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TECHNO-ECONOMICS OF USING CONCENTRATE OF MEMBRANE PROCESSES AS A LOW-COST THERMAL ENERGY STORAGE MEDIUM

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ABSTRACT

Membrane processes are used for water treatment techniques to desalinate seawater and surface water into potable water. The undesired byproduct of these processes is a high concentrate salt. In this project, the repurposed concentrate salt was studied as a storage medium for grid-scale Thermal Energy Storage (TES). The Department of Energy's (DOE) goal is to reduce the Levelized Cost of Energy of TES for concentrated solar power to be under 15 \$/kWh by 2030. In this work, a techno-economic assessment was performed to estimate the cost of TES using concentrate salt. The total cost of TES was estimated by considering costs associated with transportation of brine, evaporation of remaining water, grinding the salt content, additives added, and containment costs while considering a positive financial gain from obtaining the concentrate from water treatment facilities. It was observed that the concentrate salt that went through solid to liquid phase change provides an increase in energy density and a reduction in TES cost. The results show a financial benefit using concentrate salt as a storage medium for heat making it a feasible material to meet the Sunshot Initiative goals for TES. Depending on the source of the brine, zero liquid discharge method, and operating temperature we can observe costs as low as (-\$11.10), i.e., positive revenue. The occurrence of phase change within the operating temperature of the application significantly increases the energy storage density and reduces the cost of the TES which is seen in the results for the melting scenarios.

1. INTRODUCTION

Thermal Energy Storage (TES) systems vary greatly in design, objective and medium. The value of the medium in which thermal energy is stored plays an important role in the overall cost of storing thermal energy and in the cost of any application that uses the TES system. For example, the cost of the electricity generated by a Concentrating Solar Power (CSP) plant depends on the overall cost of TES and consequently on the cost of the TES medium. The TES medium has a very simple mission; it heats up during the charge cycle and cools down during the discharge cycle. The thermal energy is stored in the internal energy of the TES during the time between charge and discharge. An ideal TES medium stores the maximum amount of heat within a known temperature range, ΔT. If the TES medium goes through a solid-to-liquid or liquid-to-gas phase change, more energy can be stored in the TES medium, therefore, the energy storage density is increased.

The overall cost of any TES system is highly dependent on a) the cost of the TES medium (\$/m^3), b) the cost of containing the TES medium and operating the TES system, and c) the energy storage density, i.e., thermal energy stored per unit volume (or kJ/m^3) at a given temperature range ΔT. Using water as a TES medium makes economic sense only up to about 250 °C due to the fact that the vapor pressure of water

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requires the containment system to become unreasonably expensive. The state of the art of the TES for CSP utilizes solar salt (mixture of sodium and potassium nitrate) as the TES medium [1] in a 2-tank configuration [2]. Solar salt has a reasonable energy storage density in the CSP temperature range (specially for parabolic troughs up to 400 °C); however, the TES medium cost associated with solar salt and many other phase change materials do not allow the overall TES cost to meet the U.S. Department of Energy's (DOE) SunShot Initiative cost target of \$15/kWh [3] although their energy storage density is remarkably high [4,5]. The overall TES cost when solar salt is used as the TES medium is \$30/kWh, which is double the cost for the target set by the DOE for TES costs [6].

In this paper we are introducing an unconventional material for TES. Reverse Osmosis Concentrate (ROC) is the reject of the reverse osmosis water treatment processes and is classified as an industrial waste by the U.S. Environmental Protection Agency (EPA) which faces regulatory limitations on disposal. Methods of ROC disposal include surface discharge to rivers, discharge to the ocean, deep-well injection, and evaporation ponds, all of which release high concentrations of salt into the environment. The ROC's chemical composition is dependent on the feed water source. ROC is generally a mixture of salts dissolved in water (e.g., NaCl, KCl, $MgCL_2$, $MgSO_4$, etc.). Currently, there are no major applications in any industries for this high salinity mixture or the resulting solid salt mixture upon the removal of its water content. According to the National Academics [7], developing disposal alternatives for ROC is one of the foremost priorities for water desalination research [8]. The current team had previously shown that using the solid salt content of the ROC as a TES medium can potentially reduce the cost of TES below DOE cost target [9]. In the previous study [9], the cost associated with extracting the solid salt from ROC was modeled by modeling the cost of evaporation using natural gas burners or evaporation ponds. In this paper, the impact of using Zero Liquid Discharge (ZLD) technology as the salt extraction method on the techno-economic analysis (TEA) model of an ROC-based TES is explored. ZLD is a process in which additional permeate is recovered from the feedwater through multi-effect distillation in WaterFX technology [10] or through Eutectic Freeze Crystallization in the Saltworks Technologies system [11]. The reject of the ZLD process is a high salinity sludge that can be pumped. At this stage, the solid salt can be mechanically extracted from the sludge using a filter press.

