TECHNO-ECONOMIC ANALYSIS OF USING REVERSE OSMOSIS CONCENTRATE AS A LOW-COST THERMAL ENERGY STORAGE MEDIUM

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SIGNATURE PAGE

THESIS:	TECHNO-ECONOMIC ANALYSIS OF USING REVERSE OSMOSIS CONCENTRATE AS A LOW-COST THERMAL ENERGY STORAGE MEDIUM
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ABSTRACT

This thesis investigates the techno-economic analysis (TEA) of a thermal energy storage (TES) system that uses repurposed dehydrated reverse osmosis concentrate (ROC) as a phase change material (PCM) that will be the TES medium of the TES module. The ROC is an undesired byproduct of a water treatment technique used to desalinate seawater and surface water into potable water. This high concentrate salt is a helpful PCM for TES because of its high melting temperature, high heat capacity, and low costs that are explored throughout this research.

The Department of Energy's (DOE) goal is to reduce the Levelized Cost of Energy of TES for concentrated solar power (CSP) to be under 15 $/kWh by 2030. In this research, the TEA is performed to estimate the cost of TES using ROC salt from the Eastern Municipal Water District (EMWD). The overall cost of TES is estimated by considering the costs associated with transportation, evaporation, grinding, additives, heat exchangers, labor, and containment while considering a positive gain from obtaining the ROC from water treatment facilities. This analysis shows that the dehydrated ROC that goes through a phase change from solid to liquid through the process of melting supplies an increase in energy density that results in an overall reduction in TES cost. The results show a financial benefit using the dehydrated ROC as a storage medium for TES compared to the current state-of-the-art TES technology that uses solar salt that is at twice the value of the DOE's goal. All costs meet the SunShot Initiative's goal and for some cases, negative values that represent positive revenue. The inclusion of a system-level modeling analysis supplies the cost benefits for an electric-to-electric system.

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NOMENCLATURE

C_A	Cost of Additives ($)
C_C	Cost of Containment ($)
C_G	Cost of Grinding ($)
C_{HX}	Cost of Heat Exchanger ($)
C_L	Cost of Labor ($)
C_M	Cost of Miscellaneous ($)
C_{TES}	Cost of Thermal Energy Storage ($/kWh)
C_{Tr}	Cost of Transportation ($)
C_Z	Cost of ZLD ($)
$c_{p,c}$	Specific Heat of Containment (J/kg*K)
$c_{p,l}$	Liquid Specific Heat Capacity (J/kg*K)
$c_{p,s}$	Solid Specific Heat Capacity (J/kg*K)
$Ca(Cl)_2$	Calcium Chloride
$CaCO_3$	Calcium Carbonate
$CaSO_4$	Calcium Sulfate
E_{St}	Amount of Energy Stored (kWh)
G	Gain ($)
H_{fus}	Latent Heat of Fusion (J/kg)
KCl	Potassium Chloride
K_2CO_3	Potassium Carbonate
K_2SO_4	Potassium Sulfate
$MgCl_2$	Magnesium Chloride
$MgCO_3$	Magnesium Carbonate
$MgSO_4$	Magnesium Sulfate
NaCl	Sodium Chloride

$NaCO_3$	Sodium Carbonate
$NaSO_4$	Sodium Sulfate
SiO_2	Silicon Dioxide
T	Temperature (℃)
T_m	Melting Temperature (℃)
T_{max}	Maximum Temperature (℃)
T_{min}	Minimum Temperature (℃)

Greek Symbols

ρ_c	Density of Containment (kg/m^3)
ρ_l	Density of Liquid ROC (kg/m^3)
ρ_s	Density of Solid ROC (kg/m^3)
υ	Volume of ROC (m^3)
υ_c	Volume of Containment (m^3)

CHAPTER 1 INTRODUCTION

1.1 Climate Change

Global warming has proven to be one of the most impactful challenges of this 21st century. The United States National Oceanic and Atmospheric Administration (NOAA) has supplied data to show an increase in the global average surface temperature. The data describes that in the first 11 months of 2020 the global average surface temperature was in the top four warmest on record for each month. The data also shows that 2020 was ranked as the second warmest year since 1880 with respect to both the global average surface temperature of the land and the ocean. If the global average surface temperature of the land was compared to the previous years, then the data shows that 2020 was the warmest it has ever been since 1880. The data also shows that the 2020 global average surface temperature was 0.98℃ warmer than the 20th century average which has been increasing at an average rate of .18℃ per decade [1]. This increase of over five times the average shows how rapidly the average surface temperature is rising and why climate change is a global issue. The greatest contributing factor to this temperature increase is the excessive emission of greenhouse gases, primarily deriving from carbon dioxide. The atmospheric samples found in carbon dioxide direct measurements before 1950 have never exceeded a concentration of 300 ppm. Due to the increase in human activities and the use of fossil fuels, a significant increase in the concentration of carbon dioxide has appeared in these same locations with values as large as 407.4 ppm. This dramatic increase has led to projected carbon dioxide level values as large as 425 ppm found in the atmosphere by the year 2025 [2].

To combat this surge in the excessive emission of greenhouse gases, the Paris Agreement was created and adopted in 2015. This agreement was made as a legally binding treaty on climate change to reduce the average global temperature increase to a value of less than 2℃ and to achieve net-zero emissions by the year 2050 [3]. The significance of this agreement is that it was the first binding agreement to make the necessary arrangements and actions to combat climate change.

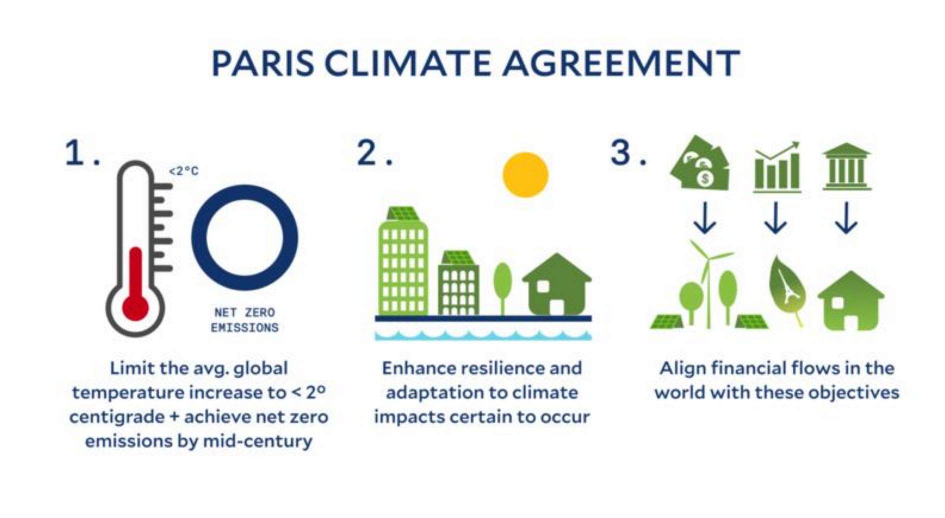

Figure 1: Paris Climate Agreement

Figure 1 shows how the goal of the agreement will lead to enhanced resilience and adaptation to the climate changes yet to happen. To achieve these goals, financial support needs to be supplied to incentivize the transition into renewable energy such as wind and solar power.

1.2 Desalination Waste Issue

Current available potable water sources that support the public such as rivers and groundwater wells are no longer enough to provide for the ever-increasing human population [4]. Therefore, alternative ways to produce potable water can be provided through the construction of desalination facilities near cities with access to large bodies of both fresh and non-fresh water. Membrane processes are used for water treatment techniques to desalinate seawater and surface water into potable water. Two of the major applied processes in desalination facilities are forward osmosis and reverse osmosis. Forward osmosis is a type of membrane technology that uses a semipermeable membrane to separate water from dissolved solutes. Reverse osmosis is performed in the same manner however the main difference is that in forward osmosis, osmotic pressure is the added pressure placed against the membrane to force the water through the membrane while in reverse osmosis, hydraulic pressure is used to press the water through the membrane. This research prioritizes the reverse osmosis (RO) process when referring to desalination facilities producing a potable water source. When desalination facilities use the RO technology, they can produce a continuous stream of fresh water from non-fresh water sources like oceans, streams, and lakes. The feedwater from the non-fresh water and brackish water is pushed through the semipermeable membrane where it is separated into the potable water and wastewater, which is highlighted below in Figure 2.

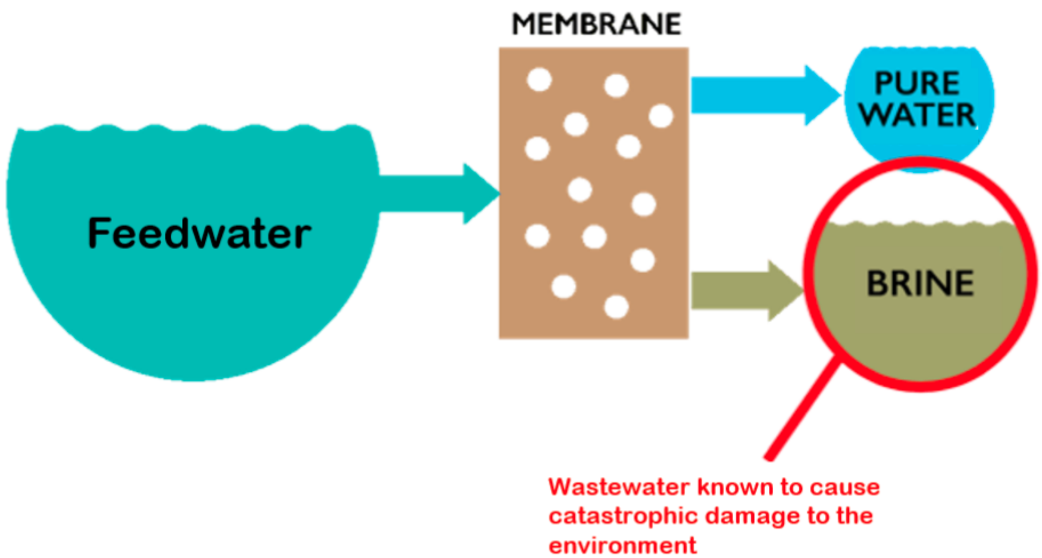

Figure 2: Membrane Process for Desalination

The undesired byproduct of the RO process is a high concentrate salt found within the wastewater brine known as ROC. The issue with this byproduct is that it cannot be reduced any further than its current state through the RO process. Therefore, this byproduct must be disposed of in a manner that varies depending upon the location of the desalination facility. For facilities that are found near the ocean, the ROC can be disposed of back into the ocean after being diluted to a salinity level that meets the permitted values using the seawater used as its feedwater source. Without this dilution process, the high salinity concentrate cannot be released back into the ocean or close to the areas with high marine wildlife populations. This can lead to negative ecological impacts on marine life in these high-density population areas [5]. For facilities that are further inland and use groundwater as their feedwater source, the disposal option back into the ocean is not a realistic option. Therefore, the facilities must use alternative disposal options to dispose of this concentrate while still producing potable water. These alternatives are listed below in Figure 3, however, all options result in negative impacts or heavy amounts of ROC accumulation to occur. The evaporation ponds, land disposal, well injection, ZLD, and sewage systems are used for these more inland facilities while the sea disposal option is only allowed for the facilities along the coast. The ZLD disposal option is expanded open throughout this research and integrated into the overall TEA model.

Figure 3: Disposal Options

An alternative disposal option to the ones presented above is to utilize this ROC as a TES medium. This does not solve the problem with storing a large amount of ROC, however it provides a beneficial use to the ROC rather than simply storing it in various methods that are harmful to the environment. This TES medium disposal option is expanded upon throughout this research.

1.3 Renewable Energy Issue

As previously mentioned, solar power and wind renewable energy sources are the keys to meeting the Paris Agreement's goal of reducing carbon emissions as the desired amount of energy increases [6]. Solar-powered renewable energy is especially useful during the summertime where the sun creates affordable energy that is provided to the grid while wind-powered renewable energy is especially useful during windy days where the wind rotates windmills that create affordable energy that is also provided to the grid. However, the main issue with these forms of renewable energy is that they are intermittent which means that they are forms of energy that are only available during specific intervals. For solar-powered renewable energy, the energy is only available when the sun is present and for wind-powered renewable energy, the energy is only available when the wind is present. To combat this intermittency, new forms of energy storage technology are being investigated to include charge and discharge cycles which will provide energy during these non-active hours. The National Renewable Energy Laboratory (NREL) has investigated battery energy storage systems on how they combat the intermittency issues with the previous forms of renewable energy by storing excess energy to be used during non-active hours [6]. The issues with batteries are their excessive cost and high competitiveness with its purpose for other technologies. However, a promising energy storage technology that was explored throughout this research is TES using a phase change material (PCM) as the TES medium.

To further understand the need for renewable energy, the areas where energy is mostly consumed must be known. The Department of Energy (DOE) has been able to provide a chart that displays the major energy sources as well as the major energy sectors.

Figure 4 shows that most of the energy consumption is found within natural gas and petroleum, totaling 69% of the overall energy consumption. Renewable energy represents 12% of the total energy consumption. The areas that consume the largest amount of energy include the industrial and transportation sectors at 71% of the total amount of energy. A vital component of this chart is found within the electric power sector that describes the overall amount of energy that is found within electricity retail sales and the electrical system energy losses. Apart from the petroleum energy source, the remaining energy sources provide a significant amount of their energy to be sold through the electricity retail sales or are lost within their respective electrical system. This inclusion of the electrical system energy losses is important towards the development of an accurate TES System Model because it shows how the efficiency of various energy-producing components causes the system to produce more energy than the desired output.

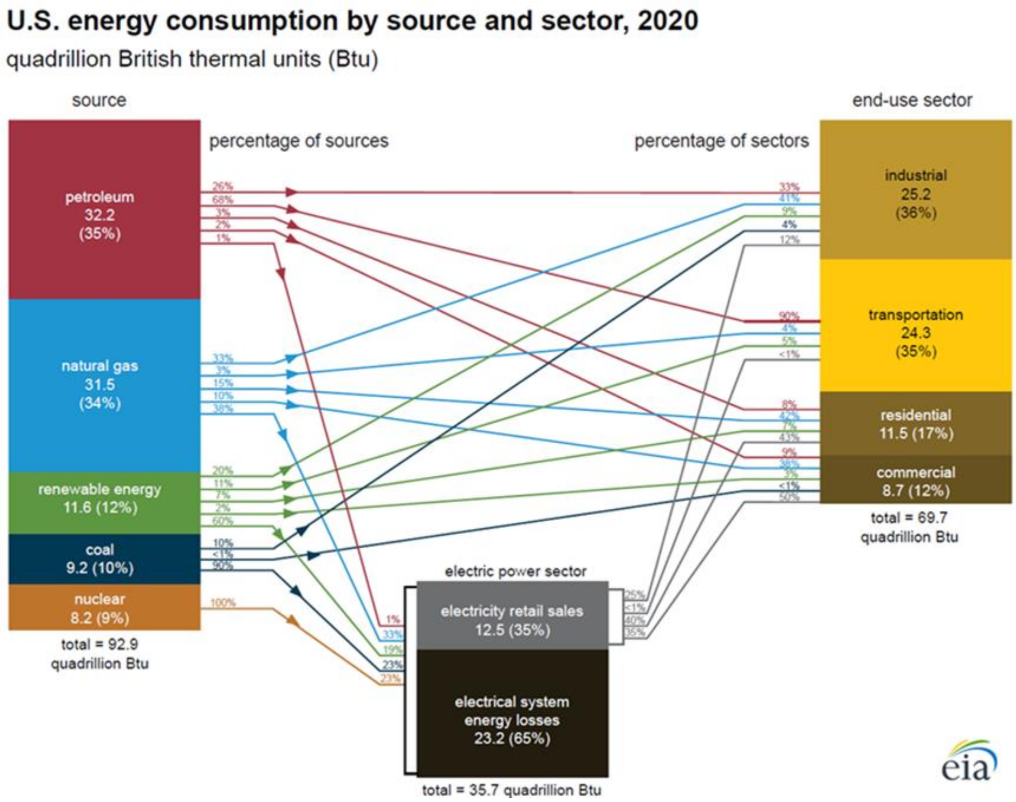

Figure 4: Energy Consumption Sources and Sectors

To further explain the need for TES as a solution for the intermittency issue of renewable energy, the relationship between the energy demand and the amount of available solar energy throughout the average day must be understood. The 'Duck Curve' shows this relationship between renewable energy production and peak demand and is shown in Figure 5 below [7]. The highlight of this curve shows how there is an overproduction of energy from solar power from 12pm-3pm which creates the need to discharge this excess energy to prevent overloading of the energy production systems. The other highlight of this graph is the increased ramp that occurs at the end of the day from 4pm-9pm which is during a time when the solar energy is decreasing due to the sun setting and no longer being able to power the solar energy systems. This problem can be addressed with TES technology which can store the excess solar energy during the overproduction period and discharge it when the demand is at its peak towards the end of the day.

