Engineers' (AEE) World Energy Engineering Conference, where thousands of energy industry professionals from hundreds of companies were available to discuss innovations. The range of products developed by companies included small-scale generator providers, custom heat exchanger fabricators, chiller companies, large engineering contractors, utilities, and more.

Energy Solutions Expo

In 2018, perhaps the most active CCHP market in the world was Ontario, Canada. Because of the unique way that the utility charges large energy customers, it was a major focus for CHP companies. Element 16 attended the Energy Solutions Expo, meeting with companies that included AB Group (a multinational cogeneration company) and Carrier (one of the largest chilling equipment manufacturers). Connecting and learning from these companies was helpful as Element 16 developed its understanding of the natural gas cogeneration power plants and chiller market. This was vital as Element 16 designed and built the combined cooling, heating, and power unit, and developed computational models for future commercial systems.

Northeast Power Producers Association Annual Conference

Beyond the equipment and project developers, other key stakeholders are the utility companies. Utility companies provide natural gas, buy and sell electricity, and often are the customers that purchase and operate CHP/CCHP plants. Among the most popular regions for CHP projects with a potential need for thermal energy storage is New England. Parts of New England are natural gas constrained in the winter, and households are prioritized over businesses because of the cold weather. Element 16 met regional utility companies, learned about their CHP and energy storage projects, and interacted with the equipment and engineering companies that installed those CHP projects.

National Plastics Expo

This Expo was one of the largest events Element 16 attended, with representatives from all segments of plastics products including production of polyethylene and polypropylene, to injection molding. These facilities use heat and electricity and range from small-scale (suitable for small-scale CHP) to some of the largest industrial campuses in the world. Element 16 met representatives from companies like Total Corbion producing bioplastics, OxyChem producing a wide variety of products, and Multitherm which makes thermal oils. After meeting Multitherm at the event, Element 16 selected one of their heat transfer oils for use in the CCHP-TES pilot for this project.

Facilities Expos

While there are many CHP and CCHP plants for industrial facilities, many are not small-scale facilities. To target small-scale CCHP customers, Element 16 attended the Southern California Facilities Expo and the Northern California Facilities Expo. These events attracted suppliers and customers of heating and cooling equipment appropriately sized for universities, corporate campuses, hospitals, and other large commercial and residential buildings. The project that Element 16 successfully demonstrated was a suitable size for these end users. Element 16 met representatives from companies like Dawson Co (Pomona-based heating equipment supplier), Sabarco (Noren Thermal Solutions supplier), and Total Environmental Management (temporary heating and cooling equipment provider).

Energy Storage North America

Element 16 attended Energy Storage North America (ESNA) multiple times, which is a showcase of all energy storage innovations. It was an excellent opportunity to meet energy storage technology developers and their suppliers. For example, ESNA was the first time Element 16 met representatives from Brenmiller Energy in person. Brenmiller is an Israeli thermal energy storage company, which was founded by the former Chief Executive Officer (CEO) of Solel Solar Thermal, which was purchased by Siemens. Brenmiller Energy was founded in 2012 and is traded on the Tel-Aviv Stock Exchange. Brenmiller Energy received funding from the Binational Industrial Research and Development (BIRD) Foundation, a collaboration between the Israeli and US governments. Element 16 applied for and was awarded BIRD funding for the first time in late 2021.

These events that were attended by Element 16 have been vital to the company's understanding of market opportunities, and to meeting new prospective partners, clients, and investors. By attending these events and speaking about Element 16's sulfur TES innovation, the team started to gain interest from industry experts and stakeholders. The events directly led to the site tours and one-on-one meetings. These events were often where Element 16 met prospective partners, clients, and investors that would invite deeper investigations into future collaborations.

Part B: Building Relationships with Potential Customers and Partners

After identifying the initial target markets and growth markets for small CHP and CCHP with thermal energy storage, Element 16 built relationships with relevant energy experts. To fully understand each market's particular energy needs and constraints, Element 16 also toured facilities with energy managers and operations staff to identify CHP-TES opportunities. The key opportunities were divided into two categories: community and industrial. Community includes district heating systems, university campus heating, large hotels and resorts, and other places where central CHP plants serve multiple buildings' electricity, heating, and cooling requirements. Industrial facilities use central CHP plants for power, heat, and cooling needs to make products. While the community group generally uses the majority of their heating and cooling for air conditioning, space heating, and other relatively modest temperature heating needs, industrial facilities have much larger heat requirements relative to electrical usage and at much higher temperatures.