2. METHOD

Figure 1 illustrates the integration of the ZLD technology with an RO plant to generate the solid salt needed for ROC-based TES. The ROC would be received from the RO facility and the RO facility is charged a disposal fee that is determined according to the geographical location of the RO facility. The ROC would then be introduced to the ZLD system of WaterFX or SaltWorks in order to extract the salt solute. The salt solute would then be grinded into finer particles using a commercial grinder. Low-cost additives (such as SiO_2) would be added to the resulting fine salt to improve thermal characteristics. The mixture would then be packed into an insulating container (e.g., concrete) and the Waste Salt Technologies™ patent-pending heat exchanger would be inserted in the salt mixture. The proposed TES system is an indirect TES and requires heat to be provided and extracted by a Heat Transfer Fluid (HTF).

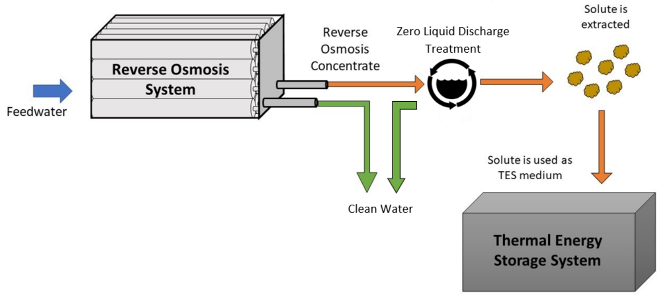

Figure 1 -- Development of a ROC-based TES system

Total thermal energy storage cost associated with the Waste Salt Technologies TES system is calculated by estimating the costs, gain from RO facility's disposal fee, and the amount of thermal energy storage potential as described in Eq. (1).

$$C_{TES} = \frac{C_{Tr}+C_Z+C_G+C_A+C_C+C_{HX}+C_M-G}{E_{St}} \left(\frac{\$}{kWh}\right) \qquad (1)$$

The costs associated with developing the proposed TES system are ROC transportation cost (C_{Tr}), ZLD operational cost (C_Z), salt grinding cost (C_G), additive cost (C_A), containment cost (C_C), heat exchanger cost (C_{HX}), and miscellaneous costs (C_M). The cost estimation details are now discussed.

<u>ROC Transportation Cost (C_{Tr}).</u>

The cost of transportation is primarily based upon the required distance traveled to transport the brine to the TES system and the cost of a pumping station [12]. The capital cost of the pipes required to transport the brine is derived based upon the distance that the brine needs to travel, its flow rate, the pressure loss within the pipe, the amount of brine needed to be transported, and the cost per mile of the pipe material [13]. The additional cost required for the pumping station is required to be able to pump the brine through these pipes to the desired storage location.

<u>ZLD operational cost (C_Z).</u>

The cost for the evaporation processes is derived from the approach for the inclusion of the ZLD processes. For the Saltworks ZLD process, the costs are derived using provided dollar per cubic meter rates for the cost of reverse osmosis recovery, evaporator, crystallizer, and treatment [14]. These costs varied based upon the volumetric amount of brine disposed of by a desalination facility. For the WaterFX ZLD process, the costs are derived using the cost amount of a crystallizer, forward osmosis, and the electrical cost for operating each piece of equipment. These costs varied based upon the number of crystallizers and the amount of forward osmosis processes required for the volumetric amount of brine provided by the desalination facility.

Grinding cost (C_G).

