FINAL SCIENTIFIC/TECHNICAL REPORT

Low-Cost Sulfur Thermal Storage for Increased Flexibility and Improved Economics of Fossil-Fueled Electricity Generating Units

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EXECUTIVE SUMMARY

The US electric grid relies on conventional fossil fuel power plants for reliable and secure power, but these plants suffer from physical and financial strain due to the influx of inexpensive and variable solar and wind electricity. Conventional power plants need to generate electricity flexibly and on-demand to accommodate these renewable resources on the grid. Integrating a low-cost thermal energy storage (TES) gives fossil assets the ability to regulate their output efficiently and optimize the plant operation to maximize revenue in the wholesale electricity market. Element 16's TES concept uses sulfur, a byproduct of the oil & gas industry, as the storage media that is 10 times cheaper than molten salt used in commercial two-tank TES technology. In this project, the team completed a detailed feasibility and technoeconomic study establishing the impact, cost and performance of molten sulfur TES system integrated with fossil assets.

We performed an engineering and economic evaluation of molten sulfur TES integration with a 656 MWe (maximum gross output) coal-fired electricity generating unit (EGU). The feasible and promising integration approach was to (a) charge molten sulfur TES by diverting steam from boiler when electricity prices are low; (b) increase plant output when electricity prices are high by discharging stored energy from the molten sulfur TES to preheat high pressure feedwater and reduce steam extraction from turbine. This approach improves plant operational flexibility by enabling 50% increase in plant's turndown ratio — defined as the ratio of maximum to minimum electricity output — from 155-583 MWe (baseline) to 110-619 MWe (with sulfur TES). From an economic perspective, this increases revenue from peak load operation when electricity demand and prices are high, and reduces the revenues losses by avoiding unit shut down or operation at low efficiency when electricity demand and prices are low. Based on a detailed technoeconomic evaluation, the installed cost of molten sulfur TES for this application was calculated to be within 95-105 $/kWhe (including balance of system such as charge and discharge heat exchanger, heat transfer fluid system, piping, pump) in comparison to 300-400 $/kWhe for Lithium-ion battery. Evaluation of different operation scenarios showed that the integration of molten sulfur TES with the coal fired EGU increases net present value (NPV) by 29-134 $/kWe$_{(gross\ capacity)}$ at coal price of 2.6 $/MMBTU, off-peak energy price of 20 $/MWh, peak energy price of 50 $/MWh and capacity payment of 50 $/kW-year, and decreases CO_2 emission by ~7 lbs/MWhe. The assessment of TES integration with combined heat and power (CHP) plant at an industrial facility in California showed 8 to 10-year payback period for molten sulfur TES resistively charged using low price electricity and discharging it to provide process heat for their operation through avoided natural gas purchase.

Overall, retrofitting existing fossil assets with Element 16's low-cost molten sulfur TES technology improves their economic competitiveness and allows fossil assets to adapt to the new, highly renewable electric grid. This will ensure the US consumer receive lower cost utilities and products. Modifying existing assets will be the most cost-effective way to allow for more renewable energy to join the grid, reducing carbon emissions without the high cost or subsidies for grid battery installations or building new fossil fuel "peaker" plants. Future work will focus on optimizing molten sulfur TES operation considering hourly variation in spot electricity prices in various markets and securing pilot

project to demonstrate economic value of sulfur TES with combined heat and power (CHP) and other power plants in partnership with Advisian (Worley), utility companies, and CHP plant operators.

The work completed in this project sets the groundwork to take the innovative molten sulfur thermal energy storage technology and apply it to existing power plants. This will allow the electric grid to be more resilient and make the best use of the electric grid assets that already exist. Since starting this project, Element 16 was accepted into the MassChallenge Food Sustainability program. Food processing companies rely on on-site fossil fueled cogeneration power plants to provide electricity and process heat. As part of this program and beyond, Element 16 was able to present this novel sulfur thermal energy storage technology to large food & beverage companies like Nestlé, General Mills, and AB InBev. These types of engagement allowed technical information about the innovation backed by this award to reach energy managers and executives at large corporations that could benefit from sulfur thermal energy storage. This grant project provided Element 16 the resources to develop an actionable feasibility study of how sulfur thermal energy storage can be integrated with power plants operated by these corporations in the US and around the world.

This project addressed the DOE Office of Fossil Energy and Carbon Management mission and Energy Storage Grand Challenge mission in enabling fossil fueled assets to adapt to the modern electrical grid through the integration of cost-effective molten sulfur TES. This technology can improve energy efficiency and reduce equipment damage, leading to lower energy costs for consumers. The integration and widespread deployment of sulfur TES with the US fleet of fossil assets would have the following positive impacts: Security: Increased reliability of powerplants improves grid resiliency, and improved energy efficiency reduces reliance on imported fuels. Repurpose aging fossil assets into storage battery banks using existing infrastructure. Environment: Enabling power plants to operate at high energy efficiency while producing electricity flexibly reduces emissions intensity. Economy: Low-cost TES provides a financial benefit to the asset owner by decreasing fuel cost, increasing plant utilization, providing energy arbitrage opportunities, and decreasing O&M expenses.

Contents

NOMENCLATURE

ASME	American Society of Mechanical Engineers
BOS	Balance of System
BPVC	Boiler Pressure Vessel Code
CA	Corrosion Allowance
CAPEX	Capital Expenses
CHP	Combined Heat and Power
DOE	Department of Energy
EGU	Electricity Generating Unit
FOM	Figure of Merit
HHV	High Heating Value
HP	High Pressure
HTF	Heat Transfer Fluid
HX	Heat Exchanger
LMP	Locational Marginal Pricing
LP	Low Pressure
MSL	Minimum Stable Load
NPV	Net Present Value
O&M	Operation and Maintenance
PV	Present Value
TES	Thermal Energy Storage
VWO	Valve Wide Open

1. OVERVIEW

In response to increased penetration of renewables, formerly baseload fossil-fired power plants are increasingly forced to operate in cycling mode with frequent start-ups and shut-downs, especially when an electricity generating unit's (EGU's) power demand goes below its minimum stable load (MSL). This cycling results in decreased efficiency and increased emissions and operating costs. The cycling cost combined with the curtailment of revenue from electricity sales could cause the plants to become economically unviable. Low-cost thermal energy storage (TES) integration provides a promising opportunity to improve fossil asset flexibility by storing energy during periods of low-demand and increasing power output during high-demand periods. Thermal energy storage integration could further improve economics by increasing plant utilization and reducing cycling associated maintenance cost.

An important and innovative aspect of Element 16's TES concept is the use of extremely low-cost sulfur as the storage fluid, which is an abundant chemical element and waste byproduct of the oil and gas industry. The price of sulfur is 40-80 $/ton [1] that is only one-tenth the cost of state-of-the-art molten salt (800-1200 $/ton), which commonly accounts for 50 to 60% of the storage system cost [2]. The molten sulfur TES design configuration involves heat transfer fluid (HTF) tubes located within sulfur bath. High pressure steam from the power plant will heat an intermediate low pressure and non-corrosive HTF such as thermal oil in a heat exchanger, which is pumped through the HTF tubes for storing heat in molten sulfur. Another charge option envisioned is using commercially available thermal oil electric heaters operated using off-peak or curtailed renewable electricity. During discharge, heat is retrieved from sulfur by the heat transfer fluid used either to generate steam or preheat feedwater (Figure 1). The combination of the forced convection dynamics in HTF and natural convection heat transfer dynamics in molten sulfur guarantees high discharge rates, low heat transfer surface area requirement (less capital cost) and high exergetic efficiency.

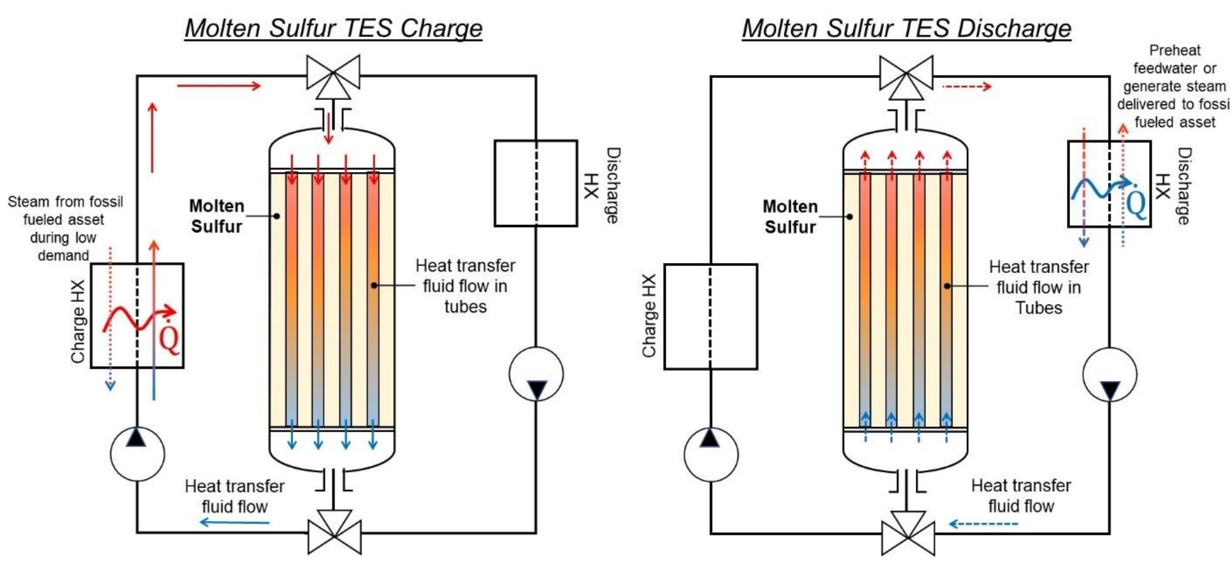

Figure 1: Schematic illustration of molten sulfur TES integrated to a fossil asset for generating steam or preheating feedwater

1.1. Summary of Findings

The overall objective of the project was to complete a comprehensive feasibility study that includes techno-economic and system performance modeling of sulfur TES integrated with fossil fueled EGUs and establish technology maturation and commercialization plans for the product. Specific activities of this project were to complete conceptual study, technoeconomic study and technology/knowledge transfer activities.

The team conducted a conceptual study of molten sulfur TES integration with Cross Generating coal-fired power unit (maximum gross power output of 656 MWe) that is owned by Santee Cooper and communicated the results to the management team. We completed process flow diagram and end-to-end heat, mass and water balances for different integration options. We established the baseline performance and economics of the fossil fueled EGU with and without molten sulfur TES integration.

From thermodynamic and integration feasibility analysis, we determined the promising integration pathway which involves:

a. Charging molten sulfur TES using steam output from the boiler during low electricity prices and thereby reducing EGU's electricity output.
b. Discharging molten sulfur TES by using the stored energy to preheat the high-pressure feedwater supplied to the boiler during peak electricity prices. Hence, less steam is extracted from the turbine to preheat the feedwater resulting in higher electric power output..

The identified integration scenario provided significant operational flexibility with 50% increase in turndown ratio – defined as the ratio of maximum to minimum output power of EGU – providing an increase in load controllability from 155-583 MWe (baseline) to 110-619 MWe (with TES). Based on the detailed charge and discharge analysis, the targeted parameters for molten sulfur TES integration with the fossil fueled EGU are:

1. Operation temperature: T_{max} = 315 °C and T_{min} = 200 °C
2. Discharge operation: 75 MWt constant discharge rate for discharge duration of 6 h for bypassing one of the high-pressure (HP) feedwater heaters.
3. Charge operation: 56 MWt constant charge rate for charge duration of 8 h (typical off-peak duration hours) charged using steam output from boiler.

We developed a thermodynamic model of the molten sulfur TES and verified its prediction accuracy by comparing it against the experimental data obtained from Element 16's in-house prototype testing system. The team developed a sulfur TES capital cost estimation tool based on detailed factorial and module costing methods validated using vendor quotes. The integrated performance and cost modeling tool was used to establish the molten sulfur TES design configuration that satisfied the performance metrics requirement identified in Task 2.0. With the technoeconomic tool, we quantified the economic and environmental benefits resulting from the integration of molten sulfur TES to fossil fueled EGU:

a. Economics: Increase in Net Present Value (NPV) by 29-134 $/kWe_{(gross capacity)}$ and TES payback period of 4-12 years. (Assumes off-peak price of 20 $/MWh, peak price of 50 $/MWh, capacity payment of 50 $/kW-year and coal price of 2.6 $/MMBTU)
b. Environmental benefits: Decrease in CO_2 emissions by ~7 lbs/MWhe

A technology gap assessment plan and a commercialization plan were also developed for this technology. As part of this project, Element 16 team interacted with customers that own/operate industrial CHP facilities and visited the Worley-operated UCLA cogeneration facility. We analyzed how sensitive the increase in net present value (NPV) of molten sulfur TES integrated fossil EGU is with the off-peak electricity price, peak electricity price and capacity payment. We also considered the baseline (no TES) configuration as part of this sensitivity study. The results showed positive economics of the molten sulfur TES integration concept across different electric power markets including CAISO, PJM and ERCOT. The molten sulfur TES provides positive economics (NPV_{TES}-$NPV_{Baseline} > 0$) for coal fuel price less than 3.5 and 3.8 $/MMBTU at off-peak electricity price of 20 $/MWh and peak electricity prices of 35 $/MWh and 75 $/MWh, respectively. For comparison, the 2020 average coal price delivered to the US electric power sector is 2 $/MMBTU and in the south Atlantic region it is 3 $/MMBTU [3], which is the highest price excluding New Hampshire in the New England census division. The annual averaged peak electricity price for 6-hour duration ranges from 35 $/MWh in the PJM market to ~50-55 $/MWh in the CAISO and ERCOT market [4-6]. A technology maturation plan (TMP) that describes the technology readiness level (TRL) of molten sulfur TES technology and post-project research and development necessary to further mature the technology was also developed.

