CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Low-Temperature, Efficient Heat Capture to Reduce Natural Gas Consumption in the Industrial Sector

January 2025 | CEC-500-2025-005

PREPARED BY:

Hamarz Aryafar
Karthik Nithyanandam
Parker Wells
Element 16 Technologies, Inc.
Primary Authors

Anish Gautam
Project Manager
California Energy Commission

Agreement Number: PIR-17-004

Cody Taylor
Branch Manager
INDUSTRY AND CARBON MANAGEMENT BRANCH

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors express their gratitude to the California Energy Commission for its support of the project. The authors thank the project manager, Anish Gautam, who was involved in this project. Element 16 Technologies additionally appreciates the time commitment of its technical advisory committee — Dr. Adrienne Lavine, Dr. Reza Lakeh, Alex Ricklefs and Don Musser — which reviewed project outcomes and provided feedback. The authors acknowledge the support of Searles Valley Minerals and the personnel involved for their invaluable commitment and contributions to the project. The SVM team demonstrated exceptional dedication and openness to innovation, which played a crucial role in the project's success. SVM's commitment to achieving zero net energy is a commendable benchmark for embracing change and sustainability within the industry.

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

Low-Temperature, Efficient Heat Capture to Reduce Natural Gas Consumption in the Industrial Sector is the final report for Contract Number PIR-17-004 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

California's industrial sector is the largest consumer of natural gas, accounting for 33 percent of total annual natural gas consumption. Increasing energy efficiency through the recovery and reuse of waste heat to reduce both energy consumed and associated greenhouse gas emissions could significantly enhance the global market competitiveness of the industrial sector.

In this project, Element 16 Technologies, Inc. successfully developed and demonstrated a low-temperature waste heat recovery system at the Searles Valley Minerals industrial facility in Trona, California. The waste heat recovery system developed by Element 16 Technologies effectively captured and repurposed vented low-pressure steam to dry V-BOR (a form of borax pentahydrate), thereby reducing the rotary dryer's natural gas consumption. Additionally, the project addressed Searles Valley Minerals' critical water-resource challenges by incorporating a water storage tank, which conserved water by recycling the cold condensate back into the facility. Implementation of this waste heat recovery system led to a measured reduction of approximately 15 percent in specific natural gas consumption for drying V-BOR. This reduction translates to energy savings of 36,700 British thermal units per ton of V-BOR product, amounting to annual savings of 5,333 metric million British thermal units.

This project's success paved the way for a follow-up grant project funded by the California Energy Commission to test and demonstrate Element 16's flagship sulfur-thermal energy storage product at its facility. This report discusses both the successful pilot demonstration of the waste heat recovery system at Searles Valley Minerals and the technology-to-market activities of the sulfur thermal energy storage technology that have provided more than $8 million in research, development, and commercialization funding since the award of this project.

Keywords: waste heat recovery (WHR), heat capture system (HCS), thermal energy storage (TES), Searles Valley Minerals (SVM), steam capture

Please use the following citation for this report:

Aryafar, Hamarz, Karthik Nithyanandam, and Parker Wells. 2024. *Low-Temperature, Efficient Heat Capture to Reduce Natural Gas Consumption in the Industrial Sector*. California Energy Commission. Publication Number: CEC-500-2025-005.

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Background

California's industrial sector is the second-highest pollution-emitting sector in the state's economy and produces approximately 23 percent of the state's greenhouse gas emissions (Kizer et al., 2019). Emission reductions in the industrial sector can contribute significantly to meeting the 2030 and 2045 mandates in Senate Bill 32 (Pavley, Chapter 249, Statutes of 2016) and Executive Order S-3-05 (issued by the Governor of California on June 1, 2005), respectively. The majority of industrial sector emissions stem from natural gas combustion for process heat. A significant percentage of this heat is lost as waste, with over 50 percent of industrial waste heat falling in the low-temperature range of 100 to 450 degrees Fahrenheit (°F) (38 to 232 degrees Celsius [°C]) (Thekdi et al., 2021). The reduction and reuse of industrial waste heat is one of the most promising means to increase energy efficiency, reduce fossil fuel usage and GHG emissions, and boost profitability.

In this project, Element 16 Technologies, Inc. (Element 16 or E16) successfully developed and demonstrated a low-temperature waste heat recovery system at the Searles Valley Mineral (SVM) industrial facility in Trona, California. The facility uses substantial amounts of fossil fuel for process heating, with a significant portion of energy lost as low-pressure steam. The heat recovery system developed by Element 16 effectively captures and repurposes the waste heat for drying V-BOR (a form of borax pentahydrate), reducing the existing rotary dryer's fossil fuel consumption.

Overall, this project demonstrates a scalable and working waste heat recovery system for energy and water savings in the industrial sector. By addressing the critical need for a cost-effective low-temperature waste heat recovery technology, this project also contributes to the realization of California's Senate Bill 350 (De León, Chapter 547, Statutes of 2015) policy aimed at enhancing energy efficiency and accelerating industrial decarbonization.

Project Purpose and Approach

The primary goal of the project was to develop an economically viable low-temperature waste heat recovery system and demonstrate its capability to reduce natural gas and GHG emissions by at least 10 percent in a real-world operating environment. Element 16 successfully installed and demonstrated a low-temperature waste heat capture system at the SVM industrial facility. The facility uses substantial amounts of fossil fuel for process heating, with a significant portion of energy lost as low-pressure steam. The developed waste heat capture system comprises compact heat exchangers that extract heat from this vented intermittent waste heat for drying V-BOR, a form of borax pentahydrate. This reduces the natural gas consumption of the existing rotary dryer. The installed system includes a water storage tank that stores the cold condensate, which is recycled periodically back into the facility, thus resulting in water savings equivalent to the amount of waste steam recovered.

Element 16 engineers, in collaboration with the SVM engineering team, developed, installed, and tested the system at SVM's facility in Trona, California. The system performance was quantified in terms of natural gas savings and reduction of GHG emissions.

This project provided valuable insights for decision-making regarding the installation of waste heat recovery systems that enhance operational sustainability. Project outcomes will therefore be of significant interest to stakeholders across various industries. Additionally, manufacturers of Organic Rankine Cycle systems and industrial heat pumps can use these results to assess the performance and economic benefits of integrating this technology with waste heat recovery systems. Research organizations and government agencies could use the results to identify and address the research needed to overcome market barriers to adoption of waste heat recovery systems in industries.

Key Results

The team conducted comprehensive testing to verify the natural gas savings from implementation of the waste heat recovery system at the industrial facility. The data collected to analyze the system's performance clearly demonstrated a reduction in specific natural gas use when compared with the baseline. The specific natural gas consumption, defined as the average natural gas consumed to raise the temperature of one ton of product by 1°F (0.6°C) , with the waste heat recovery system integration was 14.8 percent lower than the baseline. A 14.8-percent reduction in specific natural gas consumption contributes to energy savings of 36,700 British thermal units per ton of product and total yearly energy savings of 5,333 metric million British thermal units. During the testing period, the average water savings from the implementation of the waste heat recovery system was measured at 0.24 (±0.2) gallons per minute. Based on the measurement of low-pressure steam vented to the atmosphere during the same test period, it was estimated that 45 percent of the steam that would have vented to the atmosphere was instead recovered.

Knowledge Transfer and Next Steps

The technologies developed by Element 16 for industrial process heat efficiency and decarbonization are novel, meaning that educating the engineering, business, and policymaking communities is necessary for its widespread adoption. Element 16 has a dedicated website (https://element16.com) and actively maintains a LinkedIn page, where it regularly shares updates on the company's progress for various projects. The Element 16 team effectively communicated learnings and project outcomes to the public and key decision-makers through various channels: speaking engagements at events, participation in expos, summits, conferences, media releases, technical reports, test reports, and journal articles. Some notable public events include the VERGE sustainability conference in 2019, the 2019 Annual Conference hosted by the Association of Energy Engineers Southern California Chapter, the Association for the Advancement of Artificial Intelligence in 2022, the RE+ Event's United States Department of Energy Solar Energy Technologies Office Awardee Showcase in 2022 and 2023, the San Francisco Bootcamp Startup Showcase, the High-Performance Computing for Energy Innovation workshop at Livermore in 2023, and the 2023 American Nuclear Society Annual Meeting.

Although this project focused on a low-temperature waste heat recovery system, Element 16's flagship product is sulfur thermal energy storage that can be integrated with renewable energy generation for industrial process heat. This project's success laid the groundwork for the Element 16 team to establish a robust collaborative relationship with the engineering and management teams at SVM. Element 16 continues to partner with SVM in its pursuit of zero net energy and industrial decarbonization, focusing on the use of solar energy for around-the-clock 284°F to 428°F (140°C to 220°C) process heat requirements and efficiency enhancements. This partnership was further strengthened by a recent project funded by the California Energy Commission, which involved testing and demonstrating Element 16's sulfur thermal energy storage product at its facility. Element 16 also won a purchase order for paid detailed engineering of a heat capture and storage system, has multiple strong leads for paid projects by private companies, and has multiple potential financiers for future projects and technology development.

Future research efforts should focus on addressing the challenges of scaling up thermal energy storage systems for large industrial facilities and of investigating high-temperature heat pump systems, which could use and upgrade low-temperature waste heat, integrated with renewable energy and thermal energy storage for clean, dispatchable industrial process heat. This approach aligns with the broader goals of improving energy efficiency and accelerating industrial decarbonization.

CHAPTER 1: Introduction

The U.S. industrial sector accounts for 30 percent (1,360 million metric tons) of energy-related carbon dioxide (CO_2) emissions (Cresko et al., 2022), and California's industrial sector, as the third-highest emitter in the country (U.S. EIA, 2024b), accounts for approximately 23 percent of the state's greenhouse gas (GHG) emissions (Kizer et al., 2019). Manufacturers play a crucial role in the California economy, contributing over 12 percent of the total gross state product ($395 billion) and exporting $149 billion of goods (National Association of Manufacturers, 2024). In California, the industrial sector is also affected by the cap-and-trade program, which mandates emission reductions or purchase allowances for facilities annually emitting more than 25,000 metric tons of CO_2. Such regulations highlight the urgent need for innovative solutions to mitigate environmental impacts while maintaining industrial productivity and competitiveness.

Energy-efficiency improvements are one of the most critical and cost-effective decarbonization strategies for GHG emission reductions in the near term. The majority of industrial sector emissions stems from natural gas combustion for process heat requirements. In California, the industrial sector is the largest consumer of natural gas, accounting for 33 percent of total annual natural gas consumption (Kizer et al., 2019). A significant percentage of this heat is lost as waste, with over 50 percent of industrial waste heat falling in the low-temperature range of 100 to 450 degrees Fahrenheit (°F) (38 to 232 degrees Celsius [°C]) (Thekdi et al., 2021). Improving energy efficiency through recovery and reuse of waste heat to reduce the energy consumed and associated GHG emissions could significantly enhance the global market competitiveness of these sectors.

However, there is a range of institutional and personnel challenges in pursuing energy efficiency in the industrial sector. Major challenges include lack of awareness of energy-efficiency opportunities, challenges accessing technical assistance and qualified personnel, risk aversion to new technology adoption and process disruption, and limited organizational resources (time, capital) to devote to energy-efficiency assessments and projects (Kizer et al., 2019). To overcome these challenges, the project successfully demonstrated a new technology and its positive impacts on enhancing energy efficiency within the state's industrial sector.

The goals of the project were to:

(a) Demonstrate the economic viability and technical effectiveness of a low-temperature waste heat capture system (HCS) in a real-world industrial setting, achieving a technology readiness level of 8 and showcasing the system's ability to operate efficiently and reliably under actual industrial conditions.