The cost of grinding is primarily based upon the selection of the grinder where the two derived categories of costs are the capital and electrical power costs. The capital cost is derived by the machine price of the grinder required based upon its single load capacity and electrical power needed to grind a given amount of ROC. The electrical cost is derived by the electrical power needed for each grinder for a specified grinding time based upon a given amount of ROC.

Additives cost (C_A).

The cost of the additives are required to ensure that the desired thermophysical properties of the ROC are enhanced to increase the efficiency of heat transfer between the ROC and the heat transfer fluid. The thermophysical properties selected to improve in order to increase the heat transfer efficiency within the system were the ROC's density, thermal conductivity, and specific heat capacity. The additive, Silicon Dioxide, was found for a percentage weight and a cost per mass rate that was varied by the amount of salt derived from the salt [15].

Containment cost (C_C).

The storage shell, storage tube, and miscellaneous storage costs are all derived from the overall containment costs. The costs for the storage shell are the metal container to store the ROC and the concrete structure along with the inclusion of its reinforcing bar. Reinforcing bar, also known as rebar, is a steel bar that is included in the use of concrete to increase the strength of the structure and aid the concrete in tension [16]. The cost of refractory concrete was assumed at storage temperatures beyond 400 °C.

Heat Exchanger cost (C_{HX}).

The heat is transferred from the HTF to the ROC salt through a patent-pending heat exchanger that accounts for the variability of thermophysical properties of the storage fluid, i.e., ROC salt. The costs associated with material and manufacturing of the TES heat exchanger and the cost of HTF is included in this estimation. It should be noted that the HTF for T_{max} of 400 °C is Therminol while the HTF for T_{max} of above 400 °C is assumed to be Solar salt.

Miscellaneous costs (C_M).

The miscellaneous costs are pertaining to the necessary costs that have not been accounted for in the previous categories. This includes the structural support that is required to to support the weight and temperature in the TES system. The miscellaneous costs are assumed to be 5% of the Heat Exchanger cost (C_{HX}) and Containment cost (C_C) combined.

The most important capital costs from the paragraphs above are presented below in Table 1.

Table 1 – Costs of Important Equipment and Material

Product/Material	Cost
Grinding Machine	\$98,000/unit
HDPE Brine Transportation Pipes	\$3,000/km
Silicon Dioxide Nanoparticles	\$15/kg
Containment Lower Temp Concrete	\$100/tonne
Containment Refractory Concrete	\$1,000/tonne
Stainless Steel HTF Tubes	\$3,895/tonne
Storage Container	\$1,745/unit

Gain (Tipping Fee Charged to the RO Facility)

The amount of dollars received from the RO facility as tipping fee is considered as a gain for the proposed ROC-based TES system; therefore, it has been subtracted from the costs in Eq. (1) as a "negative cost." The amount of gain is dependent on the availability of an alternative ROC disposal method. Seawater Reverse Osmosis (SWRO) facilities located near coasts would not be willing to pay any disposal fees as ocean water disposal is currently accepted and performed with minimal processing. However, as the distance of the RO facility from the coast increases, there will be more potential to charge the RO facility a disposal fee. The distribution of brackish groundwater shows that most of the saline aquifers are extended across the central United States where access to ocean for concentrate disposal is not available [17]. Therefore, considering a gain charged to the RO facilities located far from the coast is feasible.

In this study, the ballpark amount of gain (G) is estimated by considering the amount that an RO facility located in Southern California will have to pay in order to use the Inland Empire Brine Line (IEBL) [18]. IEBL estimates the brine disposal cost based on the location of the customer. There are three cost categories of disposal as shown on Table 2: 1) Direct Disposal, 2) Trucked Disposal, and 3) Remote Disposal. The Direct Disposal is meant for customers that are close enough to be directly connected to the IEBL. The Trucked Disposal is meant for customers who are not close enough to be directly connected to IEBL; however, the amount of disposed brine allows for truck disposal. The trucks are dispersed from various centers and travel a maximum distance of 20 miles from any center to collect the brine from the customer and refer it back to the center to be disposed of in the IEBL. The Remote Disposal option is meant for any customer that requires IEBL to travel outside of the LA Basin to retrieve the brine.