Community

Many universities in California have on-site CHP and CCHP plants to provide campuses with electricity, heat, and cooling in a more energy efficient way than generating heating, cooling, and electricity separately. While much of the heating, cooling, and electricity is used for comfort cooling and heating in classrooms and dormitories, many universities also require steam for research laboratories and hospitals, and other specialized needs. It was also clear, when speaking with energy management at universities that many public and private schools are exploring ways to make forward-looking climate friendly decisions and are interested in pursuing new technologies like sulfur TES to reduce campus carbon emissions.

Element 16 was guided through CHP plants, boiler equipment, and district heating networks at California State Universities including Cal State Northridge and Cal Poly Pomona, and similar tours at the University of California, San Diego, and the University of California, Los Angeles (UCLA) where it met WorleyParsons (now Worley), which operates the UCLA power plant. Since then, Element 16 has since partnered with Worley on multiple non-CEC projects. Element 16 has toured and held in-depth technical review meetings with other universities in California and beyond, and developed a strong understanding of how small-CCHP with TES could have an excellent economic impact for universities and district energy systems. This is especially true as variable renewable energy resources are added to the grid, making hourly electricity price fluctuations commonplace, and creating a greater need to decouple the generation of electricity and heat in CHP plants.

Outside of California, Element 16 also toured the modern CHP power plant at the University of Massachusetts Amherst. The economics of thermal energy storage in Massachusetts is different from California because there is less regional solar power availability and limited natural gas service. The limited natural gas service means that in the winter, when natural gas is needed to keep homes warm, the university is forced to rely on other, less climate friendly, fossil fuels. Element 16 is also very interested in non-university-related district heating systems, often coupled with utility grids and micro-grids. These are less common in the United States than in Europe and Asia, but Element 16 toured a Citizens Energy Group power plant in Indianapolis, Indiana, meeting with many of their employees in the electricity and district heating services. Citizens Energy Group is a Public Charitable Trust solely for the benefit of customers and the Indianapolis community. In addition to supplying power, Citizens supplies steam through an underground network, much of which is generated from a Waste-to-Energy facility. Element 16 also had the opportunity to meet with Citizens' customers of the district heating steam network, who can purchase steam from the utility instead of burning natural gas on-site.

Through these in-person meetings and facility tours, the Element 16 team learned the requirements of each customer segment and met with decision makers. This led to an excellent understanding of what metrics sulfur thermal energy storage and CCHP-TES needs to meet to gain initial deployment, and widespread deployment, and an understanding of the specific problems that TES can solve for each of these customers. The energy economics for each location is dictated by electricity pricing scenarios, fuel prices, taxes and regulations, and customer's climate and strategic goals. Understanding each opportunity and the personnel in position to make technology pilot and purchasing decisions is not possible without multiple in-person and remote/virtual meetings.

Industrial

Most of the industrial sector from food processing to mining requires heat as the main energy input to their facilities. Unlike the majority of residential, commercial, and community CHP plants, heat is the primary driver for most industrial CHP plants. CHP plants are sized based on an industrial facility's heat needs and excess electricity is often sold to the grid. As part of the potential market impact and commercialization efforts of this project, Element 16 conducted a thorough investigation of a wide variety of types of industrial facilities to find which types are suitable for sulfur thermal energy storage and CHP-TES systems. The economic analysis included a survey of regions of the United States that are currently economically suitable for CHP-TES, those that are likely to be suitable in the future, and those that are likely to lag behind. TES is most valuable in markets where high solar and wind grid penetration worsen the economic viability of constantly operating CHP plants. Since most industrial facilities operate 24 hours a day, 7 days a week, and the heat from the CHP plants is necessary for the plant to operate, industrial CHP has no choice but to operate independent of grid pricing signals. TES allows a CHP plant to be operated when the price of electricity is high using the excess stored heat, and then storing it when the price of electricity is low and the plant is not operating. TES can also be charged with renewable energy from solar PV, solar thermal, or wind, discharging that energy as useful industrial process heat at a later time. This opportunity was conceived and refined through discussions with leaders from a variety of industrial facilities.