(b) Demonstrate at least a 10-percent reduction in natural gas consumption and GHG emissions attributable to implementation of the HCS.

By implementing a scalable and workable low-temperature waste heat recovery (WHR) system, the project overcame the technical hurdle of efficiently utilizing low-grade waste heat, which has traditionally been overlooked due to its technological and economic constraints. This initiative directly supports California's Senate Bill 350 (De León, Chapter 547, Statutes of 2015) clean-energy mandates by increasing energy efficiency, reducing reliance on fossil fuels, and decreasing GHG emissions, together enhancing the sustainability and competitiveness of the industrial sector.

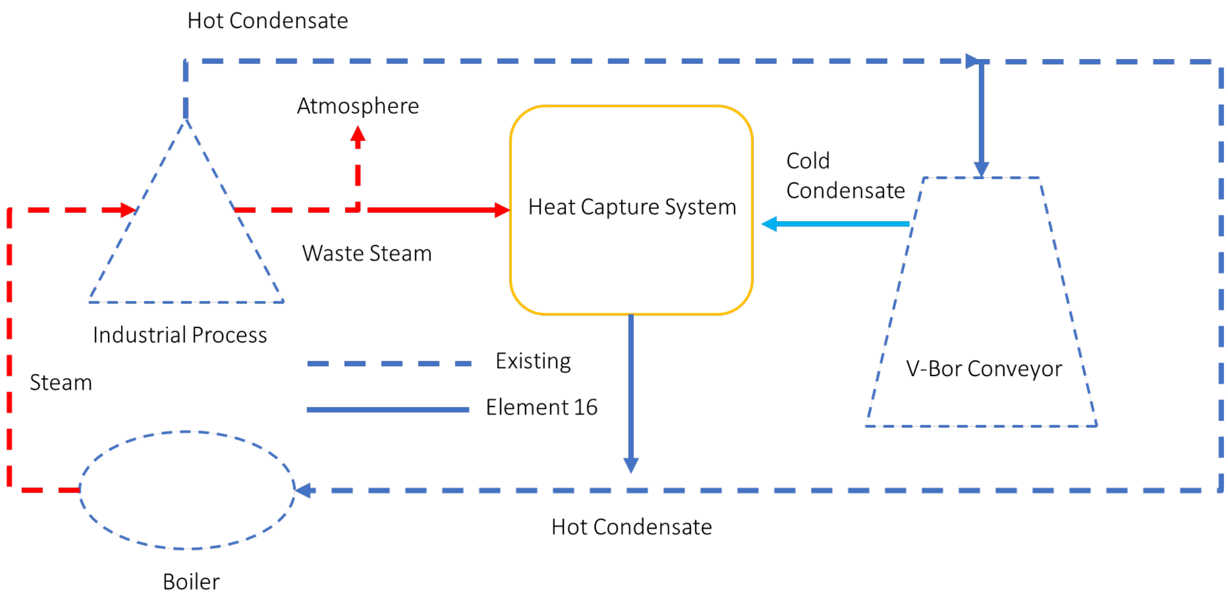
Element 16 engineers, in collaboration with the Searles Valley Minerals (SVM) engineering team, developed, installed, and tested a low-temperature HCS at SVM's facility in Trona, California. The heat recovery system effectively captures and repurposes waste heat for drying V-BOR (a form of borax pentahydrate), reducing fossil fuel consumption. The system performance was quantified in terms of natural gas savings and emission reductions. The widespread adoption of this technology promises substantial benefits for industries that implement it, as well as for California ratepayers. By reducing natural gas demand across industries, the project not only helps lower energy costs but also contributes to reducing GHG emissions and improving public health. The system's ability to store and dispatch energy from low-temperature waste heat enables industries within California to sustain their production volumes with lower natural gas consumption, directly supporting the state's clean-energy and climate laws.

The project provided valuable insights into decision-making for installation of WHR systems that enhance operational sustainability. Project outcomes would therefore be of significant interest for stakeholders across various industries. Additionally, manufacturers of Organic Rankine Cycle systems and industrial heat pumps can utilize these results to assess the performance and economic benefits of integrating their respective technologies with WHR systems. Research organizations and government agencies could use the results to identify and address the research needed to overcome market barriers to the adoption of waste heat recovery systems in the state’s industries.

CHAPTER 2: Project Approach

For this project, Element 16 successfully installed and demonstrated a low-temperature HCS at the SVM industrial facility. Figure 1 shows the schematic of the concept, which involves integration of the HCS into SVM's operation. The original process is shown as dashed lines and the integration scheme is shown as solid lines. The HCS captures heat from the low-pressure (LP) steam vent and repurposes it for drying V-BOR, reducing the natural gas consumption of the existing rotary dryer.

Figure 1: Schematic of the Proposed HCS Concept for Integration at SVM's Facility



Source: Element 16 Technologies

The technical advisory committee (TAC) was composed of experts from various technical backgrounds, including heat transfer and systems engineering. The TAC reviewed the research and development progress during TAC and critical project review meetings and provided feedback on system design and testing activities. The experts who served on the TAC included:

- Adrienne Lavine — Professor of Mechanical and Aerospace Engineering, University of California Los Angeles.
- Reza Lakeh — Assistant Professor of Mechanical Engineering, Cal Poly Pomona.
- Don Musser — Energy Manager, Searles Valley Minerals.
- Alex Ricklefs — Program Manager, The Energy Coalition.

A description of the overall project approach organization follows.

Facility Baseline Characterization

Comprehensive energy and mass analysis of the industrial operation at the demonstration facility (using existing and newly installed sensors) established the process baseline metrics. Results indicated that the annual natural gas consumption for drying V-BOR minerals was approximately 200 cubic feet per ton and that around 42 million pounds of LP steam was vented to the atmosphere annually. The calculation of the theoretical heat capture rate potential, based on data from the LP steam vent, confirmed sufficient waste heat availability to feasibly reduce natural gas usage by at least 10 percent.

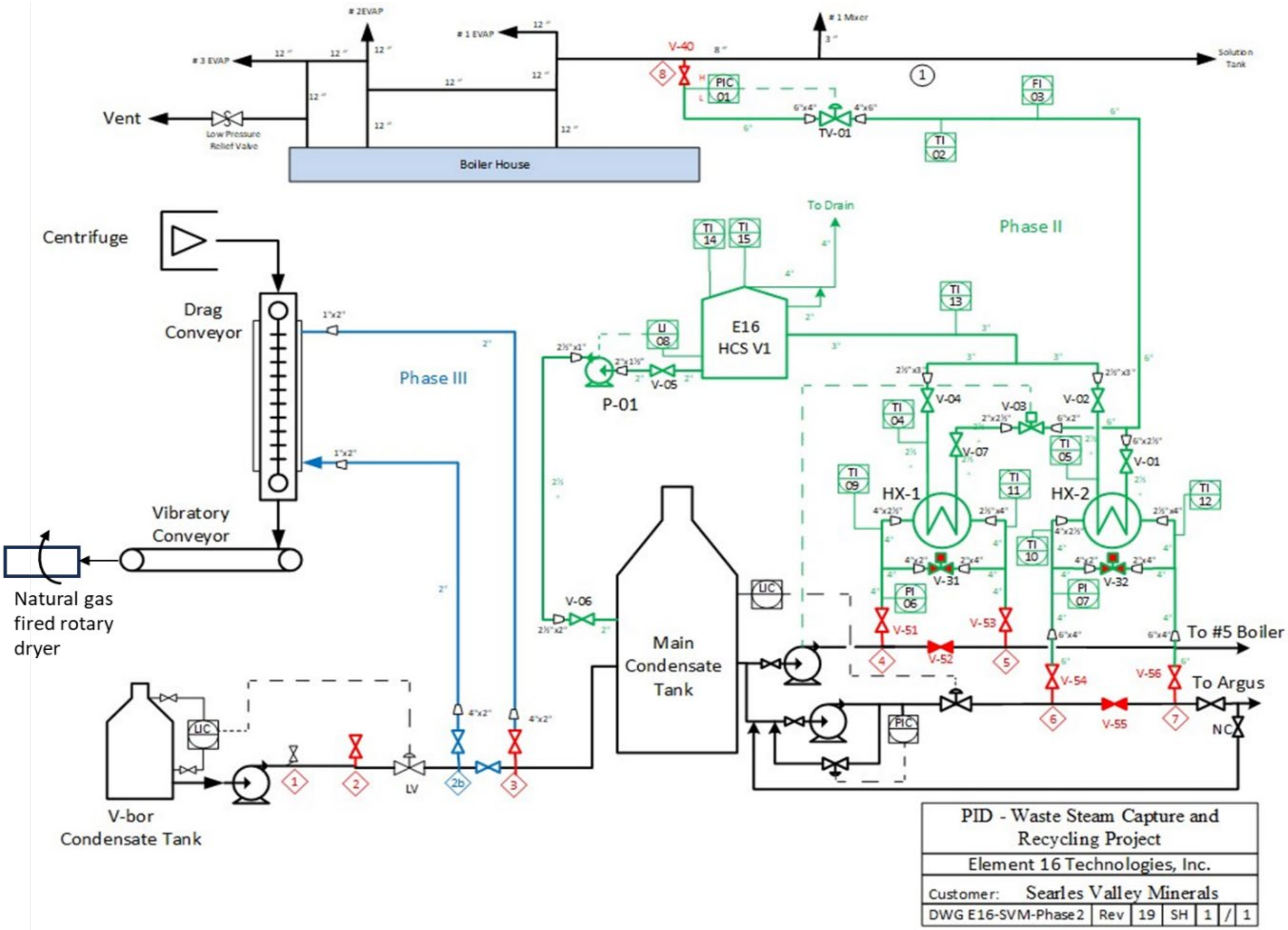
System Design and Cost Modeling

Element 16 conducted annual simulations considering the time-varying LP steam data provided by SVM and the transient thermal performance of the HCS to determine the optimal HCS configuration (based on yearly energy and water savings and capital and operational expenses). From these annual simulations, the total LP steam condensed in a year and the natural gas saved through transfer of thermal energy from hot V-BOR condensate to the V-BOR particles in the dryer were calculated for different design parameters and HCS configurations. The results showed that the HCS configuration with a 3,000-gallon condensate storage tank and plate-and-frame LP steam condensing heat exchanger (with a surface area of 15 square meters [m^2]) provided the highest net present value.

Establish HCS Configuration

Figure 2 shows the piping and instrumentation diagram of the HCS implementation at the SVM facility. The original process is shown as a black line and Element 16's integration scheme is shown as green (Phase II) and blue (Phase III) lines, and red (tie-in points) markings on the piping and instrumentation diagram. As shown in Figure 2, the major equipment of the HCS installed at the SVM facility included the E16 HCS V1 storage tank, the P-01 condensate pump, plate and frame heat exchangers HX-1 and HX-2, and the clamp-on plate-coil heat exchanger underneath the drag conveyor. LP waste steam was condensed in two plate-type heat exchangers connected in parallel (HX-1 and HX-2), using the condensate stream from the main condensate tank. Condensed steam was collected in the tank (HCS V1), where it was cooled by natural convection. The stored cold condensate was circulated through pump P-01 to the main condensate tank and subsequently to the heat exchangers HX-1 and HX-2 to increase the thermal capacity and maximize the amount of steam condensed.