2. CONCEPTUAL STUDY

The goals of the conceptual study were to complete a preliminary technical design for the integration of molten sulfur TES with a site-specific fossil fueled asset and estimate the performance of the energy storage component or subsystem and the overall integrated system. The study included the development of a process flow diagram and end-to-end heat, mass and water balances of a specific fossil asset for baseline operation without TES, and charge and discharge operation with molten sulfur TES integration. Among the various scenarios, the most feasible implementation plan involved molten sulfur TES charged using steam output from the boiler during low electricity prices and discharged to preheat the high-pressure feedwater supplied to the boiler during peak electricity prices. This integration scenario enables a 50% increase in turndown ratio (defined as the ratio of maximum to minimum output power), which means an increase in load controllability from 155-583 MWe (baseline) to 110-619 MWe (with TES).

2.1. Introduction

In response to increased penetration of variable generation (wind, solar) resources, existing conventional power plants are experiencing increased demand for operational flexibility that involves ramping up power production when electricity is needed and ramping down when adequate renewable energy is available. From a flexible operation perspective, the main limitation of fossil fuel EGUs is the minimum load achievable during times when output from variable generation peaks. The limitation is constrained primarily by the boiler combustion dynamics and is termed minimum stable load (MSL). Operating the system below MSL compromises combustion stability, reliability and increases emissions. Hence, when the electricity demand for the unit falls below MSL, the asset operator can either reduce the power output by running the boiler at the minimum stable thermal load and vent steam to match the turbine output to the demand which will result in a loss in energy efficiency, or disconnect the unit from the grid and incur loss in income.

The penetration of near-zero marginal cost resources (wind and solar) also influences the locational marginal pricing (LMP). Figure 2 shows the monthly-average hourly electricity prices in the CAISO market along with the renewable output from solar. As output from solar peaks, the average hourly energy price drops (Fig. 2) because of the near-zero marginal cost of solar. However, the 2021 average marginal cost of generating power from a fully depreciated coal power plant is 42 $/MWh [7]. Thus, operating a fossil-fired power plant during low energy price hours will accrue losses due to solar contributions, and formerly baseload fossil-fired power plants are increasingly forced to operate in cycling mode with frequent start-ups and shut-downs. This cycling results in decreased efficiency and increased emissions and operating costs due to the premature failure of thermal components from thermo-mechanical fatigue damage. The cycling cost combined with the curtailment of revenue from electricity sale could cause the plants to become economically unviable.

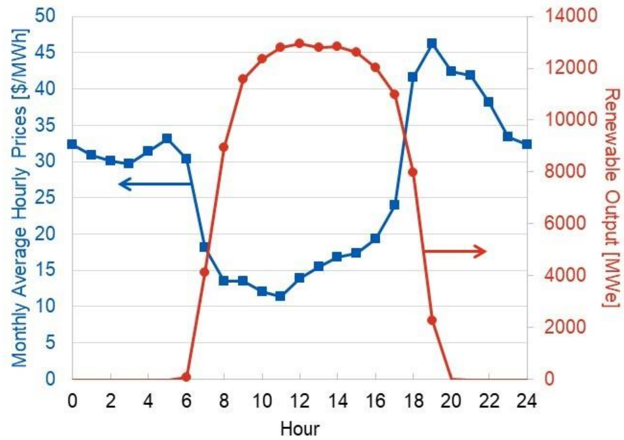

Figure 2: Average hourly electricity prices in May 2021 and solar output in the CAISO market [4]

The integration of low-cost molten sulfur TES can enable the power plant to operate below minimum stable load (MSL) during periods of low demand instead of conventional shutdown and startup or utility steam venting (loss in energy efficiency). Molten sulfur TES enables storing the excess steam when the load demand is below MSL, which typically occurs when energy prices are low, and then utilizing it later to generate electricity when energy prices are high. This results in increased net energy generation and revenues and avoids the cycling costs associated with hot start-up. The conceptual study focused on conducting thermodynamic analysis to evaluate and quantify the benefits of molten sulfur TES integration with the Cross Generating Power Station Unit #3 at Santee Cooper in South Carolina.

2.2. Thermodynamic Model and Analysis

Cross Unit #3 (built in 2007) located in South Carolina is a bituminous coal-fired subcritical power unit with gross output of 620 MWe at full boiler conditions with a turbine designed for a maximum gross output of 656 MWe. The turbine is oversized by 6% (an increase of 36 MWe) with respect to the maximum gross output achievable at full load conditions, which aligns well for the integration of the molten sulfur TES for use during peak load conditions. A simple illustration of the Cross-power plant configuration is shown in Figure 3 along with key process parameters at specific nodes. The nodes identified are potential locations that can be valved-off to extract steam for charging molten sulfur TES charge or to extract feedwater for discharging molten sulfur TES.

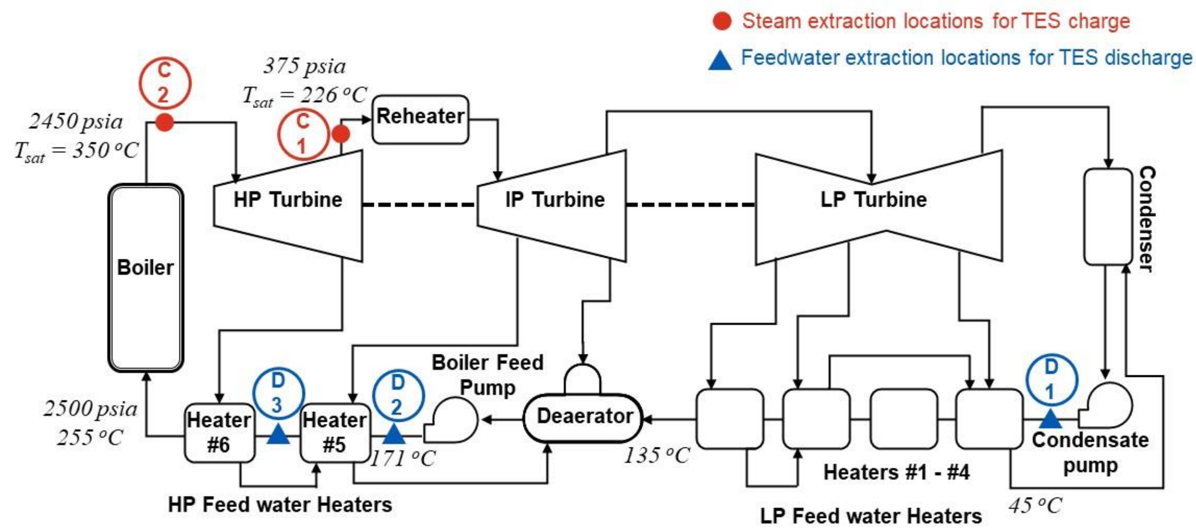

Figure 3: A simple representation of Cross power plant configuration

In order to the estimate the plant performance profile under various operating conditions, a Thermoflex [8] model was developed to simulate the plant. Figure 4 shows the baseline process configuration of the plant. The Thermoflex model predicted the operating state points of the working fluid at every node of the power plant cycle. The key outputs from the Thermoflex model used in the technoeconomic analysis were net plant output, boiler fuel consumption, plant net heat rate and net HHV efficiency for various configurations.

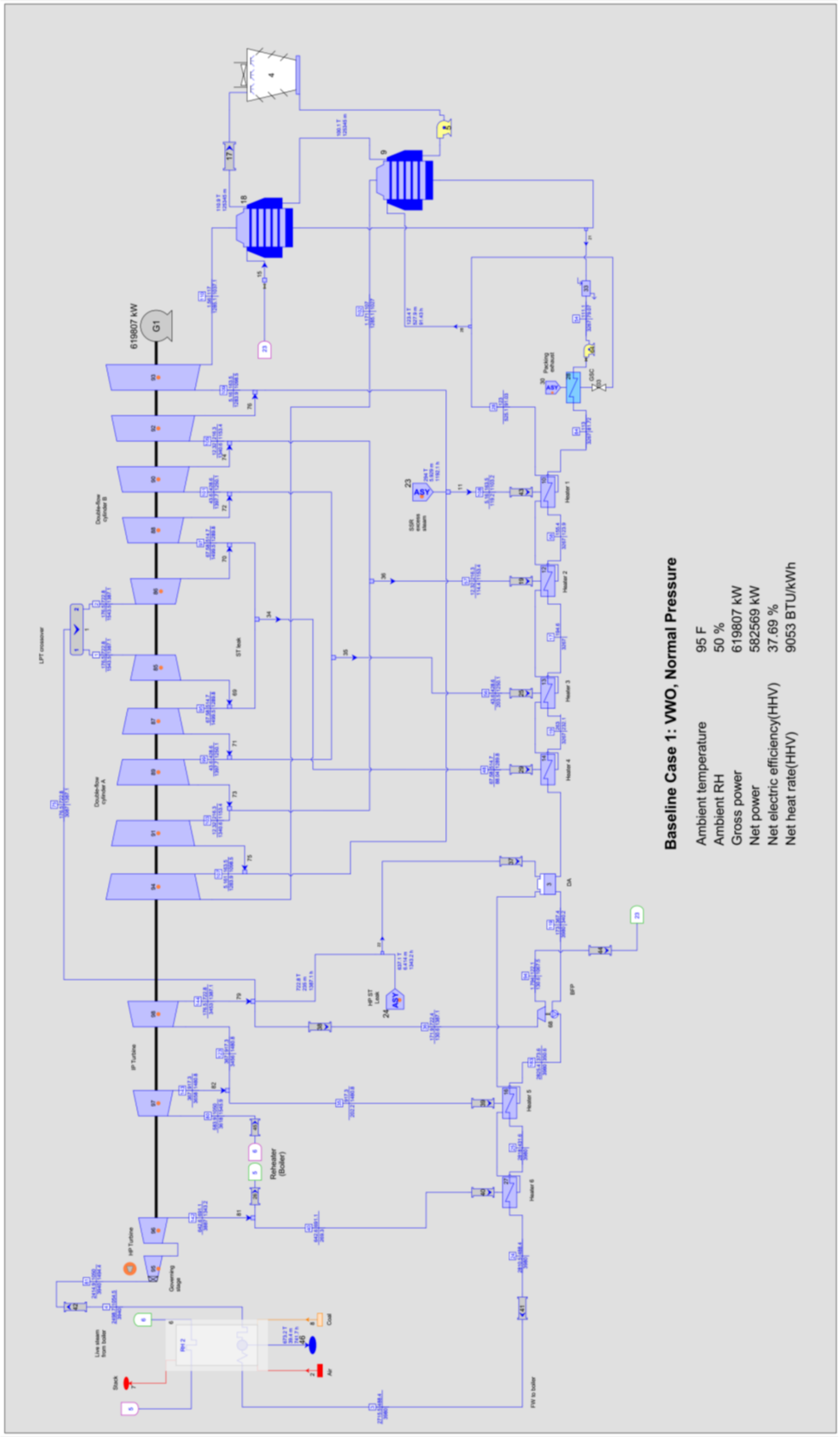
Baseline Case 1: VWO, Normal Pressure
Ambient temperature 95 F
Ambient RH 50 %
Gross power 619807 kW
Net power 582569 kW
Net electric efficiency(HHV) 37.69 %
Net heat rate(HHV) 9053 BTU/kWh
619807 kW
G1

Figure 4: Baseline heat and mass balance diagram: Valve Wide Open (VWO) condition

Since molten sulfur TES stores energy in the form of sensible heat, a temperature difference between the charge and discharge temperature is required for effective performance. To that end, charging and discharging steam at the same temperature using molten sulfur TES is thermodynamically unfavorable and we explored the technoeconomic feasibility of preheating high-pressure feedwater for TES discharge. Two different scenarios of the molten sulfur TES integration were considered for charge and three scenarios for discharge (Figure 3):

A. Charge Scenario #1 (labeled as C1 in Figure 3): Charging the sulfur TES using the cold reheat steam from the outlet of the HP steam turbine during periods of low demand.
B. Charge Scenario #2 (labeled as C2 in Figure 3): Charging the molten sulfur TES by extracting steam from the outlet of the boiler during periods of low demand.
C. Discharge Scenario #1 (labeled as D1 in Figure 3): Preheat low-pressure (LP) feedwater exiting the condenser and bypass LP feedwater heater train - Heaters #1-4.
D. Discharge Scenario #2 (labeled as D2 in Figure 3): Preheat high-pressure (HP) feedwater and bypass feedwater heater #5.
E. Discharge Scenario #3 (labeled as D3 in Figure 3): Preheat HP feedwater and bypass feedwater heater #6.

2.3. Discharge Integration Analysis

The thermodynamic analysis of the discharge integration scenarios provided details on the discharge heat rate required from molten sulfur TES and the achievable thermal to electric efficiency for the various scenarios listed above. In this analysis, we fixed TES storage duration to 6 hours. Multiple studies in the literature show that 6 to 8 hours of storage capacity is sufficient to capture 80 to 85% of the maximum arbitrage value [9-11]. Figure 5 shows the heat and mass balance for one of the discharge scenarios (discharge scenario #3) obtained using Thermoflex. In general, preheating high- or low-pressure feedwater using molten sulfur TES reduces the steam extraction from the turbine and increases power output during peak demand, while ensuring constant boiler load.

