Repurposing Reverse Osmosis Concentrate as a Low-Cost Thermal Energy Storage Medium

Reza Baghaei Lakeh, Christopher Salerno, Ega P. Herlim, Joseph Kiriakos, and Saied Delagah

***Abstract*—The reject of the reverse osmosis water treatment process (aka brine, concentrate, ROC) is a mixture of salts that are dissolved in high salinity water. The ROC is classified as an industrial waste by the U.S. Environmental Protection Agency and can face regulatory limitations on disposal. State-of-the-art of ROC disposal includes deep-well injection, surface discharge to rivers, discharge to the ocean, and evaporation ponds. In this study, the feasibility of using Reverse Osmosis Concentrate as a low-cost Thermal Energy Storage (TES) medium is explored by a techno-economic analysis. The normalized cost of TES (cost per unit volume of stored thermal energy) is estimated through a series of cost analyses and is compared to the cost targets of the U.S. Department of Energy for low-cost thermal energy storage. It was shown that the normalized cost of TES using ROC salt content is in the range of $6.11 to $8.73 depending on ROC processing methods.**

***Index Terms*—Reverse osmosis concentrate, thermal energy storage, repurposing, renewable energy.**

I. Introduction

Global warming appears to be one of the major challenges facing humans in the 21st century. According to the United States National Oceanic and Atmospheric Administration (NOAA), the 2018 average temperature across land and ocean surface areas was 0.79 ℃ above the 20th-century average. 2018 was the fourth warmest year on record, only followed by 2015, 2016, and 2017. The data also shows that 2019 is on track to be the warmest year on the recorded history of the earth [1]. Excessive emission of greenhouse gases (mainly carbon dioxide) is considered to be the main cause of global warming. Comparison of atmospheric samples contained in ice cores and more recent direct measurements show that the atmospheric carbon dioxide level had never been above 300 ppm before 1950. Human activities and excessive use of fossil fuels introduced a significant jump in the atmospheric carbon dioxide levels to about 407.4 ppm in 2018. It is projected that the carbon dioxide level in the atmosphere reaches the historic value of 420 ppm by 2025 [2].

Since the main cause of the excessive increase in earth's atmospheric carbon dioxide levels is attributed to the use of fossil fuels, the use of renewable energy sources including solar and wind has gained attention by policymakers and governments. Most of the use of renewable energy was concentrated in the power sector. It is estimated that renewable energy sources provided more than 26% of the global electricity generation in 2018. Despite progress in using renewable energy sources, the world is not on track to meet the goals of the Paris Agreement due to increased fossil fuel consumption; Global energy-related carbon dioxide emissions grew an estimated 1.7% in 2018 [3]. Therefore, further technological advancements are required to make renewable energy sources inexpensive and economically competitive with fossil fuels.

One of the major challenges in the widespread use of renewable energy sources is the intermittency of most renewable energy sources. For instance, solar power is impacted by day-night cycles as well as weather conditions, and wind energy is highly influenced by almost unpredictable wind patterns. The intermittency of renewable energy sources, as well as their low dispatchability, introduce a challenge on a power grid that relies on a significant amount of renewables in contrast to base-load conventional fuel-driven and nuclear power plants. According to the U.S. Department of Energy, there is a need for low-cost energy storage systems that should be combined with renewable energy sources to make them financially competitive.

Thermal Energy Storage (TES) systems are used to store thermal energy in the form of the internal energy of a storage medium for future use. TES systems can be considered "Thermal Batteries" that store thermal energy instead of electricity. The most common application of TES systems is solar-thermal power plants, adiabatic compressed air energy storage systems, and combined heat and power (CHP) systems. TES is an essential part of Concentrating Solar Power (CSP) to increase dispatchability and load shifting. State-of-the-art of TES includes two-tank direct, two-tank indirect and single-tank thermocline systems [4]. Molten salt mixtures (KNO_3 and $NaNO_3$) are mostly used as the storage medium in conventional TES systems due to their low vapor pressure, high specific heat, and chemical stability. The elevated demand for nitrate salts has led to higher storage fluid costs and increased the cost of thermal energy storage.

The cost of electricity generated by CSP plants is dependent on the capital and operational costs of all components including the TES. United States Department of Energy has set a challenging goal to reduce the cost of electricity generated by CSP plants to $0.06 /kWh_e$ [5]. In order to achieve this goal, all components of a CSP plant (including the TES) are expected to have a significant cost reduction. According to DOE, revolutionary and evolutionary technologies are required to reduce the cost of TES below $15/kWh_t$ and to increase the TES temperature

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beyond 720 ℃ [6]. The existing TES technologies are limited to 400 ℃ due to the thermal degradation of the storage materials at higher temperatures.

In this study, the feasibility of using reverse osmosis concentrate (an industrial waste) as a TES medium is explored by a techno-economic analysis. The reject of the reverse osmosis water treatment process (aka brine, concentrate, ROC) is a mixture of salts that are dissolved in high salinity water. The ROC is classified as an industrial waste by the U.S. Environmental Protection Agency and can face regulatory limitations on disposal. State-of-the-art of ROC disposal includes deep-well injection, surface discharge to rivers, discharge to the ocean, and evaporation ponds. All of the methods that are currently used in managing the ROC require releasing high concentrations of salt to the environment. The chemical composition of the ROC is highly dependent on the feed water source. Generally, the ROC is a mixture of salts (e.g., NaCl, KCl, $MgCl_2$, $MgSO_4$, etc.) that are dissolved in water. There are currently no applications in industry for this high salinity stream or the resulting solid salt mixture after the water content is removed. According to the National Academies, developing ROC disposal alternatives is one of the major priorities for water desalination research [7], [8].

The ROC cannot be directly used for TES and a series of processes are required to make ROC a potential candidate for TES. Although there is no cost associated with the ROC as a waste material, the necessary processes will introduce expenses that will lead to a cost for the ROC-based TES. On the other hand, the thermophysical properties of the ROC are highly dependent on the source of the RO feed water and impact the overall cost of the proposed TES system. In this paper, a techno-economic approach is utilized to estimate the overall cost of the ROC-based thermal energy storage system. Different scenarios are considered and the overall cost of the TES is compared with the goals of the U.S. Department of Energy.