Element 16 seeks to bring this technology to market immediately, and at its current stage of development, sulfur TES can achieve different price points for different industrial process heat temperature ranges. According to the technoeconomic modeling developed for this project, in most cases, sulfur TES is most suitable for industrial applications below 662ºF (350ºC) when paired with CHP. This is well-aligned with this project's objectives, as the pilot demonstration was tested, thus far, up to 572ºF (300ºC), and Element 16 designed the system to achieve higher temperatures, as will be demonstrated in the future. As a result of the technoeconomic modeling and sulfur TES experimental results and pilot demonstration, Element 16 targeted industrial applications that require heat below 662ºF (350ºC). This happens to be the majority of industrial process heat, as detailed in the project's final report. The markets with large heat requirements in the 176ºF to 662ºF (80ºC to 350ºC) temperature range that were considered were: food and beverage processing, chemical production, mining and minerals, pulp and paper mills, oil and gas production and refining, and water desalination.

Element 16 met with dozens of industrial energy experts in these fields, including tours of Pacific Coast Producers (food), California Sulphur Company (chemicals), PABCO Paper (paper mill), Searles Valley Minerals (minerals), and Petroleum Development Oman (oil). Element 16 also received multiple financial awards from the US Department of Energy to investigate how sulfur TES could support solar thermal, desalination, and CHP using data provided in part by Searles Valley Minerals. Element 16's meetings and site visits with Searles have led to an already successful project to reduce the company's natural gas consumption, with more work ongoing. Element 16 is tracking Searles's new solar developments and has built a strong working relationship with the company, as they aim for zero-net energy. Food production and minerals/mining are two of the most promising applications for CHP-TES. In food production, Element 16 was selected to give private presentations to teams at General Mills and Bühler Group and present the technology to Anheuser-Busch InBev SA/NV. Though it may be counterintuitive, the oil industry has been one of the sectors most receptive to TES for energy efficiency. On two occasions, Element 16 has toured Omani oilfields owned by two corporations and has worked with both companies to develop detailed project proposals. Petroleum Development Oman (PDO) owns and operates the world's largest solar thermal facility for steam flooding, at 300 megawatt-thermal. As discussed in Chapter 4, Element 16 has developed a strong business network in the oil and gas, minerals and mining, and food and beverage industries.

Part C: Element 16 as Experts-Invited Lectures, Panel Participation, and Advisory Positions

This project is Element 16's first as a start-up company. The initial results from the company's experiments were very promising, which the team successfully leveraged to win investment, recognition within the community, and further project awards. Over time, Element 16 was invited as an expert to share knowledge with the broader community surrounding energy storage and industrial energy. Listed below are some of the highlights from the invited lectures, panel participation, and advisory roles completed by the Element 16 team.

Invited Lectures:

AEE Southern California Presentations – Element 16 was invited to give two presentations to the Association of Energy Engineers SoCal Chapter. Element 16 presented on stage at the Annual Conference, reaching dozens of energy engineer experts in the company's local market. Element 16 was invited to speak at the annual conference after giving a featured speaker talk as part of their "Zero-Net Energy is Coming – Are You Ready?" event. The attendees of the events that Element 16 met included energy managers at hospitals, utility companies, and engineering project consultants.

International Desalination Association's American-Made Challenges Solar Desalination Prize Teaming Workshop – As part of Element 16's investigation into thermal desalination, which requires heat at a temperature well suited to CHP and sulfur TES, Element 16 was invited to present sulfur TES by the International Desalination Association. This was a virtual presentation with the members participating from around the world. Element 16 was ultimately awarded $50,000 by the American Made Challenges Solar Desalination Prize due to the suitability of sulfur thermal storage for thermal desalination.

National Energy Technology Laboratory Advanced Energy Storage Initiative Program Project Review Meeting – As part of Element 16's investigation into CHP-TES systems, the National Energy Technology Laboratory invited Element 16 to give a public talk on sulfur TES. Other presenters included Siemens Energy, Electric Power Research Institute (EPRI), Southwest Research Institute, and Malta.

Panels and Booths:

EPRI Electrification – Element 16 was invited to speak on an expert panel at EPRI entitled Big Breakthroughs: New Materials, Chemicals, and Industrial Processes. At the symposium, Fraunhofer and Greentown Labs spoke on the innovations their organizations are supporting.

TechConnect World Summit – Element 16 was invited to have a booth at the large TechConnect World Summit at the Gaylord National Resort & Convention Center near Washington, DC. The booth was provided to Element 16 to showcase its new technology to a wide range of leading innovators. The annual conference is co-located with the National Innovation Summit Conference and the National Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Conference, which brings together thousands of leading researchers at small businesses and university spin-out companies.