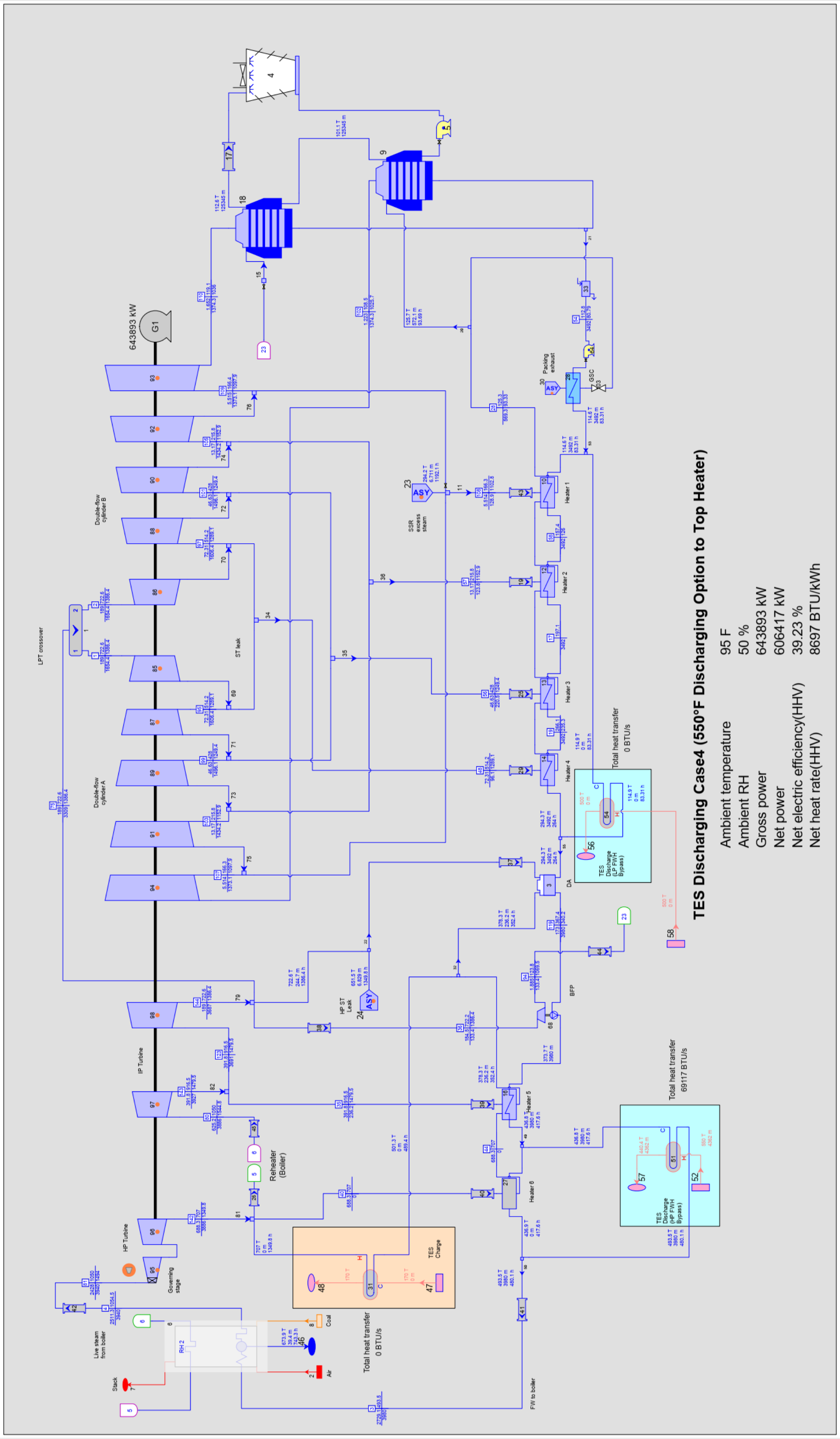

Figure 5: Heat and mass balance diagram for discharge scenario #3

Figure 6a compares the net heat rate required from molten sulfur TES for the various discharge scenarios and the corresponding net increase in electric power output achievable. As shown in Figure 6a, discharge scenario #1 that involves preheating low pressure feedwater using molten sulfur TES and bypassing LP feedwater heater train(heaters #1 to #4 in Figure 3) requires the highest heat rate. Nevertheless, the corresponding achievable increase in electric power is small because the LP feedwater heater extracts low-pressure steam from the LP turbine, which has low exergy content. Hence, discharge scenario #1 provides the least benefit in terms of increase in plant net power output. The net heat rate requirement for discharge scenarios #2 and #3 is ~75 MWt and the net increase in plant output achievable is between 23-24 MWe. At the full boiler load condition, an increase in electric power by 24 MWe from molten sulfur TES discharge scenario #3 will result in turbine output of 644 MWe that is less than the turbine nameplate capacity of 656 MWe (Section 2.2), and hence feasible.

Figure 6b shows the discharge efficiency (η_D), which is calculated as follows:

$$\eta_D = \frac{\Delta P_D}{\dot{Q}_D} \times \eta_{TES} \qquad [1]$$

where ΔP_D is the net increase in net electric power during discharge, $\dot{Q}_D$is the net heat rate required from molten sulfur TES and η_{TES} is the thermal roundtrip efficiency of the molten sulfur TES. Our heat loss analysis showed that η_{TES} with 15" thick fiber glass insulation is > 96% and in this analysis η_{TES} was fixed at 96%. Round-trip efficiency as high as 95% has been demonstrated for 105 MWh pilot scale molten salt storage system [12]. It is evident from Figure 6b that discharge scenarios #2 and #3 that involve bypassing HP heater #5 and #6, respectively provide almost similar benefits in terms of discharge efficiency at 31-33%. Preheating LP feedwater using TES results in low thermal to electric efficiency. Hence, we establish that it is desirable to preheat HP feedwater heater (discharge scenarios #2 and #3) using molten sulfur TES during peak load operation for high thermal to electric efficiency and high ΔP_D (Figure 6).

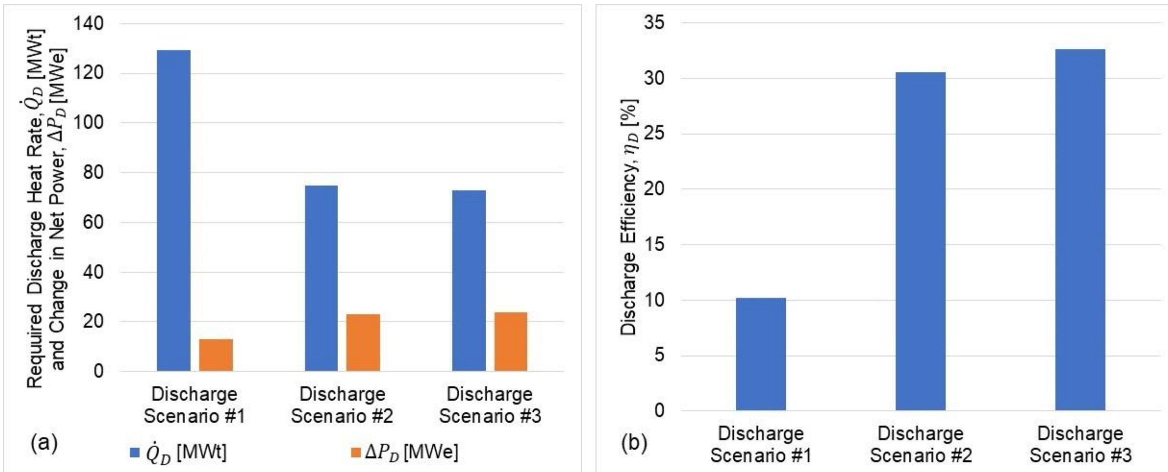

Figure 6: (a) Maximum heat rate and increase in electric power achievable and (b) Discharge efficiency for the various discharge scenarios

Figure 7 illustrates a simple process flow diagram of molten sulfur TES configured for preheating HP feedwater from the deaerator in discharge scenario #2. The inlet temperature of HP feedwater (190 ºC if bypassing heater #5 in discharge scenario #2 and 225 ºC if bypassing heater #6 in discharge scenario #3) into the discharge heat exchanger limits the minimum temperature molten sulfur TES can be cycled to during discharge operation. As shown in Figure 6a, the thermal to electric efficiency of discharge scenarios #2 and #3 are nearly same. So, we focused on discharge scenario #2 as it provided nearly 25% increase in TES volumetric energy density because sulfur TES can be cycled over a wider temperature range. As illustrated in Figure 7, high pressure feedwater from the deaerator at 190 ºC will bypass heater #5 and instead enter the discharge heat exchanger (HX). The HTF in the molten sulfur loop extracts heat from sulfur and transfers it to the HP feedwater in the discharge HX at a constant heat rate. From Figure 7, it is observed that the minimum required HTF temperature into the discharge heat exchanger is 235 ºC for discharge scenario #2. Hence, during the charge process, molten sulfur TES should be charged to temperature > 235 ºC. For 6 hours of discharge duration, the required molten sulfur TES capacity is 450 MWht for discharge scenario #2. Overall, the thermodynamic and process integration analysis of the various discharge scenarios showed that discharge scenario #2 that involves preheating HP feedwater from deaerator using molten sulfur TES and bypassing heater #5 is preferred.

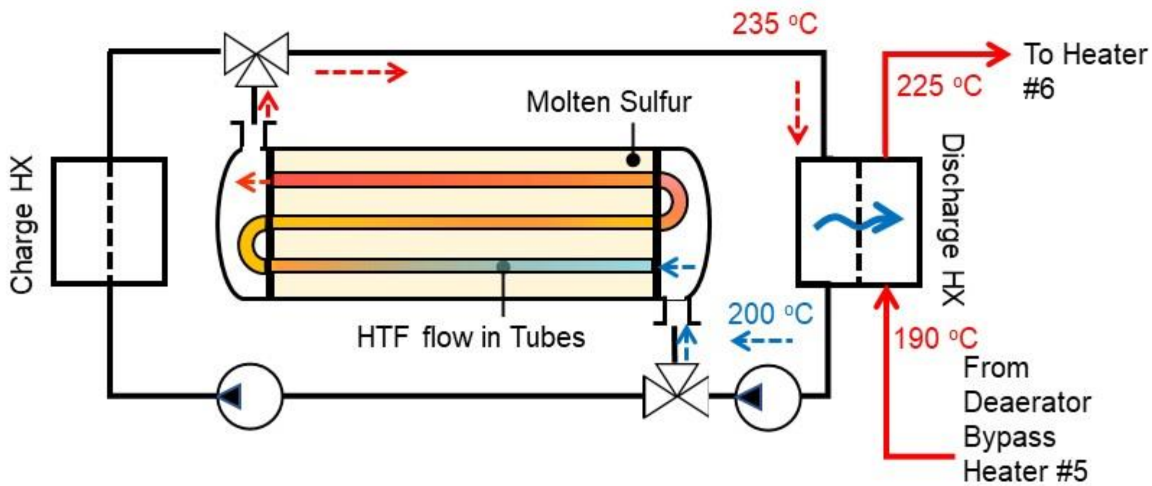

Figure 7: Discharge configuration for molten sulfur TES for bypassing high pressure feedwater heater #5 (discharge scenario #2)

2.4. Charge Integration Analysis

Figure 8 shows illustration of the two charge integration scenarios considered when the unit operates at MSL during off-peak times. Figure 8a shows visual representation of charge scenario #1 that involves charging molten sulfur TES using the ~375 psia (saturation temperature of 226 ºC), 301-311 ºC cold reheat steam. Figure 9 shows the heat and mass balance diagram obtained from Thermoflex for this integration scenario With this configuration, the maximum temperature molten sulfur TES can be charged to is ~ 235 ºC. . Charging molten sulfur TES to only 235 ºC limits the ability of molten sulfur TES to only preheat LP feedwater (discharge scenario #1) that was identified to have low discharge efficiency (Section 2.3) and hence, not considered for further evaluation.