Figure 2: Piping and Instrumentation Diagram Showing Implementation of the HCS Into SVM's Facility



Source: Element 16 Technologies

SVM's existing V-BOR processing facility operates two conveyors that transfer products from centrifuges to a rotating natural gas dryer. Since the V-BOR conveyor is not in close proximity to the LP steam vent line, the most feasible option was to use the high-temperature condensate to preheat and reduce the moisture content of the V-BOR particles before they enter the dryer. The desired moisture and/or temperature of the product exiting the dryer is controlled through control of exhaust air temperature. This control is achieved by regulating the flow of natural gas to the burner by means of a temperature controller with a thermocouple located in the exhaust air duct. Preheating and/or reducing the moisture content of the V-BOR particles entering the dryer using the high-temperature condensate will result in an increase in the exhaust air temperature and the control system will act to reduce the flow of natural gas to the burners to maintain the exhaust air temperature at its setpoint. The drag conveyor (shown in Figure 3) was identified as the best location for the high-temperature condensate from the V-BOR tank to be introduced, using a clamp-on plate coil-heat exchanger to reduce demand on the natural gas-based rotary dryer. This is depicted by blue lines on the piping and instrumentation diagram in Figure 2, labeled Phase III.

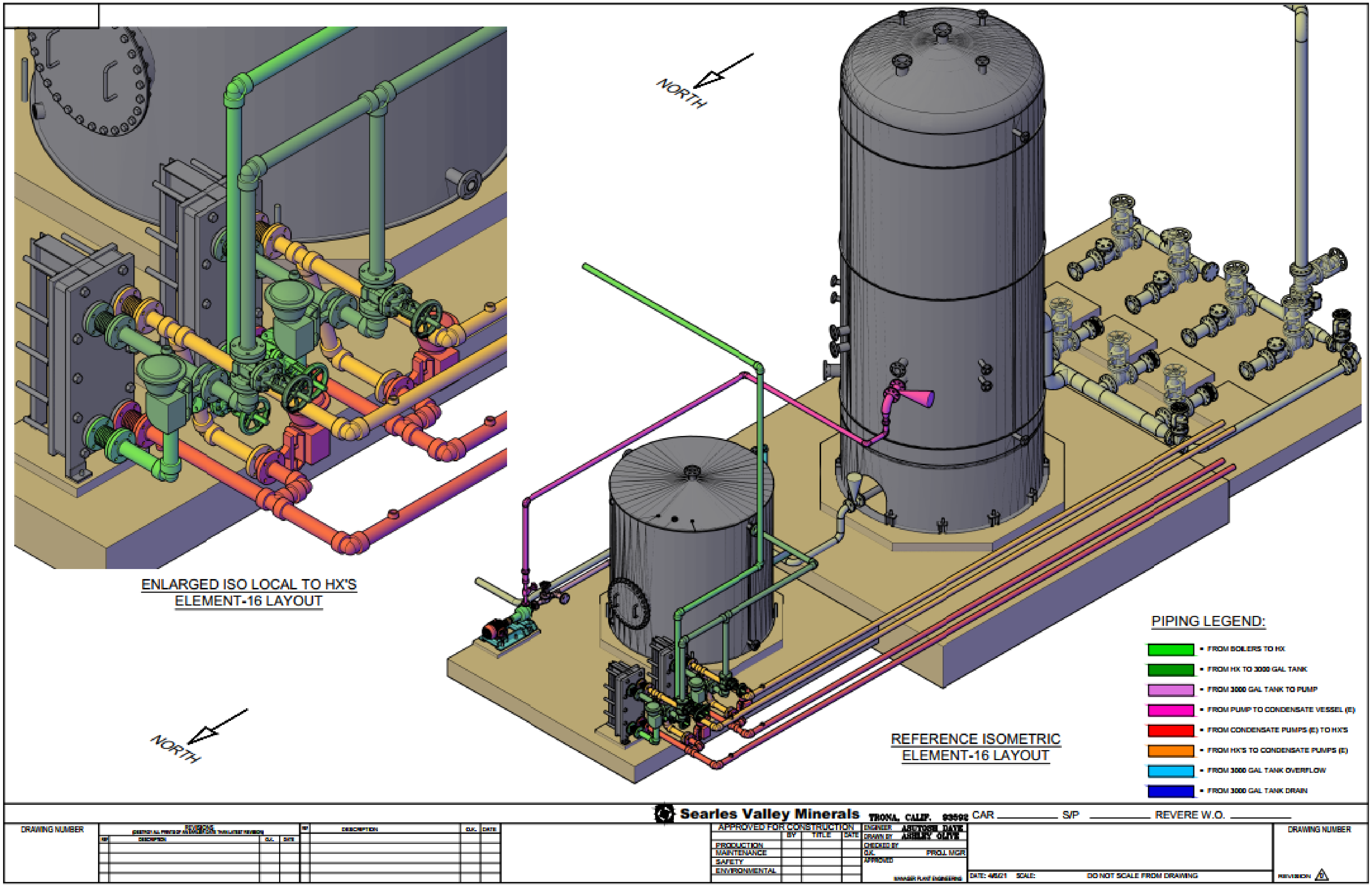
Figure 3: V-BOR Conveyor and Natural Gas Dryer at SVM Facility

Source: Element 16 Technologies

The HCS module located near the LP steam line — the E16 HCS V1, HX-1, HX-2 and P-01 (referred to as Phase II in Figure 2) — was designed to capture waste heat from LP steam that would otherwise be vented and to utilize that waste heat to pre-heat the boiler feedwater, resulting in both energy and water savings. The control valve TV-01 in Element 16's system was configured to open only when the pressure measured by PIS-01 approached SVM's LP relief valve setpoint, which ensured that only steam that would otherwise be vented to the atmosphere was recovered in Element 16's HCS. LP steam was condensed in the heat exchangers (HX-1 and HX-2), using the cooling potential of the two condensate streams from the main tank (shown in Figure 2). One stream flowed to one of the boilers and the other stream flowed to the Argus cogeneration plant; the resulting condensed steam was stored in the HCS storage tank. The condensed steam collected in the storage tank was passively cooled by heat loss to the ambient air. The stored cold condensate was then pumped into the main condensate tank, resulting in water savings that approached the amount of steam recovered.[1] Figure 4 shows the engineering drawing of the HCS Phase II layout. Designated engineering representatives at SVM performed a critical design review of all the engineering drawings and approved them for construction.

[1] Minus whatever water is lost to the atmosphere from the HCS storage tank.