Publications and Intellectual Property Disclosures

Element 16 has developed a wholly new sulfur TES technology. To encourage the necessary investment into technology development and to support commercial adoption, Element 16 has filed intellectual property disclosures in the form of patent applications. One patent (U.S. patent number 10,876,76) has already been awarded in the United States with international coverage through Patent Cooperation Treaty and Gulf Cooperation Council submissions. Element 16 has also received notice of allowance for a second patent application in the United States. Element 16 has further intellectual property in development. Due to the sensitive nature of intellectual property disclosures, Element 16 has not yet published in peer-reviewed journals but plans to publish after the submission of this project's Final Report.

Live Demonstration of the Operational CCHP-TES Unit for Stakeholders

Due to the COVID-19 pandemic, in-person demonstrations of the technology for stakeholders has been limited. This has been disappointing for the team since the project has been extremely successful, with the CCHP-TES unit not only producing power, chilled water, and hot water on demand, but doing so while exceeding the 80 percent efficiency target set at the beginning of the project. Element 16 has demonstrated the technology for partner companies on this project, like Brad Alan Woodworks, and has undergone third-party measurement and verification (M&V) with Exponent, LLC. Element 16 has also hosted Petroleum Development

Oman at the facility before completion of the CCHP-TES pilot unit and expects to demonstrate CCHP-TES in-person once non-essential international travel is commonplace between Oman and the US. In lieu of in-person visits, Element 16 demonstrated the operational CCHP-TES via video conference calls with potential customers, investors, and partners, and recorded video of the thermal energy storage in operation. Photos and video, combined with the excellent performance data and third-party M&V report by Exponent, have proven to be highly effective for stakeholder engagement. Element 16 has also extended offers for in-person demonstrations to potential customers and investors, which are expected to occur when COVID-19 is considered a lower risk for business travelers. This is anticipated only after the project's formal end date.

CHAPTER 5: Conclusions & Lessons Learned/Recommendations

Conclusions & Lesson's Learned

Element 16 set up the pilot sulfur TES integrated CCHP system at their facility in Arcadia, California. All the experimental testing tasks planned in the test plan for M&V were completed. Exponent completed independent third-party M&V of the system configuration and performance metrics of the system. The numerical model predictions obtained for the transient variation in sulfur temperature, heat rates, heat loss and pressure drop compared well against the testing results for various modes of operation. The experimental and numerical results confirmed the strong activity of natural convection currents within molten sulfur resulting in high heat transfer rates. The performance metrics of the sulfur TES were characterized in terms of average charge and discharge rates, and thermal efficiency. The measured average charge and discharge rates of the 540 kWh pilot sulfur TES system were 12.6 kW and 27.6 kW, respectively, with a calculated thermal efficiency of 85.4 percent. As system size (tank diameter) increases, the surface area per unit volume decreases resulting in decreased heat losses per unit storage capacity and consequently, higher round trip efficiency can be realized. The experimentally measured heat rates and the successful testing of various operation modes demonstrated the potential of Element 16's low-cost sulfur TES to enable flexible and efficient operation of CCHP system.

Using this information, a technoeconomic model was developed to determine the optimal sulfur TES configuration for integrating with a CHP system in a representative large commercial building located in Los Angeles that has an average electricity and thermal energy requirement of 280 kW and 206 kW, respectively. The technoeconomic benefits were quantified in terms of natural gas savings, payback period, and lifetime value of sulfur TES. The optimal sulfur TES capacity ratio (capacity of the TES system normalized with the average heat usage of the building) of 3.0 was achieved for a minimum payback period of 8.7 years. For a maximum lifetime value, the optimal sulfur TES capacity ratio was 4.6. The annual natural gas savings and emissions reductions for capacity ranging between 3.0 to 4.6 was estimated to be \$7,320 to \$9,015 and 34 tons to 42 tons of CO_2, respectively. With this framework built using validated sulfur TES performance metrics, the Element 16 team can assess the technoeconomic benefits of sulfur TES integrated to CCHP system for buildings of various types and at different locations and formulate business proposals.

The project support from the CEC was critical in de-risking the performance of the sulfur TES technology and in advancing the product from laboratory to market. As the first pilot-scale sensible sulfur thermal energy storage unit connected with an operational CCHP plant, this project proved the feasibility and efficiency of sulfur TES. The successes of this project directly led to multiple grant-funded projects from the US Department of Energy and more CEC funding. This project led to awarded patent and patent applications and brought in initial private investment into the company to progress the sulfur TES technology. This project started sulfur TES transition from the laboratory to commercialization through Element 16, which has since secured more than $6 million in projects and investment directly related to this innovation.