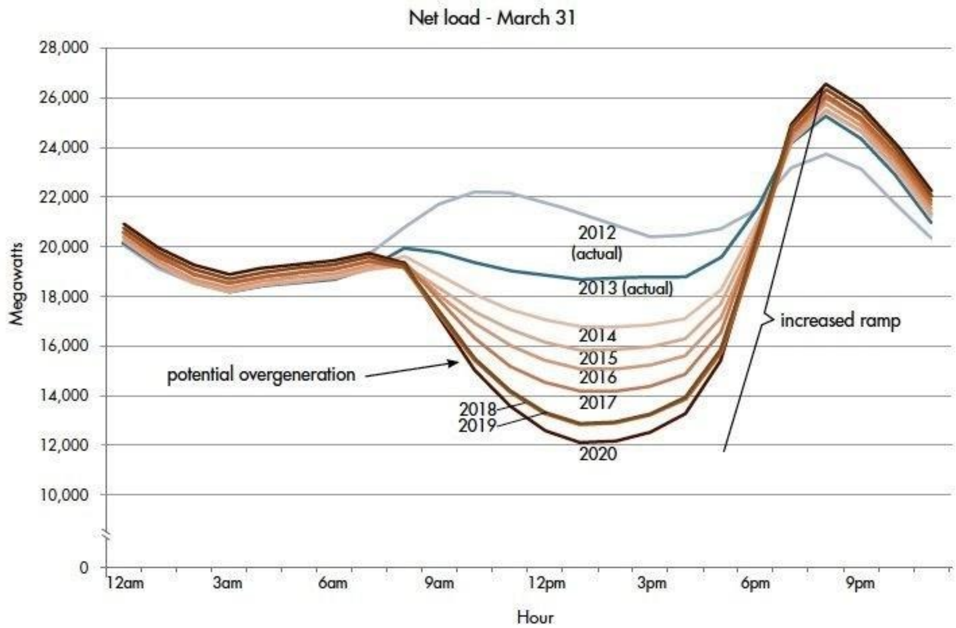

Figure 5: Electrical Demand and Supply Curve

The only downside to the use of TES is that the costs to produce this solar energy are still high enough where the investment value may not be economically feasible for desalination facilities to dispose of their waste to these TES systems. Therefore, the DOE created the SunShot Initiative to help reduce the total cost of solar energy to below 6 ¢/kWh. To achieve this goal, the cost of TES must be below $15/kWh [8]. Figure 6 shows the details of the cost of energy storage goals for all aspects of a TES system for CSP.

Parameter	2018 Benchmark[37,38]	2030 Low-Cost	2030 Balanced	2030 High-Performance
Net power-cycle efficiency	37%	40%	50%	55%
Rated thermal power	730 $MW_{thermal}$	675 $MW_{thermal}$	540 $MW_{thermal}$	491 $MW_{thermal}$
Power block cost	$1330/$kW_{ac\text{-}gross}$	$700/$kW_{ac\text{-}gross}$	$900/$kW_{ac\text{-}gross}$	$900/$kW_{ac\text{-}gross}$
Solar field cost	$140/$m^2$	$50/$m^2$	$50/$m^2$	$70/$m^2$
Site preparation cost	$16/$m^2$	$10/$m^2$	$10/$m^2$	$10/$m^2$
Tower and receiver cost	$137/$kW_{thermal}$	$100/$kW_{thermal}$	$120/$kW_{thermal}$	$120/$kW_{thermal}$
Thermal storage cost	$22/$kWh_{thermal}$	$10/$kWh_{thermal}$	$15/$kWh_{thermal}$	$15/$kWh_{thermal}$
Levelized O&M cost[39]	$9/$kW_{thermal}$-yr	$6/$kW_{thermal}$-yr	$7/$kW_{thermal}$-yr	$7/$kW_{thermal}$-yr
Levelized capacity factor	68.9%	69.2%	70.7%	71.0%
LCOE (2019 US$)[40]	**9.8¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**

Figure 6: SunShot Initiative CSP Energy Goals

The current state-of-the-art technology of TES for CSP uses solar salt as a TES medium. This solar salt is a mixture of sodium and potassium nitrate and has a reasonable energy storage density in the CSP temperature range; however, the cost of TES of the solar salt TES medium is approximately $30/kWh which is double the cost for the target set by the DOE for TES costs [9]. The TES system explored throughout this research has shown significantly lower values of the cost of TES which are expanded upon later in this research.

1.4 Thermal Energy Storage and Phase Change Materials

TES is a form of technology that stores thermal energy through the heating or cooling of a TES medium and uses the stored energy for power generation and heat transfer applications. The stored energy can take on two forms of energy: sensible heat and latent heat. Sensible heat is the heat within the system that changes with the temperature of the system while latent heat is the heat within the system when a phase change occurs at a constant temperature. Latent heat can only be present while using a

PCM that has mildly varying density between its various phases. This can be advantageous in TES because the latent heat produces a large amount of energy for the system and the liquid sensible heat typically produces more energy than the solid sensible heat from the PCM. A highly favorable PCM that has been implemented into this TES technology has been inorganic salts due to their low vapor pressure and high melting temperature [10] [11]. As well as being investigated as a TES medium throughout this research, an inorganic salt mixture known as solar salt has been used as a heat transfer fluid (HTF) for CSP plants [12] [13].

The chemical makeup of the PCMs used for TES is extremely important because their thermophysical properties are used to define their effectiveness in storing thermal energy. The thermophysical properties that were investigated for the PCMs used in this research included the density, latent heat of fusion, melting temperature, liquid specific heat capacity, solid specific heat capacity, thermal conductivity, and viscosity. The National Institute of Standards and Technology (NIST) database provides thermophysical properties for various salt mixtures and was utilized for gathering some of the thermophysical properties at varying temperatures or constant temperatures for the statistical approach used to find the final thermophysical properties of the PCMs used in this research [14]. The importance of this analysis is that the composition for various ROC samples varies due to their original location. The ROC collected from seawater is primarily composed of NaCl while the ROC gathered further inland is composed of various salts including $Ca(Cl)_2$, $MgCO_3$, $MgSO_4$, $MgCl_2$, Na_2CO_3, Na_2SO_4, K_2O_3, K_2SO_4, $Mg(OH)_2$, $CaSO_4$, $CaCO_3$, and KCl. The statistical approach uses a weighted average for the thermophysical properties of the specific salt components found in the ROC samples which provides an accurate range of values to be used for the analysis performed throughout this research. The comparison between the various ROC samples also helps define the importance of the origin location of the ROC affecting their thermophysical properties which can help define the ideal location to perform this TES.

One of the key issues with using the ROC salts as a TES medium is that they are highly corrosive. Corrosion is created by the oxidation of atoms on the surface of a metal. The addition of salt accelerates this corrosion process due to its increase in electron movement which causes the oxidation process to occur. Since the ROC is composed of high concentrate salt, the corrosion process experienced by the metal found within the containment of the TES module is increased drastically [15]. The rate of corrosion is also increased when the temperature of the ROC is increased, therefore the corrosive effects for a higher storage temperature of the TES module will increase [16]. This problem has been the deterring factor in the advancement of this type of energy storage technology. The energy benefits from the phase change result in a higher corrosion rate, therefore the cost analysis performed throughout this research helps quantify the economic feasibility of the two scenarios where phase change may or may not occur. The ways to combat these effects are to increase the corrosive resistance of the metal itself or to add a material to the metal that has a much larger corrosive resistance. Both routes to reduce the corrosive effects on the metals found within the containment of the TES module have their benefits, however, a life cycle cost analysis for the desired period provides the most cost-effective option out of the viable solutions.

1.5 Thermal Energy Storage Module

The TES module can be described as the storage containment where the PCM would be stored, heated, and cooled down. To heat the PCM, a charge cycle must be utilized to melt the ROC to go from a solid to a liquid phase. The charge cycle can be achieved using solar thermal heating through a CSP plant or through electric resistive heating, both of which were investigated throughout the system-level modeling aspects of the research. To cool down the PCM, a discharge cycle must be utilized to solidify the ROC from a liquid to a solid phase. The discharge cycle can be achieved using an organic Rankine cycle (ORC) with a steam turbine and generator to output the electricity from the heat transfer between the ROC and an HTF. The ideal design for this TES module is in the shell and tube heat exchanger style where one fluid is stationary while the other travels throughout the module in motion with the possibility of fins to increase the heat transfer between the two fluids, which can be seen below in Figure 7. The stationary fluid for the proposed design is the waste ROC while the selected HTF moves through the HTF tubes throughout the module. This design was then compared to competitors in the energy market to determine its economic feasibility and the TEA performed on this design is elaborated upon throughout this research.

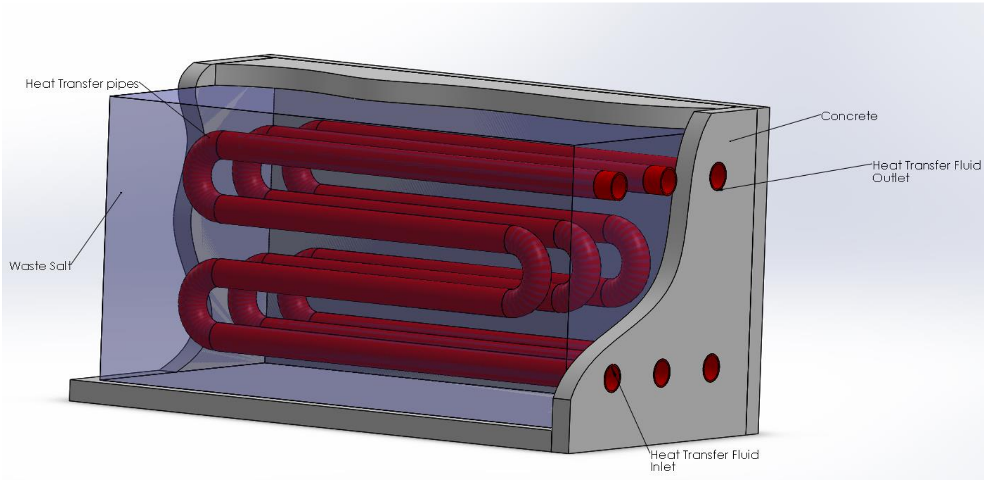

Figure 7: TES Module

1.6 System-Level Modeling

Integrating this TES module into a system-level model is a key part of quantifying the economic feasibility of implementing this form of thermal technology into practice. A top-level view of this system shows that a power generation system is generated through oil heaters that charge the ROC through an energy input when the supply is high and discharges this energy through an ORC's generator to output electricity when the supply to the grid is low. This type of modeling will investigate all aspects of the system to provide customers with a $/kWh value for a given amount of energy desired to be provided using the entire TES system. A diagram of this proposed model is provided below in Figure 8.

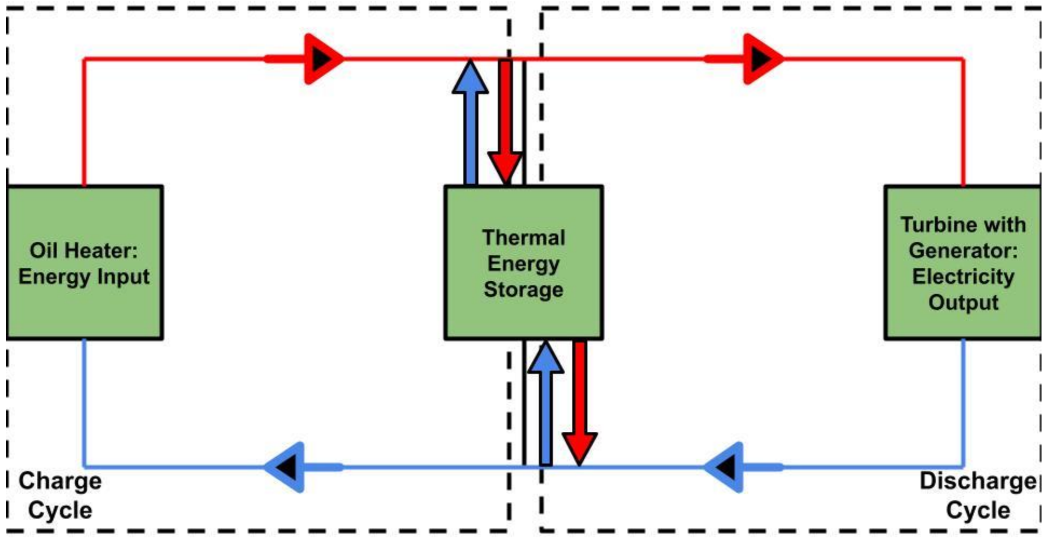

Figure 8: System Model

1.7 Techno-Economic Analysis Modeling

The design of a product or service must be proven to be economically feasible for the interest levels of customers and investors to increase surrounding it. Therefore, a TEA model was created and developed to quantify the costs associated with the proposed TES module design in this research. The purpose of a TEA model is to estimate the technical and economic performance of the entire proposed system; therefore, the TEA model was created with an initial goal of meeting the SunShot Initiative's target of $15/kWh for TES. The energy produced by the TES module was dependent upon the amount of thermal energy that could be stored from a given ROC sample and with the desired minimum and maximum storage temperature of the ROC within the module. With the varying ROC samples assessed throughout this analysis, the thermophysical properties and total dissolved solids (TDS) value for the ROC would vary resulting in varying thermal energy outputs for the same amount of ROC gathered from a facility. The other moving part for this type of modeling was the cost to transport, process, and store the ROC for its thermal energy for the overall TES system. This TEA model has already determined that the TES module using ROC as a TES medium has proven to meet the SunShot Initiative's goal using various ROC processing methods. The TEA model updates presented throughout this study further investigate costs that were not accounted for in the initial model, new forms of evaporation methods for dehydrating the ROC, and investigating similar services to quantify the revenue that can be generated by gathering brine from facilities that need to dispose of it.

CHAPTER 2 METHODOLOGY

2.1 Thermal Energy Storage System

The entire system to process the ROC as a TES medium for a TES module is shown below in Figure 9. The process begins at a feedwater source that is fed into an RO system/facility that separates it into ROC brine and clean water. The facilities that provided ROC samples for this research included the EMWD, Chino Water Desalter Authority, and the Panoche Water District. The ROC brine is then transported to a ZLD facility where processors, evaporators, and crystallizers are used to evaporate all the excess water from the ROC brine to output dehydrated ROC solute and more freshwater that is extracted from the ROC brine. The ZLD facilities that are used within this TEA model are a Saltworks ZLD system and a WaterFX ZLD system. The previous study on this TEA model did not investigate the use of ZLD technology and instead investigated the use of evaporations ponds and CNG fueled evaporation methods [17]. The dehydrated ROC is then sent to a commercial grinder to have the size of the ROC solute be reduced to much finer particles. Next, the ROC is provided with thermophysical property benefits using additives. The purpose of using these additives is to increase the heat transfer derived from the ROC to increase the overall thermal energy stored from the ROC. The ROC is then packed into an insulating container to be stored alongside a heat exchanger that will be able to transfer the thermal energy from the ROC to the rest of the TES system by increasing or decreasing the temperature of the ROC during the charge and discharge cycle. This proposed system is an indirect form of TES and requires heat to be provided and extracted using a HTF that transfers the thermal energy from the ROC to the rest of the system.

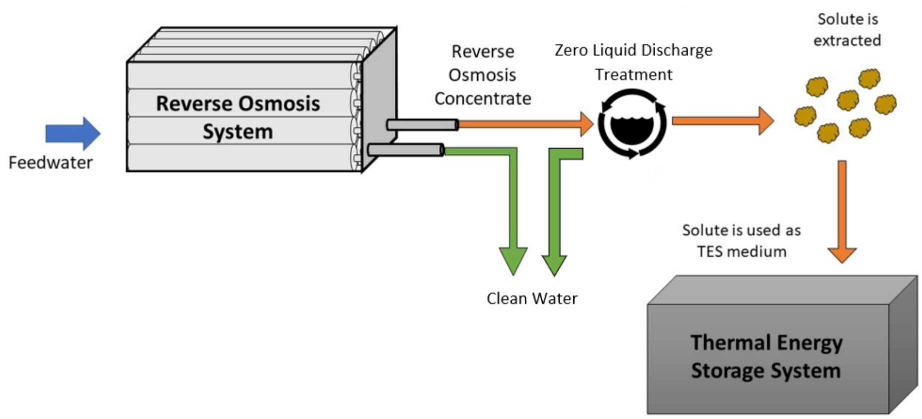

Figure 9: Development of ROC-based TES System

2.2 TEA Model Costs

The overall cost of TES within this proposed TES module is calculated using estimated costs, gain revenue from the RO facility's disposal fee, and the total amount of thermal energy that can potentially be stored using a given amount of ROC. The equation used to calculate this overall cost of TES can be seen below in Figure 10. The estimated costs that are required for processing, transporting, and storing the ROC include the ROC transportation cost, ZLD operational cost, ROC grinding cost, additive cost, containment cost, heat exchanger cost, labor cost, and a miscellaneous cost. As well as the gain fee paid by the RO facilities, these costs are divided by the total thermal energy stored (E_{St}) to determine the overall cost of TES.

$$C_{TES} = \frac{C_{Tr}+C_{Z}+C_{G}+C_{A}+C_{C}+C_{HX}+C_{L}+C_{M}-G}{E_{St}} \quad \left(\frac{\$}{kWh}\right)$$

Figure 10: TEA Cost Equation

The cost of transportation (C_{Tr}) previously consisted of the capital cost of the pipe material to transport the brine from facility to facility, the capital cost of pumping the

ROC brine from the RO facility to the ZLD facility, and the energy cost to pump the ROC brine. The updates to this category were made using previously published values from other journal articles and provided the costs associated with transporting the ROC brine through two methods: direct pipeline and trucked transportation. The costs associated with the direct pipeline transportation method include the construction cost, pipe material cost, maintenance cost, pump cost, labor cost, station cost, and a rate of cost for the overall fixed and variable cost of transportation through a pipeline. The fixed cost was established based upon the overall volumetric amount of brine required to be pumped through the pipeline while the variable cost was based upon the volumetric amount and the total miles that the brine must travel throughout the pipeline. The costs associated with the trucked transportation method include the capital cost for inlet and outlet stations to load and unload the ROC brine from the trucks and a rate of cost for the overall fixed and variable cost of transportation to use a rented single tandem trailer truck [18]. Since this information was summarized from sources published before 2016, an extra percentage cost was provided to account for the cost of inflation. This more detailed approach to transportation costs shows a more accurate and realistic investigation and has resulted in an increase in costs compared to the previous model.