II. Techno-Economic Approach

The cost of thermal energy storage is mostly reported in normalized form, i.e., per unit of thermal energy stored $/kWh$_t$. The goal of the U.S. Department of Energy is to reduce the normalized cost of TES to $15/kWh$_t$. Different types of costs are associated with the overall cost of TES. In general, the normalized cost of a TES system is a function of the TES material, the containment, and the thermophysical properties of the TES medium and containment. Reduction of the normalized TES cost can be achieved by 1) reducing the overall cost of the TES (medium and containment) and 2) increasing the potential stored thermal energy. Using ROC as a TES can combine both of these methods within the operating temperature of common Concentrating Solar Power plants.

In order to quantify the normalized cost of a ROC-based TES, it is necessary to explain the proposed system in more detail. Fig. 1 illustrates the steps required to develop a ROC-based TES. Once the feedwater (brackish water and/or seawater) is introduced to a reverse osmosis water treatment plant, two separate water streams are generated. Depending on the recovery rate of the RO plant, 50-80% of the feedwater is converted to clean, potable water while all the salt content and other contaminants of the feedwater is concentrated in the reject, aka, ROC. The clean water is used for different applications while the ROC needs to be rejected and disposed of. Most reverse osmosis facilities are expected to pay environmental and government fees for the disposal of the ROC. The proposed ROC-based TES system utilizes the ROC as a TES medium. Since the RO facilities pay for disposal of their rejects, one can consider that there is a negative cost associated with the ROC. The ROC cannot be directly used as a TES medium; however, the salt content of the ROC is a potential TES candidate. In order to develop a ROC-based TES, the ROC must be removed from the RO facility and be pumped to the processing facility. The water content of the ROC should then be removed by evaporation so that the solute is extracted. The salt content of the ROC is then processed and packed in a container to generate a TES system.

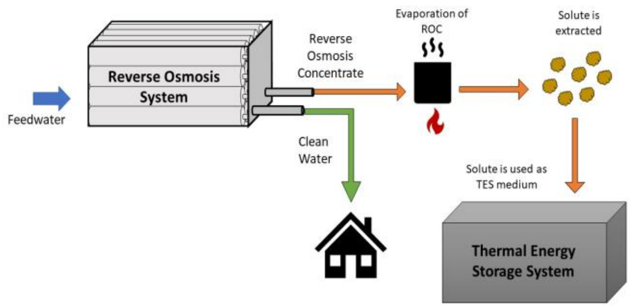


Fig. 1. Development of an ROC-based thermal energy storage system.

The normalized cost of an ROC-based thermal energy storage system can be estimated by Eq. 1

$$C_{tes} = \frac{C_t + C_e + C_g + C_c - G}{E_{stor}} \quad (\$/kWh_t) \tag{1}$$

where C_t is cost of transporting the ROC from the RO facility to the ROC processing facility, C_e is the cost associated with evaporating the water content of the ROC, C_g is the cost of grinding the salt content of ROC to enhance the heat transfer rate and enable packaging, C_c is the cost of the containment that is necessary to encompass the TES medium, and G is the sum of all fees that are paid by the RO facility for rejecting the ROC.

The denominator of Eq. 1 (E_{stor}) is considered to be the amount of the thermal energy that is stored in the proposed ROC-based TES system. Assuming that the TES operates between T_{min} and T_{max}, the amount of the stored energy depends on the heat capacity of the salt mixture and containment material. The salt content of the ROC is a mixture of salts with uncontrolled and variable composition depending on the feedwater source.

Depending on the source of the RO system's feedwater, the ROC salt content may be a eutectic salt mixture that has a melting temperature that is lower than the melting point of its constituents. If the melting of the salt content of the ROC occurs within the operating temperatures of the TES, i.e., between T_{min} and T_{max} a significant amount of thermal energy can be stored in the phase change process, leading to reduced normalized TES cost. However, due to the uncontrolled nature of the RO feedwater, it is not possible to ensure that the salt content of the ROC will go through a phase change. Fig. 2 illustrates the thermal testing performed on two separate ROC samples from two RO facilities, i.e., Eastern Municipal Water District (EMWD) and Chino Desalter Authority (CDA). It was observed that the salt samples received from the EMWD went through solid to liquid phase change in the range of 350-400 ℃, while the salt samples from CDA did not show a phase change even though the salt was heated to 900 ℃.

Fig. 2. Verification of solid to liquid phase change on ROC salt content. No phase change observed in the sample from CDA (top). Solid to liquid phase change observed in the sample from EMWD between 350-400 ℃ (bottom).

The stored thermal energy in the ROC-based TES system can be estimated by Eq. 2 in the case that the salt mixture goes through a solid to liquid phase change at T_{melt}

$$E_{stor} = m_{salt}\left(\int_{T_{min}}^{T_{melt}} c_{p,s}\, dT + h_f + \int_{T_{melt}}^{T_{max}} c_{p,l}\, dT\right) + m_{con}\int_{T_{min}}^{T_{max}} c_{p,c}\, dT \qquad (2)$$

where $c_{p,s}$, $c_{p,l}$, $c_{p,c}$ are the heat capacity of the ROC salt in the solid phase, the heat capacity of the ROC salt in the liquid phase, and the heat capacity of the containment material respectively. h_f is the enthalpy of fusion of the ROC salt and m_{salt} and m_{con} are the total mass of the ROC salt and containment material, respectively. In the case that the ROC salt does not go through a solid to liquid phase change, Eq. (2) will be reduced to Eq. (3).

$$E_{stor} = m_{salt}\int_{T_{min}}^{T_{max}} c_{p,s}\, dT + m_{con}\int_{T_{min}}^{T_{max}} c_{p,c}\, dT \qquad (3)$$

As seen in Eqs. (1-3), the normalized cost of the ROC-based TES is dependent on a variety of parameters, including gain due to the imposed fees on the RO facility, processing costs (transportation, evaporation, and grinding), containment cost as well as thermo-physical properties of the ROC salt in solid and liquid phases. In the following sections, the methods used for estimating different contributors to the normalized cost of TES are explored.