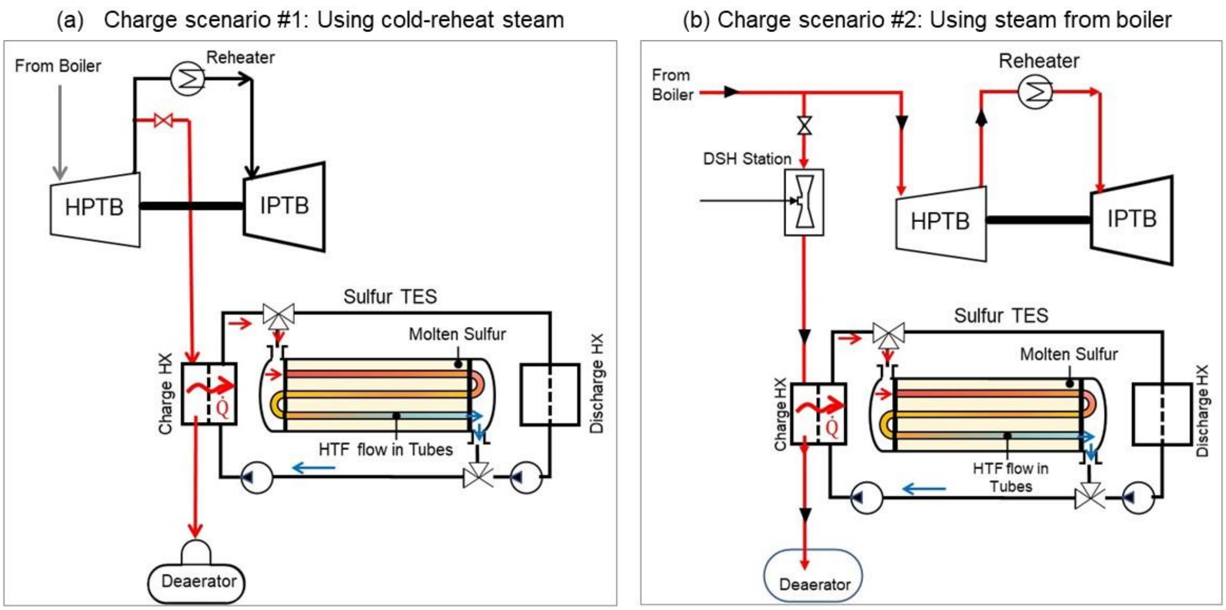

Figure 8: Illustration of charge integration scenarios

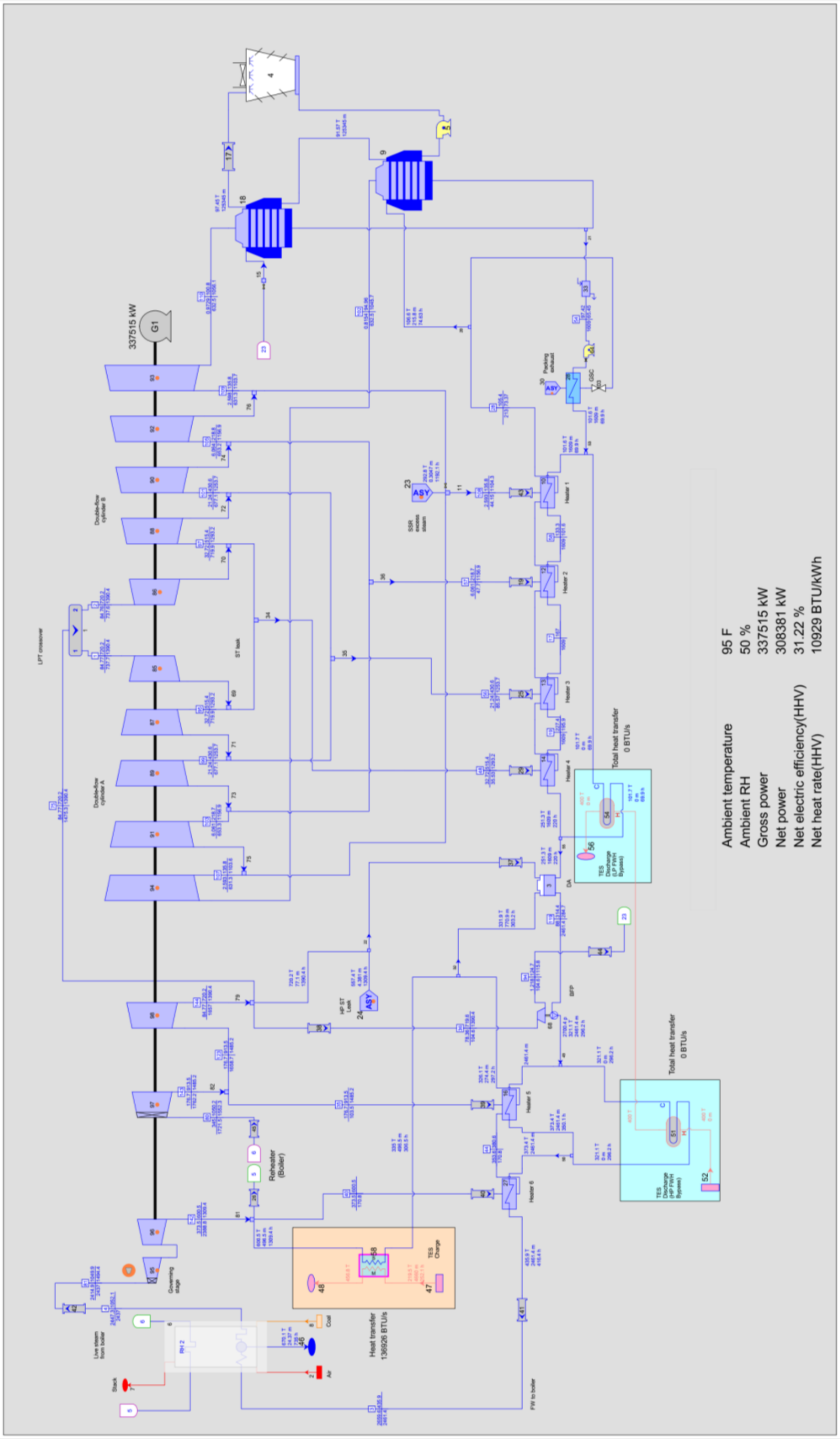

Figure 9: Heat and mass balance diagram for charge scenario #1

Charge integration scenario #2 involves charging molten sulfur TES using steam output from boiler as shown in Figure 8b. The steam is first de-superheated and throttled to 400 °C, 1250 psia (saturation temperature 300 °C) before it enters charge HX. The steam transfers heat to the HTF in the charge HX and exits as cold condensate that is returned to the deaerator. With this configuration, molten sulfur TES can be charged to a maximum temperature of 315 °C (maximum recommended continuous operating temperature of commonly available thermal oil based HTF). This method enables using the stored energy to preheat high pressure feedwater (discharge scenario #2) during the discharge process. For equal charge duration as the 6-hour discharge duration, the plant net output can be decreased by 46 MWe during minimum load operation, which represents a reduction in plant's minimum load by 29%.

A steady state oil to steam heat exchanger model based on NTU-effectiveness approach [13] was developed to determine the operation points of the charge heat exchanger and the surface area required. The model was verified by comparing against the thermal oil to steam heat exchanger design and operation data from a solar thermal plant [14]. Using the developed model, a feasible conceptual design of charge HX for charge scenario #2 was identified (Figure 10). Overall, we established that charging molten sulfur TES using steam output from the boiler (charge scenario #2) is favored because molten sulfur can be heated to higher temperature of 315 °C compared to 235 °C for charge scenario #1. Charge temperature > 235 °C is necessary to realize discharge scenario #2.

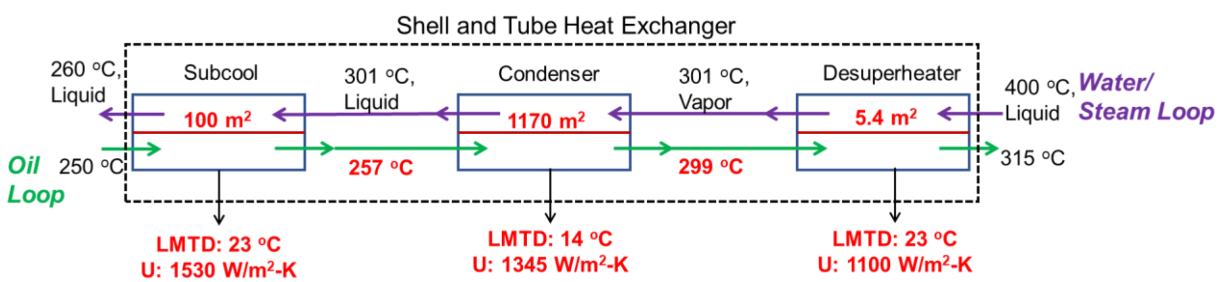

Figure 10: Feasible charge HX design and the process temperature determined from NTU-Effectiveness model for charge scenario #2.

2.5. Performance Evaluation

Depending on the integration scenario, we determined and plotted the net change in electric power during discharge and charge of the molten sulfur TES at full load (Section 2.3) and minimum load conditions (Section 2.4), respectively, in Figure 11. Overall, the lead concept that involves charging molten sulfur TES using steam output from the boiler (charge scenario #2) and bypassing HP feedwater heater #5 during discharge (discharge scenario #2) shows ~45 MWe net plant power reduction during charge and 23 MWe net power increase during discharge. The round-trip molten sulfur TES figure of merit (FOM) calculated using Eq. (2) based on the net increase in power output during discharge (ΔP_D) in relation to the reduction of the net power output during charge (ΔP_C) shows a value ≥ 0.5 for the lead concept. As defined earlier, η_{TES} in Eq. (2) is the thermal roundtrip efficiency of the molten sulfur TES.

$$FOM = \frac{\Delta P_D}{\Delta P_C} \times \eta_{TES} \qquad [2]$$

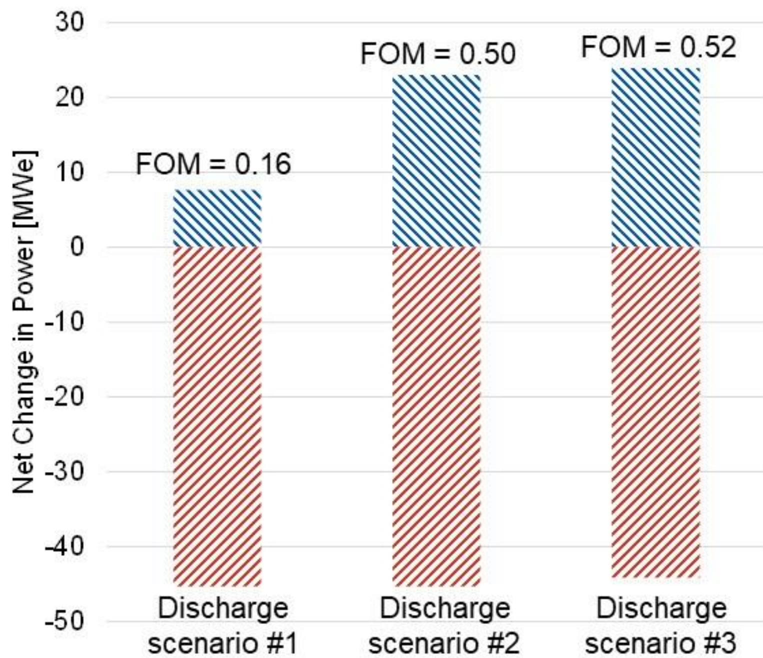

Figure 11: Figure of merit for the different discharge integration options and charge scenario #2. Values below 0.0 indicates net reduction in power achievable during molten sulfur TES charge and above 0.0 indicates net increase in power achievable during molten sulfur TES discharge

Based on the detailed charge and discharge analysis, the targeted parameters and concept for molten sulfur TES integration with the fossil fueled EGU are:

1. **Operation temperature: T_{max} = 315 °C and T_{min} = 200 °C**
2. **Discharge operation: 75 MWt constant discharge rate for discharge duration of 6 h for bypassing HP feedwater heater #5.**
3. **Charge operation: 56 MWt constant charge rate for charge duration of 8 h (typical off-peak duration hours) charged using steam output from boiler.**

3. TECHNOECONOMIC STUDY

We developed multi-domain transient system model and a cost model for the performance and economic evaluation of molten sulfur TES integrated with fossil fueled EGU to improve operation flexibility. The team developed a conjugate heat transfer model of the molten sulfur TES system and validated it against test data collected from our in-house experimental prototype. The charge and discharge rate requirements identified in Section 2 informed the design of the molten sulfur TES. We developed a cost modeling tool for molten sulfur TES based on detailed factorial and module costing methods that was verified against quotes received from manufacturers. Detailed technoeconomic analysis for different baselines and TES integration operation scenarios were conducted to quantify the economic and environmental benefits. From an economic perspective, depending on the operation difference between baseline and TES integrated plant, the net present value (NPV) for TES integrated configuration was calculated to be 29-134 $/kWe(plant gross capacity) higher than baseline at coal price of 2.6 $/MMBTU, off-peak energy price of 20 $/MWh, peak energy price of 50 $/MWh and capacity payment of 50 $/kWe with simple payback period of 4 to 12 years and decreases CO_2 emissions by ~ 7 lbs/MWhe.

3.1. Molten sulfur TES design calculations

The configuration of sulfur TES vessel as shown in Figure 1 and Figure 21 in Appendix B consist of a cylindrical shell with ASME 2:1 semi-ellipsoidal head. The storage vessel volume (*V*) depends on the TES storage capacity (Q_{TES}) and the fraction of volume occupied by the inert gas blanket at the top of the vessel, termed as ullage to allow space for molten sulfur expansion during thermal cycling.

$$V = \frac{Q_{TES}\,(1+v_{ullage})}{(\rho c)_{sulfur}(T_{max}-T_{min})\psi} \qquad [3]$$

where, $T_{max} = 315\ °C$ is the maximum temperature sulfur is charged to (Figure 10) and $T_{min} = 200\ °C$ (Figure 7) is the minimum temperature sulfur is discharged to. These values were determined from the discharge and charge integration analysis discussed in Sections 2.3 and 2.4, respectively. ψ denotes storage capacity utilization defined as the ratio of dispatched energy to the installed storage energy capacity (values between 0 and 1), that is dependent on the heat transfer between HTF and sulfur storage media, propagation of thermal front inside the molten sulfur TES during cyclic charge and discharge process, and constraints on the minimum and maximum HTF temperature exiting the molten sulfur TES during discharge and charge, respectively. The value of ψ was determined from molten sulfur TES thermodynamic simulations as discussed in Section 3.3. Figure 12 shows a visual illustration of the key process parameters that determine the sulfur storage capacity utilization.

The shell and head thickness (t) are determined from the ASME Boiler and Pressure Vessel code (BPVC) and includes corrosion allowance, as discussed below.

$$t = \frac{PD}{2 \times S \times E - 1.2P} + CA \qquad [4]$$

P is the summation of ullage pressure and hydrostatic pressure and D is the inner diameter of the molten sulfur TES vessel. The vapor pressure of sulfur at the top temperature of 315 °C is only 1 psia (sulfur boiling point: 444 °C) and so its contribution to the vessel pressure is minimal. CA is the corrosion allowance for a system lifetime of 25 years, E is the joint efficiency and S is the maximum allowable stress of the shell material at the design temperature.

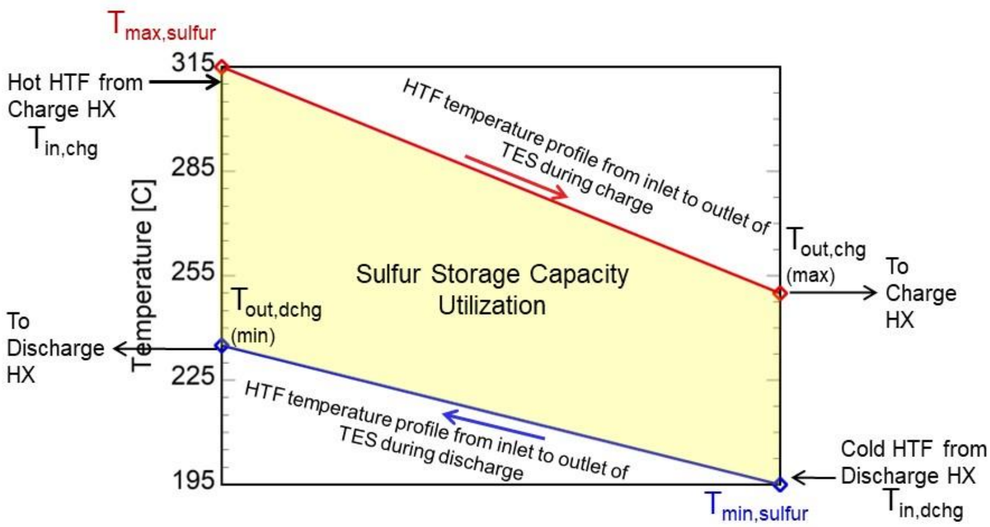

Figure 12: Visual illustration of the key process parameters that determine the storage capacity utilization.

3.2. Molten sulfur TES performance model

The dynamic performance model of sulfur TES was critical for design evaluation. With the integration of sulfur TES and fossil asset performance model, techno-economic analysis was conducted to identify the optimal configuration based on the assessment of net present value, payback period, etc. for various operating scenarios. The performance of the sulfur thermal storage system was modeled based on energy transfer between each component, including sulfur, tube wall, and heat transfer fluid (HTF). Each component was modeled as cross-sectionally lumped but the variation of temperature with axial location (from inlet to outlet) was accounted for. Each component was discretized, and energy conservation was applied to each grid and solved to predict its transient temperature field during thermal cycling. Appendix D provides mathematical details of the model.