Recommendations

Future efforts should focus on advancing the development of solar thermal integrated with sulfur TES for solar CCHP technologies in accordance with the CEC Renewable Energy and Advanced Generation Program research initiative on Solar Heating, Cooling, and Power for Industrial Applications. The industrial sector would benefit the most because of its large consumption of energy associated with fossil fuel use.

In California, process heating accounts for approximately 85 percent of natural gas use in industrial sectors, which contributes to roughly one-fourth of the state's greenhouse gas emissions. Adoption of proven solar thermal collector technologies or PV assisted electric heating having the potential to meet most of these demands for heat can displace the on-site burning of natural gas and reduce emissions. The sectors that are particularly well-suited for adoption of solar technologies are industries that produce metals, plastics, rubber products, and chemicals, which together account for roughly one-fifth of the energy used by industry in the state (Hasanbeigi et al. 2012). These sectors have heavy demands for heat and their working temperature requirements are feasible for solar thermal and PV-assisted electrotechnology applications.

The primary challenge is solar intermittency that reduces its capacity, decreases its reliability to supply continuous and on-demand heat, and increases levelized cost of heat. Integration of Element 16's low-cost sulfur thermal energy storage will lead to performance and cost improvements of solar CCHP and move the technology closer to techno-economic parity with natural gas equipment that improves adoption in California's industrial and commercial sectors. Sulfur TES will increase overall system resiliency providing an on-demand/flexible heat supply that meets the individual requirements of the industrial process, achieves lower levelized cost of energy; thus, increasing the share of renewable energy and reducing the CO2 footprint of industrial processes, and enable industries to become independent from increasing fuel and CO2 prices.

CHAPTER 6: Benefits to Ratepayers

By storing thermal energy at high temperatures, sulfur TES allows smaller systems to produce effective amounts of cooling at times of peak value. The improved economics of small-scale CCHP will translate to increased distributed generation, and increased cogeneration systems that provide cooling, in addition to the standard heat and power systems, which leads to many benefits to natural gas ratepayers.

- *Environmental benefits:* By increasing the overall efficiency of natural gas and alternative fuel usage, sulfur TES is expected to decrease greenhouse gas emissions. This technology is extensible to a variety of distributed cogeneration systems from residential to industrial use and independent of the prime mover. This approach directly addresses energy goals and emissions reduction goals described in the following laws and policies: Assembly Bill (AB) 32 - Global Warming Solutions Act of 2006, Senate Bill (SB) 32 - California Global Warming Solutions Act of 2006, Senate Bill (SB) 226 – Environmental Quality of 2011, and CPUC's Energy Efficiency Strategic Plan (2008).

  The U.S. Department of Energy's CHP Technical Potential Database estimated CHP technical potential of 4.4 GW (gigawatts) in California in the 50 kW to 1 MW (megawatts) size range (DOE 2016). Most potential sites in this size range come from the commercial and institutional sectors. With 25 percent market penetration, the packaged system could reduce CO2 emissions generated from commercial/institutional buildings in California by 330,000 metric tons per year. This is comparable to removing 72,000 cars off roads for a year (the U.S. Environmental Protection Agency uses 4.6 metric tons as the annual average CO2 emissions of a typical passenger vehicle).

- *Improved economics* – TES allows for exhaust from smaller prime movers to drive outsized absorption chillers at times of peak need. By including cooling as an option, ratepayers in California can use exhaust heat to cool facilities, which has a higher value than heating, especially in summer months when electricity is most expensive. Additionally, due to the nature of high temperature storage, the heat can be used for both heating and cooling, adding flexibility in use when compared with conventional chilled water or ice storage.

  The technoeconomic results conducted in this study showed that the integration of sulfur TES can result in an annual savings of $65,000/MWe (megawatt-electric) of installed CHP prime mover capacity. Assuming a 25 percent market penetration in California can result in annual fuel savings of $71 million.

- *Greater reliability:* the sulfur TES system's improved economics and flexibility will increase small, distributed generation. By increasing the cooling generated by natural gas and adding electricity generation at times of peak demand, the packaged system helps to both reduce load and increase generation when the grid is under its greatest stress. In Southern California, heat waves can often lead to rolling blackouts, which can be harmful to ratepayer safety and economic output.