III. Transportation Cost

In this techno-economic analysis, it is assumed that the RO facility is located far from the processing facility of the ROC salt. Therefore, the generated ROC must be pumped through a pipeline to the location of the processing facility. The cost associated with this process is estimated by Eq. (4)

$$C_t = C_{pipe} + C_{pump} + C_{pp} \qquad (4)$$

where C_{pipe} and C_{pump} are the capital cost of the pipeline and pumps respectively and C_{pp} is pumping power cost that is estimated by Eq. (5)

$$C_{pp} = C_{ele}\left[f\left(\frac{L}{D}\right)\left(\frac{v^2}{2}\right)\rho V \eta\right] \qquad (5)$$

where C_{ele} is unit cost of electricity used for running pumps ($/kWh$_e$), f is the friction factor associated with the ROC flow in the pipeline, L is the length of the pipeline (distance between the RO and the ROC processing facilities), D is the diameter of the pipeline, v is average velocity of the ROC in the pipeline, ρ is the density of the ROC, V is the volume of the pumped ROC, and η is the efficiency of the utilized pumps.

IV. Evaporation Cost

Once the ROC is received at the processing facility, the water content must be evaporated to extract the ROC salt. This process can be done in active and passive ways. In the active evaporation, energy from a fuel or power grid is employed to increase the temperature of the ROC to the saturation temperature at the local pressure and the water content is removed through boiling. In the passive evaporation, the ROC is introduced to shallow evaporation ponds where the water content of the ROC is evaporated at the atmospheric temperature.

In the active evaporation method, the cost of the evaporation is caused by the amount of fuel or electricity used for boiling the ROC as estimated by Eq. (6)

$$C_e = \frac{C_f \rho V\left(c_{p,w}(T_b - T_{atm}) + h_{fg}\right)}{HHV\ \eta_b} \qquad (6)$$

where C_f is the cost of the fuel used to heat the ROC, $c_{p,w}$ is the heat capacity of ROC, T_b is the boiling temperature of the ROC at atmospheric pressure, T_{atm} is the local temperature, h_{fg} is the enthalpy of vaporization of ROC, HHV is the high heating value of the fuel, and η_b is the efficiency of the boiling process.

The cost of the passive evaporation method is considered to be dominated by the cost of the land that is utilized as an ROC evaporation pond. The amount of the land that is required for evaporating the ROC is determined based on the local solar irradiant. Considering the solar irradiant I (kWh/m^2.Day), the cost of evaporating ROC using evaporation ponds can be estimated by Eq. (7)

$$C_e = \frac{C_l \rho V \acute{h}_{fg}}{N_D\ I\ \eta_p} \tag{7}$$

where C_l is the local average cost of the land (\$/acre), $\acute{h}_{fg}$ is the enthalpy of vaporization at T_{atm}, N_D is the number of days, and η_p is the efficiency of the evaporation pond.

V. Grinding Cost

The salt extracted from the ROC evaporation of water content cannot be directly used for TES. It is important to grind the salt content to a homogenous powder that can be packed inside the container material. For this purpose, commercial large-scale grinders are considered. Increasing the number of grinders will lead to a faster process; however, it will introduce additional capital and operational costs. The cost of grinding (C_g) can be estimated using Eq. (8)

$$C_g = N_g C_{cg} + \frac{m_{salt} P_g C_{ele}}{R_g N_g} \tag{8}$$

where N_g is the number of grinders, C_{cg} is the capital cost of a single grinder, P_g is the power rating of the grinder, and R_g is the processing rate of a grinder.

VI. Containment Cost (C_c)

The extracted and processed ROC salt must be packed inside a containment to form a TES module. Each TES module consists of a number of TES tubes (elements) and a shell that holds the TES elements. This creates a geometry that is similar to a conventional shell and tube heat exchangers with one of the fluids being stationary. In this analysis, a variety of configurations for the containment is evaluated while the total mass of the ROC salt (m_{salt}) is kept the same in all configurations. Fig. 3 shows different designs of the TES module that are considered in the techno-economic analysis.

The containment cost depends on whether the ROC salt is stored inside the TES elements (i.e., the tube side) or outside the tubes (i.e., in the shell side). In the former case, the Heat Transfer Fluid (HTF) will pass through the shell side of the module, while in the latter case, the HTF fluid flows through the tubes. Different configurations of Fig. 3 will have different values for the containment material (SS 316) while the total mass of salt is kept equal in all of them. The containment cost can be estimated by Eq. (9)

$$C_c = N_m (C_{ele} + C_{sh}) \tag{9}$$

where N_m is the number of modules required to store m_{salt} , and C_{ele} and C_{sh} are the cost of all TES elements (tubes) and shell respectively. Different containment designs lead to a different number of tubes and different amounts of containment material.