The model inputs were 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 model predicted the spatial and temporal evolution of temperature profile in the tank during charge and discharge process, the transient variation in outlet HTF temperature and evaluated key performance metrics such as charge and discharge rates.

The conjugate heat transfer model of the molten sulfur TES component was developed using a finite volume approach to predict the spatial and transient variation in HTF temperature, sulfur temperature and heat rates. The model was verified using experimental test data obtained from our in-house 350 kWh prototype. Figure 13 compares the predictions from the numerical model for two different charge experimental runs and two different discharge experimental runs. The inputs to the model are the initial temperature, inlet HTF temperature and inlet HTF mass flow rate from experimental data. The average errors (standard deviation) between the numerical model predictions and experimental data for the results shown in Fig. 13a and b are 1.2% (1.6) and 1.4% (5.6), respectively. Overall, the numerical model results agree closely with the experimental data and can be used for making design decisions with high level of confidence.

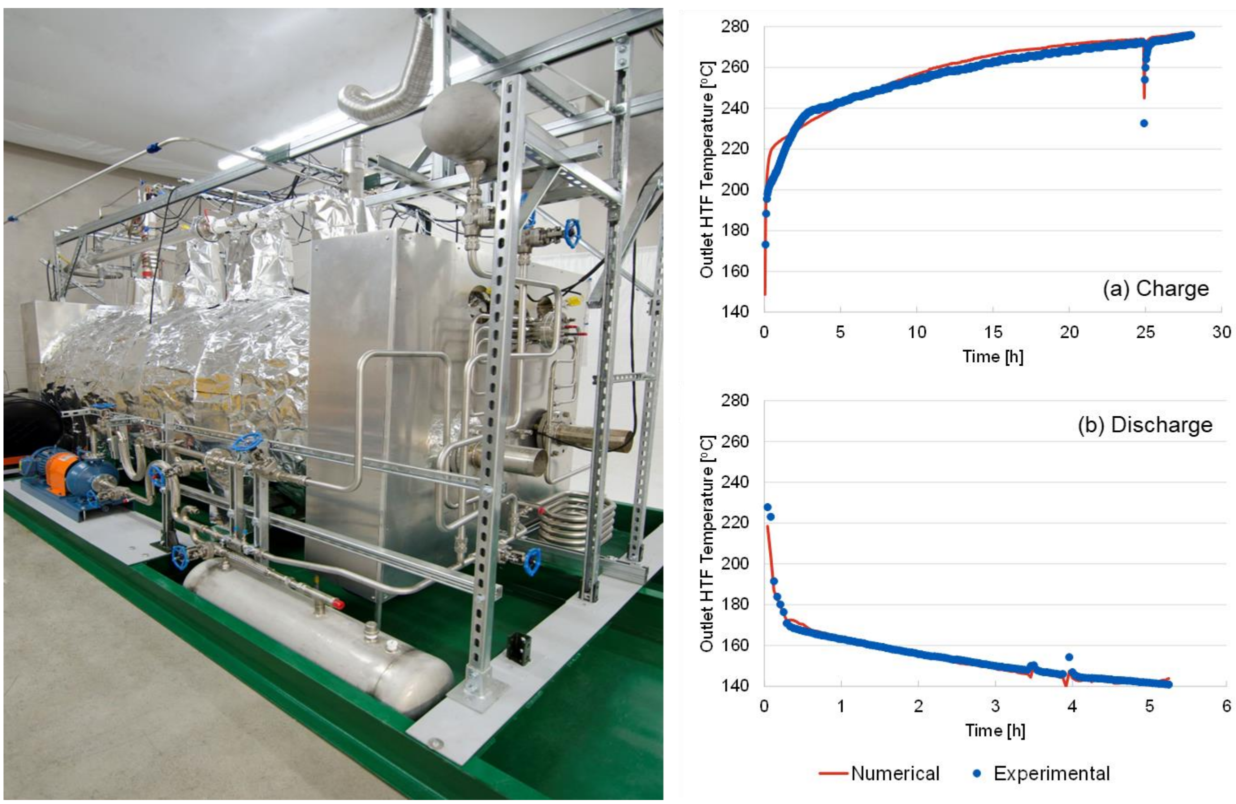

Figure 13: Photograph of 350 kWh sulfur TES prototype at Element 16's facility. Comparison between the experimental data and numerical predictions of the HTF outlet temperature obtained for charge and discharge runs

3.3. Molten sulfur TES design

Figure 14 shows the results obtained from the molten sulfur TES performance model for the operation parameters, viz. inlet temperature of HTF into the TES during charge and discharge ($T_{in,chg}$ = 315 ºC and $T_{in,dchg}$ = 200 ºC), required discharge/charge heat transfer rates, discharge/charge duration, and the discharge/charge cut-off temperatures ($T_{out,chg(max)}$ = 250 ºC, $T_{out,dchg(min)}$ = 235 ºC) discussed in Section 2 and schematically depicted in Figure 12. Figure 14a and 14b shows the spatial temperature profile of the HTF within the tubes inside molten sulfur TES at various time instants and it observed that a stable thermocline is formed. The thermocline enables discharging the TES at the highest temperature for most of the discharge duration. Note that in Figure 14a charging was simulated for 8-hour duration or until the HTF temperature exiting the molten sulfur TES reached $T_{out,chg(max)}$ and the discharge process in Figure 14b was simulated for 6-hour duration or until the HTF temperature exiting the molten sulfur TES reached $T_{out,dchg(min)}$. Cyclic simulations were continued until the system reached a periodically repeating steady state and it was determined that at least 4 to 5 charge/discharge cycles were required. Figure 15 shows the end of cycle spatial sulfur temperature profile within the molten sulfur TES and the percentage of shaded area in Fig. 15 provides a visual representation of the utilized energy (ψ) for this application.

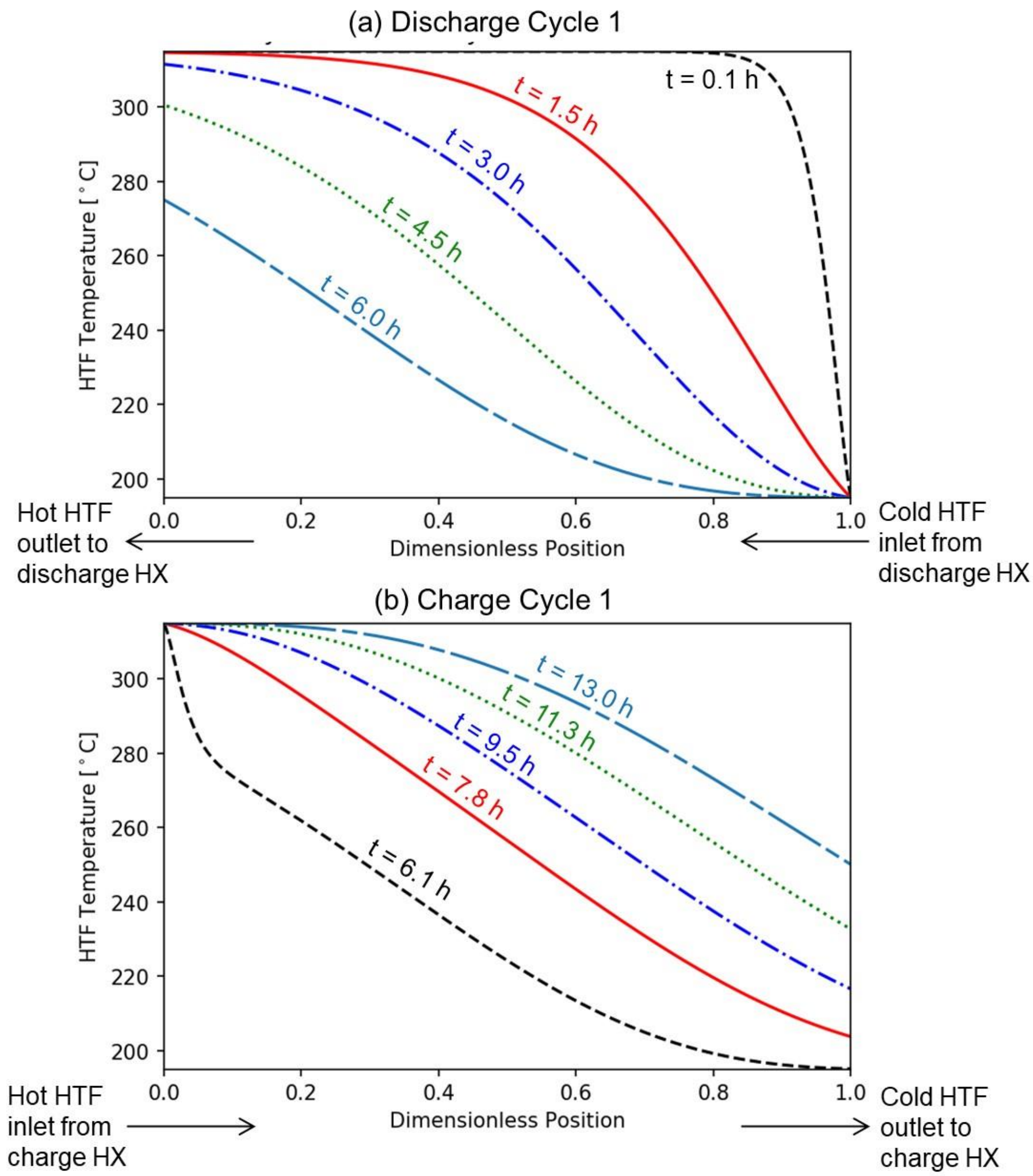

Figure 14: Transient and spatial HTF Temperature profile within molten sulfur TES during a charge/discharge cycle

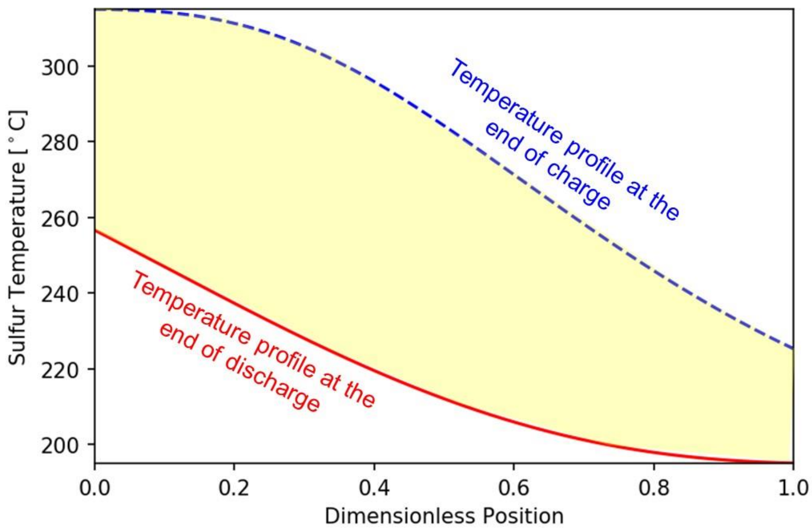

Figure 15: Temperature profile inside molten sulfur TES at the end of charge and discharge cycle after cyclic steady state is achieved. The shaded area provides a visual representation of the utilized energy.

Based on the evaluation using the performance model, the determined sulfur TES design specifications for integration with fossil asset are shown in Table 1 below.

Table 1: Molten Sulfur TES specifications for integration with fossil fueled EGU

Parameters	Value
Operating Temperature	200-315 °C
Discharge Rate	75 MWt
Discharge Duration	6 hours
Average Charge Rate	56-65 MWt
Charge Duration	< 8 hours
Sulfur Mass	17760 tons
Internal HX specific surface area	0.1 m^2/kWh
Tank Volume	12040 m^3

3.4. Molten sulfur TES cost model

To inform the sulfur TES system cost for techno-economic analysis, we developed a cost model validated using vendor quote. It accounts for the relative contributions of the various major components such as internal heat exchanger design, containment vessel, and sulfur on the total cost.

$$C_{direct} = C_{sulfur-TES} + C_{charge-HX} + C_{discharge-HX} + C_{BOS} \quad [5a]$$

$$C_{sulfur-TES} = C_{vessel} + C_{sulfur} + C_{htf} + C_{htf-tube} + C_{insulation} \quad [5b]$$

The CAPEX also includes the cost of balance of system (BOS) namely, heat exchanger, heat transfer fluid pump, heat transfer fluid expansion tank, piping, etc. The operation cost due to thermal oil pumping in feedwater heaters, TES, HX and the parasitic electricity consumption was also accounted for. The variable O&M cost related to cost of inert blanketing of the TES and other miscellaneous consumables was informed from literature and consultation with experts.

We compared the predictions from our cost model against quotes received from manufacturing firms for a ~ 1 MWh molten sulfur TES system (ΔT = 150 ºC). The storage vessel dimensions are 72" diameter, 233" tangent-to-tangent length, ¼" wall thickness with ASME 2:1 semi-elliptical head and made of stainless steel 316L. The internal HX geometry was based on tubes with a specific surface area of ~6 m^2/m^3 for a total surface area of 102 m^2. Table 2 compares the current prediction values against the manufacturer quote and satisfactory agreement is observed.

Table 2: Comparison of cost model prediction against quote received from manufacturers

	Tank Cost [$]	Internal HX Cost [$]	Total [$]
Cost Model Prediction	$126,433	$92,530	$218,963
Quote from manufacturing firm #1	$121,074	$88,452	$209,526
Quote from manufacturing firm #2			$241,303
Difference [%]	4.4%	4.6%	4.5-9%

Using the verified cost model, the molten sulfur thermal battery cost for integration with fossil asset was determined to be 95-105 $/kWhe.

3.5. Technoeconomic Evaluation

With molten sulfur TES CAPEX established, we conducted technoeconomic analysis for two different integration scenarios. The analysis assumed a peak duration of 6 hours and off-peak duration of 8 hours. The 6-hours of peak duration for the TES discharge is estimated to be a sufficient storage capacity to address intraday fluctuations of supply and demand (e.g. day/night solar cycle) and the typical off-peak duration is between 6 to 8 hours.