Figure 4: Engineering Drawing of HCS Phase II Layout Approved For Construction

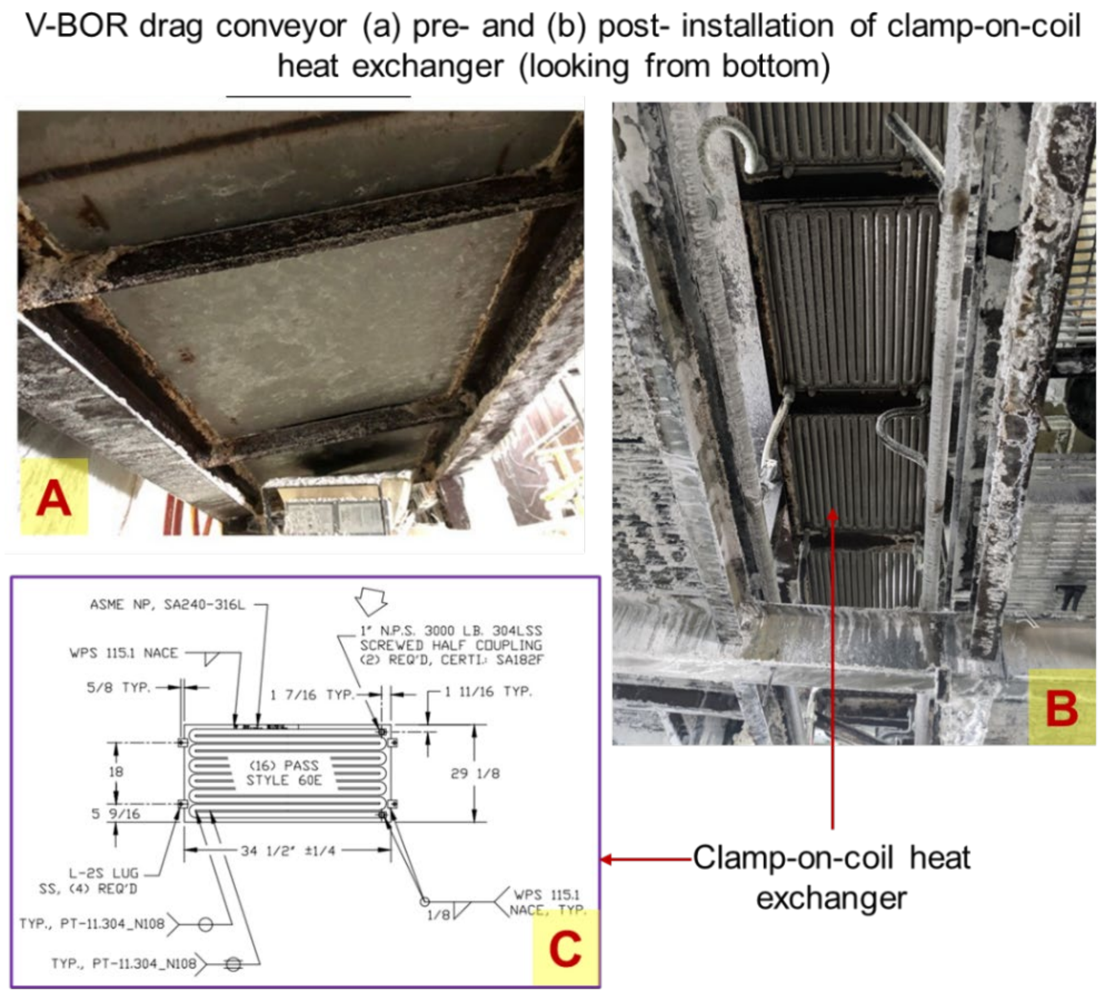


Source: Element 16 Technologies

HCS Construction and Integration Into SVM Facility

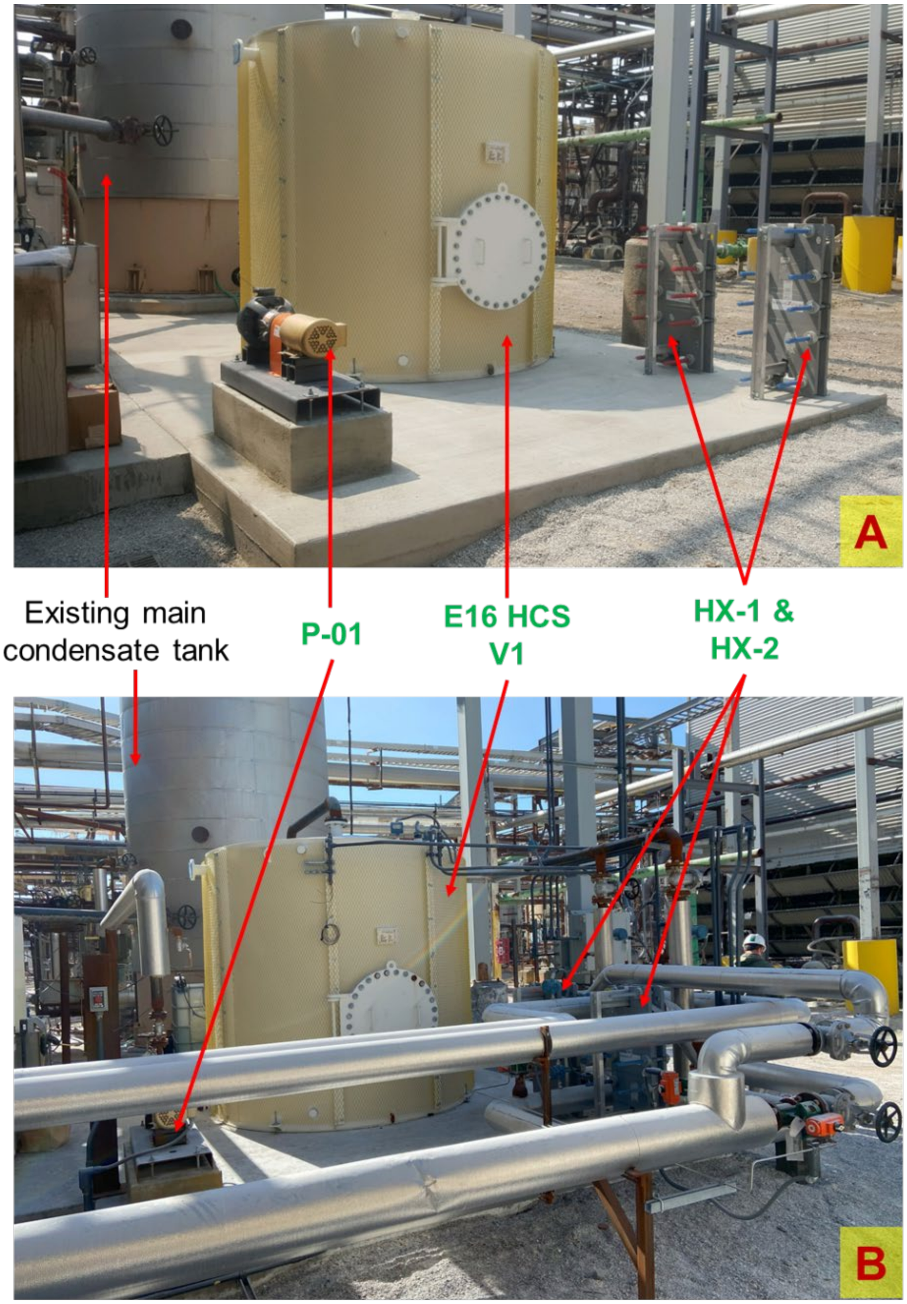
Figure 5 and Figure 6 show photographs of the installed HCS Phase II and Phase III modules, along with the piping that connected to the facility tie-in points. The clamp-on coil heat exchangers (HCS Phase III module) were procured from Tranter (Figure 5). The E16 HCS V1 storage tank shown in Figure 6 was fabricated by PCL Industrial Services, Inc., located in Bakersfield, California. Based on a recommendation by SVM, the plate-heat exchangers (HX-1 and HX-2) and pump (P-01) were procured from Brax Company, Inc., located in Ontario, California. The construction of the foundation, equipment, piping installation, and leak check, and the radiographic installation of welds were done by Caraway Construction, Inc., located in Trona, California. Ardent Service, LLC, located in Carson, California, handled the electrical installation for instruments and valves. System inspection, safety procedures, control system verification, and initial testing were carried out in collaboration with SVM's designated engineering representatives to ensure the system's readiness for demonstration, measurement, and verification activities. Figure 7 and Figure 8 show photographs installed during the construction phase and site walk-down inspection.

Figure 5: Schematic of Clamp-on Coil Heat Exchanger (HCS Phase III Module), and Photographs of Installation Location (From Beneath the V-BOR Drag Conveyor)



Source: Element 16 Technologies

Figure 6: Photographs of HCS Phase II Module Near LP Steam Line Installed at SVM Facility



Source: Element 16 Technologies

Figure 7: Photographs From Construction and Installation Inspection of HCS Phase II Module

Source: Element 16 Technologies

Figure 8: Photographs From Construction and Installation Inspection of HCS Phase III Module

Source: Element 16 Technologies

CHAPTER 3: Results

Existing System Performance Characterization

Rotary Natural Gas Dryer:

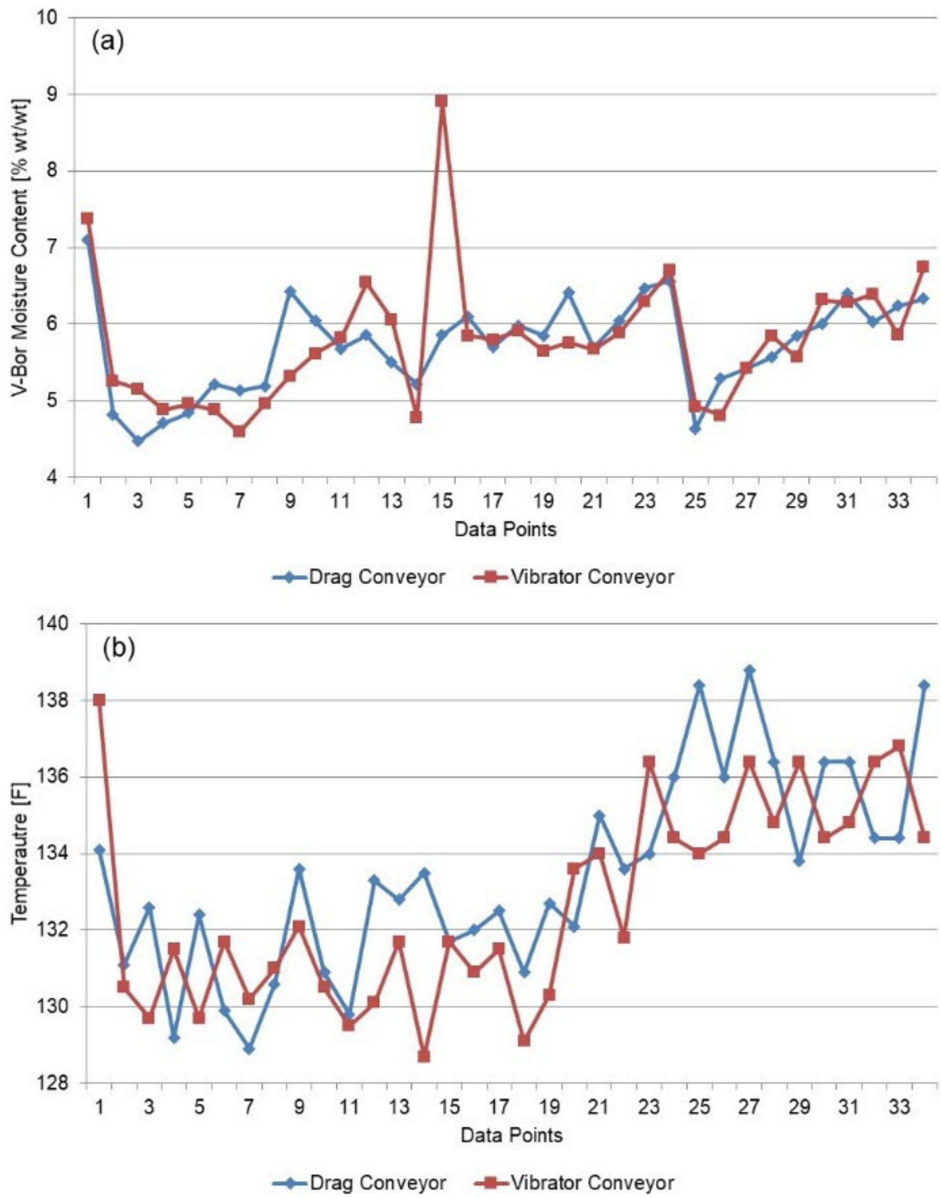
Before installation of the HCS, measurements were taken of the product to understand both the behavior of the chemical product as it traveled on the conveyors and the impact of introducing heat to the conveyors. The moisture content of product samples was analyzed via a Mettler Toledo HC-103 moisture analyzer, and the temperature of the product was also measured. Figure 9a and Figure 9b show the moisture content and the temperature, respectively, of the V-BOR samples that were transported through the drag and vibrator conveyor. The 34 data points shown in these figures correspond to the moisture content of samples taken at different times of day and different days, over a 6-month period. It was observed that the moisture content and the temperature of the V-BOR had little temporal variation. The average moisture content of the V-BOR particles was calculated to be 5.75 percent weight/weight and the average temperature was 133°F (56.1°C).

The natural gas flow rate in the rotary dryer was measured using an existing thermal mass flow meter. Existing sensors at SVM also recorded the V-BOR exit product temperature and the V-BOR production rate. SVM shared the 15-minute interval sensor data with the Element 16 team for performance characterizations. Figure 10 shows measured data for natural gas flow rates, the V-BOR product temperatures, and the V-BOR production rates for the last three years. As seen in Figure 10, since the V-BOR production rate and the product temperature showed significant variations, it was reasonable to calculate the dryer's average natural gas use to raise the temperature of one ton of product by 1°F (0.6°C). This is referred to as specific natural gas use ($\dot{V}''_{ng}$), mathematically expressed as:

$$\dot{V}''_{ng} = \frac{\dot{V}_{ng}}{\dot{m}_{vbor} \times (T_{o,vbor} - T_{i,vbor})}$$

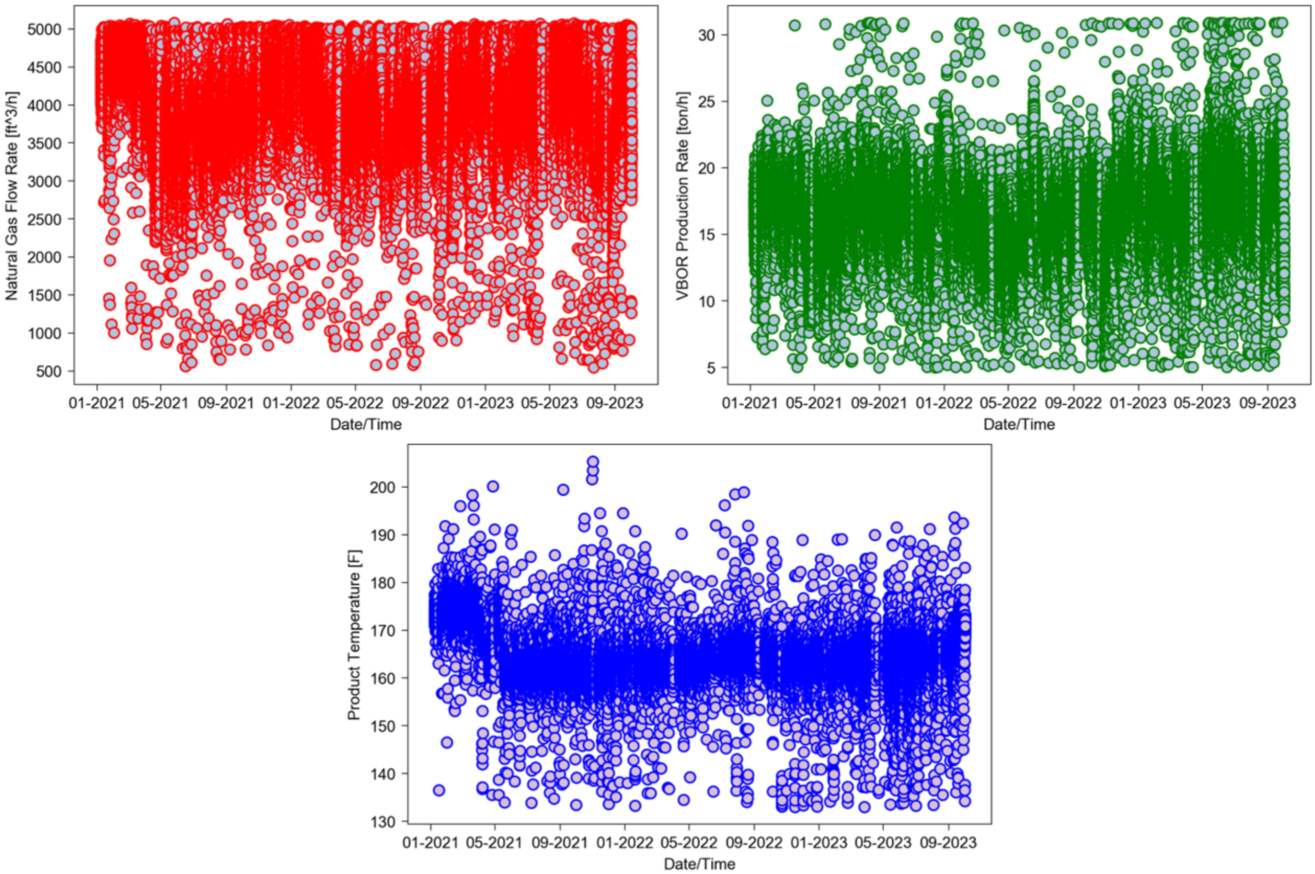
Where $\dot{V}_{ng}$ is the natural gas flow rate measured by the thermal mass flow meter, $\dot{m}_{vbor}$ is the V-BOR production rate, $T_{o,vbor}$ is the V-BOR product temperature exiting the rotary natural gas dryer (measured by existing sensors at the SVM facility), and $T_{i,vbor}$ is the V-BOR product temperature entering the drag conveyor. Figure 11 shows the calculated specific natural gas use consumption of the rotary dryer.