Therefore, the ballpark of the gain (G) is from \$0.00/L for SWRO facilities to around \$66,050/L for remote RO facilities, located in the central United States which can be seen below in Table 2.

Table 2 – Cost of ROC disposal using IEBL

Direct Disposal	**Trucked Disposal**	**Remote Disposal**
\$528/L of Brine	\$13,210/L of Brine	\$66,050/L of Brine

Cost of TES (C_{TES}) is inversely proportional to the amount of energy that can potentially be stored in the TES system when operating between a lower temperature (T_{min}) to a higher temperature (T_{max}). The lower temperature for CSP application is considered to be 290 °C which is consistent with the low temperature of conventional and thermocline 2-tank systems [19]. The maximum thermal energy storage temperature (T_{max}) is assumed to be a variable in this study, changing from 400 °C (for parabolic troughs) to 600°C (for dish or power tower).

The amount of thermal energy stored in the ROC-based TES, i.e., the thermal energy storage density is highly dependent on whether or not solid-to-liquid phase change takes place between T_{min} and T_{max}. The investigating team's previous study [9] show that the ROC salt extracted from Eastern Municipal Water District (EMWD) goes through solid-to-liquid phase change below 500 °C while ROC salt samples from Chino Water Desalter authority did not show any signs of phase change even when heated to 900 °C. Figures 2-4 show the ROC salt samples from various RO facilities at low and high temperatures. The ROC samples from Panoche Water District and EMWD go through solid-to-liquid phase change while the ROC salt sample from Chino Desalter Authority do not show any phase change at elevated temperatures.

Figure 2 – Right: The ROC salt from Panoche Water District at 400 °C – Left: The molten ROC salt sample at 600 °C

Figure 3 – Right: The ROC salt from EMWD at 250 °C – Left: The molten ROC salt sample at 450 °C

Figure 4 – Right: The ROC salt from Chino Water Desalter Authority at 250 °C – Left: The ROC salt sample at 900 °C

The amount of stored thermal energy can be estimated by Eq. (2) for an ROC-salt that goes through solid-to-liquid phase change and by Eq. (3) if the ROC salt does not go through solid-to-liquid phase change between T_{min} and $T_{max.}$

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

$$E_{St} = \rho_s \upsilon \int_{T_{min}}^{T_{max}} c_{p,s} dT + \rho_c v_c \int_{T_{min}}^{T_{max}} c_{p,c} dT \qquad (3)$$

The first and last terms of Eq. (2) and Eq. (3) are the amount of sensible heat stored in the solid ROC salt and containment respectively. Equation (2) includes additional terms to account for the latent heat storage and sensible heat storage in the liquid phase of the ROC salt. The thermophysical properties of the ROC salt such as ΔH_{fus}, T_m, ρ_s, ρ_l, $c_{p,s}$, and $c_{p,l}$ are highly dependent on the RO feed water chemistry and will vary based on the location of the RO facility. In the absence of experimental data for thermophysical properties, a statistical approach was undertaken to estimate the ballpark of the ROC salt thermophysical properties, knowing the chemical composition of the ROC. Depending on the feedwater source, the chemical composition of the ROC is comprised of various salt species such as $Ca(Cl)_2$, $MgCO_3$, $MgSO_4$, $MgCl_2$, Na_2CO_3, Na_2SO_4, $NaCl$, K_2CO_3, K_2SO_4, $Mg(OH)_2$, $CaSO_4$, $CaCO_3$, and KCl. The dominant salt species considered in this study are $Mg(OH)_2$, $CaSO_4$, $CaCO_3$, and NaCl. Using the weight percentage of each salt species along with the molar mass of the salt composition, the weighted average value was found for major thermophysical properties. The solid-state specific heat capacity at the minimum and melting temperature of these various salts were obtained from the National Institute of Standards and Technology (NIST) [20], i.e., two data points were gathered for each salt composition. The heat capacity values are plotted on a temperature vs solid heat capacity graph in Fig. 5 to visually depict the range between the two values at each temperature for all salt compositions. Each salt is labeled along with the overall weighted value depicted by an orange circle. The weighted average value of heat capacity of dominant salt species was considered as a representative of the heat capacity of the solid ROC mixture. This statistical approach led to a solid heat capacity value of 1,100 J/kg*K. Similarly, the liquid heat capacity was estimated as the weighted average of 1,710 J/kg*K.