<u>Scenario #1</u>: (Figure 16) In the baseline (no TES) configuration, power plant undergoes daily startup and shutdown. For the baseline plant with no TES, the plant is assumed to be shut down during the off-peak hours since its load falls below MSL. For the plant integrated with molten sulfur TES, since the TES allows the plant to extend operation below MSL, it is assumed that the plant generates electricity at off-peak prices during the low-demand hours while keeping the boiler load

constant. Integration of molten sulfur TES avoids cycling cost associated with daily startup and shutdown.

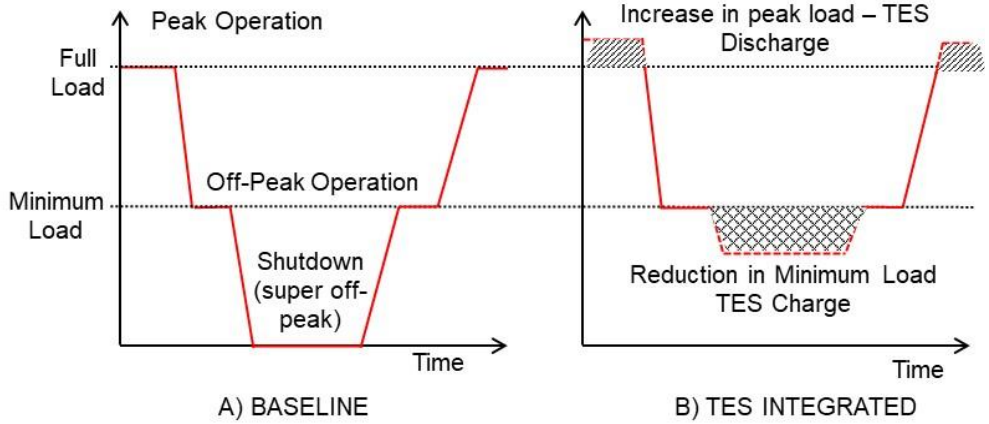

Figure 16: Scenario #1 operation profile of baseline fossil fueled EGU and in a TES integrated case

Scenario #2: (Figure 17) In the baseline (no TES) configuration, when the load requirement is below that of MSL, the boiler is operated at minimum stable thermal load and steam is vented to reduce electric power output and there is no cycling cost in the baseline case. Integration of molten sulfur TES recovers the waste steam and stores it for later dispatch when electricity prices are high. The fuel consumption is the same for both baseline and TES integrated mode of operation

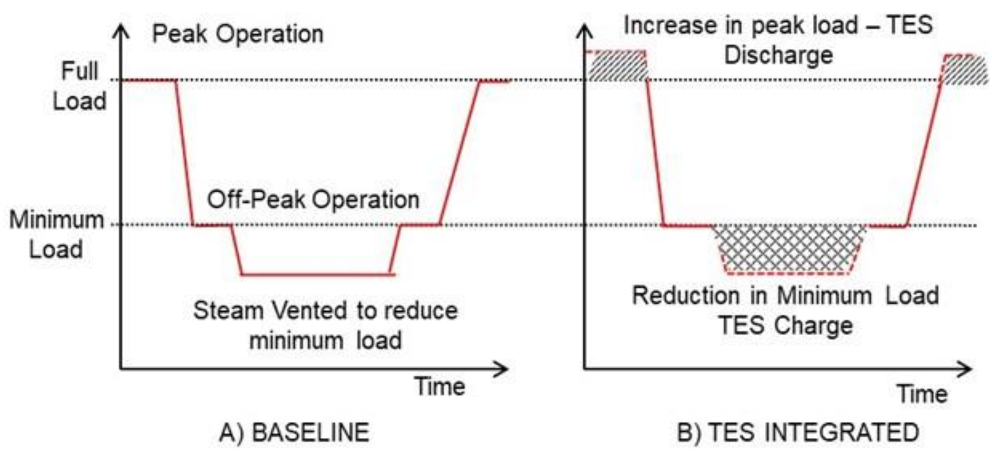

Figure 17: Scenario #2 operation profile of baseline fossil fueled EGU and in a TES integrated case

Table 3: Inputs used in the economic model

Inputs	Value

Discount Rate, R_{Disc}	3 %
Percent Equity	50 %
Interest on Debt	3 %
Plant Book Life, y_{PL}	25 years
General Escalation	2 %
Fuel Cost [15]	2.6 $/MMBTu
Owners Costs	10 %
Construction Period	24 months
Annual Operating Factor (Operating Hours/8760 hours)	78 %
Off Peak Duration	8 hours
Peak Duration	6 hours
Electricity Selling Price, off peak	20 $/MWh
Electricity Selling Price, peak	50 $/MWh
Cycling Cost	56 $/MW (capacity)
Cycling Frequency	1 per day

We determined that molten sulfur TES integration increases capacity factor of the plant by 33% in Scenario #1 (Figure 16) and by 3% in Scenario #2 (Figure 17). The results from the economic model for the above inputs (Table 3) show that the NPV of molten sulfur TES integrated case is higher than the baseline case for both the scenarios (Figure 18). Figure 18 clearly indicates that the increase in present value of revenue with integration of TES compared to the present value of installed CAPEX and increased O&M cost is higher for both scenarios, thus reflecting positive economic results for the molten sulfur TES integration. Depending on the energy market, power plant generators can also participate in the capacity market, in addition to making revenue from selling electricity in the wholesale market. For instance, PJM energy market provides capacity payment for power generators that are available to provide reserve capacity during periods of high demand or low availability from variable energy resources. Hence, Figure 18 also shows the economics for capacity credit of 50 $/kW-year based on the recent PJM reliability pricing model auction results [16]. As seen from Figure 18, due to added capacity of molten sulfur TES, the power plants participating in the capacity market can generate additional revenue with TES. Table 4 compares the increase in net present value with molten sulfur TES integration and simple payback period for various scenarios.

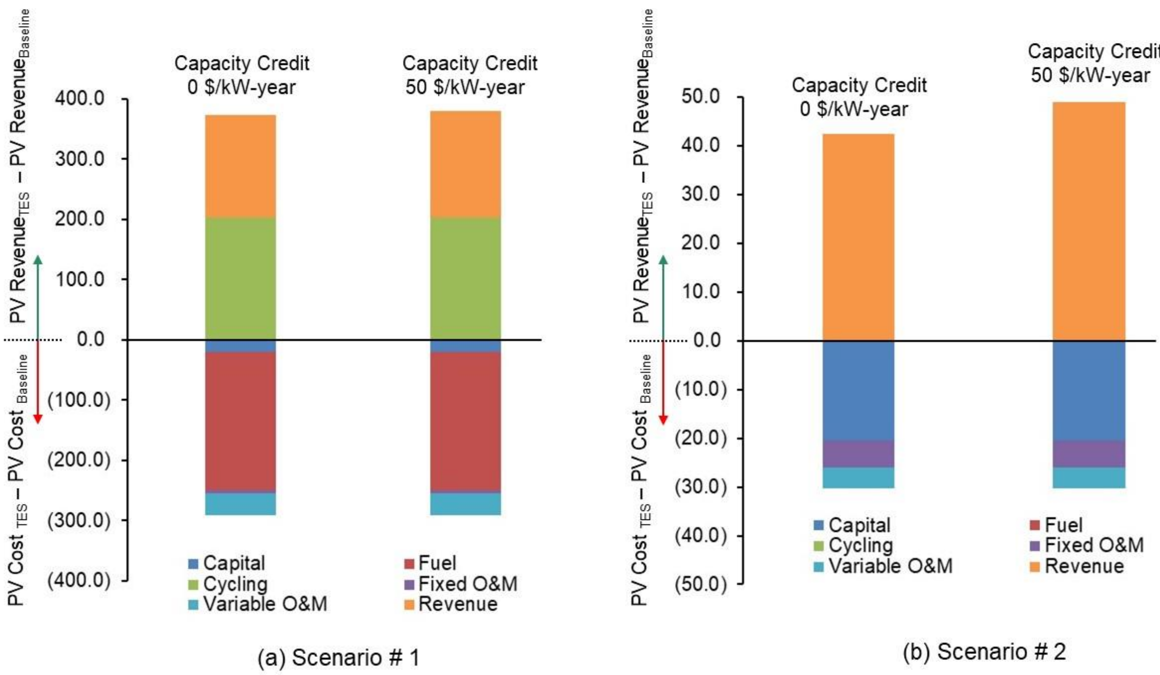

Figure 18: Comparison of Present Value (PV) for baseline and TES integrated plant configurations in both scenarios

Table 4: Technoeconomic comparison for the various scenarios

Operation Scenarios	NPV_{TES}-$NPV_{Baseline}$		TES Payback Period	
	Capacity Payment 0 $/kW-year	Capacity Payment 50 $/kW-year	Capacity Payment 0 $/kW-year	Capacity Payment 50 $/kW-year
Scenario #1 (Figure 16)	+81.5 $MM	+87.8 $MM	4.4 years	4.2 years
Scenario #2 (Figure 17)	+12.2 $MM	+18.7 $MM	13.8 years	11.5 years

Hence, the integration of molten sulfur TES can increase NPV of fossil fueled EGU by 19 to 88 $MM (29-134 $/kWe gross plant capacity) with a TES payback period of 4 to 12 years at off-peak electricity price of 20 $/MWh, peak electricity price of 50 $/MWh, capacity payment of 50 $/kWe and coal fuel price of 2.6 $/MMBTU.

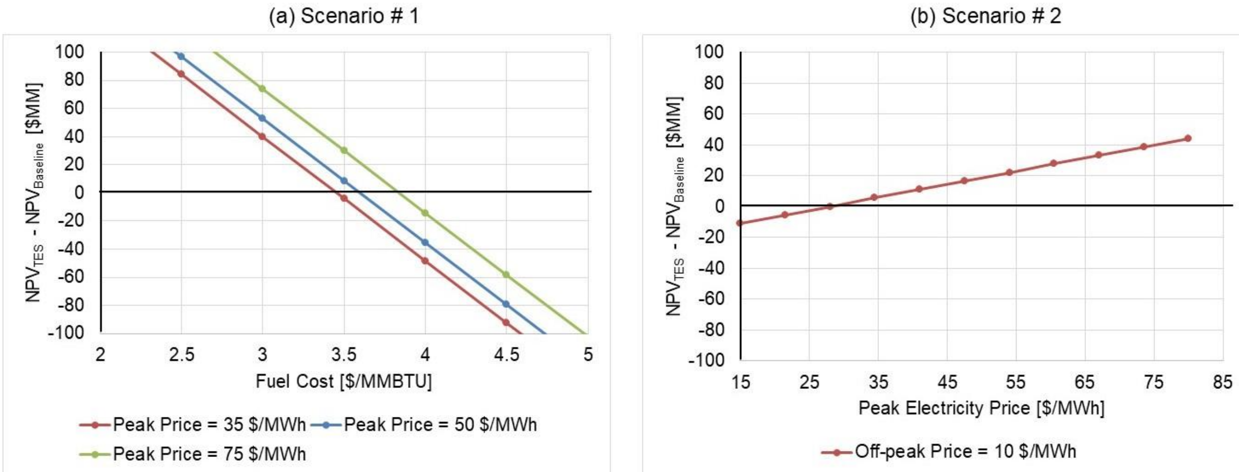

Figure 19: Sensitivity of fuel cost and peak electricity price on the technoeconomic of molten sulfur TES integrated plant compared to the baseline plant with no TES.

Figure 19a shows the sensitivity study of the coal fuel price and peak electricity price on the difference in NPV between TES integrated plant and baseline plant in scenario #1. The coal fuel price did not impact the economics of scenario #2 (Figure 18) because the fuel consumption is same in both baseline and TES integrated case. For scenario #2, only the impact of peak electricity price is shown in Figure 19b. The off-peak price was fixed at 20 $/MWh (Table 3). As expected, Figure 19a and 19b shows that the increase in peak selling price increases the NPV of TES integrated plant. In Scenario #1, the molten sulfur TES provides positive economics (NPV_{TES}-$NPV_{Baseline}$ > 0) for coal fuel price less than 3.5 $/MMBTU and 3.8 $/MMBTU at peak electricity prices of 35 $/MWh and 75 $/MWh, respectively (Figure 19a). The NPV of TES integrated plant is greater than baseline plant at higher coal prices because the increase in fuel cost price surpasses the revenue obtained from extended operation during the off-peak duration. For comparison, the 2020 average coal price delivered to the US electric power sector is 2 $/MMBTU and in the south Atlantic region it is 3 $/MMBTU [3], which is the highest price excluding New Hampshire in the New England census division. Hence, the sensitivity analysis in Figure 19a shows that molten sulfur TES integration concept described here provides positive economics for power plants located in various regions across US. The reported coal price in New Hampshire state in New England Census division is 4.2 $/MMBTU [3], which is higher than the threshold price of 3.8 $/MMBTU for TES to provide positive economics. Figure 19b shows that peak electricity price of 27 $/MWh, which is 1.35 times higher than the assumed off-peak electricity price of 20 $/MWh, is sufficient for molten sulfur TES integration concept to provide positive returns. For comparison, the annual averaged peak electricity price for 6-hour duration ranges from 35 $/MWh in the PJM market to ~50-55 $/MWh in the CAISO and ERCOT market [4-6]. **Overall, in the light of the obtained results from this conceptual study, integration of the low-cost molten sulfur TES to a fossil plant increases its cost effectiveness while adapting the fossil plant operation to increased penetration of non-dispatchable renewable generating capacities.**

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APPENDIX A – Technology Maturation Plan

TECHNOLOGY READINESS LEVEL

The sulfur thermal energy storage (TES) product development at the start of the project was at Technology Readiness Level: TRL-5.