Figure 9: Data Collected to Evaluate the (a) Moisture Content, and (b) the Temperature of V-BOR Particles Entering the Drag Conveyor



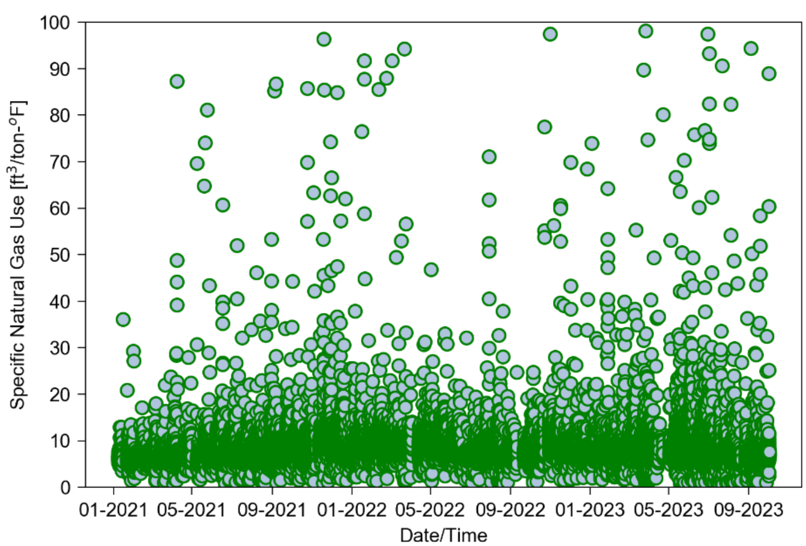
Source: Element 16 Technologies

Figure 10: Measured Natural Gas Flow Rate, V-BOR Production Rate, and Product Temperature Exiting the Rotary Natural Gas Dryer at SVM Facility



Source: Element 16 Technologies

Figure 11: Specific Natural Gas Use of the Rotary Dryer at SVM Facility

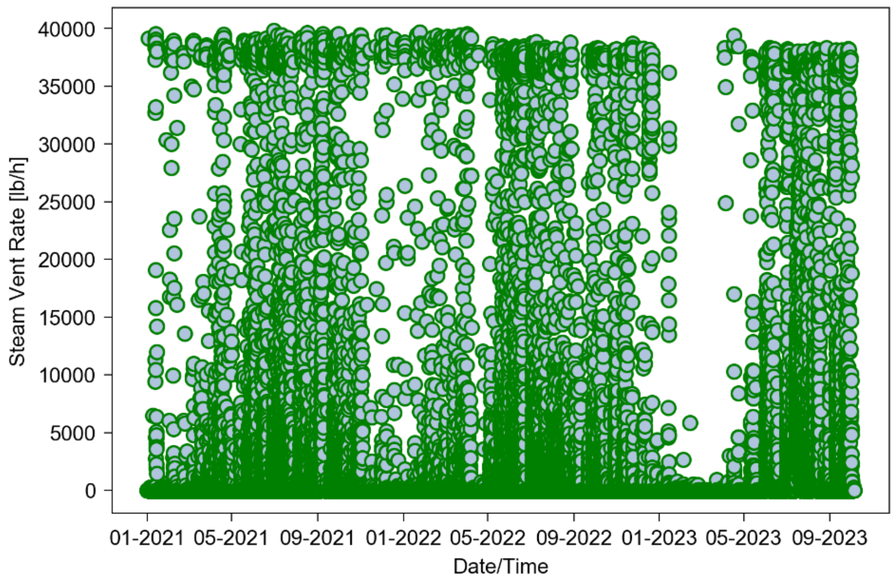


Source: Element 16 Technologies

LP Steam Vent

Figure 12 shows the LP steam flow rate vented to the atmosphere from 2021 to 2023. The waste steam vented to the atmosphere exhibited a highly fluctuating and spiky nature, characterized by frequent and rapid changes in its release. This spikiness is a result of the sudden demand fluctuations and the inherent variability that enable smooth operation of the ammonia compressors.[2] The average flow rate of steam vented to the atmosphere between 2021 to 2023 was calculated to be 1,964 pounds per hour (4.14 gallons per minute [GPM]).

Figure 12: Flow Rate of LP Steam Vent at SVM Facility



Source: Element 16 Technologies and SVM

Modified System Performance Characterization

Testing, measurement, and characterization were conducted according to the demonstration test plan and were verified by experts from the independent third party, Exponent, Inc.

Natural Gas and Energy Savings From Preheating V-BOR

Experimental testing demonstrated the concept and verified the natural gas savings from implementation of the HCS module. For Phase III HCS module testing, hot condensate was routed through the clamp-on coil heat exchanger installed underneath the drag conveyor to determine the reduction in the rotary dryer's natural gas usage from pre-heating and drying V-BOR particles with the hot condensate stream. The baseline (pre-testing) for average specific natural gas usage was characterized based on the sensor data recorded in the three years prior to testing of the HCS module's performance. The difference between the dryer's average specific natural gas use during testing and the baseline dryer's average specific natural gas

[2] Due to a lack of capacity in evaporators, the LP steam produced by the ammonia compressors was vented to prevent back pressure.

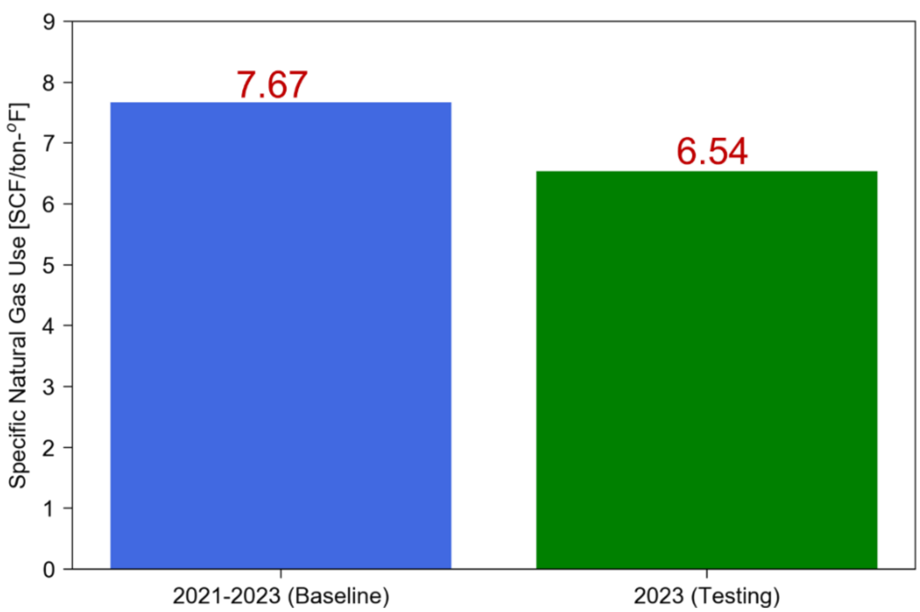
use (pre-testing) yielded the average specific natural gas savings from implementation of the HCS, $NG_{savings}$:

$$NG_{savings}\left[\frac{SCF}{ton - °F}\right] = \int_{t_{i,b}}^{t_{f,b}} \dot{V}''_{ng,b}.\,dt - \int_{t_{i,t}}^{t_{f,t}} \dot{V}''_{ng,t}.\,dt$$

where $t_{i,b}$ and $t_{f,b}$ are the initial and final times of the baseline duration, $\dot{V}''_{ng,b}$, is the specific natural gas use calculated during the testing of the HCS module, and $t_{i,t}$ and $t_{f,t}$ are the initial and final times of the test duration; the standard cubic feet (SCF) of gas was noted at 60°F (16°C) and 14.7 pounds per square inch absolute (psia).

The baseline specific natural gas use was calculated to be 7.67 (SCF / ton – °F). During the testing phase (when hot condensate was routed through the clamp-on coil heat exchangers to preheat the V-BOR products), the specific natural gas use was calculated to be 6.54 (SCF / ton – °F). As shown in Figure 13, this represents a 14.8-percent decrease in specific natural gas use consumption with implementation of the Phase III HCS module.

Figure 13: Comparison of Dryer's Average Specific Natural Gas Use During Baseline (Pre-Testing) and Testing Phases



Source: Element 16 Technologies

Between 2021 and 2023, the average natural gas consumption of the rotary dryer was 3,971 cubic feet per hour, and the V-BOR production rate was 16.6 tons per hour. A 14.8-percent reduction in specific natural gas consumption contributed to energy savings of 36,700 British thermal units per ton (Btu/ton) of product and total annual energy savings of 5,333 metric million British thermal units (MMBtu).

Water and Energy Savings From LP Steam Capture

During the testing of the Phase II HCS module, feedwater from the main condensate tank (Figure 2) was flowing only to Boiler #5, so only HX-1 was operational. The rate of heat transfer from the LP steam to the condensate in HX-1 was calculated from the condensate side of HX-2 as follows:

$$\dot{Q}_{Hx-1}[kW] = \frac{\dot{m}_{feedwater} c_p (T_{11} - T_9)}{1000}$$

where $\dot{m}_{feedwater}$ is the mass flow rate of the feedwater to Boiler #5. As noted in the piping and instrumentation diagram, the on/off valves V-31 and V-32 were fully closed during the testing period, and their positions were confirmed using the valve position indicators. T_{11} is the temperature of condensate exiting HX-1, measured by the thermocouple TI-11 in Figure 2, and T_9 is the temperature of condensate entering HX-1, measured by the thermocouple TI-09 in Figure 2. C_p is the specific heat of water at the average temperature of T_9 and T_{11} and at the pressure measured using PI-06 in Figure 2.