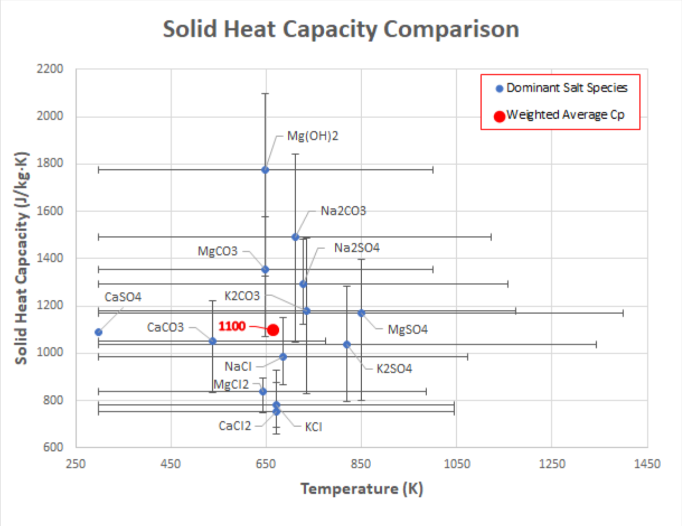

Figure 5 -- Sensitivity Analysis of Solid Heat Capacity of ROC

The latent heat of fusion of different salt species is also gathered from the NIST and the weighted average of dominant salt species was used in this TEA. This statistical approach led to a latent heat of fusion value of 350,632 J/kg for the ROC. Figure 6 displays a bar graph representing the latent heat of fusion comparison for all salt compositions and other potential species along with the calculated weighted average value.

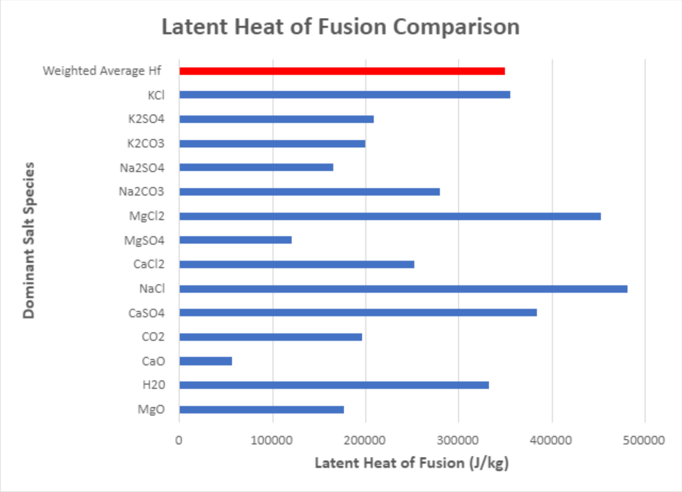

Figure 6 -- Sensitivity Analysis of Latent Heat of Fusion of ROC

The density value was estimated at a constant temperature for all salt compositions. The densities from all salt compositions were gathered from the NIST database and the weight percentage of each salt was incorporated to calculate the weighted average density for the ROC. This statistical approach led to a density value of 2,503 kg/m^3. Figure 7 seen below displays the bar graph representing the density comparison for all salt compositions along with the weighted average value.