In a previous research & development effort funded by ARPA-E and led by UCLA, a 10 kWht and 30 kWht lab-scale sulfur TES (sulfur sealed inside pipes and air heat transfer flow fluid flowing in the shell) prototype was designed and tested up to temperatures of 600°C. For target applications < 400°C that are applicable for industrial process heat and electricity generating units (EGUs), Element 16 technologies adopted a different TES design that involves molten sulfur in a tank with heat transfer fluid tubes suspended within — sulfur bath configuration — after identifying opportunities for cost reductions and manufacturing scalability. Element 16 received grants from California Energy Commission (CEC) to develop the sulfur TES technology for combined cooling heat and power systems (CCHP), industrial waste heat capture systems and electrical storage. The product development and testing activities completed prior to this project were as follows:

1. Element 16 Technologies built a laboratory-scale 50 kWht sulfur TES prototype and operated the system in the temperature range of 120-250°C. This prototype is the first sulfur TES design to use sulfur bath configuration. Sulfur was thermally charged to 250°C via electric resistive heaters. During discharge, ambient pressurized water was pre-heated to 120°C before it entered the sulfur TES (to avoid solidification of sulfur) and generated 220°C superheated steam at the outlet of the TES at a discharge rate of ~5 kWt.
2. Element 16 designed a 350 kWht sulfur TES prototype integrated with CCHP funded by CEC that was fabricated by PCL Industrial Services located in California. The system is integrated with a thermal oil heat transfer fluid loop and other CCHP components such as microturbine, absorption chiller, etc. and being tested in our facility. The system is designed to be charged using 300°C exhaust gas from a microturbine at a constant heat rate. During discharge, the system is designed to output hot thermal oil using a separate internal heat exchanger loop for generating hot water at 80°C to operate an absorption chiller. The sulfur TES performance model that will be used in this project to explore integration options with fossil assets will be verified and validated using some of the testing data collected from 350 kWht sulfur TES pilot prototype.
3. Element 16 recently completed design of a 1500 kWht sulfur TES system for the electric grid energy storage project funded by CEC. The engineering drawings of sulfur TES have been submitted to PCL Industrial Services for fabrication. The system is not expected to be built and tested until mid or late 2022.

Of the product development and testing activities listed above, the 50 kWht prototype represented most significant increase in system fidelity because of the major design change to a sulfur bath configuration, which is anticipated in all future commercial systems. It also increased system fidelity due to testing and validation of a laboratory scale unit performance in a relevant environment for this project's application. During this project, the following progress was made on each of the three activities above:

1. The 50 kWht prototype testing was complete before this project started.
2. The 350 kWht sulfur TES was tested, fully integrated with CCHP components in a relevant environment. Hence, based on the description provided in the TRL appendix, the sulfur TES technology advanced from a TRL-5 to a TRL-6 before the end of this project term, as anticipated in the initial Technology Readiness Plan.
3. Element 16's 1500 kWht sulfur TES systems for electric grid energy storage was fabricated and the entire system design was completed. Most of the system is fabricated and ready for installation.

Element 16's lowest cost molten sulfur TES has been developed for the 150 – 400°C temperature range. This low-cost TES presents many market applications including storing solar thermal industrial process heat for nighttime production, industrial waste heat capture, and integration of renewable energy with conventional fossil electric generation units (EGUs). Integration with fossil EGUs has been consistently suggested as a strong opportunity for Element 16's TES. Given the strong interest in improving the economics of fossil plants and the $93B market size of coal and natural gas plants in the US alone, this single application could represent the entire near-term commercialization effort for Element 16. As part of the project, Element 16 developed a Commercialization Plan which outlines key market segments and a clearly defined strategy to reach widespread product adoption.

A. COMPLETED WORK

The overall scope of the project was to complete a detailed feasibility study establishing the impact, cost and performance of sulfur TES system integrated with fossil energy applications. Planned activities included system performance and cost modeling for detailed techno-economic evaluation to derive optimal integration plan for increasing flexibility and improving economics of fossil-fueled electricity generating units. In addition, the scope involved developing a commercialization plan and technology gap assessment plan that lists future R&D required to commercialize the technology by 2030.

This project was successful in completing the proposed work, which involved creating a preliminary technical design for the integration of sulfur TES with fossil fuel asset, estimating the cost to construct and operate sulfur TES, estimating the performance of the sulfur TES component and the overall integrated system, and estimating benefits, both monetary and non-financial, to the asset owner, the electric grid, and the environment. Through these efforts, the integration of sulfur TES with fossil fuel EGU was developed for subsequent integrated system field test at a power plant, if the design work received future private or public funding. The level of project planning, cost estimation, and technical risk for a subsequent field test was significantly advanced including a combination of cost reduction, technical risk reduction, increased performance, increased benefits, improved cost and performance estimation, and matured commercialization planning.

The determined targets for the performance attributes of sulfur TES are:

(a) storage operation temperature range of 200 – 315°C: The temperature range is apt for integration with several sub- and super-critical fossil fuel assets. The results from this study showed that the intermediate thermal oil heat transfer fluid can be heated up to 315 °C using steam output from the boiler during periods of low demand for charging sulfur TES. This ensures boiler load is constant while the turbine power output is reduced. The top temperature of 315°C also ensures sulfur is below its atmospheric boiling point of 445°C that reduces the storage vessel cost. The bottom temperature of 200 °C ensures that the temperature of heat transfer fluid exiting the molten sulfur TES is hot enough to preheat high- pressure feedwater. Hence, less steam is extracted from the turbine to preheat the high-pressure feedwater supplied to the boiler, which increases power output during periods of peak demand.

(b) storage cost per unit capacity of 30-33 $/kWht: Using the verified cost model in Section 3.4, the molten sulfur thermal battery cost for integration with fossil asset was determined to be 30-33 $/kWht. The thermal to electric discharge efficiency as defined in Eq. (1) for using TES to preheat high pressure feedwater from the deaerator is 31%. Therefore, the storage cost per unit electricity generating capacity is 95-105 $/kWhe.

(c) discharge duration of atleast 6 hours: Storage duration of 6 hours addresses the goal of intermediate duration needs by being able to provide sufficient storage to address intraday fluctuations of supply and demand (e.g., day/night solar cycle, errors in forecasted demand). In addition, studies in the literature show that 6 to 8 hours of storage capacity is sufficient to capture 80 to 85% of the maximum arbitrage value [9-11].

(d) discharge rate of 3.25 MWt per 1 MWe increase in plant electric power output and thermal charge rate ≥ 75% of the discharge rate. The identified charge and discharge rates enable a 50% increase in power plant's turndown ratio (defined as the ratio of maximum to minimum output power).

The 350kWht CCHP-TES test loop built for the CEC project was instrumented with thermocouples, pressure sensors, flow meters etc. and connected to a data logger. The collected data from the CEC project was used to validate Element 16's sulfur TES performance model. This experimentally validated performance was used in this Fossil Energy project's technoeconomic modeling..

B. POST-PROJECT PLANS

At the end of this project's first phase, Element 16 provided a comprehensive feasibility study that includes technoeconomic and digital twin modeling of molten sulfur TES integrated with example EGUs, with real world data provided by project partners Worley, and provided commercialization plans for the product. The next step for post-project work is to use the results of the feasibility study to design molten sulfur TES integrated with fossil EGUs that are interested in exploring sulfur TES integration.

This project was a computational study which did include scope for physical prototype or pilot development of the molten sulfur TES technology itself. Pilot projects are ongoing under federal and non-federal funded efforts. Piloting this technology is critical for commercial adoption of molten sulfur TES, which requires capital expenditure from large energy and heavy industrial customers. To achieve full market readiness for molten sulfur TES integration with fossil EGUs, Element 16 must complete testing and data analysis of the 1500 kWht TES. This work is ongoing under CEC grant, the lessons of which are being implemented in the next generation of molten sulfur TES pilot test designs.

Power plant integration is not the only market application for sulfur TES. Since this project ended, Element 16 received a $1 million grant to pursue molten sulfur TES for industrial process heat applications. During this project, Element 16 received funding from the BIRD Foundation for similar sulfur TES production readiness efforts. Perhaps the biggest breakthroughs for Element 16 are its progress with commercial partners and clients. Element 16 has received management approval from a large international energy company for its first customer paid sulfur TES pilot project, which indicates the strong market demand for this technology and the provable maturity of this product development.

Beyond technology product development, a technology-to-market plan and financial investments are necessary to achieve market readiness. Prior to this project, Element 16's commercialization studies have not included integration with fossil EGUs and the potential to provide value to traditional and cogeneration power plants. The Commercialization Plan completed for this project, included findings from interviews with potential deployment partners in the identified target markets. Through conversations with power plant operators, power plant owners, renewable energy providers, utility partners, and potential industrial customers, "beachhead" early-adopter markets and early growth markets were discovered. If discussions continue as anticipated, Element 16's first paid pilot project is likely to use electricity from a cogeneration power plant and be integrated with solar thermal energy, which would be a strong confirmation that the commercialization analysis in this project had merit.

APPENDIX B – Technology Gap Assessment

Current state of the art:

None of the energy storage technologies have been demonstrated as a system integrated with a full-scale fossil EGU. Electro-chemical battery technology is cost-prohibitive at 300–400 $/kWhe, discharge durations are shorter (< 6 h), and have limited system lifetime (5-15 years) [18]. Among TES options, the most common configuration uses high-cost solar salts ($800-$1300/ton) [19] in expensive two-tank configurations. Other TES options such as latent heat-based phase change materials (PCMs) and sensible-based solid-state thermal storage media (concrete, rocks) are being investigated. The salts used in PCM 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 [20]. The main challenge associated with concrete based TES systems is heat transfer. Heat transfer is problematic due to the conduction dominated thermal transport from HTF to concrete, which has poor thermal conductivity. Hence, investigators have either pursued to chemically modify concrete to improve its heat capacity or use expensive embedded structures such as thermosyphons [21] or use large number of cast-in steel pipes to improve heat transfer between 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.

How the sulfur TES technology overcomes challenges:

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: (1) Sulfur is less than one-tenth the cost of molten salt at $40-$80/ton, compared with $800-$1200/ton for conventional salts, which commonly accounts for 60% of the storage system cost [19]. Figure 20 shows the cost of the sulfur storage fluid in $/kWh operating between 200-315 °C and compares it with state-of-the-art solar salt. The lower temperature for solar salt in Figure 20 was fixed at 240 ºC due to its high freezing point (220 ºC). The storage fluid cost of Hitec XL molten salt with low-freezing point which enables operation in the same temperature range as sulfur TES is also shown for comparison. The storage cost of molten sulfur TES system per unit electrical energy dispatch is ~95-105 $/kWh ($TES\ system\ cost/[\eta_{roundtrip} \times \eta_{thermal-electric}]$), which is ~3-4 times less than Li-ion batteries (TES system cost includes BOS such as discharge and charge HX, HTF system, piping, pump). (2)

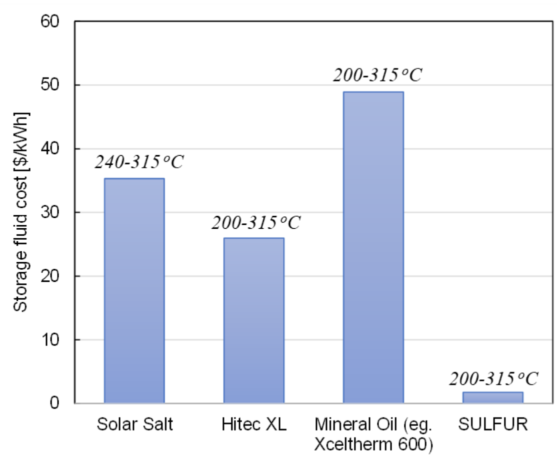

Figure 20: Comparison of sulfur storage fluid cost against other alternatives

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. (3) Sulfur requires little-to-no electrical trace heating to keep it molten due to its low freezing point (~105 °C), which ensures low parasitic load and low operation and maintenance cost. (4) Element 16 uses a single-tank design with sulfur contained within a vessel (Figure 21), and an intermediary thermal oil heat transfer fluid with low freezing point (typically less than 0 °C) is used. Table 5 compares molten sulfur TES attributes against lithium-ion battery.

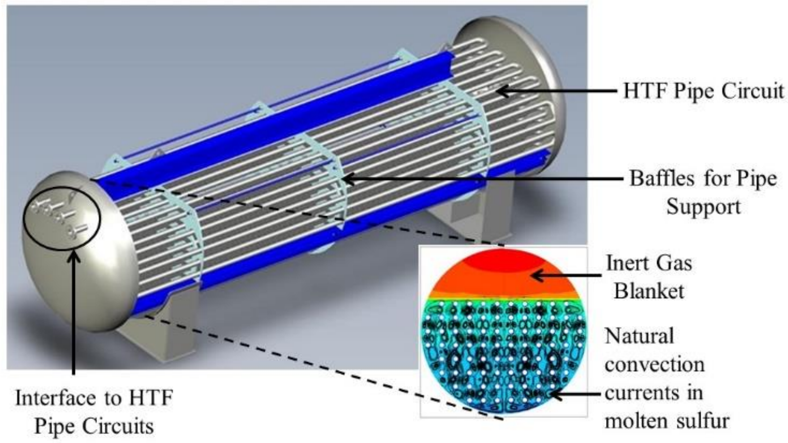

Figure 21: Schematic illustrating the internal structures of molten sulfur TES. The inset plot shows representative temperature contour and natural convection current streamlines in molten sulfur.

Table 5: Comparison of molten sulfur thermal battery attributes against electrochemical battery

Comparable Attributes	*Li ion Battery [17]*	*Molten Sulfur Thermal Battery*
LCOS	0.6-1.0 $/kWhe	0.2-0.3$/kWhe
Storage Cost	300-400 $/kWhe	95-105 $/kWhe (Includes BOS such as discharge and charge HX, HTF system, piping, pump)
Storage Duration	2-4 hours	6-8 h
Lifetime	~2-5 years	20-30 years
Number of charge/discharge cycles	300-500	>5,000
Degradation Rate	0.3% per day	N/A

<u>Key Technical Risks/Issues Associated with sulfur TES Technology</u>

A key technical challenge is to identify materials compatible with sulfur at the proposed operation temperature range. Based on corrosion studies conducted in collaboration with Intertek, we have identified low-cost alloys that exhibit high corrosion resistance against sulfur. The results from our recent accelerated diurnal thermal cyclic corrosion test of various samples immersed in molten sulfur thermally cycling between 150 ºC and 300 ºC for duration greater than 1000 h show that austenitic stainless steel 300 series are very compatible with sulfur under the conditions expected in our thermal storage technology with corrosion rates less than 20-25 microns per year. In addition, mechanical testing on the thermally cycled samples showed that the difference in tensile strength and yield strength between the thermally cycled samples exposed to sulfur and unexposed sample was less than 3% suggesting that stainless steel alloys are compatible with molten sulfur and the required corrosion allowance for system lifetime of 30 years is minimal. The corrosive nature of sulfur that is widely reported in literature is limited to molten sulfur stored in carbon steel tanks and exposed to air. However, Element 16 uses a single tank configuration with molten sulfur stored in a vessel that is hermetically sealed and blanketed with inert gas such as nitrogen (see Figure 21). Extensive long duration corrosion testing of stressed and welded samples in hot molten sulfur showed no evidence of stress corrosion cracking and intergranular corrosion of the weldments.