The cost of using the proposed ZLD systems (C_Z) varies between the WaterFX and Saltworks technologies. The cost of using the Saltworks ZLD system is determined by using a rate that leads to costs dependent upon the desired volumetric input of ROC brine into the system. Once this volumetric amount is known, the cost of the RO processors, evaporators, crystallizers, and treatment can be calculated [19]. The cost of using the WaterFX ZLD system is determined by calculating the costs of pretreatment, RO processors, solar arrays, heat storage, heat exchangers, crystallizers, and operating costs for the entire system. These values are provided by WaterFX for a smaller scale design that was scaled up by using the desired volumetric input of ROC brine to calculate the final operational costs to construct and utilize this ZLD system [20].

The cost of grinding the dehydrated ROC (C_G) into finer particles is primarily derived from the grinding machine selected [21]. The main costs associated with the selection of grinder include the capital cost of purchasing the machine and the electrical power cost required to grind all the dehydrated ROC particles. The selection of the grinder is decided based upon its single load capacity and electrical power required to provide the most cost-effective grinding process for the desired ROC input. With the selection of a grinder that produces a higher single load capacity for cheaper electrical power input, the time required to grind all the desired ROC into finer particles is reduced and can help speed up the processing of the ROC so that it may be utilized as a TES medium quicker.

The costs of the additives added to the ROC (C_A) to improve its thermophysical properties are derived from the capital cost of the additive material and the processing costs. The thermophysical properties that are important to improve are the density, thermal conductivity, and specific heat capacity of the ROC to improve the heat transfer from the ROC. Silicon dioxide nanoparticles were found for a weight percentage and a cost per mass rate that would provide a cost determined upon the overall mass of ROC derived from the initial brine intake [22]. This additive specifically improves the thermal conductivity of the ROC and the specific heat capacity which helps improve the rate of heat transfer between the ROC and HTF and increases the amount of thermal energy stored from the total ROC stored.

The cost of containment (C_C) is primarily derived from the storage shell to provide structural support for the overall TES module. The costs include the capital cost of the material and construction cost for the metal shipping containment surrounding the module, the concrete structural shell, the reinforcing bar placed within the concrete structure, and the epoxy resin added to the concrete [23] [24]. The reinforcing bar, also known as rebar, is embedded within the concrete structure to increase its overall structural strength and improve the concrete's behavior in tension [25]. The rebar is made of steel which causes corrosion to occur within this material. The corrosion occurs from the increase in volume created by the combination of oxygen ions that produce internal stress cracks within the concrete [26]. Epoxy resin is one solution to prolong the life of the steel rebar within the concrete structure by applying it as a coating to the exterior of the rebar to help protect it from the oxidation process [27]. Since the corrosion rate increases as the temperature increases due to the electrochemical reactions found within the material to increase faster from the additional energy added, the cost of the epoxy resin increases for the melting scenarios. This temperature increase for the melting scenarios also requires that higher quality concrete be used for those applications. Refractory concrete was investigated due to the regular concrete material not having a high enough maximum temperature threshold [28].

The cost of the heat exchanger (C_{HX}) includes the capital cost of the HTF pipe material and HTF material throughout the TES module. Since corrosion is the major issue with the HTF pipe, the need for a HTF pipe material with high corrosion resistance is required to prolong the life of the pipe materials. The HTF pipe material used throughout this research is Inconel 625 due to its high strength properties, resistance to elevated temperatures, and corrosion resistance [29]. The chromium found in this superalloy combines with the oxygen to form a protective oxide that provides corrosion resistance up to 700℃, therefore the aluminum is added to provide corrosion resistance at elevated temperatures. This specific material is used in marine applications therefore it has proven to improve the corrosion resistance experienced from salts found in desalination facility's feedwater sources [30]. These costs are important because they transfer the heat from the dehydrated ROC to the HTF. The heat transferred to the HTF is then taken out of the TES module to be output through the discharge cycle. Therminol HTF is used for the summertime lower temperature applications due to its high thermal stability, low viscosity, and precise temperature control [31]. Solar salt is used for higher temperature applications due to its higher melting temperature and its ability to reduce the overall cost of TES by replacing a water or oil based HTF with this salt mixture [32].

The cost of labor (C_L) is primarily derived from the operating costs to produce thermal energy and the construction costs for the containment. These costs are important because they provide a more complete TEA model by including a cost that is finalized during the construction and prototype period of the design process. These costs contribute a significant amount to the overall cost of TES and must be included to ensure that the entire TES system is created in a cost-effective manner. Minimizing these costs would result in a decrease in the quality of the system that would have repercussions later in its life cycle and demand for investment costs in the future. At its current state, the theoretical model has generously integrated these costs into the labor structure and will be adjusted as the prototype period progresses and produces meaningful results.

The miscellaneous cost (C_M) is necessary to this TEA model because it accounts for costs that may have been overlooked and not included within the TEA module itself. This includes the additional support and materials required to support the weight and temperature in the TES module. This cost was assumed to be 5% of the overall heat exchanger cost and containment cost combined. As the project progresses, this percentage will change and eventually be reduced after promising iterations produce valuable results.

Table 1 provided below shows the most important costs to construct and operate this TES module.

Table 1: Costs of Important Equipment and Materials

Product/Material	**Cost**
Grinding Machine	$98,000/unit
WaterFX ZLD Cost	$16.53/m^3 of brine
Saltworks ZLD Cost	$15.93/m^3 of brine
Fixed Cost of Using Rented Tandem Trailer Truck	$5.47/m^3 of brine
Fixed Cost of Using Pipeline	$0.70/m^3 of brine
Silicon Dioxide Nanoparticles	$15/kg
Containment Lower Temp Concrete	$100/tonne
Containment Refractory Concrete	$1,000/tonne
Inconel 625 HTF Tubes	$29,000/tonne
Storage Container	$1,745/unit

Alongside the previously mentioned positive costs to construct and operate the TES module, a negative gain value (G) is also included within this TEA model. This gain value is derived from the number of dollars received from a RO facility as a disposal fee to receive the brine from these facilities. Since this value is received as revenue, it is considered as a negative value within the overall cost of TES equation. This gain value is dependent upon the chemical composition found within the ROC brine, the amount of ROC brine, and the available disposal options for the RO facilities. The Seawater Reverse Osmosis (SWRO) facilities that are located near the coast with ocean fronts would not be interested in paying a disposal fee when the option of diluting the wastewater to below the regulation level and disposing of it into the ocean is available. For the RO facilities that are further inland from the coast, this option is not available, and they must look for alternative disposal methods. A current disposal option for inland RO facilities involves the use of pipelines to transfer the brine from the RO facilities and process it to eventually dispose of it into the ocean. This disposal option provides evidence that the inland RO facilities would consider being charged a gain value to dispose of their brine to the proposed TES system.

This study specifically investigates a current service offered to wastewater-producing facilities located in Southern California known as the Inland Empire Brine Line (IEBL) to help estimate a reasonable disposal fee to charge as revenue for this TES system. The IEBL is a way for customers to dispose of their wastewater through manufacturing and water treatment processes which are transported through a brine pipeline that stretches throughout Southern California. This treatment process is required to meet the TDS restrictions created to prevent high concentration levels of wastewater from being disposed of back into the ocean. This treatment takes place in a treatment plant operated by the Orange County Sanitation District (OCSD) and is then discharged into the Pacific Ocean. The purpose of this service is to reduce the amount of salt found in the groundwater of various watersheds. This is specifically important to protect the groundwater in the upper Santa Ana River Watershed since it is used to provide drinking water to the surrounding population. Desalination facilities in the Inland Empire that work towards increasing the amount of potable water produced use brackish water found in aquifers as their feedwater source. The leftover brine produced from this RO process is sent through the brine line alongside the wastewater from various industries including water softening, power plants, food processors, and computer chip manufacturers. The IEBL provides two main methods of disposing and transporting the wastewater from these facilities: direct pipeline disposal and trucked disposal. The direct disposal option is available for customers who produce a large volumetric amount of brine and are located within a short enough distance to the IEBL that a direct connection may be created between the facility and Brine Line. This disposal option allows for the facilities to directly connect to the Brine Line and dispose of their wastewater by purchasing a portion of the pipeline to continuously dispose of their brine. The trucked disposal option allows for facilities to have their brine disposed of via a wastewater hauler gathering the brine and transporting it to various collection stations that connect to the overall Brine Line where it is treated and disposed of into the Pacific Ocean. There are a total of four collection stations that are within a 20-mile drive from any desalination facility and are available for customers that generate a small amount of wastewater or that are too far to create a direct connection to the Brine Line. There is a third alternative option, defined as the remote disposal, which is specified as an alternative option for facilities elsewhere in the LA basin that are not close enough for direct connection to the Brine Line nor within a reasonable distance to the trucked collection stations. Due to the extra distance required to transport the brine, this option is valued at the most premium disposal fee of the three options [33]. The values that are associated with the disposal fee charged to the facilities are the cost of pipeline capacity, treatment and disposal cost, the monthly amount of flow cost, monthly capacity cost, and a trucked varying fee depending upon the volumetric amount of wastewater transported for the trucked and remote disposal options [34].

This gain analysis has led to the range of gain beginning at $0.00/G of wastewater for SWRO facilities near the ocean to $0.275/G for facilities elsewhere in the LA basin that are not close enough for direct disposal nor a regular trucked collection station [35]. These values are summarized below in Table 2.

Table 2: Cost of ROC Disposal Using IEBL

SWRO Facilities	**Direct Disposal**	**Trucked Disposal**	**Remote Disposal**
$0.000/G	$0.091/G	$0.114/G	$0.275/G

The overall cost of TES is inversely proportional to the amount of energy that can be stored within the TES module. One of the important parameters for energy that can be stored is the minimum and maximum storage temperature of the TES module. The minimum storage temperature (T_{min}) for the TES module is set at 290°C which is comparable to the low temperature for thermocline 2-tank TES systems [35]. The maximum temperature (T_{max}) varied between 400°C (for parabolic troughs) for non-phase change scenarios and 600°C (for power towers) for phase change scenarios with the melting temperature being at 450°C for the EMWD ROC sample used throughout this

TEA model [36] [37]. The melting temperature for this EMWD ROC sample used was found in the previous investigating team's study where a thermal cycling test was performed on the ROC sample and the temperature where the phase change occurred was determined [17].

2.3 Thermal Energy Stored

The amount of thermal energy stored in this TES module is highly dependent on whether a phase change from solid to liquid occurs for the ROC between its T_{max} and its T_{min}. The previous study of the TEA model investigated the melting temperature of various ROC samples from the EMWD, Chino Water Desalter Authority, and Panoche Water District. The melting tests performed during the previous study had shown that the EMWD ROC melted at 450°C, the Panoche ROC melted at 600°C, and the Chino Water Desalter Authority ROC did not show signs of phase change at temperatures as high as 900°C [17]. Figure 11 displays the EMWD ROC sample at a 250°C temperature at its solid phase while Figure 12 displays the EMWD ROC sample at a 450°C temperature at its liquid phase after exceeding its melting temperature. Figure 13 displays the Panoche ROC sample at a 400°C temperature at primarily its solid phase while Figure 14 displays the Panoche ROC sample at a 600°C temperature at its liquid phase after exceeding its melting temperature. Figure 15 displays the Chino Desalter Authority ROC sample at a 250°C temperature at its solid phase while Figure 16 displays the Chino Desalter Authority ROC sample at a 900°C temperature still at its solid phase. The figures below highlight the importance of the melting temperature of the ROC being stored because this difference can affect the amount of latent heat and liquid sensible heat that can be absorbed from the ROC while remaining at the lowest maximum storage temperature to lower the costs required to contain and operate the ROC at such temperatures.

Figure 11: EMWD ROC at 250°C

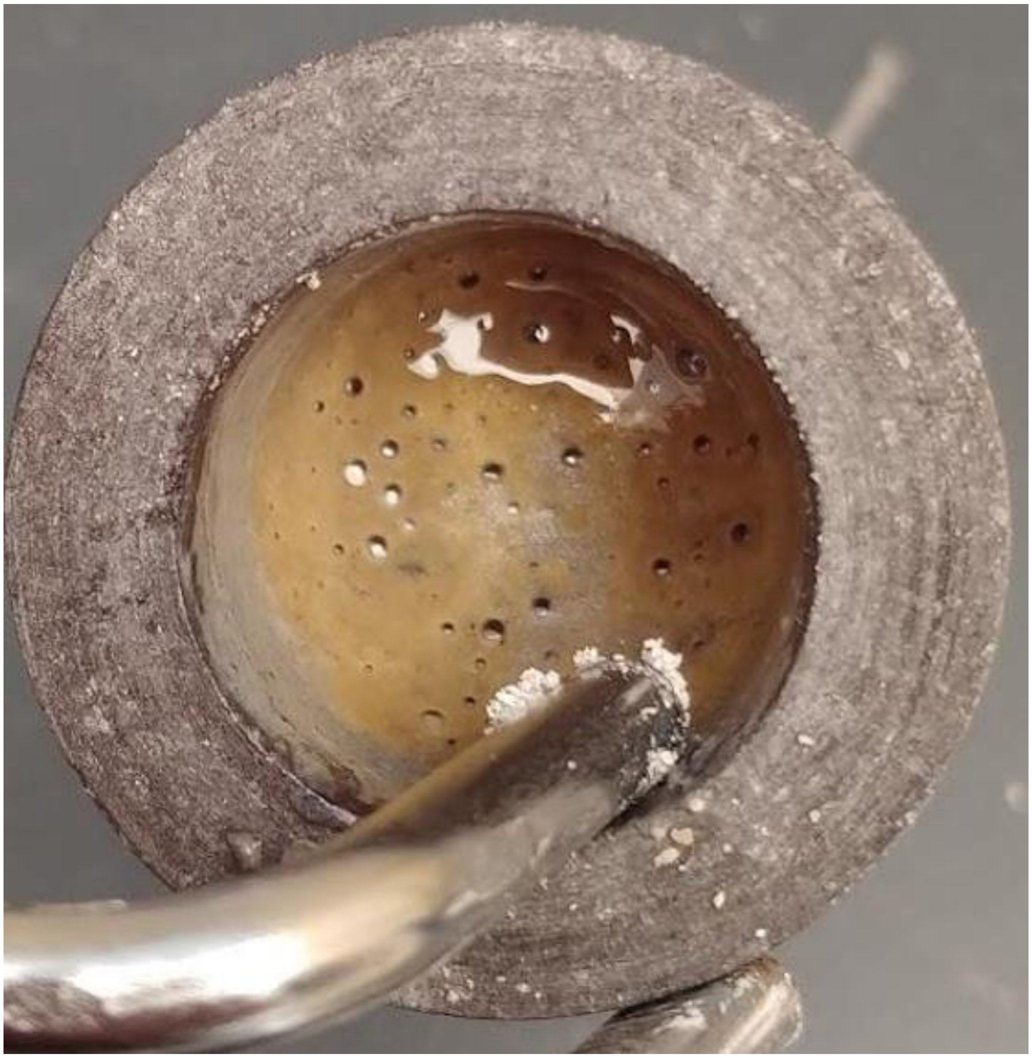

Figure 12: EMWD ROC at 450°C

Figure 13: Panoche Water District ROC at 400°C

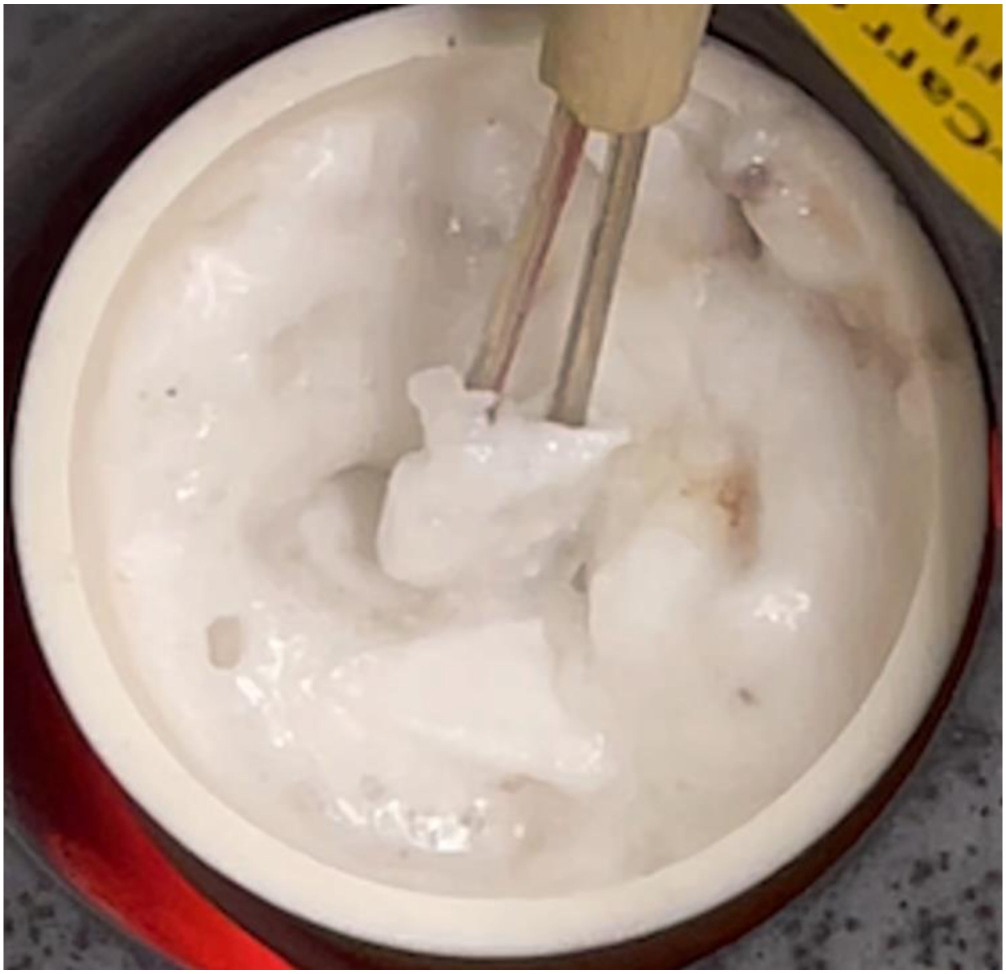

Figure 14: Panoche Water District ROC at 600°C

Figure 15: Chino Desalter Authority ROC at 250°C

Figure 16: Chino Desalter Authority ROC at 900°C

The amount of stored thermal energy generated from the ROC when going through a solid-to-liquid phase change can be calculated using Equation 1 seen below. For ROC that does not go through a phase change, the amount of stored thermal energy can be calculated using Equation 2 seen below.

$$E_{St} = \rho_s \upsilon \int_{T_{min}}^{T_m} c_{p,s} dT + \rho_s \upsilon \Delta H_{fus} + \rho_l \upsilon \int_{T_m}^{T_{max}} c_{p,l} dT + \rho_c v_c \int_{T_{min}}^{T_m} c_{p,c} dT \quad (1)$$

$$E_{St} = \rho_s \upsilon \int_{T_{min}}^{T_{max}} c_{p,s} dT + \rho_c v_c \int_{T_{min}}^{T_{max}} c_{p,c} dT \quad (2)$$

The first term of both equations represents the sensible heat produced by the solid ROC while the last term of both equations represents the sensible heat produced by the containment materials. Equation 1 also includes two terms that represent the latent heat storage and the sensible heat storage while the ROC is in its liquid state. The importance of these added terms is to highlight the increase in the amount of stored thermal energy that is generated when a phase change occurs. These two equations are used in combination with the specific thermophysical properties for the ROC samples to calculate the overall thermal energy stored for all scenarios investigated.