Figure 14 shows the feedwater temperature measured at the inlet and outlet of HX-1 and the heat rate calculated using the equation just described. From the heat rate value, the steam condensation rate was calculated from:

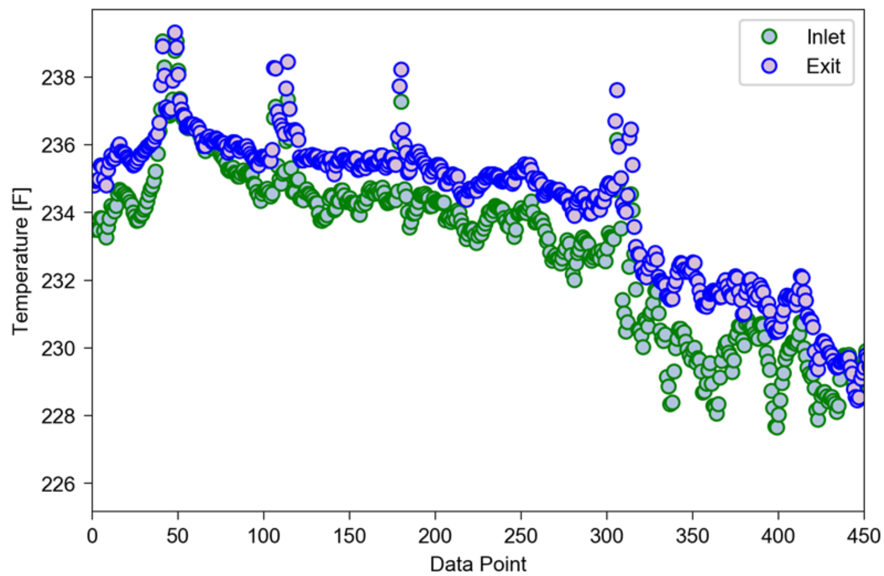
$$\dot{m}_{steam,condensed}[kg/s] = \frac{\dot{Q}_{Hx-1}}{h_{sat,vap} - h_{sat,liq}}$$

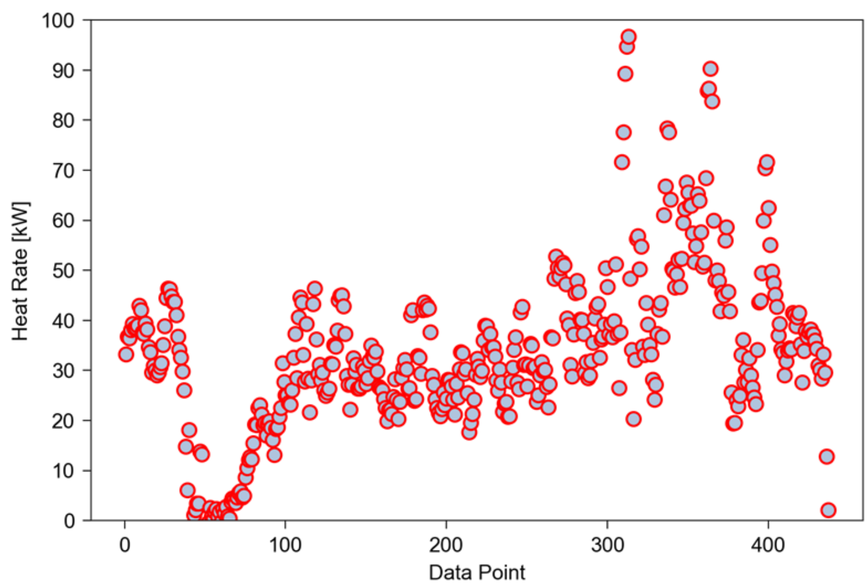
where $h_{sat,vap}$ is the enthalpy of saturated vapor in kilojoules per kilogram (kJ/kg) and $h_{sat,liq}$ is the enthalpy of saturated liquid in kJ/kg. The enthalpy values were calculated from steam tables at the pressure value measured by PIC-01. The water collection rate was then calculated as follows:

$$\dot{m}_{water}[\frac{kg}{s}] = \frac{\dot{m}_{steam,condensed}}{\rho_{cond}}$$

where ρ_{cond} is the density of condensate calculated at its saturation state.

Figure 14: (Top) Measured Temperature at the Inlet and Outlet of HX-1, Connected to the Boiler #5 Feedwater Line and (Bottom) Calculated Heat Transfer Rate





Source: Element 16 Technologies

Figure 15 shows the steam condensation rate in pounds per hour (lbs/h) and the water collection rate in GPM. The average steam condensation rate and the water collection rate over the test duration were calculated from:

$$\dot{m}_{water,avg} = \frac{\sum_{i=1}^{n} \dot{m}_{water} \times \Delta t}{t_{i=n} - t_{i=1}}$$

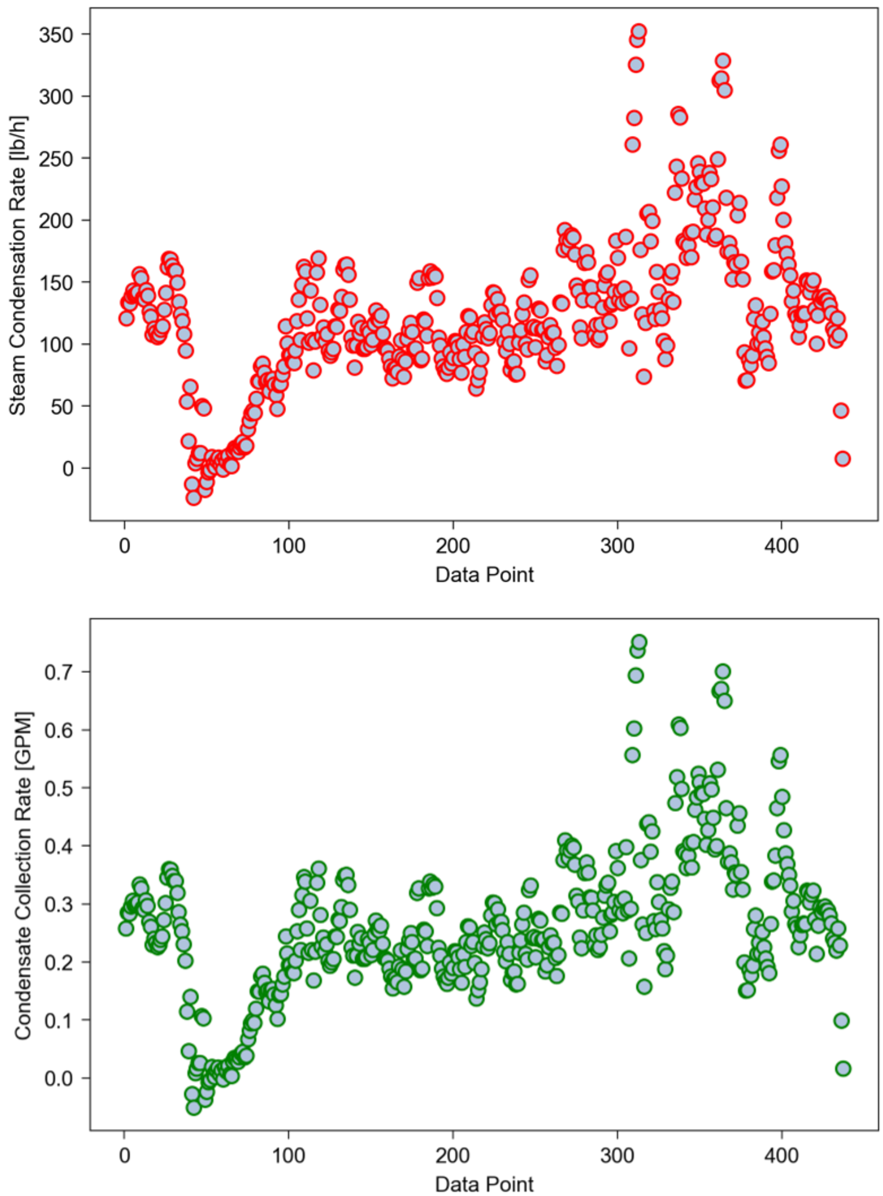
where *n* is the number of data samples recorded during the test duration and Δt is the time interval between data samples. The average water collection rate was computed to be 0.24 (±0.02) GPM. During the same test duration, based on the LP steam relief valve opening measurement, the average steam vent rate was calculated to be 145 lbs/h, which equates to 0.3 GPM. Without the HCS module, the average steam vent rate would have been 0.54 (±0.02) GPM. Hence, 45 percent of the steam that would have vented to the atmosphere during the test duration was recovered. With a conservative assumption of average water savings of 0.5 GPM when both HX-1 and HX-2 were operational, annual bill savings were estimated to be $3,400 at the water cost of $13 per 1000 gallons.

The average savings in thermal energy demand by preheating boiler feedwater due to the implementation of the Phase II HCS module were calculated from:

$$\dot{Q}_{savings}[BTU/h] = \frac{\sum_{i=1}^{n} \dot{Q}_{HX-1} \times \Delta t \times 3412.14}{t_{i=n} - t_{i=1}}$$

where the value 3,412.14 is the conversion factor from kilowatts (kW) to British thermal units per hour (Btu/h). The average thermal energy savings were calculated to be 104,156 (±9,450) Btu/h, which equates to natural gas savings of 100.5 (±9) SCFH; SCFH denotes standard cubic feet of gas per hour at 60°F (16°C) and 14.7 psia. Natural gas savings were calculated by dividing thermal energy savings by 1,036, which is the Btu content of one cubic foot of natural gas, as stated on the United States Energy Information Administration website (U.S. EIS, 2024a).

Figure 15: Calculated Steam Condensation Rate (Expressed in lbs/h) and Water Collection Rate (Expressed in GPM)



Source: Element 16 Technologies

Techno-Economic Assessment

The LP annual steam vent data provided by SVM in Figure 12 show considerable dynamic variations. Therefore, annual simulations considering both the time-varying LP steam availability and the transient thermal performance of HCS were conducted to determine annual energy and water savings and to evaluate the project's economics.

A logarithmic mean temperature difference method determined the overall heat transfer rate based on the inlet condensate temperature, the LP steam temperature, and the heat transfer surface area. The overall heat transfer coefficient for a specific mass flux was obtained from the heat exchanger specifications provided by the vendor. The heat transfer coefficient for other mass fluxes was determined using appropriate scaling relationships ($h' \propto \dot{m}''^{0.67}$ where h' is the convective heat transfer coefficient and $\dot{m}''$ is the mass flux) established in the literature for plate-heat exchangers.

The mass and energy balance equations that govern the performance of the condensate storage tank can be expressed as:

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$mc\frac{dT}{dt} = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} - \dot{Q}_{loss}$$

In the equations shown, m is the mass of condensate in the tank, $\dot{m}_{in}$ is the mass flow rate of condensed LP steam that enters the tank, $\dot{m}_{out}$ is the mass flow rate of condensate that is pumped from the storage tank to the main tank by pump P-01 (Figure 2), T is the temperature of condensate in the tank, h_{in} is the inlet enthalpy of condensed LP steam, h_{out} is the exit enthalpy of the condensate from the tank, and $\dot{Q}_{loss}$ is the heat lost from the tank to the ambient.