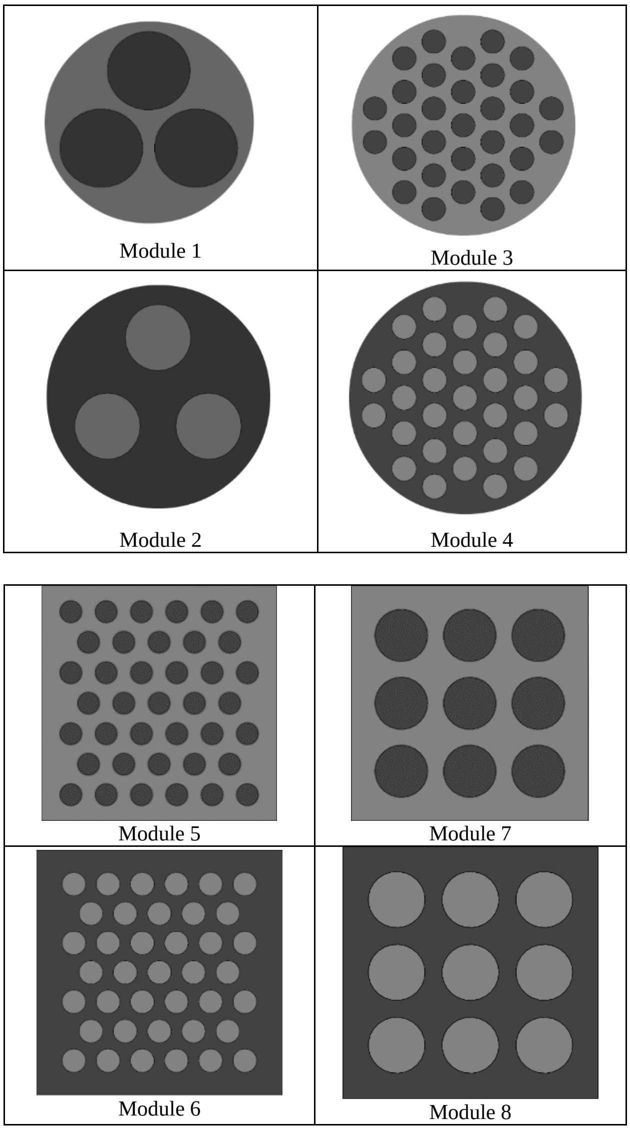


Fig. 3. Different containment designs of the TES module. The volume of ROC salt is equal in all cases. Module 8 corresponds to the minimum overall TES cost (baseline) – Dark color: ROC Salt, light color: heat transfer fluid.

VII. Gain

The ROC is considered an industrial waste and is subject to disposal costs and government fees. The cost of ROC disposal is one of the major budget items for most RO facilities. Since the RO facilities pay for removing the ROC from their facility, the amount paid by the RO facility can be considered to be a gain (negative cost) for an entity that is processing the ROC. The amount of gain depends on several parameters, including the location of the RO facility, the volume of the generated ROC and the disposal method. It is difficult to quantify the gain; therefore, this study is performed with a range of gain from $0.00-$0.20/gal.

VIII. Results and Discussion

In this section, the results of the techno-economic are presented using Eqs. 1-9. The costs associated with transportation and processing of the ROC is calculated by Eqs. 4-9 and the amount of stored thermal energy was calculated using Eqs. 2-3. Equation 1 provides a normalized cost of thermal energy storage in $/kWh$_t$. The normalized cost of the proposed ROC-based TES is compared with the cost target of the United States Department of Energy, i.e., $15/kWh.

The sensitivity of the normalized TES cost was studied with respect to different types of costs associated with developing a ROC-based TES as described in the previous section. The analysis was initiated with a baseline model and the effect of different parameters were evaluated with respect to the baseline model. The details of the baseline model are shown in Table I.

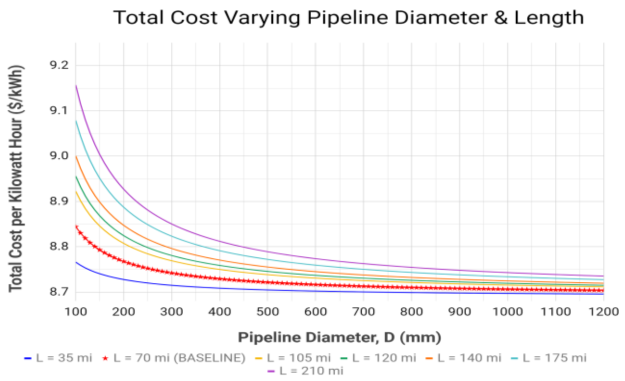
TABLE I: Details of the Baseline Model Used for the Techno-Economic Analysis

Minimum Temperature, T_{min}	290 ℃
Maximum Temperature, T_{max}	800 ℃
Melting Temperature, T_{melt}	450 ℃
Volume of ROC	600,000,000 gal
ROC Total Dissolved Solid	50 g/l
ROC salt heat capacity in solid phase, [10]	0.853 kJ/kg.K
ROC salt heat capacity in liquid phase, [11]	1.150 kJ/kg.K
ROC salt heat of fusion [12]	492 kJ/kg
Containment material	Stainless Steel 316
Containment type	Module 8
Number of tubes per module	9
Module size	0.45m X 0.45 m
TES element (tube size)	0.05 m
Salt storage	Shell side
ROC water evaporation	CNG or Solar Ponds
Distance from Treatment Plant	70 mi
Gain per Gallon	$0.0375
Number of Grinders used	3
Cost of Electricity per Kilowatt Hour [13]	$0.1516
Cost of Steel SS316 [14]	$3,860/ton
Cost Per Grinder Unit [15]	$98,000
Diameter of Piping for Transportation	400 mm
Absolute Roughness for Piping [16]	0.0015 mm
Transportation Pump Efficiency	85%
All Fuel Efficiency	90%

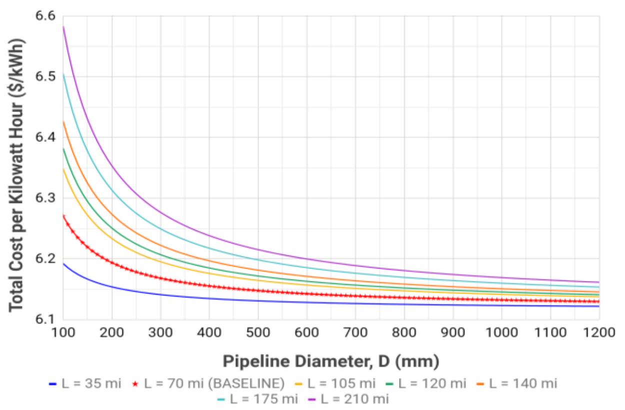
In the following subsections, the effect of different variables on the overall normalized TES cost, i.e., C_{tes} is studied and is compared with the target cost of $15/kWh.