2.4 ROC Composition

The ROC composition is derived from its feedwater source that is fed into its desalination facility. The feedwater sources contain salts that are carbonates, chlorides, hydroxides, and sulfates. The most common carbonate salt that is found in these seawater sources is calcite, $CaCO_3$. The most common hydroxide salt that is found in these seawater sources is magnesium hydroxide, $Mg(OH)_2$. The most common sulfate salt that is found in these seawater sources is calcium sulfate, $CaSO_4$. The most abundant salt component found in these seawater sources remains to be sodium chloride, NaCl. An example of this seawater composition can be found below in Figure 17 to show the weight percentage for each chemical component.

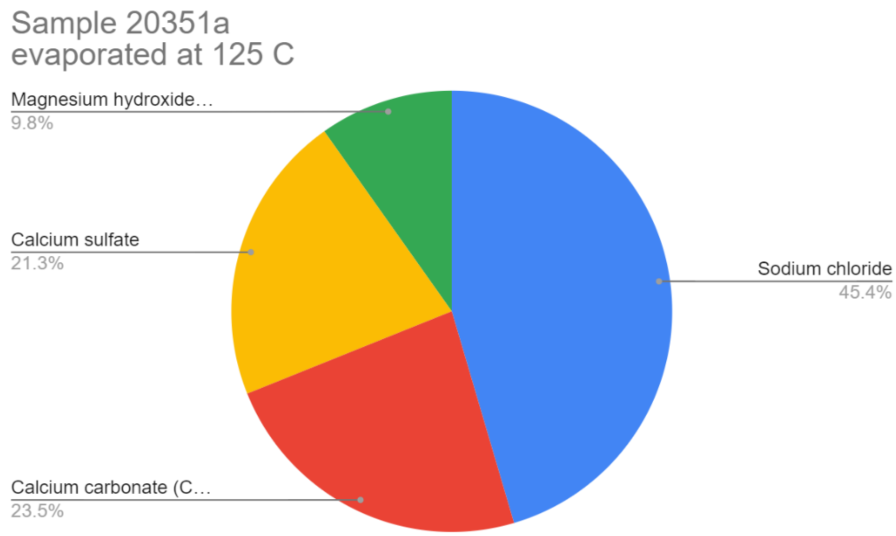

Figure 17: Chemical Composition of EMWD ROC Sample

After receiving a ROC sample, the composition of this sample is important in determining the overall thermophysical properties of the sample. Therefore, the thermophysical properties of the individual salt components are used to predict the thermophysical properties of the overall ROC sample. These properties were found using chemistry analysis and thermodynamic software to determine the expected weight percentage of each chemical component found within a ROC sample. The EMWD ROC sample referenced throughout this TEA model was analyzed by the company Expert Chemical Analysis, Inc (ECA Inc.) for the ionic composition of the ROC sample. The information gathered from this analysis was used to determine the weight percentage for each chemical component found within the ROC sample to then be used in thermodynamic software to find the overall thermophysical properties of the ROC sample

[38]. Table 3 shown below summarizes the chemical composition of this EMWD ROC sample.

Table 3: Chemical Composition of EMWD ROC

Component	**Chemical Formula**	**Weight Ratio**
Sodium chloride	NaCl	0.45
Calcium carbonate (Calcite)	$CaCO_3$	0.23
Calcium sulfate	$CaSO_4$	0.21
Magnesium hydroxide (Brucite)	$Mg(OH)_2$	0.10

2.5 Thermophysical Properties

The thermophysical properties that are most important for the heat transfer between fluids are density, latent heat of fusion, liquid specific heat capacity, melting temperature, solid specific heat capacity, thermal conductivity, and viscosity. The melting temperature for the EMWD ROC was found using an electric furnace and observing the ROC's state as the temperature increased and decreased for a desired length of time. This thermodynamic analysis led to the conclusion of a 450°C melting temperature that would be used throughout the TEA model for this EMWD ROC sample [39]. Due to the abundantly available thermophysical properties for the individual chemical components found within the ROC sample, the need for experimental data is not required and allows for the use of a statistical approach.

This statistical approach is performed by using a weighted average of all salt components found within the ROC sample and estimating their weight average for each desired thermophysical property from the National Institute of Standards and Technology (NIST) material database [40]. For the solid specific heat capacity statistical approach, the values are found for each salt species at the minimum storage temperature and their respective melting temperature is plotted on a temperature vs solid specific heat capacity graph that is shown below in Figure 18. The inclusion of the values at both temperatures is important because the thermophysical properties for this TEA model are temperature independent at this current moment. The average between these two values is used in combination with the weighted average found from the ROC composition analysis to find the overall weighted average solid specific heat capacity value for the ROC sample. The graph has each dominant salt species labeled along with the weighted average solid specific heat capacity value. This statistical approach led to a solid heat capacity value of 1,100 J/kg*K. This is an important thermophysical property because it determines the amount of heat required to increase the temperature of a fluid, which affects the amount of thermal energy that can be stored within the TES module.

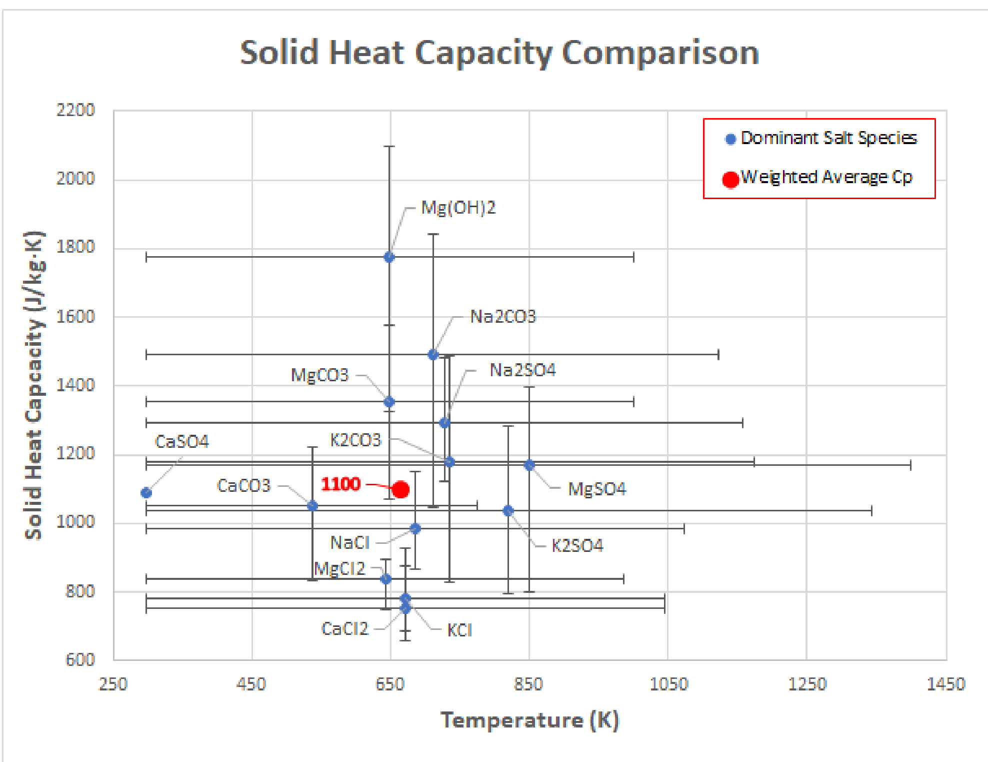

Figure 18: Sensitivity Analysis of Solid Heat Capacity of ROC

The weighted average for the liquid specific heat capacity value is calculated using the average value for each salt component in a ROC sample found within the NIST database and plotted on a bar graph shown below in Figure 19. This value is estimated to be 1,710 J/kg*K. This is also an important thermophysical property because it quantifies the amount of heat required to increase the temperature of the fluid even after melting has occurred.

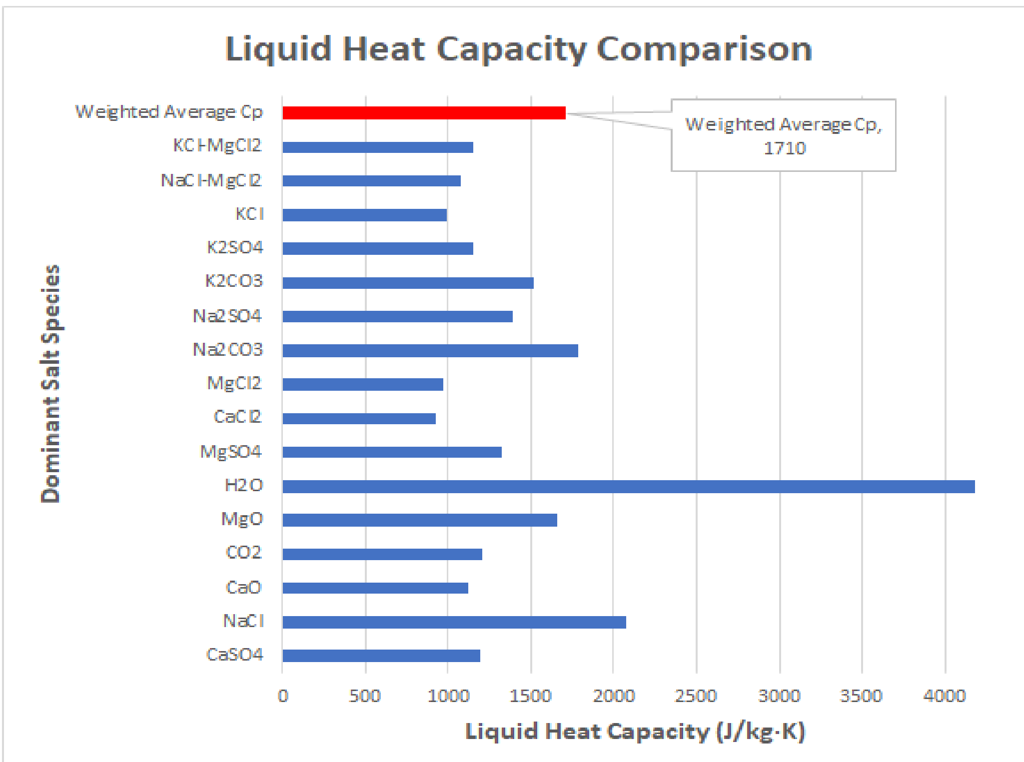

Figure 19: Sensitivity Analysis of Liquid Heat Capacity of ROC

The latent heat of fusion is an important thermophysical property because it represents the phase change from a solid-to-liquid and is referenced as the enthalpy required to perform this phase change. This value for the various dominant salt species is gathered from the NIST database and the weighted averages of the ROC sample are used to calculate the overall weighted average for the latent heat of fusion that was found to be

350,632 J/kg. This value and the latent heat of fusion for all the dominant salt species are displayed below in Figure 20 as a bar graph.

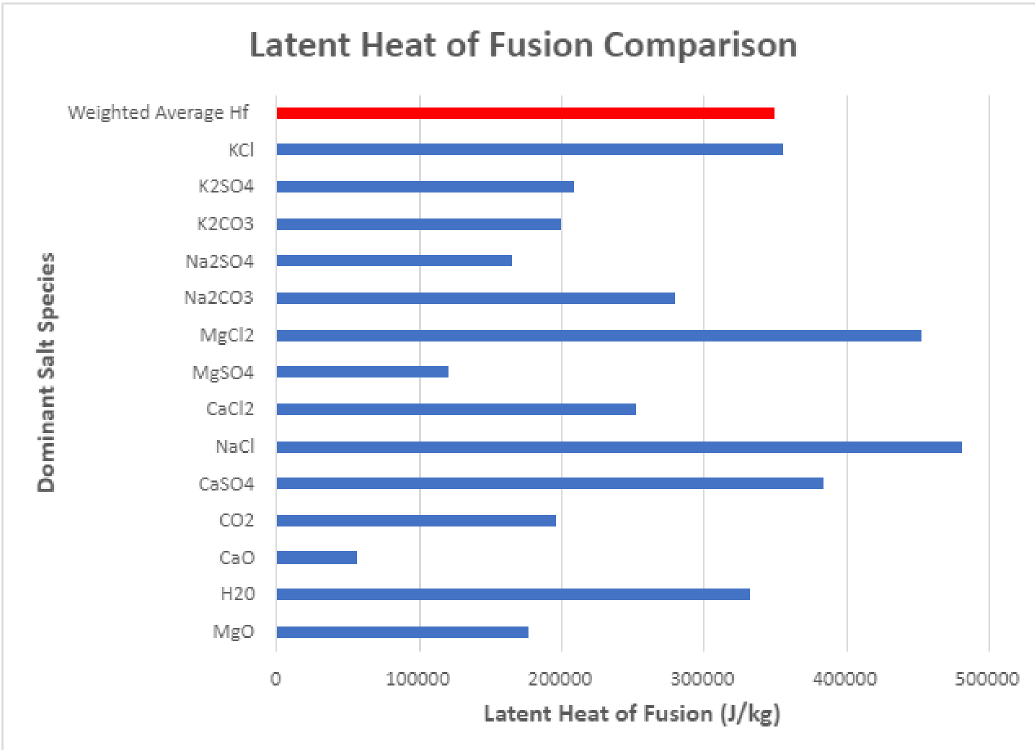

Figure 20: Sensitivity Analysis of Latent Heat of Fusion of ROC

The density value is calculated at a constant temperature for all dominant salt species using the NIST database to gather this value. Using this value alongside the weight percentage of each salt species within the ROC sample, the weighted average for the density of the ROC sample is found to be 2,503 kg/m^3. Figure 21 shows the bar graph representing the density value for the dominant salt species compared to the overall weighted average value.