- *Economic development:* The construction of the demonstration was completed in the Los Angeles Basin and all project funds were spent in California. The demonstration also funded salaries for Element 16 Technologies and its contractors, all of which are based in California.
- *Public health:* By improving natural gas efficiency, fewer natural gas reservoirs will be required. Also, by improving natural gas efficiency, more harmful coal-fired generation can be reduced throughout the country.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
$/kWh	dollars per kilowatt-hour
AEE	Association of Energy Engineers
ASME	American Society of Mechanical Engineers
BIRD	Binational Industrial Research and Development
CCHP	combined cooling heat and power
CEC	California Energy Commission
CEO	Chief Executive Officer
CHP	combined heat and power
EPRI	Electric Power Research Institute
ESNA	Energy Storage North America
GW	gigawatt
HTF	heat transfer fluid
kWh/m^3	kilowatt-hours per cubic meter
M&V	measurement and verification
MMBtu	million British thermal units
MW	megawatt
MWe	megawatt-electric
NSF	U.S. National Science Foundation
PDO	Petroleum Development Oman
SBIR	Small Business Innovation Research
STTR	Small Business Technology Transfer
TES	thermal energy storage
UCLA	University of California, Los Angeles
USC	University of Southern California

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ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Experimental Procedure

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APPENDIX A: Experimental Procedure

Experiments are conducted for multiple independent charge and discharge cycles and simultaneous charge-discharge cycles to characterize the system performance for various operation modes and verify the performance metrics. The key performance metrics calculated are the charge rate, discharge rate, energy charged, energy discharged, and round-trip efficiency. The charge rate is calculated using the mass flow rate, inlet temperature and exit temperature of the exhaust gas from the TES:

$$\dot{Q}_{charge} = \dot{m}_{gas} c_{gas} (T_{in,gas} - T_{out,gas}) \quad [1]$$

In Equation 1, the mass flow rate of the exhaust gas is calculated from:

$$\dot{m}_{gas} = \pi \frac{D_i^2}{4} \sqrt{2\rho_{gas}\Delta P} \quad [2]$$

Since the composition of the exhaust gas from capstone microturbine is similar to that of air, the density of gas is calculated from ideal gas law: $P_{gas} = P_{atm} / R_{gas} T_{pitot}$, where P_{atm} is the atmospheric pressure (the pitot tube is located near the tail end of the exhaust pipe open to atmosphere, R_{gas} = 287 J/kg-K is the gas constant and T_{pitot} is the temperature of the gas close to the location of the pitot tube. D_i in Equation 2 is the inner diameter of the exhaust pipe and ΔP is the dynamic pressure (pressure difference between the total pressure and static pressure) measured by the pitot tube. $T_{in,gas}$ and $T_{out,gas}$ is temperature of exhaust gas measured at the inlet and outlet of TES. c_{gas} is the specific heat of exhaust gas. The total energy charged during a thermal cycle (Q_{charge}) is calculated by integrating Equation 1 over the entire thermal cycle duration.

The discharge rate is calculated using the mass flow rate, inlet temperature and exit temperature of the water from the oil to water heat exchanger as follows:

$$\dot{Q}_{discharge} = \dot{m}_{water} c_{water} (T_{out,water} - T_{in,water}) \quad [3]$$

$T_{in,water}$ and $T_{out,water}$ is temperature of water measured at the inlet and outlet of oil to water heat exchanger. The volumetric flow rate of water measured using turbine flow sensor is divided by the density of water to convert to mass flow rate (m_{water}). C_{water} is the specific heat of water. The energy discharged during a thermal cycle ($Q_{discharge}$) is calculated by integrating Equation 3 over the entire thermal cycle duration.

The round-trip efficiency of the system is calculated from:

$$\eta_{RTE} = \frac{Q_{discharge}}{Q_{charge} + Q_{parasitics}} \quad [4]$$

The parasitic heat load is the energy input from the nine electric heating elements that are installed on the outer surface of the sulfur TES. They are programmed with proportional-integral-derivative controls to maintain the sulfur temperature at 266ºF (130ºC). The total parasitic load from all the electric heaters at any given time is calculated from: $Q_{parasitic}$ where

Q_{rated} is the rated power output from each of the nine electric heaters and ω is the measured duty cycle of the electric heaters. The parasitic load is a good measure of the heat loss from the system when it is at 266ºF (130ºC) (before the start of thermal cycle). Since the electric heaters are programmed to maintain the sulfur temperature at 266ºF (130ºC), during a typical cyclic operation the electric heater duty is significant only when the internal temperature of sulfur is in the vicinity of 266ºF (130ºC).