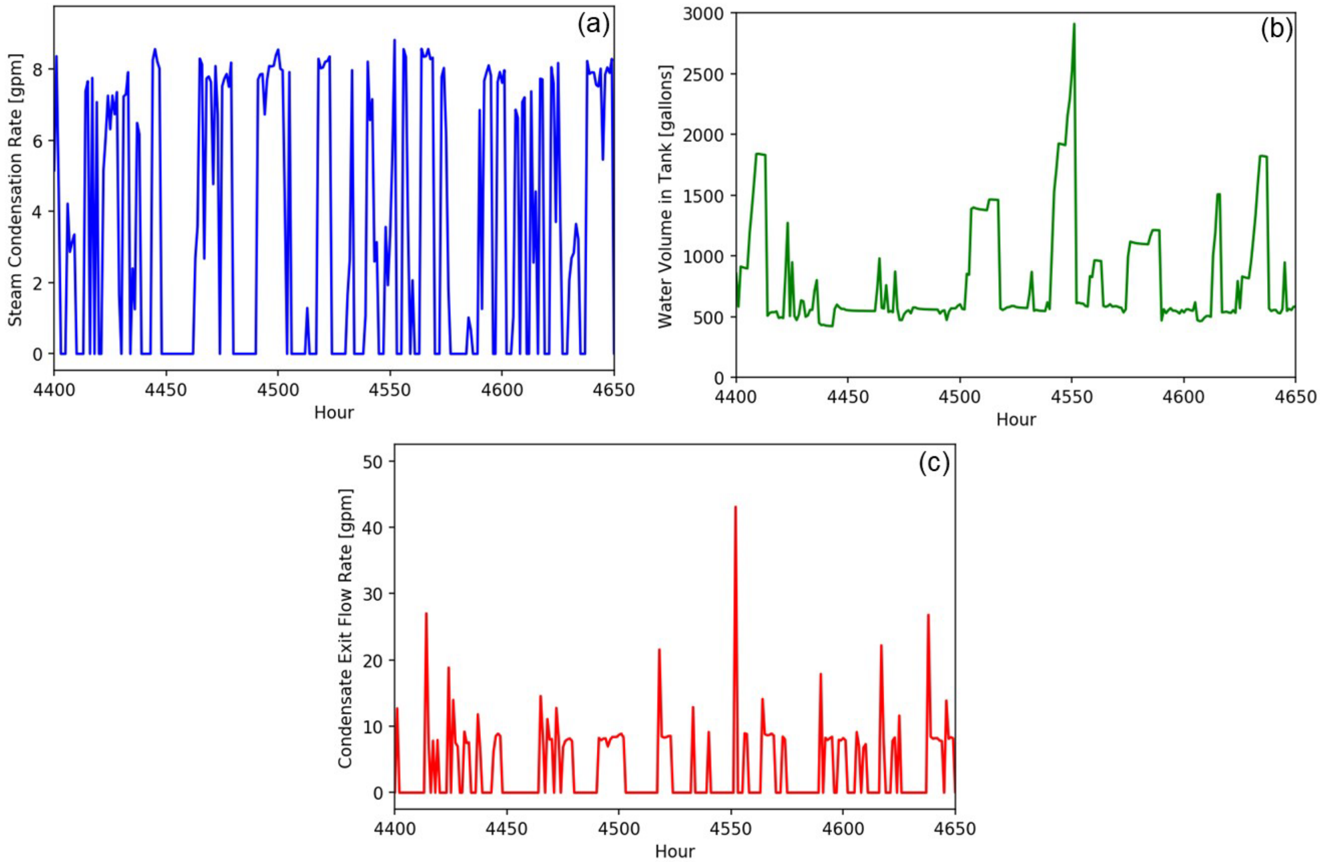
Depending on LP steam availability at any given time and the performance of the heat exchanger, $\dot{m}_{in}$ can be determined from:

$$\dot{m}_{in} = \dot{Q}_{HX} / (h_{sat,steam} - h_{sat,liquid})$$

where $\dot{Q}_{HX}$ is the heat transfer rate obtained from the heat exchanger model, $h_{sat,steam}$ is the enthalpy of LP steam, and $h_{sat,liquid}$ is the enthalpy of condensed LP steam. Depending on the available LP steam at any given time and the heat exchanger surface area, the required $\dot{m}_{out}$ to maximize LP steam condensation was first calculated. The pump transfer was calculated at $\dot{m}_{out}$ from the storage tank to the main condensate tank, or when the level of condensate in the tank reaches 85 percent of the tank volume (until the level reaches 10 percent of the tank volume).

Figure 16 shows the transient variations in steam condensate rate with the HCS for 10 consecutive days in a year. The predicted hourly variations of the condensate level in the tank, and the condensate extraction rate from the tank ($\dot{m}_{out}$), are also shown in Figure 16. From these annual simulations, the total LP steam condensed in a year and the natural gas saved through transfer of thermal energy from hot V-BOR condensate to the V-BOR particles in the dryer were calculated. The annual savings were computed using an industrial natural gas price of $7.5/MMBtu, a $29/ton carbon price, and water cost of $13 per 1000 gallons. The annual operational expenses included pump parasitic power consumption and maintenance costs. The capital expenses of the storage tank, heat exchangers, pump, insulation, valves, pipes, and fittings were obtained from vendor invoices. The labor cost for installation was obtained from contractor invoices. Based on this information and an approximate 4-year simple payback period, calculated project economics were very attractive at the over-24-percent internal rate of return for a system lifetime of 30 years.

Figure 16: Transient Variations in the (a) Steam Condensation Rate, (b) Condensate Volume in the Tank, and (c) Flow Rate of Condensate Out of the Tank for 10 Consecutive Days in a Year



Source: Element 16 Technologies

Technology/Knowledge Transfer

The technologies that Element 16 developed for industrial process heat efficiency and decarbonization are novel, meaning that educating the engineering, business, and policymaking community is necessary for their widespread adoption. The Element 16 team effectively communicated its knowledge and project outcomes to the public and key decision-makers through various channels, including speaking engagements; participation in expos, summits, and conferences; issuances of media releases; and publication of technical reports, test reports, and journal articles.

Element 16 technologies were accepted into multiple selective and prestigious cleantech startup programs, including the Techstars accelerator, Creative Destruction Lab, Energy Stream, and SparkLabs Energy. Element 16 built a network of technology and financial partners. One key example is the partnership formed with an international energy company through SparkLabs, which was the client for Element 16’s first corporate contract for paid detailed engineering of a heat-capture and storage system.

Some notable public events where Element 16 personnel made presentations include the VERGE sustainability conference in 2019, the 2019 Annual Conference hosted by the Association of Energy Engineers Southern California Chapter, the Association for the Advancement of Artificial Intelligence in 2022, the RE+ event's United States Department of Energy Solar Energy Technologies Office Awardee Showcase in 2022 and 2023, the San Francisco Bootcamp Startup Showcase, the High-Performance Computing for Energy Innovation Workshop at Livermore in 2023, and the 2023 American Nuclear Society Annual Meeting. Element 16 has a dedicated website (https://element16.com) and maintains a LinkedIn page, where it regularly shares updates on the company's progress and projects.

Although this project focused on a low-temperature WHR system, Element 16’s flagship product is sulfur thermal energy storage (TES) that can be integrated with renewables for industrial process heat. This project’s success laid the groundwork for the Element 16 team to establish a robust collaborative relationship with the engineering and management teams at SVM. Element 16 continues to partner with SVM in its pursuit of zero net energy and industrial decarbonization, focusing on solar energy for its around-the-clock 284°F to 428°F (140°C to 220°C) process heat requirements and efficiency enhancements. This partnership is further strengthened by a recent project funded by the California Energy Commission that involves testing and demonstration of Element 16’s sulfur TES product at its facility.

In response to a request for information from the United States Department of Energy Office of Clean Energy Demonstrations, Element 16 wrote a white paper discussing the technoeconomic benefits of solar thermal and sulfur TES integration with SVM for process heat requirements, shown in Appendix A. The technoeconomic analysis shows that integration of sulfur TES is critical for improving the utilization of renewable energy resources and achieving lower levelized costs of heat.

CHAPTER 4: Conclusion

Element 16 successfully developed and demonstrated a low-temperature WHR system at the SVM industrial facility in Trona, California. The WHR system — featuring compact heat exchangers — effectively captured and repurposed vented LP steam for drying V-BOR, a form of borax pentahydrate, that reduced the natural gas consumption of the existing rotary dryer. The installed system featured a water storage tank that stored the cold condensate, which was periodically recycled back into the facility, resulting in water savings equivalent to the amount of waste steam recovered. The demonstration and testing phases, verified by independent third-party experts from Exponent, completed all experimental tasks for measurement and verification, as outlined in the test plan.

The analysis of collected data reveals a significant reduction in specific natural gas use, defined as the average natural gas consumed to raise the temperature of one ton of product by 1°F (0.6°C), when compared with a baseline. The decrease in specific natural gas use was calculated to be 14.8 percent lower, indicating a significant improvement in energy efficiency and resource conservation. A 14.8-percent reduction in specific natural gas consumption translates to energy savings of 36,700 Btu/ton of V-BOR product and total yearly energy savings of 5,333 MMBtu. During the testing period, the average water savings from the implementation of the HCS module were measured to be 0.24 (±0.2) GPM. Based on the measurement of LP steam vented to the atmosphere during the same test duration, it was estimated that 45 percent of the steam that would have otherwise been vented to the atmosphere was instead recovered. Comprehensive annual simulations considering the time-varying LP steam availability and the transient thermal performance of the HCS were conducted to determine the annual energy and water savings and to evaluate project economics. The findings indicate highly attractive project economics, with an internal rate of return exceeding 24 percent for a system lifespan of 30 years, with an approximate 4-year simple payback period. Overall, this project showcased a scalable and functional WHR system that offers tangible energy and water savings for California's industrial sector.

Irregular and abrupt surges in waste-steam releases presented significant challenges for energy efficiency, underscoring the necessity of exploring alternative methods to minimize waste and its associated cost. Implementing alternative technologies such as air-cooled condensers to condense vented steam efficiently and reliably can facilitate the steam's full recovery and reuse. This approach aligns with the broader goals of achieving energy efficiency and minimizing environmental impacts, making it a promising avenue for advancing steam management practices across a broad spectrum of industrial facilities.

This research project's success paved the way for a follow-up grant project funded by the California Energy Commission (CEC) involving the testing and demonstration of Element 16's flagship sulfur TES product at its facility. This report discusses both the successful pilot demonstration of the WHR system at SVM and the technology-to-market activities of the sulfur

TES technology, which allowed for more than $8 million in research, development, and commercialization funding since award of this project.

Future research efforts should focus on mitigating the challenges associated with scaling up large industrial heat-capture and thermal energy storage systems. Future research should also delve into high-temperature heat pump systems capable of utilizing and upgrading low-temperature waste heat (integrated with renewable energy resources and thermal energy storage), to provide clean, dispatchable industrial process heat. The industrial sector will benefit the most, because of its large consumption of energy associated with fossil fuel use. In California, process heating makes up around 85 percent of natural gas usage in industrial applications, contributing to about a quarter of the state's GHG emissions; improving industrial process heat efficiency and decarbonization can meaningfully impact the state’s reduced emission mandates. The adoption of established solar thermal collector technologies or solar photovoltaic-assisted electric heating could also potentially meet most of that heat demand and displace the onsite burning of natural gas. Industries that require heat in this temperature range include chemical production, ethyl alcohol manufacturing, nonmetallic mineral production (for example, soda ash, potash, and borax mining), paper mills, and food processing. These sectors have heavy heat demands and their working temperature requirements are compatible with solar thermal and solar photovoltaic-assisted electrotechnology applications.