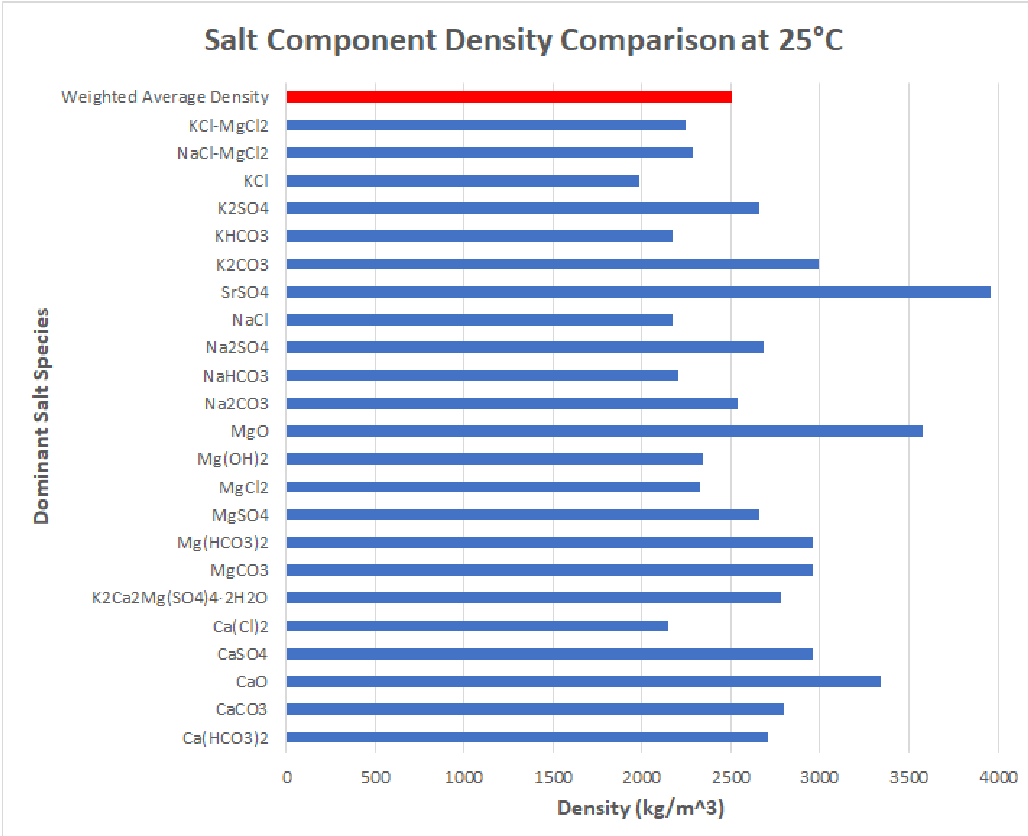

Figure 21: Sensitivity Analysis of Density of ROC

All thermophysical properties calculated above are summarized below in Table 4. These values were used throughout the TEA model with slight improvements to the specific heat capacities explained throughout the additive study.

Table 4: Weighted Average Thermophysical Props. of EMWD ROC

Thermophysical Property	**Value**
Solid Heat Capacity	1,100 J/kg*K
Liquid Heat Capacity	1,710 J/kg*K
Latent Heat of Fusion	350,632 J/kg
Density	2,503 kg/m^3

2.6 System-Level Modeling Setup

As previously mentioned, the system-level modeling aspect of this research has provided a more complete analysis of the entire project. The main aspects of this setup involve the inclusion of the costs required for the charge cycle and discharge cycle, the type of energy generation and energy output, the amount of energy desired by the customer, the required energy to output this desired amount of energy, and the electricity variation costs. These additions will provide a final cost of electric-to-electric energy storage value to operate the entire TES system and prove the economic feasibility of storing and utilizing repurposed ROC as a TES medium.

The cost of generating the energy to charge the ROC in the TES module includes the capital costs of an oil heater [41]. The cost of utilizing the energy stored within the TES module and discharging it to the grid or to be used elsewhere includes the capital costs of an ORC with a steam turbine and generator [42]. These additional costs for the charge and discharge cycle are included with the costs to operate the TES module as a total investment to operate the entire TES system. This total investment cost required for the entire system is important for the overall $/kWh value to quantify the cost to operate the entire TES system. The most important costs are labeled below in Table 5.

Table 5: Important Charge and Discharge Cycle Costs

Product/Material	Cost
Oil Heater Capital Cost	$100,000/unit
Steam Turbine & Generator Capital Cost	$350/kW

The amount of energy desired by the customer is an important parameter because it must be transferred through various components throughout the system from the generation of energy to its output during the discharge cycle. Due to perfect energy transfer between components not being a real-world scenario, efficiencies of the various machines and components of the system alongside the transfer of forms of energy going from heat to electricity and vice versa will create the need for a much larger amount of energy required to be input into the system to output the desired amount of energy. These efficiencies are considered when deciding the ideal components to go into the charge and discharge cycles to ensure that the system remains a cost-effective concept that can be placed into the highly competitive energy market.

Due to the important level of energy required to output a desired amount of energy using this type of TES system, the cost of input electricity is extremely important. The cost of electricity throughout the day varies due to the supply and demand of energy that was visually depicted through the "Duck Curve" [7]. The importance of this phenomenon is that it shows when the cost of energy is at its cheapest and when it is at its most expensive. When the energy demand is low and the supply of energy is high at the middle of the day, the cost of energy is at its lowest value which is when the proposed TES system would purchase the required energy input. When the energy demand is high and the supply of energy is low at the end of the day, the cost of energy is at its highest which is when the proposed TES system would sell its energy output during the discharge cycle. Throughout the year, the cost of electricity changes due to the length of the days changing and the amount of sunlight throughout the day changing. Therefore, the range of costs for the input and output electricity will vary and must be known throughout the various seasons in a year. The cost of energy in California throughout the day is tracked and the data is presented below at various seasons of the year.

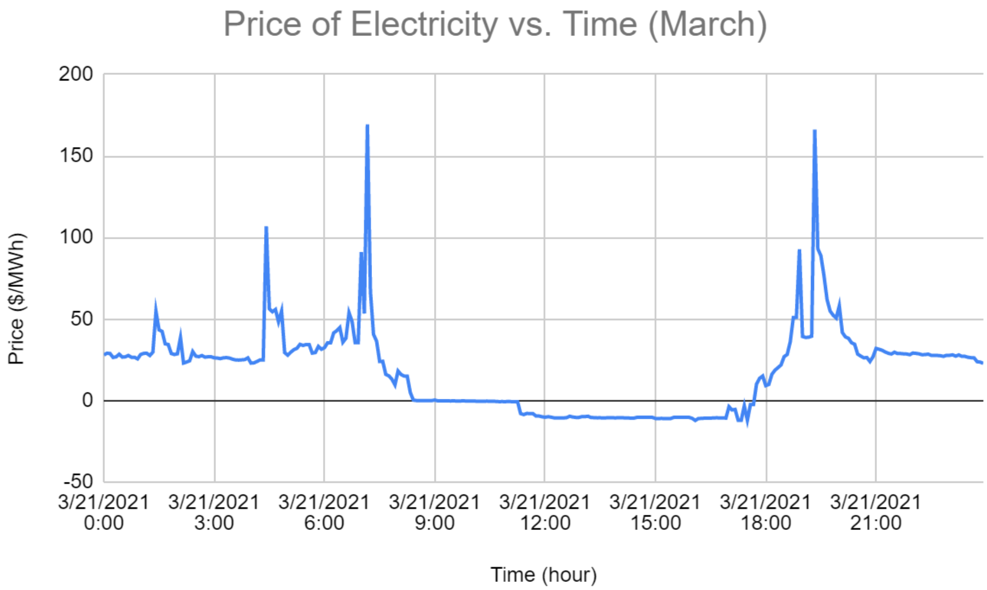

Figure 22: Price of Electricity in CA vs Time: March

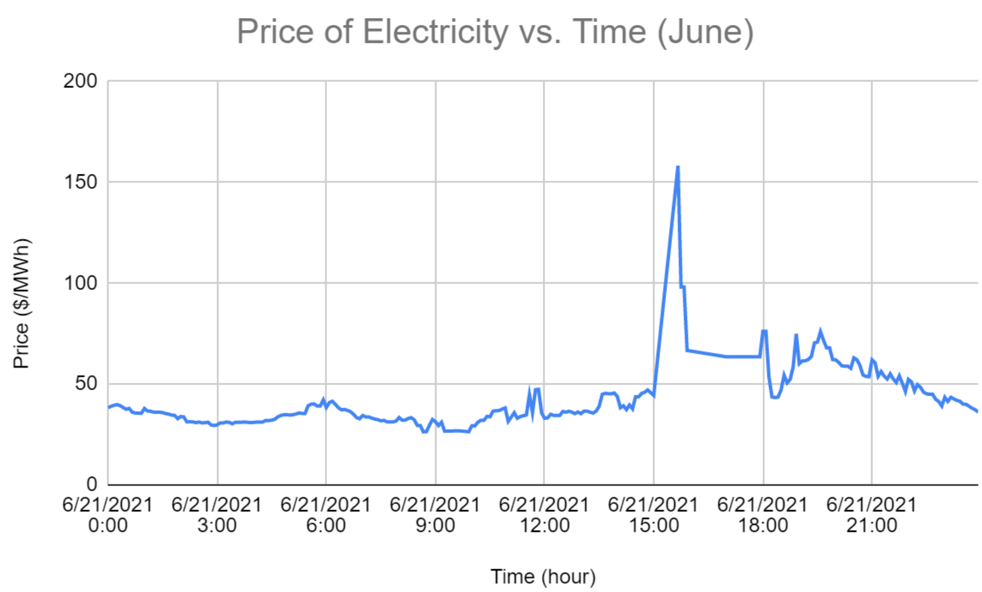

Figure 23: Price of Electricity in CA vs Time: June

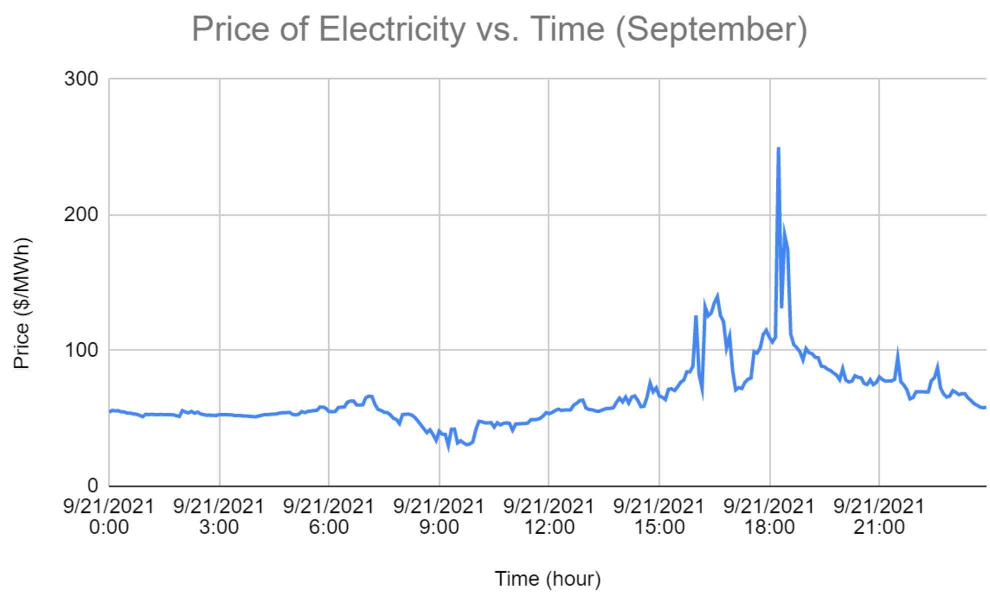

Figure 24: Price of Electricity in CA vs Time: September

Figure 22 shows the price of electricity in California throughout the day in March of 2021. The significance of this data is that it shows a negative price of electricity from 11:00 pm to 5:00 pm. This means that the supply of energy is so high that the energy generation systems would pay systems to use their electricity. This is beneficial for a TES system like the one proposed throughout this research where the energy during this time would be purchased at this low value. The time between 6:00 pm and 8:00 pm would be the ideal window to sell the electricity produced by the discharge cycle because that shows where the cost of electricity is at its highest. This produces the highest net revenue per cycle possible to help make this proposed TES system more desirable. Figure 23 and Figure 24 show the same “Duck Curve” that is expected with the supply and demand throughout the day [43]. The main difference between the graphs is the range for each price value because of the expected variance with the change of temperature and amount of sunlight throughout the year.

This process creates a net revenue per cycle that is considered the amount of money made or cost to run an entire cycle using the TES system proposed throughout this research. This format of selling the energy when its price is high and buying the energy when its price is low contributes to the payback period and return of investment for the use of the TES system. The payback period is a value that is determined by using the total cost of the TES module, charge cycle, and discharge cycle and dividing it by the net revenue to go through one full cycle of charging the ROC and discharging energy. To make the TES system a more desirable option compared to its competitors, the payback period should be minimalized so that customers will get their initial investment back at the soonest possible time. The rate of return represents the net gain or loss from an investment over a period of a year. This value was determined using the net revenue generated from the cost of electricity and dividing it by its initial investment to determine how much of the investment would be made back at the end of the year. This value works directly alongside the payback period and should be at a larger value to ensure that the customer would receive their money back on their investment as soon as possible to make this energy storage system more desirable.

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Cost of Thermal Energy Storage: Varying Temperature

The TEA was performed on the EMWD ROC sample described above which includes the TDS value of 10,000 mg/L and 2.27 million gallons of brine delivered to the system per day (MGD). The TDS value determines the ratio between solid ROC and water content found within the brine. This amount of brine chosen for this TEA is the amount of brine delivered into the IEBL per year by the EMWD. An increase in this amount of brine intake increases the amount of ROC stored in the overall TES system which helps describe the important of scaling up the system to store as much ROC as possible to held solve the problem of the concentrate management and increase the amount of potable water produced. This amount of ROC generated from the proposed amount of brine is used to calculate the thermal energy stored for the scenarios investigated below.

The overall cost of TES using a ROC-based TES module was calculated using the equations and costs mentioned in the previous section. The way to properly display these values is through a stacked column chart with varying operating conditions. This section specifically focuses on comparing the varying maximum storage temperature of both scenarios utilizing each ZLD system.

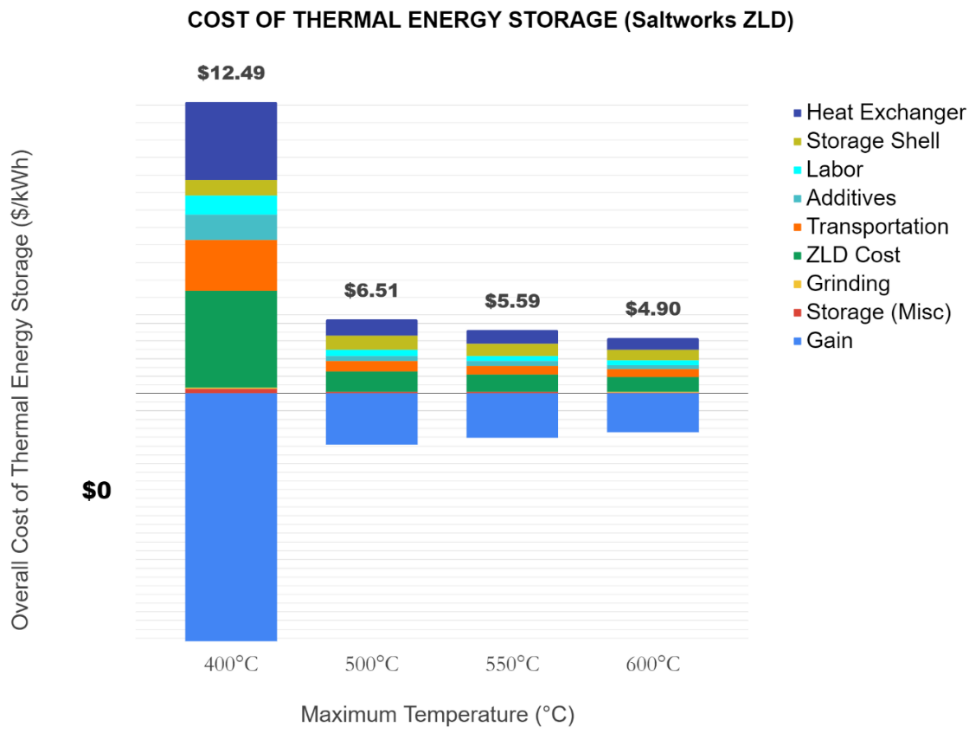

Figure 25: Overall Thermal Energy Cost Varying Temp: Saltworks ZLD, Trucked

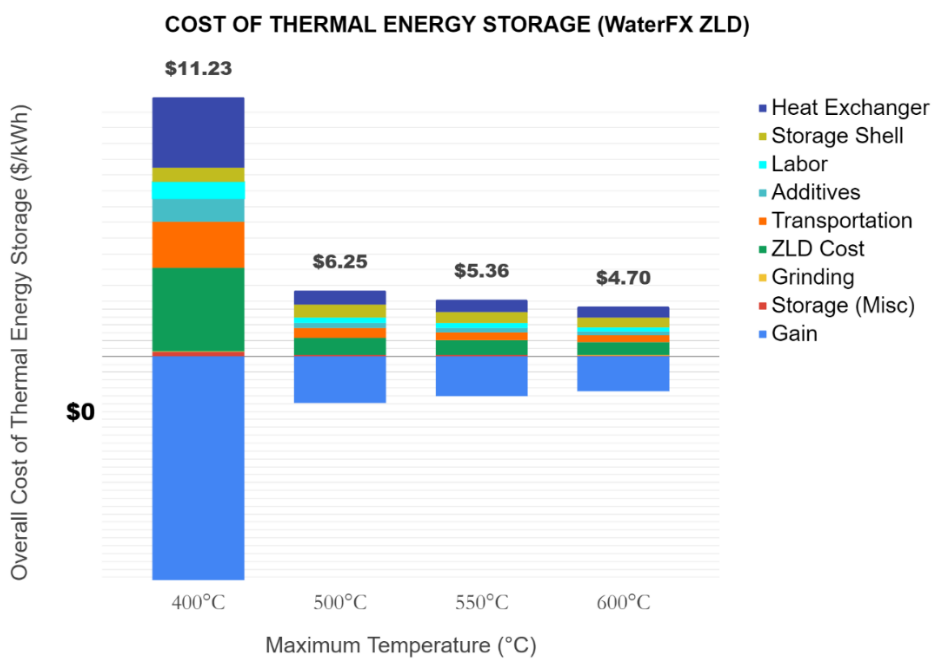

Figure 26: Overall Thermal Energy Cost Varying Temp: WaterFX ZLD, Trucked

Figure 25 and Figure 26 highlight the cost of TES using Saltworks and WaterFX ZLD systems while comparing the maximum storage temperature of the TES module. Due to the melting temperature of the ROC sample being 450℃, the 400℃ column represents the non-melting scenario where the phase change does not occur, and the other columns represent the melting scenarios where phase change from a solid to a liquid occurs. The cost of TES dramatically reduces once the phase change occurs, and this is due to the increase in thermal energy stored created from the latent heat from the phase change and the sensible heat from the ROC in its liquid form. Since the thermal energy stored increases inversely with the overall cost of TES, this increase in thermal energy storage from the phase change causes the overall decrease in the cost of TES which is seen in the final three columns of the figures above. As previously mentioned, the two ZLD processes are approached in two different manners: Saltworks calculates their cost using a rate depending upon the volumetric intake of ROC brine and WaterFX calculates their cost using the individual capital and operating costs to construct and operate their technology system. The differences in these approaches are made comparable to one another after finding that the values calculated provide comparable results and are seen by the similarities in the overall cost of TES found within both figures above.