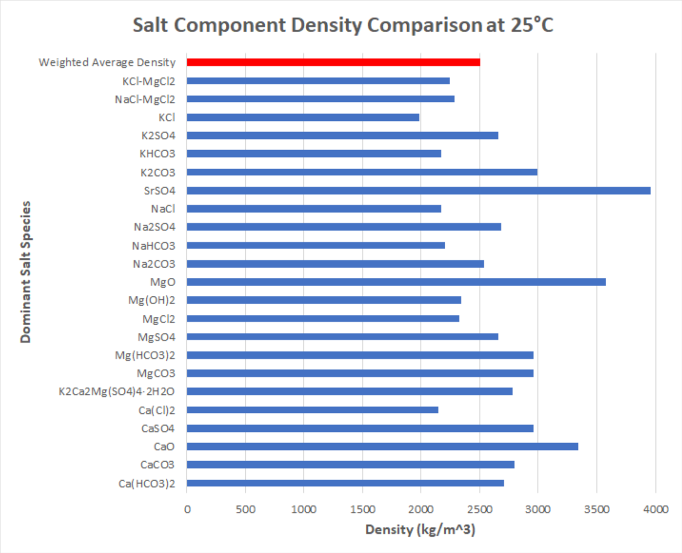

Figure 7 -- Sensitivity Analysis of Density of ROC

3. RESULTS AND DISCUSSION

The cost of ROC-based TES was calculated using Eq. (1) and the methods discussed in the previous section. Attention is now turned to the TES cost in different operating conditions. The impact of three operating conditions on the TES cost, i.e., ZLD technology (WaterFX vs. SaltWorks), maximum storage temperature (T_{max}), and gain (G) are discussed in this section.

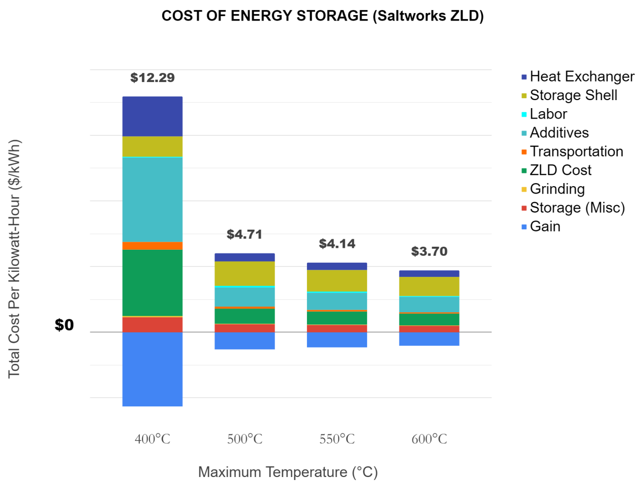

Figure 8 -- Analysis of the Overall Energy Cost Using Saltworks ZLD – Assuming Trucked Disposal gain values.

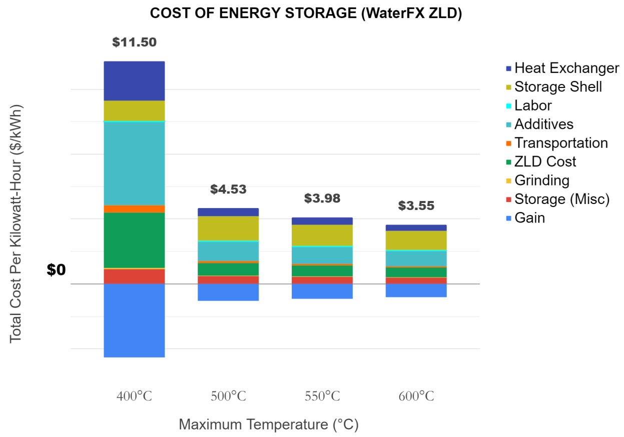

Figure 9 -- Analysis of the Overall Energy Cost Using WaterFX ZLD - Assuming Trucked Disposal gain values.

Figures 8 and 9 show the TES cost analysis using Saltworks and WaterFX ZLD technologies respectively. The results are shown for non-melting ROC salt at 400 °C and for melting ROC salt beyond 500 °C (assumed melting temperature for ROC salt is T_m = 450 °C). The TES cost reduction at maximum temperatures of 500, 550, and 600 °C is due to spanning the melting temperature of the ROC salt and the latent heat storage benefits. The Saltworks ZLD cost estimation is done by an analytical approach and is reported in reference [13], while the WaterFX ZLD cost estimation is performed by estimating the cost of all components in the system.