The effect of the distance between the RO facility and the ROC processing facility (L) on the overall normalize TES cost is illustrated in Fig. 4.

As shown in Fig. 4 (1) and (2), the normalized TES cost of the baseline model using CNG (as the fuel used for ROC water evaporation) and using Solar Ponds $8.73/kWh$_t$ and $6.11/kWh$_t$. According to Eqs. 5 and 1, the overall TES cost is linearly related to L, the distance between RO and ROC processing facilities; however, the slope of variations is very low (about 0.02%). Therefore, the value of L does not appear to impact the overall normalized cost of TES. Using larger pipeline diameters will reduce the pumping power cost and overall normalized TES cost; however, this reduction appears insignificant especially if the value of L (distance between RO and ROC processing facility) is small.



(1)



(2)

Fig. 4. Effect of the distance between RO and ROC processing facilities and pipeline diameter on the total normalized TES cost using 1- CNG and 2- Solar Pond.

The attention is now turned to the ROC water evaporation process and the costs associated with extracting the solute from the ROC. In this study, the cost of adopting two different methods for salute extraction is studied. In the first method, the ROC water is heated using different types of fuels. The effect of using different fuels on the overall normalized TES cost can be evaluated by Eqs. (1) and (6). Fig. 5 illustrates the effect of using different fuels for evaporating the water content of ROC. The results are provided for three different maximum temperatures of storage (T_{max}), i.e., 600 ℃, 800 ℃, and 1000 ℃. The maximum temperature of TES is consistent with the maximum temperature obtainable with the highly concentrating CSP reflectors (e.g., power towers).

The results show that the target of $15/kWh can be achieved using all the studied fuel types. This analysis is performed based on the HHV and the cost of the fuels. The reduction of overall TES cost at higher T_{max} values is due to the increase of the denominator in Eq. 1. The effect of using different types of fuels for evaporating ROC water appears to be an important player in the overall TES cost. There is a variability of about \$2.5/kWh$_t$ if a different type of fuel is used. The lowest cost is associated with Compressed Natural Gas (CNG), followed by BioDiesel (B20). Using Propane for the purpose of evaporating ROC water will lead to the maximum overall normalized TES cost. The TES cost of the baseline case obtained at 800 ℃ and using CNG is about \$8.73/kWh$_t$ which is almost 50% less than the U.S. Department of Energy's goal of \$15/kWh$_t$.

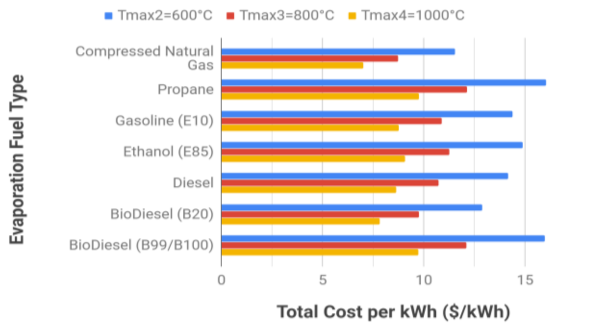


Fig. 5. Sensitivity of normalized cost of ROC-basted TES system with respect to evaporation fuel type.

The other method that is studied for salute extraction is utilizing shallow evaporation ponds. In this method, solar energy is absorbed by the ROC, leading to the evaporation of ROC water at near atmospheric temperatures. The costs associated with using solar ponds will be a function of the location of the pond (cost of the land, C_l) and solar irradiation of the location (I). These two parameters were considered for this techno-economic analysis in the range of 2-6 kWh/m2/day and \$500-\$15000/acre. Figure 6 illustrates the effect of the location of the solar pond on the normalized TES cost. The results show that using a solar pond instead of fuels for evaporating ROC water significantly reduces the TES cost (from \$8.73 to \$6.11 per kWh$_t$, a decline of about 30%). However, the location of the solar pond does not appear to have a significant impact on the overall normalized TES cost. The effect of the location of the solar pond on the TES cost is less than 5% within the continental United States [9].

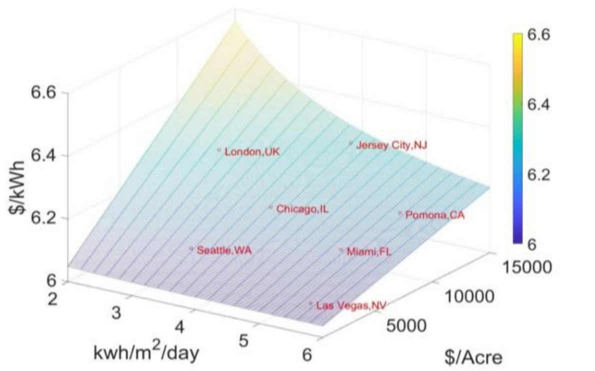


Fig. 6. Normalized TES cost using evaporation ponds in different locations. C_{tes} is plotted with respect to local cost of land C_l and solar irradiance, I.

Grinding the ROC salt is one of the steps before the salt can be packed in the proposed TES element. Equations 8 and 1 are used to calculate the cost of grinding using a commercial large-scale grinder and to calculate the overall normalized TES cost. The specifications of the grinder are shown in Table II. Fig. 7 illustrate the effect of the number of commercial grinders on the processing time and the normalized cost of TES. The number of the grinders (N_g) plays a role in the time required for grinding the mass of the salt (m_{salt}); however, the impact of the number of the grinders on the normalized cost of TES is small. Conclusively, using a greater number of grinders is advisable to reduce the processing time.