The results from this analysis show that in all cases of ROC-based TES the cost of TES proved to be below the DOE's SunShot Initiative goal of $15/kWh. Although the WaterFX ZLD technology proved to be more cost-effective than the Saltworks ZLD technology, the two systems both provide cost-effective results that are seen in all scenarios investigated. The cost of TES proved to dramatically decrease after the phase change occurred and the selected trucked gain used for all cases showed to provide enough revenue to outweigh the costs associated with processing and storing the ROC effectively. Since the cost of TES behaves inversely compared to the behavior of the total thermal energy stored, the effect of each individual cost and revenue category is much larger when the amount of thermal energy stored decreases. This can be seen in the blue-colored categories on the figures above that are solely located in the negative direction of the overall cost of TES. When comparing the non-melting and melting scenarios, the blue category representing the gain is much larger for the non-melting scenarios which will be highlighted in the section where the gain will be varied for each cost of TES investigated. The most dominant costs for all cases were the ZLD and transportation costs. Since the primary end goal for the ROC brine investigated throughout this research is that it is disposed of within a brine line, the costs of transporting this brine and the costs of evaporating as much brine as possible to receive its economic benefits would be the most important.

3.2 Cost of Thermal Energy Storage: Varying Gain

The varying parameter for the graphs in Figure 27 and Figure 28 is the specific gain used with each figure being for a different ZLD technology: Saltworks and WaterFX. These figures below specifically highlight the non-melting scenario at 400°C for the maximum storage temperature. The transportation and gain values both depend directly upon one another. As the gain value increases, the cost of transportation also increases to account for the need for trucked transportation as well as the excess miles required to travel for the remote disposal option. As expected, the overall cost of TES dramatically decreased as the gain value increased due to it being a negative revenue source to the overall net cost. In both ZLD technologies, all cases of TES met the

SunShot Initiative's goal of $15/kWh. The importance of looking into the remote disposal option is that the gain charged to RO facilities for this option is so large that the overall cost of TES produces a net revenue. This negative revenue makes this ROC-based TES system desirable to an investor. When investigating the TEA model of the overall TES system, the costs of the charge and discharge cycle will cause a dramatic increase in the cost of TES. Therefore, this revenue-generating disposal option will help offset these costs and produce a more cost-effective TES system.

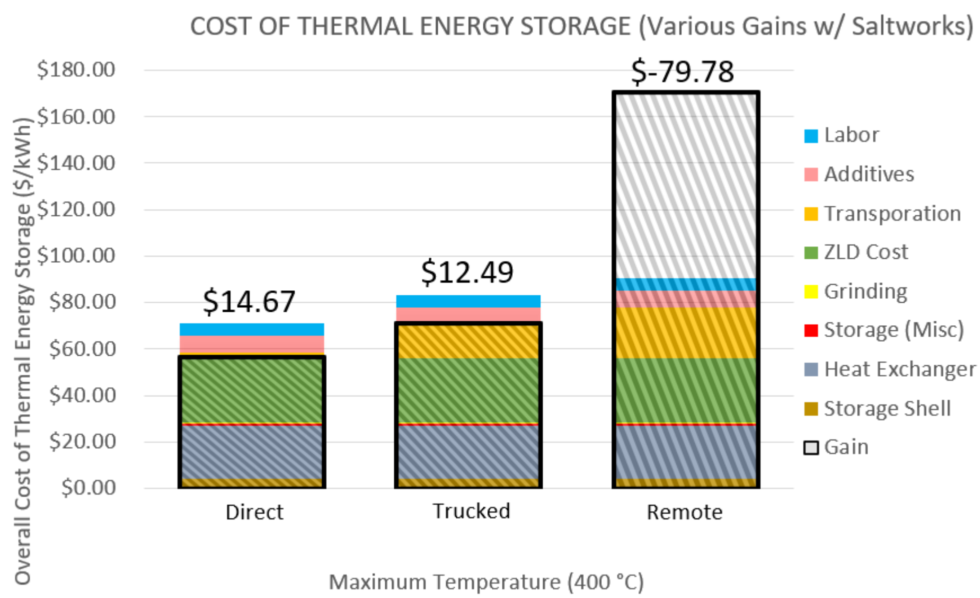

Figure 27: Overall Thermal Energy Cost Varying Gain: Saltworks ZLD, 400°C

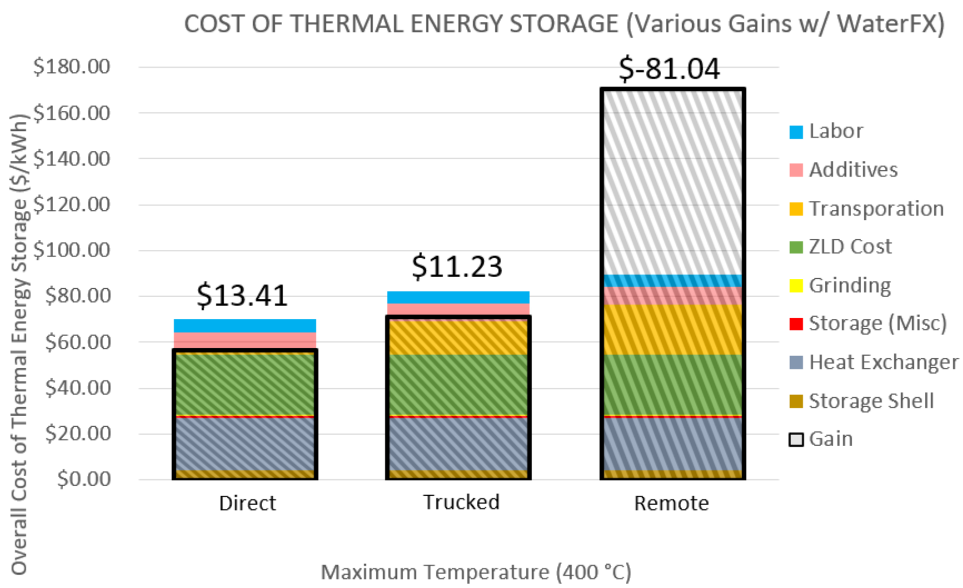

Figure 28: Overall Thermal Energy Cost Varying Gain: WaterFX ZLD, 400°C

The varying parameter for the graphs in Figure 29 and Figure 30 is the specific gain used with each figure being for a different ZLD technology: Saltworks and WaterFX. These figures below specifically highlight the melting scenario at 600°C for the maximum storage temperature. As previously mentioned, the phase change that occurs from the melting scenario causes an increase in the TES density that leads to a dramatic decrease in the overall cost of TES that is seen in the figures below. This phenomenon is directly highlighted when comparing these values to the non-melting values in the previous figures above. The direct and trucked values are significantly reduced between the non-melting and melting scenarios and the non-melting remote disposal case generates significantly more revenue than the melting scenario because of this. In all cases displayed below, the cost of TES for ZLD technologies is below the DOE's target of $15/kWh when the phase change occurs.

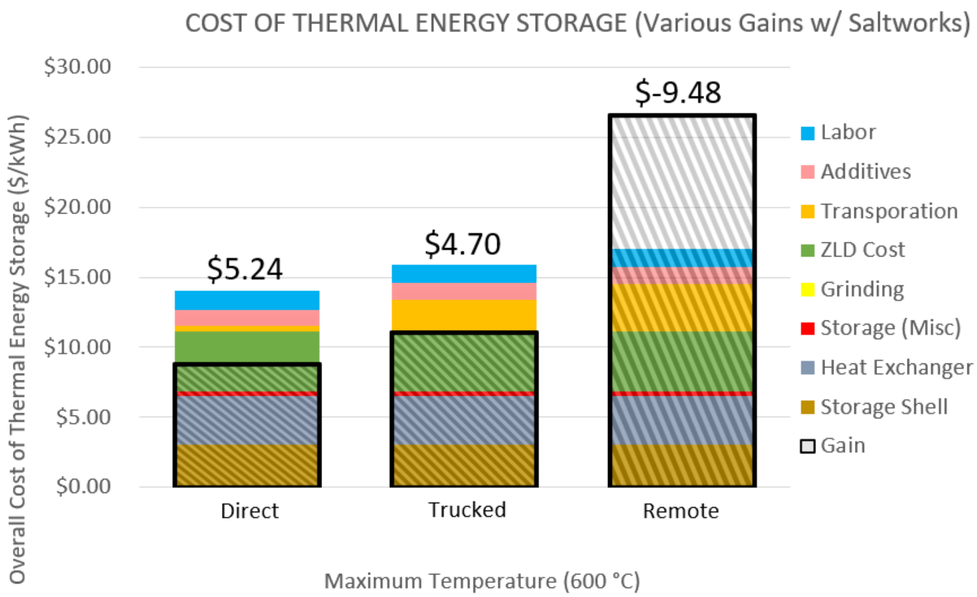

Figure 29: Overall Thermal Energy Cost Varying Gain: Saltworks ZLD, 600°C

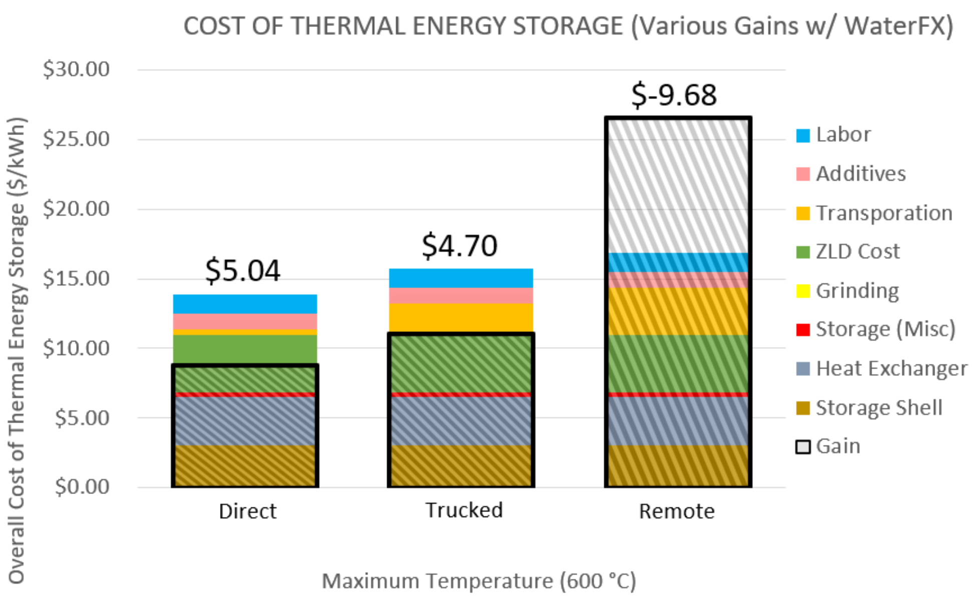

Figure 30: Overall Thermal Energy Cost Varying Gain: WaterFX ZLD, 600°C

3.3 Cost of Thermal Energy Storage: Varying TDS

The TDS value was found to be an extremely important parameter throughout the development and progress of this TEA model. Since this value represents the total dissolved solids within a given fluid, the TDS value for this research determines the ratio of solid mass (ROC) found within the intake amount of ROC brine through a mg/L value. The significance of this value is that it determines the amount of ROC that can be extracted from a given amount of brine intake which determines the amount of thermal energy that can be stored from the ROC. The goal for this TDS value study is to keep the amount of brine delivered to the proposed TES system the same as the 2.27 MGD value provided by the EMWD. To vary the TDS, the amount of ROC processed must vary to understand how important the TDS value is for the overall cost of TES. The range of TDS values investigated is from 2,000-40,000 mg/L. This range was selected because it encompasses the many feedwater sources that are used for desalination facilities. The TDS value for seawater is at a range above 35,000 mg/L while the TDS range of value for the brackish water used as a feedwater source for the further inland desalination facilities investigated is from 1,000 mg/L to 10,000 mg/L. The range between 10,000 mg/L and 35,000 mg/L can be defined as the TDS for saline water that can be used for some desalination facilities closer to the coast but not directly from the seawater [44]. The range of TDS values selected incorporated both the brackish feedwater source for the inland desalination facilities and the seawater feedwater source for the desalination facilities located on the coast. The figures presented below represent the relationship between the cost of TES and the TDS value for the various gain options. The cost of TES used for the figures below is calculated using the 400°C non-melting scenarios with the WaterFX ZLD information utilized.