The results show that the total cost of TES using ROC salt as the storage medium in all cases is below the DOE's cost target of $15/kWh. The storage cost is significantly reduced if the ROC salt goes through a solid-to-liquid phase change. The gain (charged to the RO facility) has an important role in the overall energy storage cost, specially at lower storage temperatures at which solid-to-liquid phase change is not available. The effect of gain on the TES cost at high storage temperatures is moderate. In all cases, the cost of containment and heat exchanger dominate the overall cost of TES. WaterFX ZLD technology appears to provide a lower ZLD cost (and consequently TES cost) mainly attributed to using solar-thermal energy for the thermal desalination process.

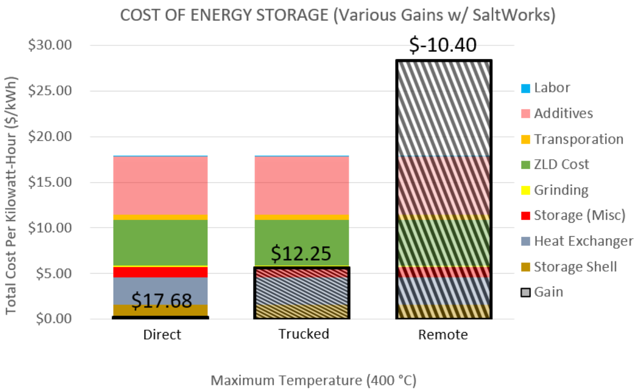

Figure 10 -- Analysis of the Overall Energy Cost Using Saltworks ZLD at Various Gains at 400C – hashed area correspond to negative cost (gain) from RO facility

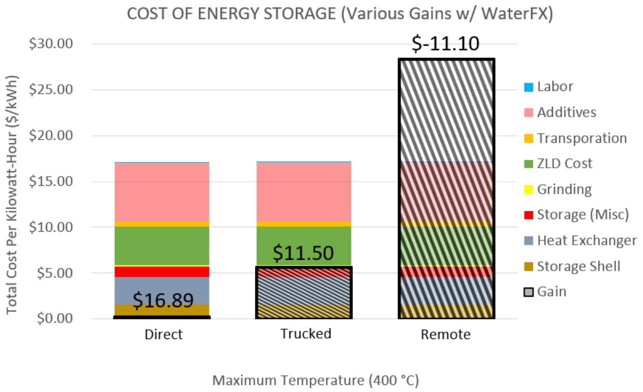

Figure 11 -- Analysis of the Overall Energy Cost Using WaterFX ZLD at Various Gains at 400C – hashed area correspond to negative cost (gain) from RO facility

Attention is now turned to the effect of gain, G, on the TES cost for non-melting salt with maximum storage temperature of 400 °C. Figures 10 and 11 provide the total TES cost assuming a variable gain value as described in Table 1 for $T_{max} = 400$ °C using Saltworks and WaterFX ZLD technologies. The result shows that the gain from RO facility can significantly reduce the overall TES cost to the point that the cost of TES becomes negative (profit) if gain values corresponding to Remote Disposal of Table 1 is used for this analysis. In both ZLD technologies (Figs. 10 and 11), even with no gains charged to the RO facility, the TES cost is about $17.68/kWh (SaltWorks) and $16.89/kWh (WaterFX) which is in the ballpark of the DOE's cost target of $15/kWh when the maximum storage temperature is 400 °C and the ROC-salt does not go through phase change.

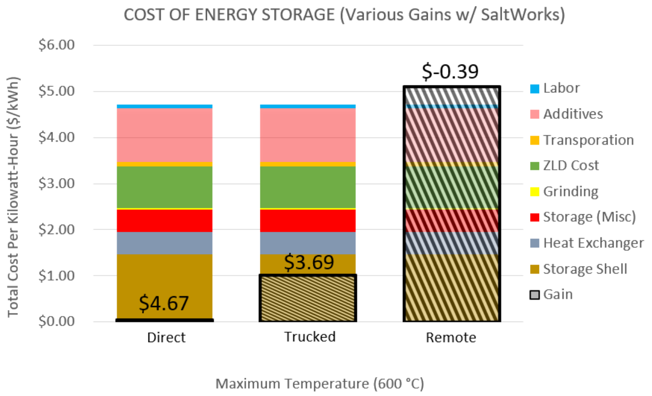

Figure 12 -- Analysis of the Overall Energy Cost Using Saltworks ZLD at Various Gains at 600C