TABLE II: SPECIFICATIONS OF THE COMMERCIAL GRINDER ASSUMED FOR THE TECHNO-ECONOMIC ANALYSIS

Intermediate diameter of the millstone (mm)	1400
Quantity of the rollers (piece)	3
Granularity of the feeding material D90 (mm)	< 10 Max 20mm
Capacity (t/h)	50
Fineness (mm)	Generally in 0.045-0.02, Finest is 0.01
Power of the main motor (KW)	355
Power of multiple powder concentrator & quantity	15KW x 7
Application Material	Barite, basalt, bentonite, calcite, calcium carbonate, coal, dolomite, feldspar, granite, gravel, gypsum, micro silica, pebble, quartz, slag
Input Size	< 30 mm
Output Size	80-2500 mesh

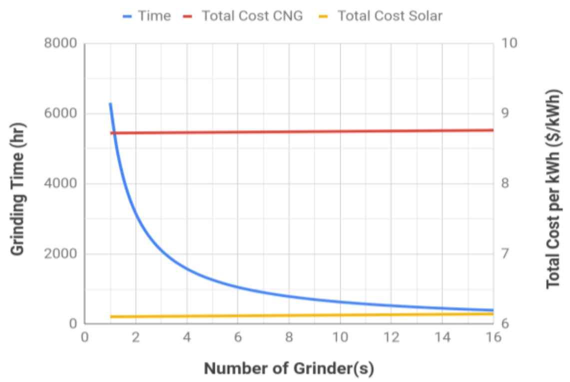


Fig. 7. Effect of the number of commercial grinders on the processing time and the normalized cost of TES using CNG and Solar ponds. Baseline case assumes 3 grinders.

In this study, 8 different TES module designs are explored as shown in Fig. 3. The mass of ROC salt is kept constant in all of the modules; however, the mass of the containment material, i.e., SS 316 is different depending on the number of tubes in the module, the shape of the shell, and the location of ROC salt storage (inside or outside TES tubes). The techno-economic analysis suggests that module 8 provides the minimum overall TES cost; therefore, the baseline calculations are done with module 8. The details of all modules, as well as the overall TES cost of all modules, are provided in Table III.

TABLE III: SENSITIVITY OF THE NORMALIZED TES COST WITH RESPECT TO CONTAINMENT GEOMETRY. MODULES 1-8 ARE SHOWN IN FIG. 3

Module 1	
Shell Diameter (m)	0.75
Tube Diameter (m)	0.285
# of Element	3
Shell Mass (kg)	1,115.89
Tube Wall Mass (kg)	1,244.07
Number of Modules	52,713
Cost per Module (\$)	\$9,109.46
Total Cost (\$)	\$480,190,273.53
Total Cost per Kilowatt Hour (\$/Kwh)	\$15.15

Module 2	
Shell Diameter (m)	0.535
Tube Diameter (m)	0.15
# of Element	3
Shell Mass (kg)	791.68
Tube Wall Mass (kg)	633.35
Number of Modules	51,767
Cost per Module ($)	$5,500.60
Total Cost ($)	$284,751,432.50
Total Cost per Kilowatt Hour ($/Kwh)	$9.86

Module 3	
Shell Diameter (m)	1.00
Tube Diameter (m)	0.105
# of Element	31
Shell Mass (kg)	1,492.88
Tube Wall Mass (kg)	4,440.96
Number of Modules	49,583
Cost per Module ($)	$22,904.62
Total Cost ($)	$1,135,683,225.49
Total Cost per Kilowatt Hour ($/Kwh)	$32.87

Module 4	
Shell Diameter (m)	0.51
Tube Diameter (m)	0.05
# of Element	31
Shell Mass (kg)	753.98
Tube Wall Mass (kg)	1,869.88
Number of Modules	52,335
Cost per Module ($)	$10,128.09
Total Cost ($)	$530,048,840.01
Total Cost per Kilowatt Hour ($/Kwh)	$16.50

Module 6	
Shell Base/Height (m)	0.5
Tube Diameter (m)	0.049
# of Element	39
Shell Mass (kg)	753.98
Tube Wall Mass (kg)	2,293.61
Number of Modules	52,356
Cost per Module ($)	$11,763.72
Total Cost ($)	$615,900,365.60
Total Cost per Kilowatt Hour ($/Kwh)	$18.82

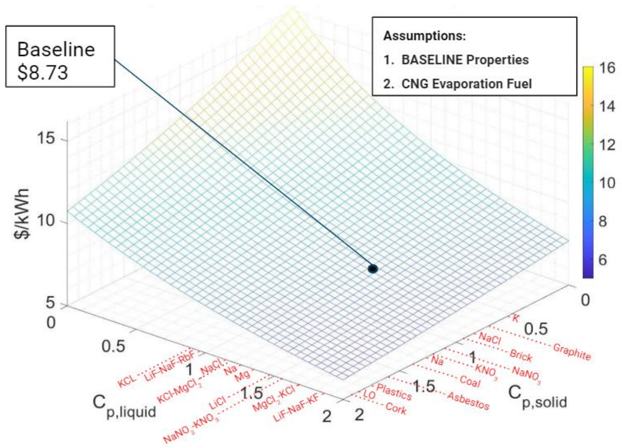
Module 5	
Shell Base/Height (m)	1.0
Tube Diameter (m)	0.094
# of Element	39
Shell Mass (kg)	1,900.80
Tube Wall Mass (kg)	4,940.09
Number of Modules	52,000
Cost per Module ($)	$26,405.84
Total Cost ($)	$1,373,110,767.75
Total Cost per Kilowatt Hour ($/Kwh)	$39.29

Module 7	
Shell Base/Height (m)	1.000
Tube Diameter (m)	0.173
# of Element	9
Shell Mass (kg)	1,900.8
Tube Wall Mass (kg)	2,212.184
Number of Module	52,712
Cost per Module ($)	$15,876.12
Total Cost ($)	$836,859,491.62
Total Cost per Kilowatt Hour ($/Kwh)	$24.79