The primary challenge is solar intermittency, which reduces the technology’s capacity, decreases its reliability to supply continuous and on-demand heat, and increases levelized-heat costs. This project led directly to a new CEC grant funded to implement Element 16’s new sulfur TES technology. Integration of Element 16’s low-cost TES will lead to performance and cost improvements for solar and move the technology closer to techno-economic parity with natural gas equipment; that, in turn, would improve its commercial adoption in California’s industrial sector. A case study in Appendix A discusses the techno-economic advantages of integrating solar thermal with sulfur TES for SVM's process heat needs. Sulfur TES can increase overall system resiliency to provide an on-demand, flexible heat supply to meet individual requirements of the industrial process, achieve lower levelized energy costs (increasing the share of renewable energy and reducing the CO_2 footprint of industrial processes), and enable industries to become independent of rising fuel and CO_2 prices. This approach aligns with the objectives of California's Senate Bill 350 (De León, Chapter 547, Statutes of 2015) policy mandates, which aim to improve energy efficiency and accelerate industrial decarbonization.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Btu	British thermal units
Btu/h	British thermal units per hour
Btu/ton	British thermal units per ton
°C	degrees Celsius
CEC	California Energy Commission
CO_2	carbon dioxide
E16 or Element 16	Element 16 Technologies, Inc.
°F	degrees Fahrenheit
GHG	greenhouse gas
GPM	gallons per minute
HCS	heat capture system
HX	heat exchanger
kJ/kg	kilojoules per kilogram
kW	kilowatt
lbs/h	pounds per hour
LCOH	levelized cost of heat
LP	low-pressure
m^2	square meters
MMBtu	metric million British thermal units
psia	pounds per square inch absolute
SCF	standard cubic feet
SCFH	standard cubic feet of gas per hour at 60°F (16°C) and 14.7 psia
SVM	Searles Valley Minerals
TAC	technical advisory committee
TES	thermal energy storage
V-BOR	commercially packaged borax pentahydrate
WHR	waste heat recovery

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Project Deliverables

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

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

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Sulfur TES Integration Pathway for Natural Gas Savings at SVM Facility

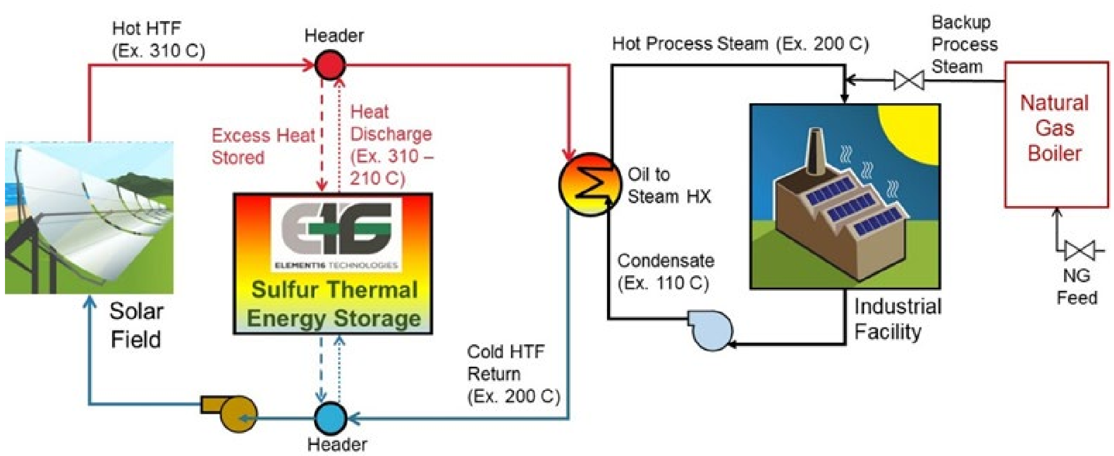
January 2025 | CEC-500-2025-005

APPENDIX A:
Sulfur TES Integration Pathway for Natural Gas Savings at SVM Facility

Searles Valley Minerals uses 150,000 lbs/h, 400 psig steam for their continuous process heat requirement that equates to a constant heat demand rate of 150 MMBtu/h (45 MWt). As the prices of clean renewable energy solutions such as solar continues to drop, adopting them to meet the demand for heat offers natural gas saving and green-house gas (GHG) emission-reduction opportunities. However, energy supply from solar is intermittent and only available during the day, while industries require continuous energy supply to meet the 24/7 load requirement. Hence, integration of low-cost thermal energy storage (TES) is critical to make solar energy dispatchable by storing excess heat during peak solar periods and meet the process heat demand when solar is unavailable. This increases system reliability and can enable achieving lower levelized cost of heat (LCOH) than that of natural gas boiler.

Figure A-1 shows the solar thermal and sulfur TES integrated system configurations considered for the analysis. The solar field array concentrates sunlight to heat thermal oil heat transfer fluid flowing through the receiver tubes. Excess heat during peak solar period is stored in the sulfur TES and dispatched as needed to meet the constant process heat requirement. Due to the variable nature of solar insolation and the dynamic behavior of solar thermal system, the existing natural gas boiler would be used as a back-up system to guarantee always meeting the thermal load.

Figure A-1: Concentrated Solar Thermal Integrated With Sulfur TES for Process Heat Requirement at SVM Facility

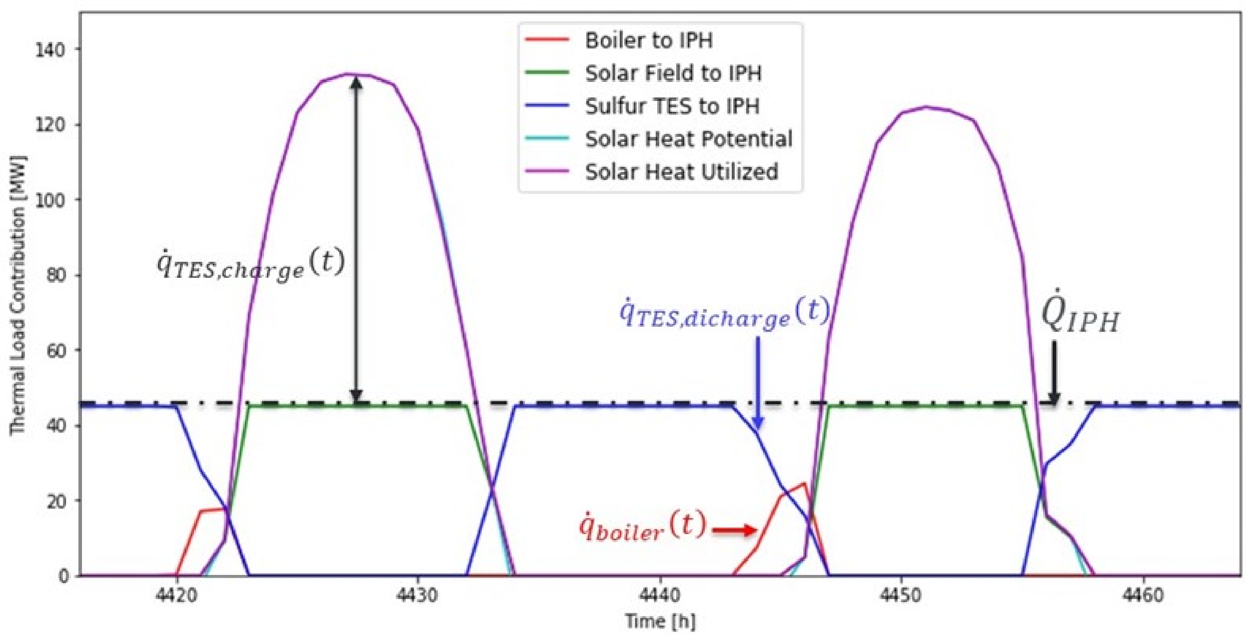


Source: Element 16 Technologies

Hourly simulation for a year is carried out to determine the annual performance of the hybrid solar-sulfur TES-boiler system. From the performance model, the key performance metric evaluated is capacity factor of solar and TES defined as annual fraction of energy provided by solar and TES to satisfy the annual process heat demand ($\dot{Q}_{IPH} \times 8760$). From the results of the annual simulations, the LCOH for a system lifetime of 30 years is computed considering the direct capital cost, indirect capital cost, annual operation and maintenance cost, and back-up natural gas fuel cost.

Figure A-2 illustrates the transient output obtained from the hybrid solar thermal-TES-boiler model that shows the dynamic variation in net solar heat delivered by the solar field, and the hourly load contributions from the solar field, sulfur TES and the backup boiler to the constant industrial process heat demand requirement for three days in the month of July. The plot shown in Figure A-2 is for solar multiple of 3 and sulfur thermal energy storage capacity of 16 hours. Solar multiple is a non-dimensional way of quantifying the size of solar field that equals actual solar field aperture area to that of the field size sufficient to deliver design heat load ($\dot{Q}_{IPH}$) at nominal peak load conditions. Increasing the solar multiple, increases the solar field size and cost proportionally.

Figure A-2: Transient (Hourly) Variation in Solar Field, Sulfur TES, and Boiler Operation Dynamics

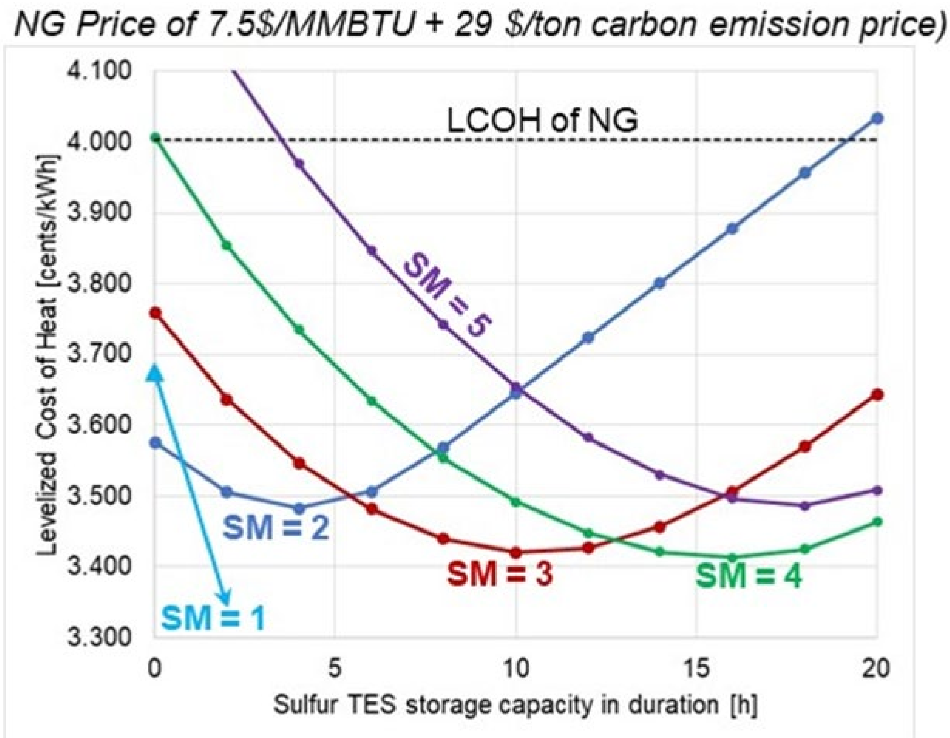


The plot here is shown for solar thermal system installed at Searles Valley Mineral mining facility in Trona, California (DNI = 8 kWh/m^2/day) with solar multiple of 3 and TES capacity of 16 hours.

Source: Element 16 Technologies

The variation in LCOH as a function of storage capacity for various solar multiples are illustrated in Figure A-3. The analysis was conducted for natural gas price of $7.5/MMBtu which is the 20-year average industrial natural gas price in California. We also included 29 $/ton ($1.5/MMBtu) carbon emission price to the natural gas price based on the 2023 average auction settlement price in California's Cap-and Trade program. Figure A-3 shows that for a fixed solar multiple, there is an optimal sulfur TES storage capacity that minimizes the LCOH. The LCOH of natural gas boiler for industrial process heat , assuming the CAPEX of boiler is fully depreciated is also plotted in Figure A-3 for comparison. Solar multiple of 4 and sulfur TES storage capacity of 14–16-hour duration provides the least LCOH with CO_2 emissions reduction of 1900 tons for the 150 MMBtu heat demand requirement at SVM mineral facility over the 30-year system lifetime.

Figure A-3: Influence of Sulfur TES Storage Capacity on LCOH for Hybrid Concentrated Solar Thermal-Sulfur TES-Natural Gas Boiler Configuration.



The LCOH of natural gas corresponds to natural gas price of $7.5/MMBtu with carbon emission price of $29/ton.

Source: Element 16 Technologies