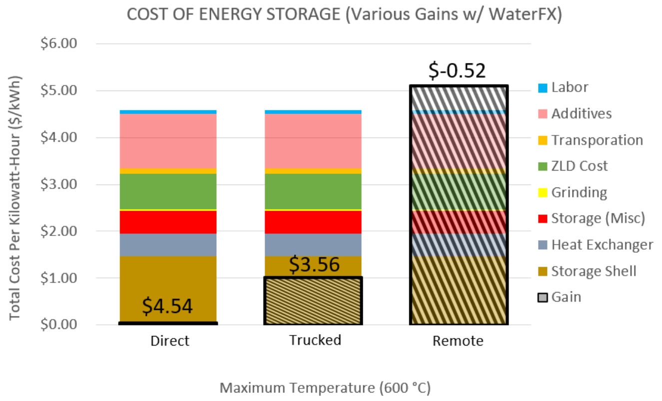

Figure 13 -- Analysis of the Overall Energy Cost Using WaterFX ZLD at Various Gains at 600C

Figures 12 and 13 demonstrate the TES cost analysis at a maximum storage temperature of 600 °C (melting ROC salt) at different gain levels using the Saltworks and WaterFX ZLD technologies respectively. Similarly, if high gain values are charged to the RO facility, the TES cost can virtually approach zero. At moderate or no gain levels (corresponding to Trucked and Direct disposal in Figs. 12 and 13), the TES cost is significantly lower than the DOE's cost target. This significant drop in TES cost is attributed to the increased energy storage density in presence of solid-to-liquid phase change at $T_{max} = 600$ °C.

4. Concluding Remarks

In this paper, an unconventional material, i.e., unseparated and minimally processed solid salt content of the

ROC is explored as a low-cost medium for TES to meet the cost targets of the U.S. DOE’s SunShot initiative. ROC disposal is one of the major challenges facing the inland water desalination industry. The capacity of most seawater desalination plants is regulated based on the volume of ROC disposal to the ocean to protect marine life.

A detailed TEA was performed to estimate the TES cost ($/kWh) using ROC salt as the storage medium. The costs associated with liquid ROC transportation (C_T), solid salt extraction through ZLD (C_Z), solid salt grinding (C_G), additives (C_A), concrete containment (C_C), heat exchanger (C_{HX}), and 5% miscellaneous costs (C_M) are considered. In addition to costs of developing an ROC-based TES system, the gains associated with ROC disposal tipping fee is integrated in the analysis. The tipping fee is determined based on the availability of alternative ROC disposal methods. In this study, the ballpark of the tipping fee is estimated by benchmarking the cost of brine disposal through the IEBD line in Southern California.

The results show that using ROC salt as a TES storage medium can significantly reduce the cost of TES while preventing disposal of high concentration of salts to the environment. Depending on the location of the ROC generation and existence of alternative disposal methods, the tipping fee (gain) may completely cover the cost of TES and additional revenue is generated. Comparing the values found in the Results section of this paper to the $30/kWh cost associated with the current TES medium of solar salt, this further proves how using ROC as a TES medium produces a more favorable option in achieving the TES cost goal created by the DOE.

Future plans for this type of analysis include evaluating an ROC material similar to that of the Chino Water Desalter authority to account for a much higher melting temperature. This would still require utilizing the higher temperature HTF and storage shell while no phase change occurs. This is an important addition to the analysis because it helps broaden the spectrum for the application of this process for varying ROC samples.

Testing salt samples from various RO facilities shows that liquid-to-solid phase change takes place in temperatures as low as 450 °C and latent heat storage potential is available if the TES temperature spans the melting temperature of the ROC salt which is a eutectic mixture.

ACKNOWLEDGEMENTS

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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_M	Cost of Miscellaneous ($)
C_{TES}	Cost of Thermal Energy Storage ($)
C_{Tr}	Cost of Transportation ($)
C_Z	Cost of ZLD ($)
$c_{p,l}$	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
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 Latent Heat (kg/m^3)
ρ_s	Density of Sensible Heat (kg/m^3)
υ	Volume of ROC (m^3)
υ_c	Volume of Containment (m^3)

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