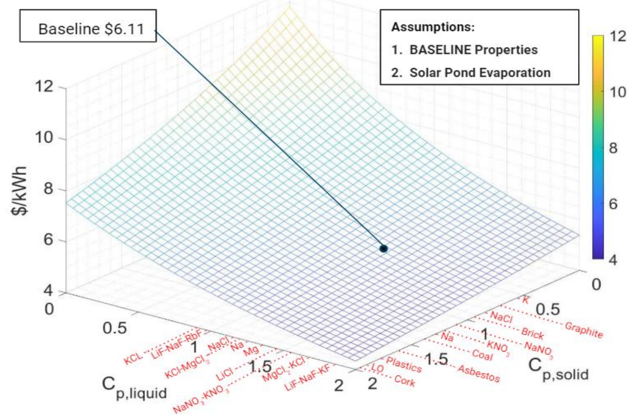
Module 8	
Shell Base/Height (m)	0.45
Tube Diameter (m)	0.05
# of Element	9
Shell Mass (kg)	663.504
Tube Wall Mass (kg)	542.867
Number of Module	52,154
Cost per Module ($)	$4,656.59
Total Cost ($)	$242,861,247.38
Total Cost per Kilowatt Hour ($/Kwh)	$8.73

The thermophysical properties of the ROC salt, i.e., heat capacity in the liquid phase, heat capacity in the solid phase, and heat of fusion directly impact the amount of energy that can be stored in the ROC-based TES. Eqs. 2-3 are utilized to find the amount of energy that can be stored in the ROC-based TES. The thermophysical properties of the ROC are hard to control and are highly dependent on the RO facility feedwater source. Therefore, in order to perform this techno-economic analysis, a common range of thermophysical properties of salts are considered and the sensitivity of the normalized TES cost is explored. In this analysis, the heat capacities in liquid and solid phases are allowed to change from 0.1-2 kJ/kg.K. Figures 8-1 and 8-2 illustrate the effect of heat capacity variations on the normalized cost of TES.

It is observed that the effect of ROC salt heat capacity on the overall normalized TES is noticeable; however, even the projected cost of the ROC-based TES with extremely low heat capacities is below $15/kWh$_t$ which is the U.S. Department of Energy cost goal for TES.



(1)



(2)

Fig. 8. The effect of heat capacity of the ROC salt in solid and liquid on the normalized TES cost: (1) using CNG to evaporate the; (2) using solar evaporation pond.

Fig. 9 shows the effect of solid-to-liquid heat of fusion on the normalized TES cost. It appears that the heat of fusion has a significant impact on the overall normalized TES cost. Smaller values of heat of fusion are associated with increased TES cost. Since the actual value of the heat of fusion for the ROC is variable and uncontrolled, the x-axis of figure 9 is marked with the value of common salts. The projected normalized TES cost remains below the cost target even with very low values of heat of fusion. However, since the sensitivity of the TES cost is significant with respect to the heat of fusion, it is important to narrow down the range of ROC salt heat of fusion in future studies.

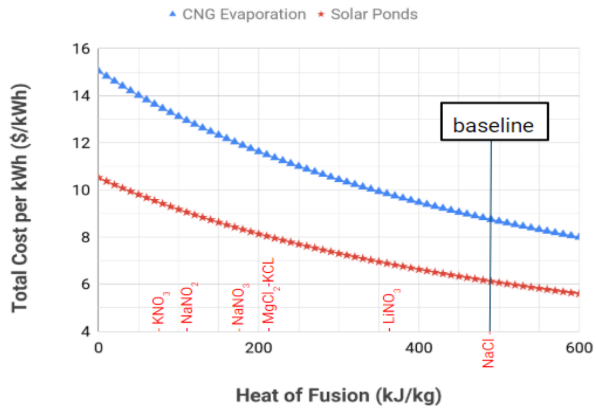
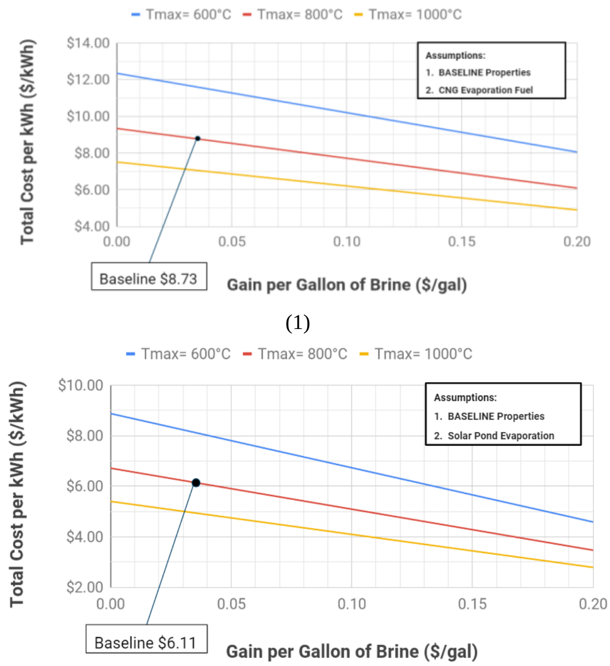


Fig. 9. The effect of ROC salt heat of fusion on the normalized TES cost.

According to Eq. 1, the disposal cost that RO facility pays is assumed to be a gain for the ROC-based TES system. The value of gain depends on the location of the RO facility, the type of the disposal, and the amount of generated ROC. In this techno-economic analysis, the gain is assumed as a variable that is in the range of $0.0-0.2/gal. Figure 10 shows the sensitivity of the normalized TES cost with respect to the gain. The value of gain seems to have a significant impact on the overall cost of the TES system; however, the proposed ROC-based TES system meets the cost targets of the U.S. Department of Energy without considering the gain. The projected TES cost of the ROC-based system with zero gain is in the range of $7.5-$12.4/kWh$_t$ if CNG is used and in the range of $5.5-$8.9/kWh$_t$ if the solar pond is used for evaporation.