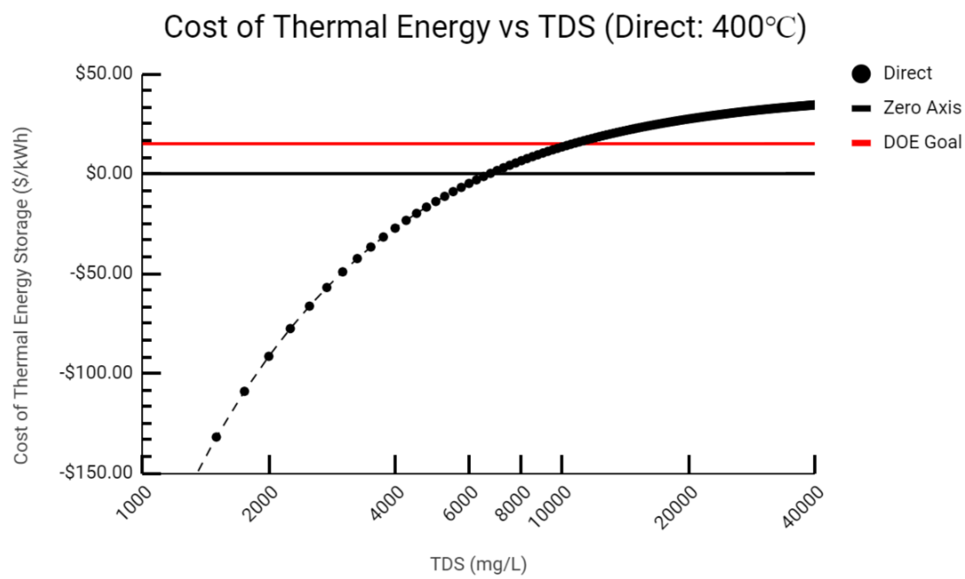

Figure 31: Overall Thermal Energy Cost Varying TDS: Direct: 400°C

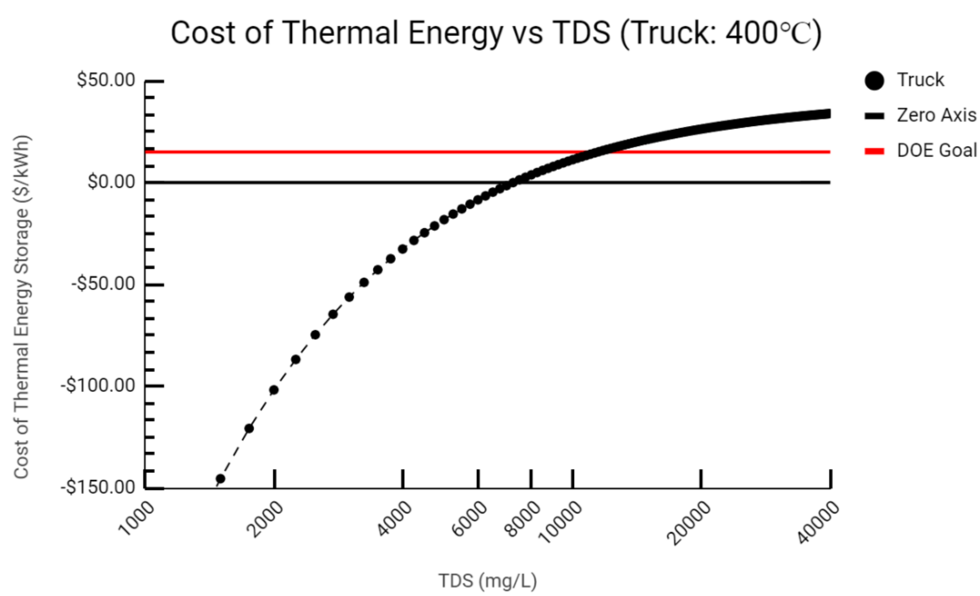

Figure 32: Overall Thermal Energy Cost Varying TDS: Trucked: 400°C

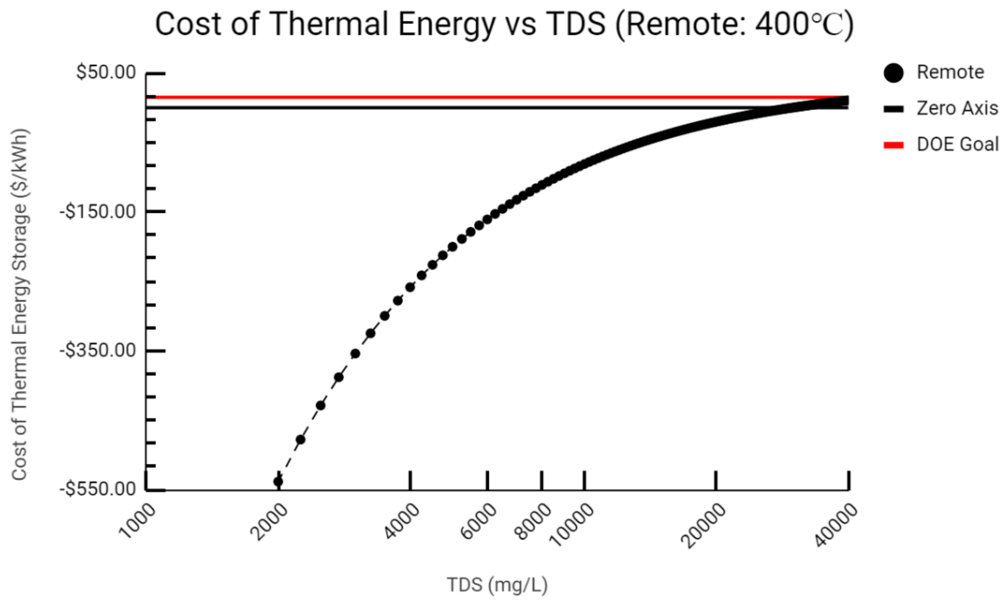

Figure 33: Overall Thermal Energy Cost Varying TDS: Remote: 400°C

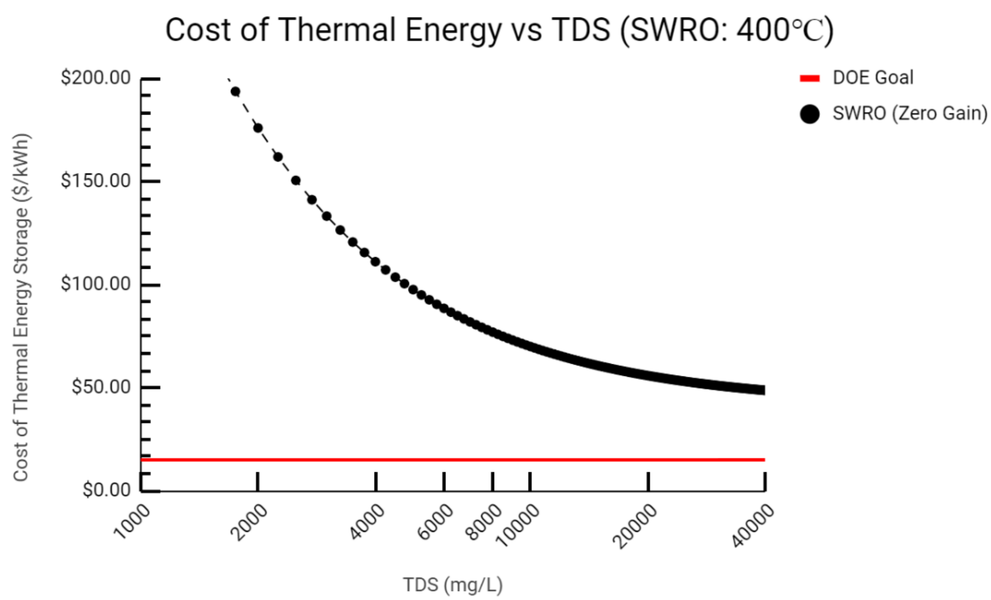

Figure 34: Overall Thermal Energy Cost Varying TDS: SWRO: 400°C

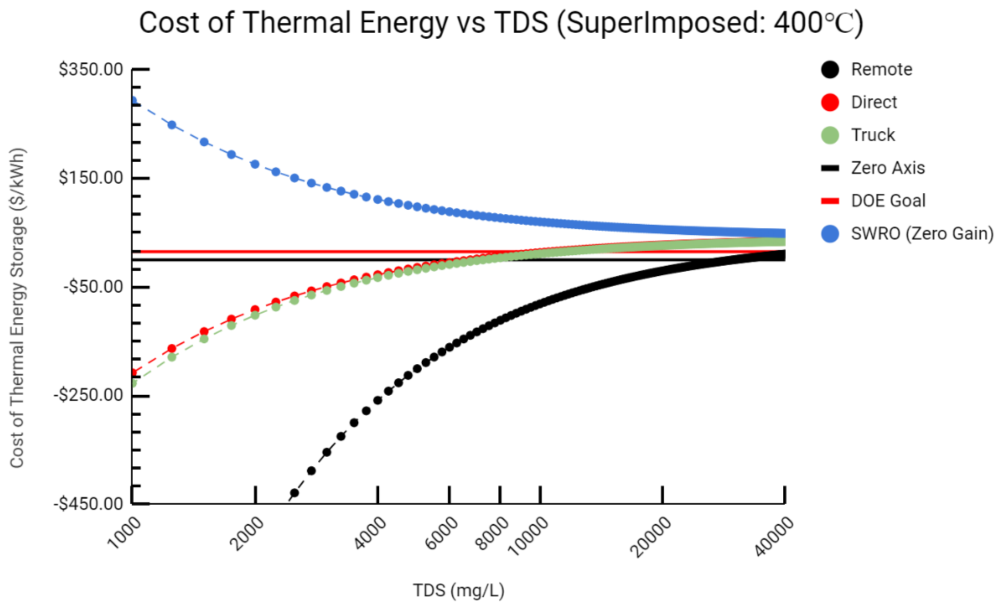

Figure 35: Overall Thermal Energy Cost Varying TDS: SuperImposed: 400°C

Figure 31 and Figure 32 show comparable results as the direct and trucked disposal options provide comparable results seen throughout this analysis. The results show that the cost of TES is most profitable as the TDS value decreases with low TDS values providing a revenue source for the cost of TES of the direct and trucked disposal options. Figure 33 shows the remote disposal option as it expectantly provides revenue for all TDS values investigated. This proves again how this disposal option is the most profitable of the three and would allow for the most diverse range of TDS values of feedwater sources to utilize this TES system. Figure 34 shows the SWRO facilities cost of TES where no gain is charged to these facilities due to their access to the ocean disposal option. The purpose of this figure is to describe the behavior of the costs as the amount of ROC processed and stored increases. This effect is important to understand that the increase in ROC stored within the proposed system will progressively lower the overall cost of TES. Figure 35 is included to highlight the significant advantage of using the remote disposal option for these TDS values and still being profitable for all cases. The red solid line is meant to represent the $15/kWh SunShot Initiative goal that is achieved for TDS values below 10,750 mg/L for the direct disposal option, below 11,500 mg/L for the truck disposal option, and below 47,000 mg/L for the remote disposal option.

The analysis in the previous study was also investigated for the scenarios where a phase change occurs. The same TDS range was investigated with the overall cost of TES calculated assuming a phase change had occurred and a maximum storage temperature of 600℃ within the TES module while still using the WaterFX ZLD information. All disposal options were investigated and the results from this analysis are shown in the figures below.

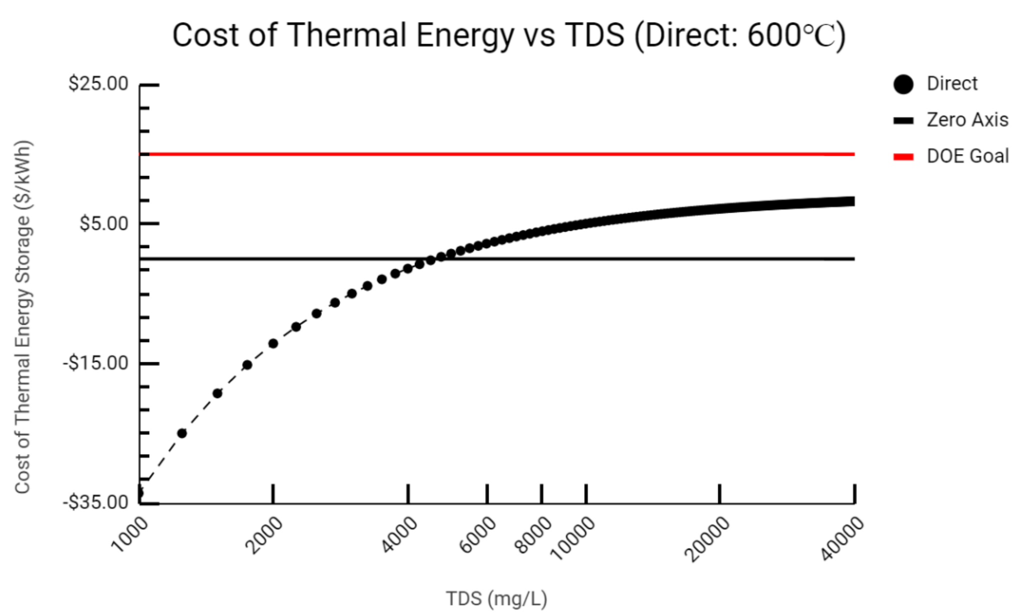

Figure 36: Overall Thermal Energy Cost Varying TDS: Direct: 600°C

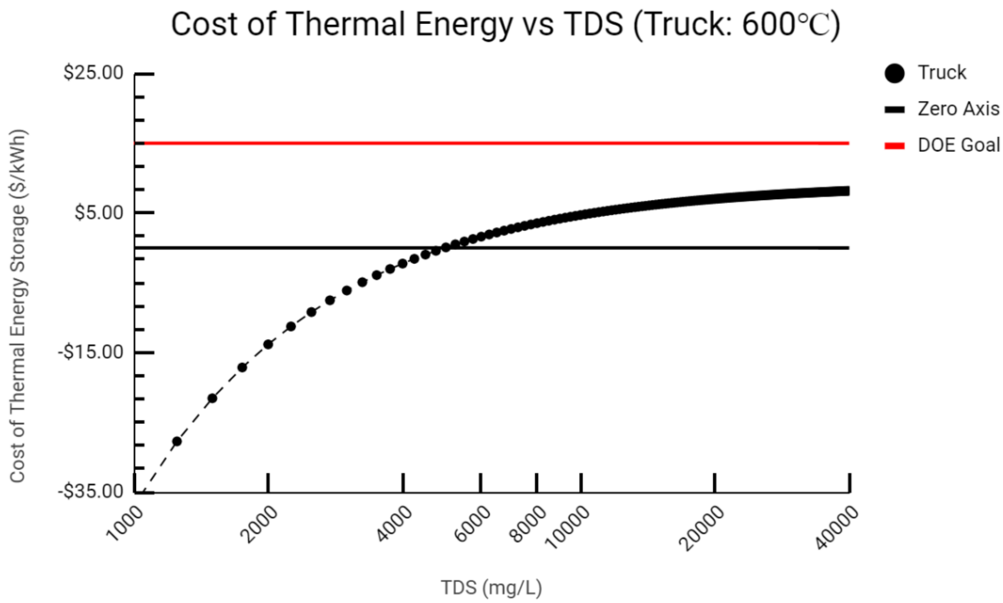

Figure 37: Overall Thermal Energy Cost Varying TDS: Trucked: 600°C

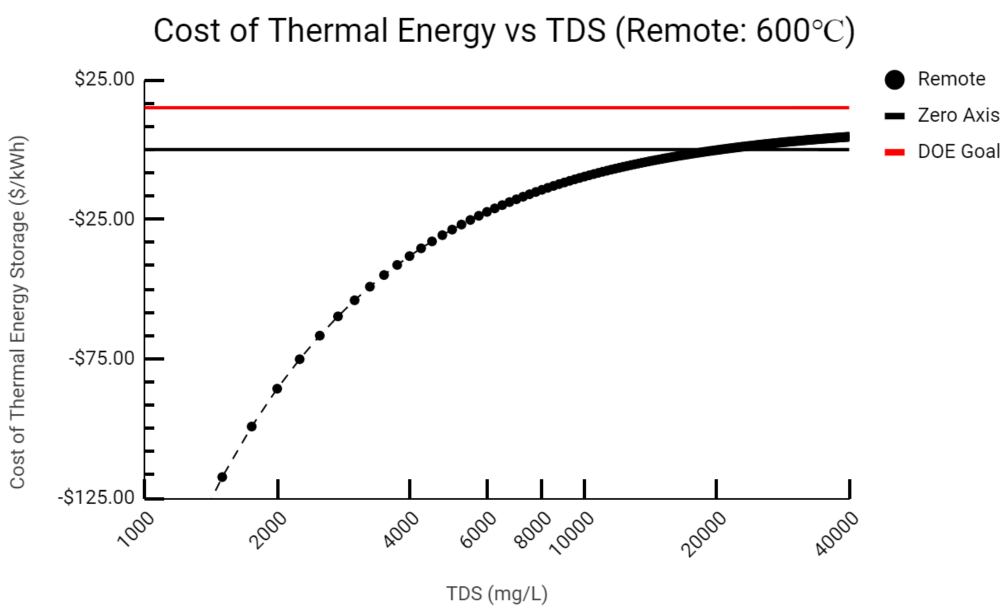

Figure 38: Overall Thermal Energy Cost Varying TDS: Remote: 600°C

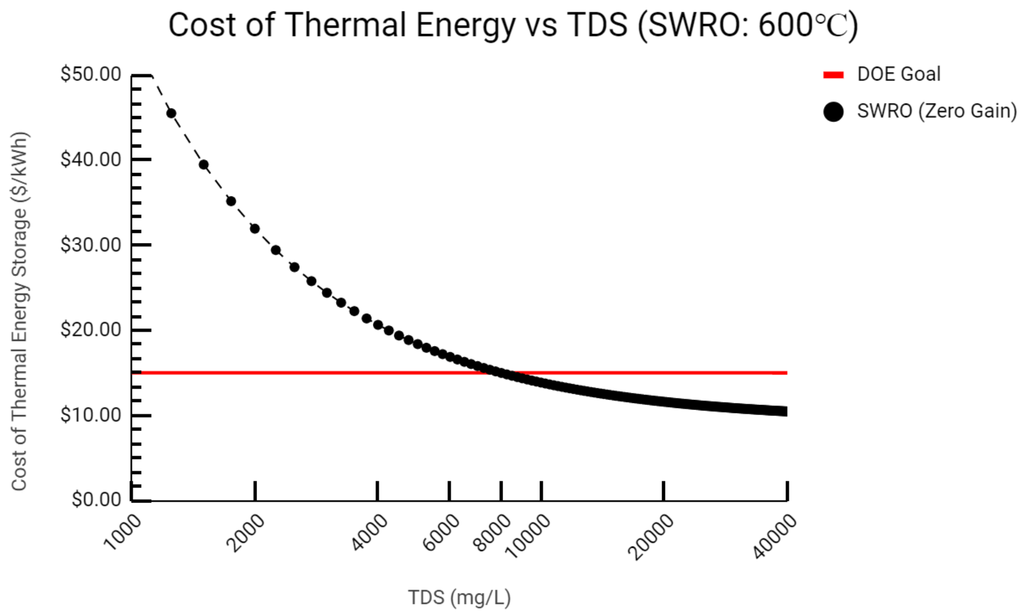

Figure 39: Overall Thermal Energy Cost Varying TDS: SWRO: 600°C

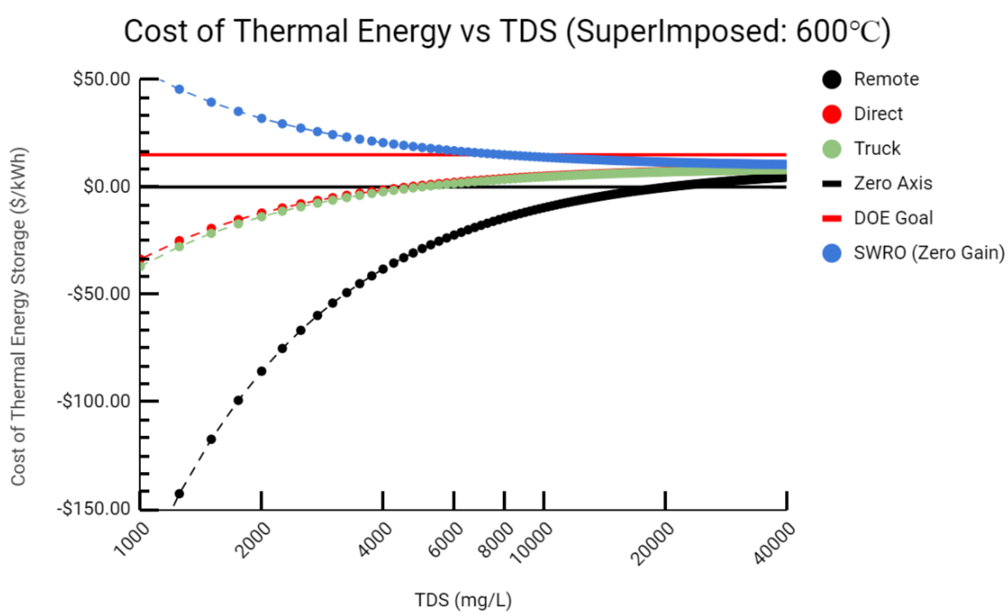

Figure 40: Overall Thermal Energy Cost Varying TDS: SuperImposed: 600°C

Figures 36 through 40 follow the same trend as the previous study investigating the direct, truck, remote, and SWRO zero gain disposal options as the TDS value is varied. The red solid line is meant to represent the $15/kWh SunShot Initiative goal that is achieved for all TDS values investigated in this study for the direct, truck, and remote disposal options while the SWRO zero gain option meets this goal for TDS values of 8,000 mg/L and above. The significance of this dramatic different in costs for the melting scenario is due to the phase change increasing the energy storage density and thus producing more energy out of the same amount of ROC that lowers the overall cost of TES. The significance of this is that it allows for a much wider range of TDS values for all disposal options when the phase change is experienced. This expands the range of desalination facilities that could utilize this proposed system and still meet the overall cost of TES goal proposed. The significance of the findings of the SWRO results is that the presence of a phase change allows for the disposal of ROC on the coast to be integrated into this system while still being below the DOE's goal of $15/kWh.