Numerical Model

The performance of sulfur thermal storage system was modeled based on energy transfer between each component, including sulfur, tube wall, and heat transfer fluid (HTF). Each component is modeled as cross-sectionally lumped, but the variation of temperature with axial location (from inlet to outlet) is accounted for. Each component is discretized, and energy conservation is applied to each grid and solved to predict its transient temperature field during thermal cycling. The coupled set of governing equations solved using an iterative finite volume framework are:

HTF: $$(\rho c)_{htf}\frac{\partial T_{htf}}{\partial t} + (\rho c)_{htf} v_{htf}\frac{\partial T_{htf}}{\partial x} = k_{htf}\frac{\partial^2 T_{htf}}{\partial x^2} - \frac{(T_{htf} - T_{wall})}{V_{tube,\Delta x}\{\mathcal{R}_{i,wall} + \mathcal{R}_{htf}\}} \quad [5a]$$

Tube Wall: $$(\rho c)_{wall}\frac{\partial T_{wall}}{\partial t} = k_{wall}\frac{\partial^2 T_{wall}}{\partial x^2} + \frac{1}{V_{wall,\Delta x}}\left\{\frac{(T_{htf} - T_{wall})}{\{\mathcal{R}_{i,wall} + \mathcal{R}_{htf}\}} - \frac{(T_{wall} - T_{su})}{\{\mathcal{R}_{o,wall} + \mathcal{R}_{su}\}}\right\} \quad [5b]$$

Sulfur: $$(\rho c)_{su}\frac{\partial T_{su}}{\partial t} = \frac{1}{V_{su,\Delta x}}\left\{\frac{(T_{wall} - T_{su})}{\{\mathcal{R}_{o,wall} + \mathcal{R}_{su}\}} - \frac{(T_{su} - T_{amb})}{\{\mathcal{R}_{tank} + \mathcal{R}_{ins} + \mathcal{R}_{eff,amb}\}}\right\} \quad [5c]$$

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 from the experimental runs 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 (R_{htf}), was based on the Gnilenski correlation for single phase heat transfer fluid and Shah correlation for boiling heat transfer fluid obtained from literature. The heat transfer coefficient on the sulfur side (h_{sulfur}), which appears in the sulfur natural convection thermal resistance term (R_{htf}) for sulfur bath configuration has not been studied before. So, Element 16 team developed a computational finite volume model of the system configuration to characterize the sulfur heat transfer behavior for the temperature range of interest and derive sulfur heat transfer coefficient from systematic parametric studies. The finite volume model is based on the conservation of mass, momentum, and energy (Navier-Stokes) equations solved in Ansys Fluent.

Advisory and Expert Roles:

Technical Advisory Committee for the Institute of the Environment & Sustainability, UCLA – Element 16's CEO, Parker Wells, served on the Technical Advisory Committee for UCLA's Institute of the Environment & Sustainability which led a California Energy Commission project, "Community Scale Solar Water Heating." In this role, Parker provided insight into district heating opportunities and technical challenges.

Guest Editor MDPI Energies Journal – Dr. Karthik Nithyanandam served as guest editor of the peer-reviewed journal MDPI. Karthik was selected for the thermal storage topic of MDPI Energies, in part because of his position at Element 16, his experience at Axiom Exergy, as a postdoctoral scholar at UCLA and Virginia Tech, and his more than 40 publications.

Advisor at UCLA Modeling of Complex Thermal Systems Laboratory – Dr. Hamarz Aryafar, Element 16's Chief Technology Officer, served as an advisor for the UCLA Modeling of Complex Thermal Systems Laboratory. Hamarz supported the research of an ammonia-hydrogen thermochemical energy storage project funded by the US Department of Energy Sunshot program.

Part A: Network Developed Through Business-Related Programs

As a university spin-out company led by an engineering graduate student and a postdoctoral scholar, Element 16 did not immediately have a large investor or corporate network. To accelerate the growth of the start-up's network, Element 16 quickly developed its understanding of the market opportunity, leaned into the company's technological expertise, highlighted the technological progress that the young company made in public forums, and then used these advantages to gain access to the most exclusive start-up programs. Top start-up programs (such as accelerators and incubators) have extensive networks due to the success of previous program graduates. Element 16 took part in the following six programs, only one of which required equity for their investment and support. So, Element 16 became part of an extensive network, with strong start-up credentials, and its first private investment, all while maintaining autonomy to bring the technology to market quickly:

Techstars – Techstars is one of the world's most prestigious and selective start-up programs. The program is ranked second by Inc. Magazine (The 15 Best Startup Accelerators in the U.S.) and Eqvista (Top 100 Startup Accelerators List in 2021), and third by Forbes (10 Startup Accelerators Based on Successful Exits) and Entrepreneur (America's Top 7 Startup Accelerators and What Makes Each Unique). Graduates of the accelerator include 14 "unicorns" including: Remitly, SendGrid, and ClassPass. The accelerator is unusual among the top start-up programs since it operates in dozens of cities around the world, not only tech hubs like San Francisco or New York City. Element 16 joined the program in Dubai, which allowed the company to make connections with foreign investors and international industrial companies that use CHP. Through Techstars, Element 16 receive investment from Ginco International, which has subsidiaries in aluminum, metal industries, general contracting, and chemicals. Element 16 took part in 2019.

National Science Foundation i-Corps – The US National Science Foundation's (NSF) Innovation Corps program is a federally funded program that helps researchers gain skills in entrepreneurship, starting a business, and overcoming industry challenges. This is a rigorous program that supports researchers in transitioning academic breakthroughs into market-ready products. NSF requires the start-up leaders to take part in a program outside their home city, and Element 16 took part in the 2018 program in Indianapolis, Indiana.

Creative Destruction Lab Energy Stream – Creative Destruction Lab is a highly competitive start-up program that operates in 16 verticals, or "streams." The Energy Stream, based in the Canadian energy ecosystem's center, Calgary, selects a small number of promising start-ups to present to a selective panel of venture capitalist, angel investors, and executives every eight weeks, where their business is critically reviewed. The companies must be selected by one of the panel members to continue in the program after each meeting, which means only a small number of companies are able to graduate. Element 16 was selected by the panel after each meeting and is a successful graduate of the program. One panel member offered to invest into Element 16. Element 16 took part in the program between 2019 and 2020.

MassChallenge Food Sustainability – MassChallenge is a highly selective start-up accelerator, which was ranked as high as fourth by Entrepreneur in their Top 7 Accelerators list. MassChallenge is based in Massachusetts but operates programs in multiple countries based on the location's strength. Due to the ability of CHP-TES to support food processing and beverage manufacturing industries, and Element 16's reputation, the company was offered the chance to apply to the Food Sustainability program in Switzerland for free. After gaining acceptance into the accelerator, Element 16 presented its innovation to the world's largest and most innovative food companies like Nestlé, General Mills, Südzucker, Bühler, Givaudan, and Ricola. Element 16 took part in this program in 2021.

Sparklabs Energy – SparkLabs Energy is unlike the other programs in this list because it is largely a pilot seeking program. SparkLabs Energy is a collaboration between SparkLabs Global Ventures, Phaze Ventures, and PDO. The program brought Element 16 to Muscat, Oman, and held dozens of meetings with senior executives in PDO, including a presentation to the company's CEO. PDO has built the world's largest solar thermal field for steam flooding (a type of process heat), replacing heat that normally is generated from CHP and natural gas boilers. Element 16 was flown to the company's Amal Oilfield for an in-person tour of this renewable energy facility and CHP units. Element 16 continues frequent communication with PDO as the company's work together to develop a suitable sulfur thermal energy storage pilot project. Element 16 took part in this program from 2019 to 2020.

USC Viterbi Summer Smasher – The University of Southern California (USC) Viterbi Summer Smasher was the first start-up acceleration program that Element 16 participated in. Viterbi, the engineering college at USC, operated the program for current researchers and recent graduates in Los Angeles. The program curriculum was designed and taught by Aaron Fyke, an energy entrepreneur, investor, and engineer. He is currently the founder and managing partner of Thin Line Capital, a Venture Capital fund focused on climate opportunities. When Mr. Fyke led the program, he had already founded Energy Cache, an energy storage technology company, and led Heliogen, a solar thermal company. Element 16 took part in the program in 2017.

These six programs are selective programs with large networks, especially in the renewable energy, cleantech, and deep tech ecosystems. Element 16's successful acceptance into, and graduation from these programs lent credibility to the company and afforded the company rapid learning in commercializing a breakthrough technological innovation. Element 16 now has a network of energy venture capital and angel investors, and top executives at major corporations because of the start-up's success in these programs. These programs have given the company and the innovation exposure and means that Element 16 can often schedule meetings with highly selective individuals and corporations across market segments, and is invited to join selective programs and events, building continuous momentum toward sulfur TES commercialization.