(1)

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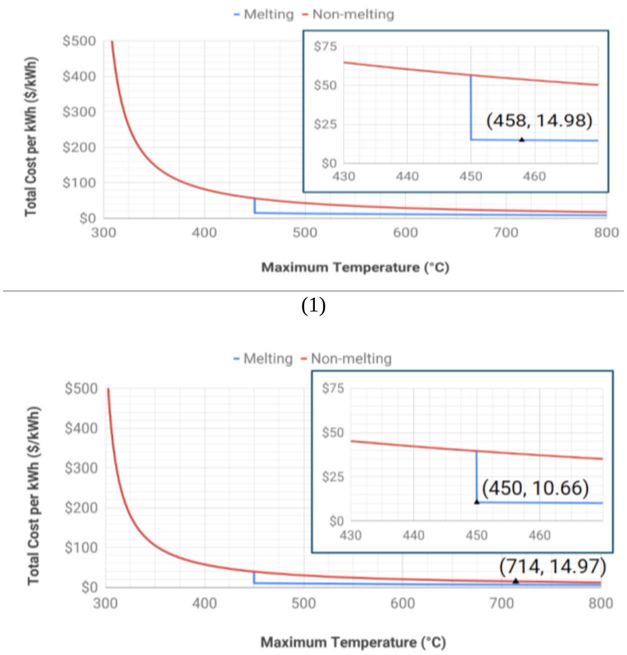
Fig. 10. The effect of gain (ROC disposal costs) on the normalized cost of TES: (1) using CNG to evaporate the; (2) using solar evaporation pond.



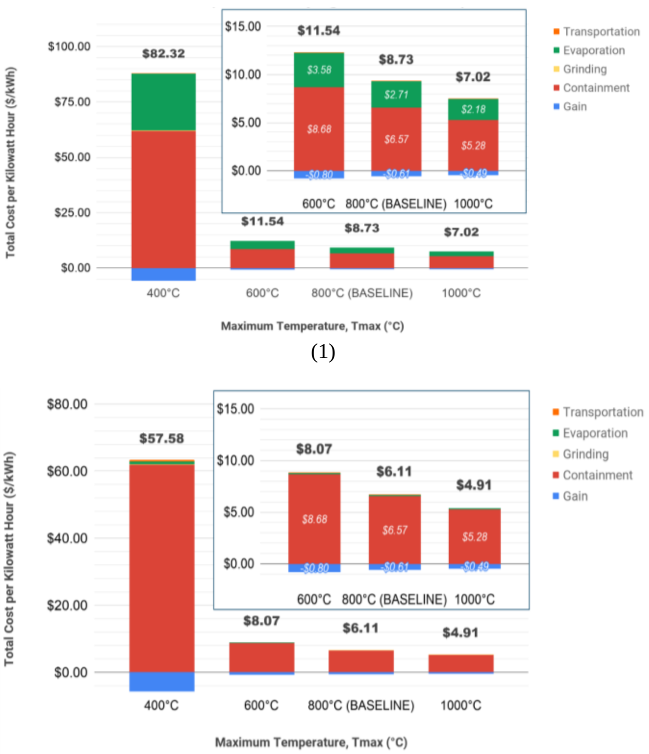
(1)

(2)

Fig. 11. Effect of solid-to-liquid phase change of ROC salt and maximum storage temperature on the TES cost for (1) using CNG and (2) using solar ponds for evaporation.

Depending on the source of the feedwater of the RO facility, the ROC salt content may or may not go through a solid-to-liquid phase change as described earlier. The solid-to-liquid provides a significant amount of TES potentials due to the fact that the heat of fusion of the salt mixture is included in the stored thermal energy according to Eq. 2. Fig. 11 illustrates the effect of the heat of fusion (melting) on the projected overall cost of the ROC-based TES at different maximum temperatures of heat storage. The heat of fusion of the ROC salt significantly reduces the cost of TES. In the case, that solid to liquid phase change is present the ROC-based TES meets the cost target of \$15/kWh at lower temperatures. If the ROC salt does not go through a phase change, the cost target is achieved at higher temperatures due to the fact that the heat is only stored as sensible heat of the solid ROC salt and the containment.

The sensitivity analysis is summarized by summarizing all of the contributors to the normalized TES cost as described before. Fig. 12 provides a comparison of the role of different costs/gains on the normalized TES cost, i.e., C_{tes}.



(1)

(2)

Fig. 12. Summary of sensitivity analysis; omparison of different costs/gain on the normalized TES cost using (1) CNG and (2) solar ponds for evaporation.

The results show that in both cases (evaporation of ROC water content using CNG or solar pond), the proposed ROC-based TES meets the cost targets of the U.S. Department of Energy at maximum temperatures that are consistent with concentrating solar power plants. The containment and evaporation costs are the dominating costs associated with the proposed TES system. The value of gain impacts the overall TES cost; however, the proposed TES system has a projected cost below \$15/kWh$_t$ with negligible gains. Using evaporation ponds instead of fuel has a noticeable impact on the overall TES cost. It is seen that using solar ponds to evaporate the water content of the ROC leads to a reduction of the TES cost by about \$2-\$3.5/kWht.

IX. Concluding Remarks

Reverse Osmosis Concentrate is considered an industrial waste and does not have an application in industry. In this study, a techno-economic analysis was performed to evaluate using the salt content of reverse osmosis concentrate as a thermal energy storage medium. Different costs associated with developing the proposed TES system were considered in this analysis. The considered costs include transportation of the concentrate from the RO to the ROC processing facility, evaporating the water content of the ROC, grinding the salt content, and containment. In addition to the costs, the effect of the disposal fees of the RO facility (gain for the TES development) was considered. The results show that the proposed TES system meets the cost requirements of the U.S. Department of Energy, i.e., \$15/kWh. The baseline cost of the proposed system is \$6.11/kWh when solar ponds are used and are \$8.73/kWh when CNG fuels are used for evaporating the ROC water content. The effect of transportation and grinding on the TES cost is negligible in all cases. The value of gain can significantly reduce the TES cost; however, the proposed TES system meets the cost targets in the absence of the gain.

In the next steps of this effort, utilizing ROC-based indirect two-tank thermal energy storage systems will be investigated. In addition, the effect of using the ROC-based thermal energy storage on the levelized cost of energy (LCOE) of solar-thermal power will be investigated.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

RB Lakeh is the project PI and main author. Christopher Salerno, Ega P. Herlim, and Joseph Kiriakos performed calculations and anxalysis, and Saied Delagah provided insight in ROC disposal methods.

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