3.4 Cost of Thermal Energy Storage: Varying ROC Amount

The issue of concentrate management is a limiting factor to the amount of potable water that can be produced. Therefore, the ability to increase the size of the TES system is extremely important in addressing this issue. A study was performed for both non-melting and melting scenarios for all disposal options to investigate the effects of the overall cost of TES as the amount of ROC stored in the modules increased. The results from this analysis are displayed in the figures below. The range of ROC investigated in this study is from 10,000,000-100,000,000,000 kg of ROC to ensure that the capacity of the TES storage can meet the desire production of potable water.

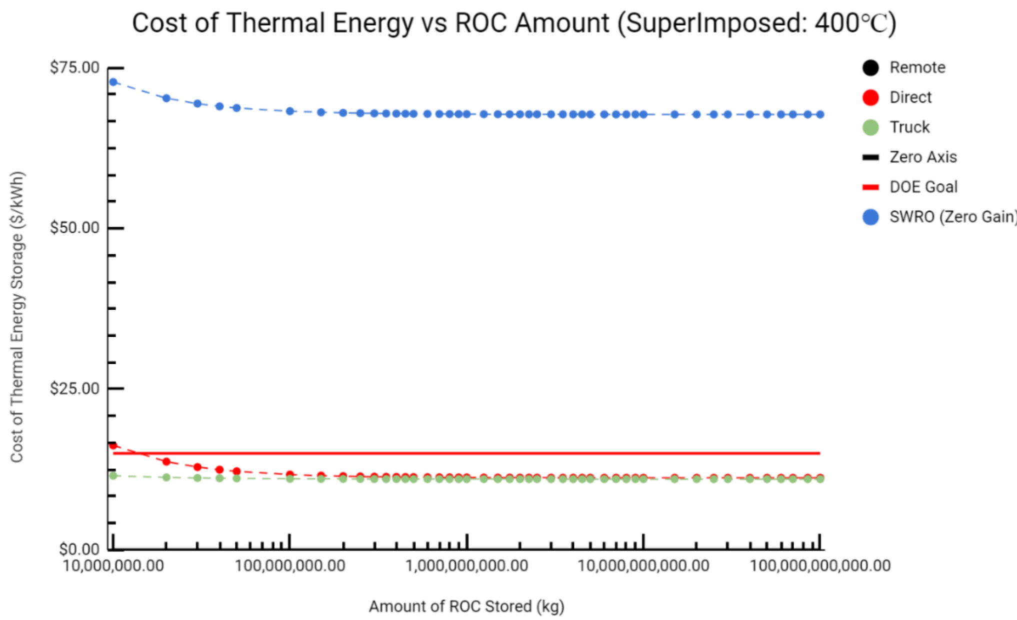

Figure 41: Overall Thermal Energy Cost Varying Amount of ROC: 400°C

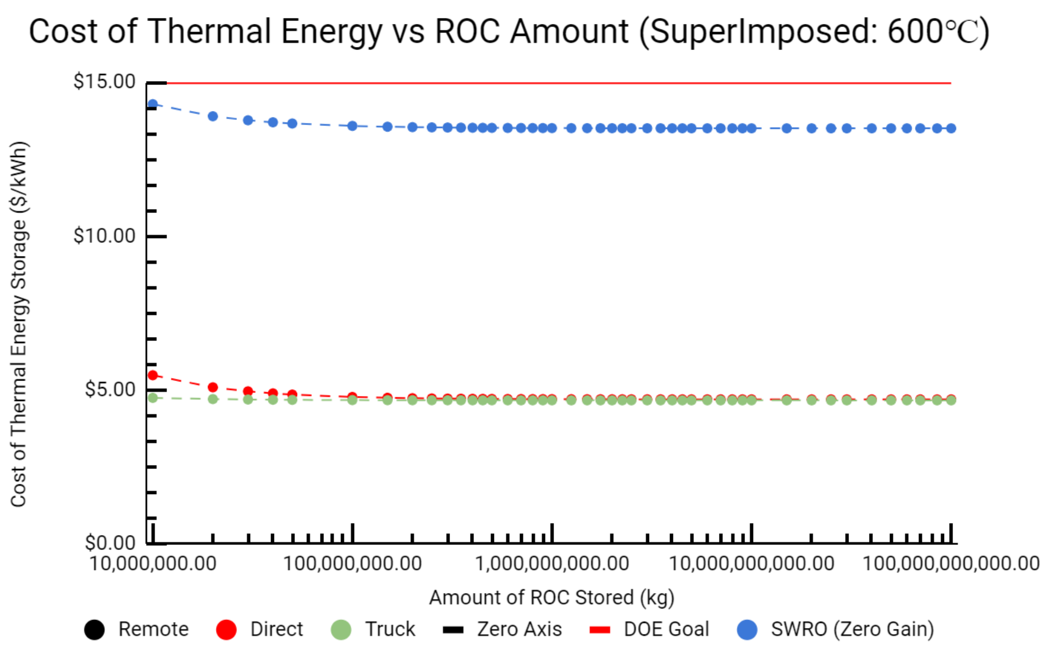

Figure 42: Overall Thermal Energy Cost Varying Amount of ROC: 600°C

Figures 41 and 42 show the overall cost of TES for all disposal options for the non-melting and melting scenarios while varying the amount of ROC stored within the TES modules. The importance of these results is that they show the increase in ROC causes the overall cost of TES to decrease. This is important because it allows for the scale of the TES system to be increased to store and process as much ROC as necessary to help concentrate the amount of ROC produced from the desalination facilities. Although the containment and processing costs are increased as the amount of ROC is increased, the SWRO results can show that the thermal energy benefit from storing the increased amount outweighs the additional costs. It is also important to highlight that the phase change causes the overall cost of TES to meet the SunShot Initiative's goal for all cases. This is important because it shows that capacity of the ROC storage for all locations investigated can be met to keep the amount of disposed ROC contained while produced as much potable water as possible to keep up with the ever-increasing population.

3.5 Cost of Electric-to-Electric Energy Storage

The previous results have all provided the cost of TES for the process and storage of the ROC within the TES module. This section highlights the overall cost of electric-to-electric energy storage for the entire TES system that includes the costs of the charge and discharge cycles and the net revenue generated from the consumption and production of energy. The analysis performed was to compare the overall cost of energy storage while varying the TDS value. The same TDS range was used as the previous TDS studies to investigate the range that is most profitable for the TES system. The results using the direct, truck, remote, and SWRO zero gain disposal options for the cost of electric-to-electric energy storage are integrated and presented in Figure 43 below for the non-melting scenario at 400℃.

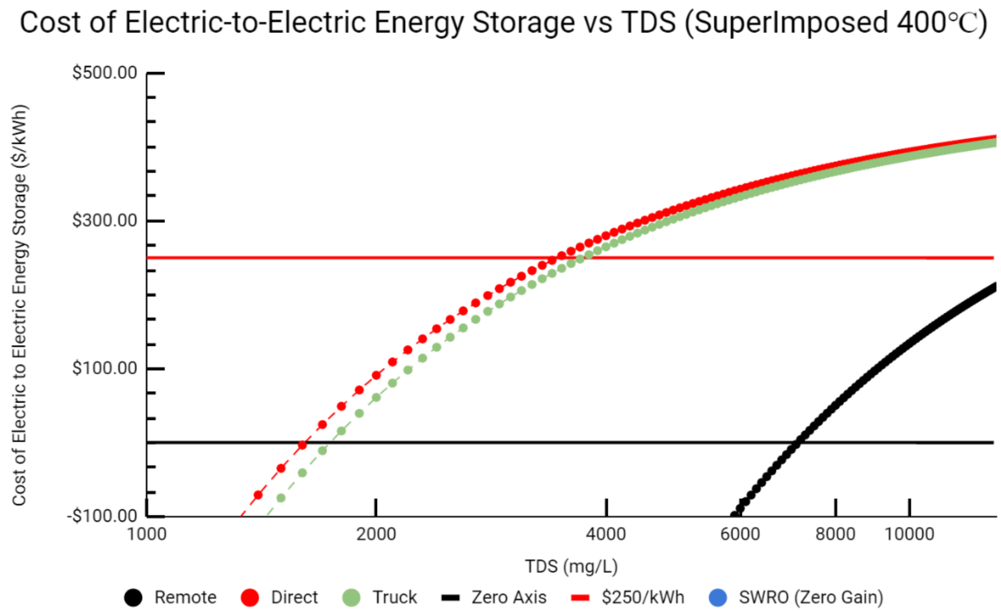

Figure 43: Overall Electric-to-Electric Energy Cost Varying TDS: 400°C

Using the three figures representing the cost of electricity throughout the day for three months throughout 2021, the cost of energy during the charge and discharge cycle was calculated and is displayed below. These values were then used and integrated into the TES module to determine the payback period and return of investment. These were then iterated with the proposed costs found in the charge and discharge cycles to determine the overall cost of electric-to-electric energy storage goal to produce a desirable payback period and return of investment. These values are summarized below in Table 6.

Table 6: Electricity Variation Important Values

Date	Net Revenue ($/cycle)	Payback Period (years)	Return of Invest (%)
3/21/21	29,535.28	3.48	28.70
6/21/21	14,208.26	7.24	13.81
9/21/21	20,526.51	5.01	19.95

The dates investigated during this electricity variation study provided a net cycle that generated a payback period below the desired 10-year goal. This provides a reasonable time that an investor can see and determine to be acceptable to get a return on their initial investment to operate this TES system. From this analysis, a goal of $250/kWh was established to create the most effective payback periods and return of investments. This goal is highlighted above using the red line to show where the three disposal options meet the goal. The analysis has proven that the direct disposal option can be utilized to meet this goal for TDS values up to 3,500 mg/L, the truck disposal option can be utilized to meet this goal for TDS values up to 3,800 mg/L, and the remote disposal option can be utilized to meet this goal for TDS values up to 15,400 mg/L. This analysis has shown that the proposed TES system can produce cost-effective results for TDS values up to 15,400 mg/L assuming the most profitable disposal option and without the presence of a phase change. In combination with the electricity variation costs, this design can result in a competitive system for the energy market that investors can be interested in. Although the EMWD ROC sample produced a 10,000 mg/L TDS value, this analysis still provides useful insight for the appropriate range of feedwater sources that can still use this proposed TES system for a cost-effective investment. With the proposed future work of the system-level modeling, the overall cost of electric-to-electric energy storage can be reduced for larger TDS values to increase the range of feedwater sources that can effectively utilize this system.

Although the presence of a phase change produces a cost of TES that is lower than the DOE's goal of $15/kWh, the increase in thermal energy density causes the costs of the charge and discharge to outweigh the revenue earned from the disposal of brine.

This means that the range of TDS values that meet the proposed $250/kWh for the most profitable disposal option is much lower than the non-melting scenario and must be improved through the future works of this TEA. The analysis for this melting scenario was performed with the results shown below in Figure 44 at a maximum storage temperature of 600℃.

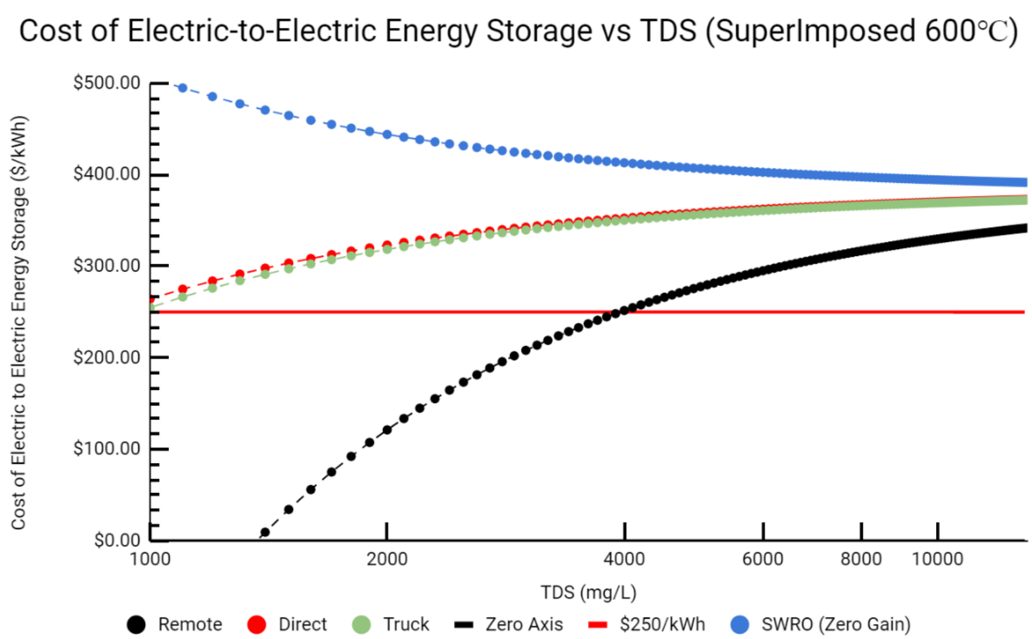

Figure 44: Overall Electric-to-Electric Energy Cost Varying TDS: 600°C

CHAPTER 4 CONCLUSION

The research developed throughout this study has proven that the TEA model shows that using a ROC-based TES system can significantly reduce the cost of TES while preventing the disposal of high concentrate salt to the environment. The gain charged to RO facilities to dispose of their brine shows to be the most contributing factor to the overall cost of TES. The availability of the disposal options for the RO facilities as well as their location produces the possible opportunities to work with these facilities and gather their brine for TES.

The TDS study has proven that the cost of TES target can be met for all disposal options in the absence of a phase change up to a value of 10,000 mg/L which is accurate to the brackish feedwater source that is typically used for the inland facilities. The inclusion of a phase change produced valuable results for this TDS study by producing an overall cost of TES below the DOE's goal for values above 8,000 mg/L for SWRO facilities that allows for this technology to be useful for facilities on the coast. This research is also able to prove that the ability to upscale the capacity of the TES system can be increased to match the potable water production of these investigated facilities. This proposed TES system has shown to be much more desirable to the current state-of-the-art TES technology utilizing solar salt as its TES medium.

The analysis performed to improve the understanding of the effects of all costs associated with operating an entire TES system has proven to further show the importance of the TDS value of the ROC. The currently proposed system utilizing oil heaters as the charge cycle and a steam turbine and generator as the discharge cycle has provided a TDS range up to 15,400 mg/L to operate the TES system at a cost-effective value below $250/kWh using the most profitable disposal option.

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CHAPTER 5 FUTURE WORK

5.1 Salt Characterization

The current salt characterization has provided the weighted average thermophysical properties for the EMWD ROC sample that created a more accurate TEA model and thus a more accurate overall cost of TES. To find the right market/area to utilize the proposed TES system, the salt characterization of various ROC samples is important. Future work with the salt characterization from ROC samples in various states or further inland from the coast will help determine the most profitable and suitable locations for the use of this TES system.

5.2 Experimental Prototypes

Experimental data is extremely important to validate theoretical data and calculations. Therefore, the inclusion of a prototype using the materials and equipment specified throughout the TEA model would either validate the current costs attributed to the model or require updates to the current model. These updates would include the materials used for the containment and heat exchanger categories for the TES module. These changes could be necessary due to the temperature being exhibited throughout the storage module as well as the corrosive issues experienced while using such corrosive salts and performing thermal tests with them. These changes would alter the costs and material properties used throughout the model which would further affect the TEA model's overall cost of TES.

5.3 Cash Flow Analysis

Cash Flow Analysis is used to determine the costs and revenue experienced by a business over a given time. This is an important form of analysis because it quantifies the possibility of success for the business and provides an upfront value for how much the system will cost investors or customers interested in using this service provided. Cash Flow Analysis can also be used to create a Future Worth Value or Present Worth Value which brings all costs and revenue values to a single point in time using a desired rate of return or inflation percentage. This will be effective for this research once the costs described throughout the model are precisely separated into the categories of capital and operating costs while including the lifespan of the equipment used in this model as well as its salvage value at the end of its life cycle. After these aspects are successfully integrated into the TEA model, the overall cost of electric-to-electric energy storage over a desired period can be accurately provided to an interested investor or customer to determine how much the system will cost and/or save them. This integration is essential for the success of this service in the market of TES and providing alternative forms of renewable energy during peak hours where the supply from solar energy is no longer sufficient.

5.4 TES System Model

The initial approach for developing a TES System Model has been described above and proven to show conclusive results that meet the desired goal for the overall cost of electric-to-electric energy storage for the TES system. However, the components of the charge and discharge cycles may be changed to improve the overall cost of electric-to-electric energy storage. The optimization process for the variation of electricity costs will also help reduce the payback period for the investment put into this TES system and will increase the rate of return which makes this concept much more desirable to investors. Using the most profitable disposal option, remote disposal, the cost of integrating the charge and discharge cycles can be outweighed to heavily favor this proposed design.

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