Perceived Technology Gap and R&D needed for commercialization

Element 16 technologies built a 350-kWh molten sulfur prototype for integration with small scale combined cooling heat and power unit (Figure 13). The molten sulfur TES prototype is designed to collect heat from Capstone microturbine exhaust that has similar properties to hot air. Hence, the internal heat exchanger in the sulfur TES used for charging is designed for accommodating gaseous phase heat transfer fluid. Waste heat in the form of exhaust gas from the microturbine is pumped into the sulfur TES at a constant mass flow rate and temperature. The molten sulfur TES discharges heat to an absorption chiller, which requires hot water around 80 °C, a negligible technical hurdle compared with preheating feedwater to 200-220 °C in the identified integration concept with Santee Cooper fossil electricity generating unit. The system was successfully tested for multiple charge/discharge cycles and the collected data was used for initial validation of computational models that was developed in this project. Table 6 below shows a quick overview of current R&D status of the sulfur TES technology development and compares it against the proposed target that is necessary for it to be ready for site-specific engineering scale prototype.

Table 6: Sulfur TES Product Specification Sheet

Metric	*Where we are*	*Where we want to be?*
TES Maximum or HTF Inlet Temperature	290 °C	300-345 °C
Storage Capacity	350 kWht	>5 MWht
Discharge Output	Hot water Generation at 80°C	Pressurized hot water generation at 200-220 °C
Operating Life	5 years	25 years

Regulatory Standards	N/A	Product design and qualification meets the ASME standards.
Flexible Operation	N/A	Advanced control technology for dynamic daily operation and flexible operation modes.

We have on going R&D grants sponsored by California Energy Commission that involves design and testing a 1.5 MWht sulfur TES that is charged to an upper temperature of 300 ºC using thermal oil heated in an electric heater. During discharge, the hot thermal oil output from the sulfur TES will generate hot water in a heat exchanger to drive a power generation unit. The sulfur TES unit being fabricated is designed to operate between the temperature range of 150 – 400 ºC. We have completed engineering drawing of the sulfur TES unit that was fabricated by PCL industrial services. In a recently funded DOE project, Element 16 aims to pilot a sulfur thermal energy storage system integrated with an outdoor solar thermal facility for industrial process heat applications that require process steam at temperatures of ~ 200 °C. The sulfur TES will be designed and tested to charge using variable heat load profile during peak hours of the day that outputs hot thermal oil at temperature of 300 °C, and discharge hot oil at temperature > 205 °C at a constant heat rate when renewable is unavailable. The metrics planned for pilot testing through the DOE SETO project closely aligns with the performance metrics required for the sulfur TES integration concept with fossil EGU. Successful testing will advance the TRL of the proposed technology to 6 and other pilot demonstration, testing and commissioning activities will be necessary to advance the TRL to 8 and above.

APPENDIX C – Commercialization Plan

1. Market Opportunity:

The competitive advantage of our product is the breakthrough in cost reduction of TES, which will make integration with fossil assets cost effective for the first time. This cost reduction is achieved through the use of extremely low-cost molten sulfur as the storage fluid. Sulfur is $80/ton, compared with $800-$1300/ton for state-of-the-art conventional salt storage media, which comprises ~80% of the cost of current TES systems. Other thermal storage technologies current in development includes solid storage like cement and rocks, but their extremely low thermal conductivity requires expensive heat transfer enhancements and large footprint. By maintaining the benefits of liquid thermal storage media like molten salt, while dropping the cost by an order of magnitude, Element 16 can offer solution that outperforms and undercuts all TES currently at pilot scale.

Element 16's lowest cost molten sulfur TES has been developed for the 150 – 400 ºC temperature range. This ultra-low-cost TES presents a large number of market applications including storing solar thermal industrial process heat for nighttime production, industrial waste heat capture, and integration of renewable energy with conventional fossil electric generation units (EGUs). Integration with fossil EGUs has been consistently suggested as a strong opportunity for Element 16's TES and could be a component of the market applications mentioned previously.

Element 16 has also started working with Searles Valley Minerals (SVM) to develop a molten sulfur TES pilot under an agreement with the California Energy Commission. SVM uses a fossil cogeneration power plant to supply electricity and process heat. Element 16 is working with SVM and solar project developers to better understand the opportunity to develop integrated renewable and conventional energy systems. Element 16 is also working with Advisian and Worley, which conducts pre-FEED and FEED studies and operates fossil EGUs around the world. With these partners, Element 16 designs sulfur TES for the ultimate end use customer's and project partner's real-world engineering and financial considerations. Element 16's 350 kWh demonstration project was fabricated by PCL Industrial Services. PCL is one of the largest contracting and construction companies in North America and has the capability to construct TES systems at the scale required by fossil EGUs.

As is the case with SVM and Worley partnerships, this project supported the integration of TES with conventional EGUs. Element 16 previously supplied similar project proposals to companies such as Occidental Petroleum and Petroleum Development Oman, both of which use natural gas combined heat and power plants to support thermal enhanced oil recovery operations. In the US, Occidental also operates some of the nation's largest cogeneration power plants for chemical production facilities. For early product sales, Element 16 expects to work closely with the end user (the EGU owner, e.g. Rio Tinto, AB InBev), the supply chain (e.g. PCL, EnFab), and engineering partners (e.g. Worley, Intertek). After the initial product deployment, Element 16 will seek distribution partnerships with engineering partners or major equipment suppliers (e.g. Siemens, Babcock & Wilcox). The market for integrated TES-EGU systems has not yet been developed, but relatively few competitors (Siemens Gamesa and Energy Nest – both solid state technologies) are expected to enter the market around the same time as Element 16.

While there are many potential applications for molten sulfur TES, this analysis is limited to TES-EGU integrations. Given the strong interest in this improving the economics of fossil plants and the $93B market size of coal and natural gas plants in the US alone, this single application could represent the entire near-term commercialization effort for Element 16. Due to inherent challenges with ramping electrical production in coal power plants, this was the first market for exploration for this project. In 2018, the US had 738 coal generators active with a net capacity of more than 240 GW (EIA). By increasing power output at all facilities by 15% (our results in Section 3.5 showed that TES can increase plant's capacity factor by as much as 33%) and assuming a 48% (EIA) current capacity factor, TES would produce an additional 150,000 GWh net power annually. With an average value of $20/MWh, this represents a value of $3B per year in total. Starting with a single installation, the increase in power generation for the average coal fired generator represents $4 million annually. Assuming a 25-year economic lifetime for TES, a single installation represents $100 million in electricity. There are approximately 10,000 coal, natural gas, and oil generators in the US with a total nameplate capacity of over 800,000 MW. If similar power output increases are possible across fuel types, TES integration could represent a $10B value. The value TES will provide to EGUs will likely be much higher than the increased electricity production value, since TES will reduce O&M costs due to avoided thermal cycling as discussed in Section 3.5.

Future markets for this technology could combine the two most active market areas molten sulfur TES: fossil EGUs and solar. Similar to Siemens Gamesa's ETES integration with wind and coal power plants, molten sulfur TES could allow solar thermal heat to provide steam to coal plants on-demand or 24-hours per day. In fact, these types of project that has received commercial interest ranging from California's deserts, Southern Italy, Arabian Peninsula, and the Australian Outback.

2. Company/Team:

Element 16 Technologies, Inc. is a startup company based in the Los Angeles area, founded in 2016. Started by Parker Wells as a graduate student at UCLA and his adviser, Professor Richard Wirz. Dr. Hamarz Aryafar and Dr. Karthik Nithyanandam, now CTO and Engineering Director of Element 16, were Postdoctoral Scholars at UCLA also developing thermal energy storage technologies. In addition to this project, Element 16 has received $9 million in research and development funding and private investment from the Department of Energy Solar Energy Technology Office, California Energy Commission, Techstars, GINCO Investments, and the BIRD Foundation. Element 16 also completed the National Science Foundation i-Corps program, Creative Destruction Lab Energy Stream, and MassChallenge. The company has received numerous awards and recognition, and has received multiple patents on its core thermal energy storage technology inventions. Through public and private funding/awards, and the startup programs that Element 16 has successfully completed, Element 16 has built a network of supporters, advisors, and partners who support the commercialization of the patented thermal energy storage technology.

Element 16 works directly with pilot partners and potential end users. Widespread deployment would be best supported by a company like Siemens (project partners on other proposals to the DOE), which already designs and sells related heavy industrial equipment. Element 16's demonstration TES equipment was fabricated by PCL Industrial Services, which provides once through steam generators

(OTSGs) to around the world. Element 16 has also worked with Worley for an EH&S Preliminary Review, the report from which has been provided to commercial partners, Intertek to support material compatibility studies, and Exponent on measurement and verification of sulfur thermal energy storage demonstrations. These on-going relationships eliminate significant supply chain risk with PCL Industrial Services for fabrication, Siemens for controls and integration, and Worley for establishing safety standards, permitting, and supporting Pre-FEED and FEED studies.

3. Intellectual Property:

There are an extensive number of patents for thermal storage technology but very few in the concept of using sulfur for thermal storage. From our existing patent literature, we found only one patent related to using sulfur as energy storage media viz., WO2010025692A1 assigned to Flagsol GmbH. The patent discloses methods of pumping low-viscosity sulfur saturated with hydrogen sulfide for use as both heat transfer fluid and storage media in solar thermal plants.

We strongly believe that our method is novel and substantially different from existing approaches. Our method avoids pumping hydrogen sulfide saturated sulfur which poses safety risk. Our concept involves sulfur stored in a tank with heat transfer fluid carrying tubes preferentially located within molten sulfur and the natural convection dynamics in molten sulfur promotes efficient heat transfer interaction between sulfur and the heat transfer fluid. Element 16 previously received two patents:

1. Aryafar, H., Nithyanandam, K. and Wells, P., Element 16 Technologies Inc, 2022. Systems and methods of thermal energy storage. U.S. Patent 11,280,518.
2. Aryafar, H., Nithyanandam, K. and Wells, P., Element 16 Technologies Inc, 2020. Systems and methods of thermal energy storage. U.S. Patent 10,876,765.

Element 16 has since received a notice of allowance on a third patent. The largest potential IP risks are due to the significant international interest in Element 16's developments of sulfur TES. In 2019, Element 16 held meetings in the United Arab Emirates, Oman, Bahrain, China, the Netherlands and Canada. Though COVID has slowed international in-person meetings, Element 16 still held in-person meetings in Switzerland, and with Italian and British company representatives. Patent Cooperation Treaty (PCT) and Gulf Cooperation Council Arab States (GCC) applications for select IP was filed for international protection.

4. Revenue Forecast:

Element 16 plans to sell molten sulfur TES to power plant owners, solar thermal project developers, and large industrial processing corporations through financeable projects. Element 16 Technologies, Inc. estimates sales revenues of $900 million and licensing revenues of $0 during the first 10 years of commercialization. There are two key reasons why Element 16 forecasts this level of success.

A) The market opportunity is large. By demonstrating TES-EGU integration, Element 16 is developing a product that works in $93B fossil power generation market and can keep existing power plants competitive in future high renewable penetration scenarios.

B) Element 16 has already proposed pilot projects under consideration. Element 16 is working with Petroleum Development Oman and has an ongoing waste heat demonstration project with Searles Valley Minerals (SVM) in California. PDO currently has a 300 MWt solar thermal process heat facility and two cogeneration power plants at the Amal Oilfield. SVM operates a fossil powered cogeneration power plant with another (currently non-operational) nearby. Element 16 has also built relationships with US-based food production and oil companies with cogeneration plants, which are potential pilot partners and early customers. During this project, Element 16 expanded its reach to start relationships with potential customers with cogeneration power plants and/or renewable energy installations locally and around the world. The demand for this type of product is strong and we have already developed early stage working relationships with companies that are tracking our technical and commercial successes.

APPENDIX D – Sulfur TES Thermodynamic Model Details

The coupled set of governing equations solved using an iterative finite volume framework for molten sulfur TES performance characterization are:

HTF: $$(\rho c)_{htf}\frac{\partial T_{htf}}{\partial t}+(\rho c)_{htf}v_{htf}\frac{\partial T_{htf}}{\partial x}=k_{htf}\frac{\partial^2 T_{htf}}{\partial x^2}-\frac{(T_{htf}-T_{wall})}{V_{tube,\Delta x}\{\mathcal{R}_{i,wall}+\mathcal{R}_{htf}\}} \quad [6a]$$

Tube Wall: $$(\rho c)_{wall}\frac{\partial T_{wall}}{\partial t}=k_{wall}\frac{\partial^2 T_{wall}}{\partial x^2}+\frac{1}{V_{wall,\Delta x}}\left\{\frac{(T_{htf}-T_{wall})}{\{\mathcal{R}_{i,wall}+\mathcal{R}_{htf}\}}-\frac{(T_{wall}-T_{su})}{\{\mathcal{R}_{o,wall}+\mathcal{R}_{su}\}}\right\} \quad [6b]$$

Sulfur: $$(\rho c)_{su}\frac{\partial T_{su}}{\partial t}=\frac{1}{V_{su,\Delta x}}\left\{\frac{(T_{wall}-T_{su})}{\{\mathcal{R}_{o,wall}+\mathcal{R}_{su}\}}-\frac{(T_{su}-T_{amb})}{\{\mathcal{R}_{tank}+\mathcal{R}_{ins}+\mathcal{R}_{eff,amb}\}}\right\} \quad [6c]$$

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 $\mathcal{R}$ 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 ($\mathcal{R}_{htf}$) was based on the Gnilenski correlation for single phase heat transfer fluid and Shah correlation for boiling heat transfer fluid obtained from literature [13]. The heat transfer coefficient on the sulfur side (h_{sulfur}) which appears in the sulfur natural convection thermal resistance term ($\mathcal{R}_{htf}$) is based on heat transfer coefficient for natural convection in an enclosure.