AN INTEGRATED APPROACH TO WATER-ENERGY NEXUS IN SHALE-GAS PRODUCTION

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\textbf{ABSTRACT-}  Shale gas production is associated with significant usage of fresh water and discharge of wastewater. Consequently, there is a necessity to create the proper management strategies for water resources in shale gas production and to integrate conventional energy sources (e.g., shale gas) with renewables (e.g., solar energy). The objective of this study is to develop a design framework for integrating water and energy systems including multiple energy sources, cogeneration process, and desalination technologies in treating wastewater and providing fresh water for shale gas production. Solar energy is included to provide thermal power directly to a multi-effect distillation plant (MED) exclusively (to be more feasible economically) or indirect supply through a thermal energy storage system. Thus, MED is driven by direct or indirect solar energy, and excess or direct cogeneration process heat. The proposed thermal energy storage along with the fossil fuel boiler will allow for the dual-purpose system to operate at steady-state by managing the dynamic variability of solar energy. Additionally, electric production is considered to supply a reverse osmosis plant (RO) without connecting to the local electric grid. A multi-period mixed integer nonlinear program (MINLP) is developed and applied to discretize operation period to track the diurnal fluctuations of solar energy. The solution of the optimization program determines the optimal mix of solar energy, thermal storage, and fossil fuel to attain the maximum annual profit of the entire system. A case study is solved for water treatment and energy management for Eagle Ford Basin in Texas.

Keywords: Cogeneration, Process integration, Solar energy, Thermal storage, Desalination, Optimization
INTRODUCTION

Recently, major discoveries of shale gas reserves have led to substantial growth in production. For instance, the US production of shale gas has increased from 2 trillion ft$^3$ in 2007 to 17 trillion ft$^3$ in 2016 with estimated cumulative production of more than 400 trillion ft$^3$ over the next two decades [1]. Consequently, there are tremendous monetization opportunities to convert shale gas into value-added chemicals and fuels such as methanol, olefins, aromatics, and liquid transportation fuels [2-9]. A major challenge to a more sustainable growth of shale gas production is the need to address natural resource, environmental, and safety issues [10-11]. Specifically, the excessive usage of fresh water and discharge of wastewater constitute major problems. Hydraulic fracturing and horizontal drilling are the essential technologies to extract natural gas from shale rock. Water plays a significant role in shale gas production through mixing millions of gallons of water with sand, chemicals, corrosion inhibitors, surfactants, flow improvers, friction reducers, and other constituents to produce fracturing fluid. Under the high pressure, the fracturing fluid is injected into the wellbore to make cracks within the rock layers to increase the production [12-13]. Large quantities of water are used in the fracturing and related process [14]. The typical annual water consumption per well for hydraulic fracturing ranges between 1,000 and 30,000 m$^3$ leading to substantial amounts of water usage. For instance, the annual water usage in shale gas production is estimated to be about 120 MM m$^3$. In the Eagle Ford Shale Play, the annual water use is 18 MM m$^3$ for 1040 wells [15]. Wastewater associated with shale gas production is discharged in two forms: flowback water (which is released over several weeks following production) and produced water (which is the long-term wastewater) [14, 16]. Treatment of shale gas wastewater followed by recycle and reuse can provide major economic and environmental
benefits [12-17]. Regrettably, a small fraction of the shale-gas wastewater is recycled. A recent study [18] reported that in 2014, less than 10% of the roughly 80,000 wells in the US used recycled water after proper treatment. Lira-Barragán et al. [18] developed a mathematical programming model for the combination of water networks in the shale gas site by taking into consideration the requirement of water, the uncertainty of used and flowback water, and the optimal size of treatment units, storage systems, and disposals. Gao and You [12] addressed the shale-gas water problem as a mixed integer linear fractional programming (MILFP) problem to maximize the profit per unit of freshwater consumption. Yang et al. [14] developed a two-stage mixed integer linear programming (MINLP) model has been proposed for shale gas formations with the uncertainty of water availability. Several technologies may be used for treatment including thermal desalination and membrane separation [13–20]. These technologies require significant usage of thermal and/or electric energy. Some of the energy may be provided by shale gas, flared gases, or other on-site sources [21]. Additionally, renewable energy (such as solar) may be utilized to enhance the sustainability of the system. Therefore, it is important to consider the water management problem for shale gas production via a water-energy nexus framework.

This work is aimed at developing a new systematic approach to design, operation, integration, and optimization of a dual-purpose system which integrates solar energy and fossil fuels for producing electricity and desalinated water while treating shale-gas wastewater. In addition to fossil fuels, a concentrated solar power field, a thermal storage system, conventional steam generators, and cogeneration process are coupled with two water treatment plants: reverse osmosis (RO) and multiple-effect distillation (MED). A multi-period mixed integer nonlinear program (MINLP) formulation is developed to account for the diurnal fluctuations of solar energy.
The solution of the mixed integer nonlinear program (MINLP) determines the optimal mix of solar energy, thermal storage, and fossil fuel and the details of wastewater treatment and water recycle.

**PROBLEM STATEMENT**

Consider a shale-gas production site with the following known information:

- Flowrate and characteristics of produced and flared shale gas.
- Demand for fresh water (flowrate and quality).
- Flowrate and characteristics of flowback and produced wastewater.

The site is not connected to an external power grid.

It is desired to systematically design an integrated system which:

- Treats the wastewater for on-site recycle/reuse.
- Uses solar energy and fossil fuels to provide the needed electric and thermal power needs.
- Satisfies technical, economic, and environmental requirements.

Given are:

- Flowrate and composition of shale gas (sold and flared).
- Flowrate and purity needs for fresh water.
- Total volumetric flow of wastewater (flow-back and produced water) of shale gas play.
- Flowrate of flared gases that may be used in the cogeneration process.
- Electric energy requirement for RO and MED, (kWh/m³).
- Thermal energy requirement for MED, (kWh/m³).

To solve the problem, the following questions should be addressed:
• What the maximum annual profit of the whole system for producing desalinated water, electricity for the various percentage contribution of RO and MED in the total desalinated water production?

• What the minimum total annual cost of the entire system?

• What is the economic feasibility of the system?

• What is the optimal mix of solar energy, thermal storage, and fossil fuel for MED plant and the entire system?

• What is the optimal design and integration of the system?

• What are the optimal values of the design and operating variables of the system (e.g., minimum area of a solar collector, maximum capacity of a thermal storage system, etc.)?

• What is the feasible range of the percentage contribution of RO and MED in the total desalinated water production?

The Superstructure integrates primary components of solar energy and fossil fuels for producing electricity and desalinated water, as shown in Figure 1:

• To achieve a steady supply of thermal power to the whole system, solar energy (as direct solar thermal power), fossil fuel (shale gas, flared gas), and a thermal energy storage (as indirect solar thermal power) are used.

• Solar energy is used as a source of heat to provide thermal power directly to MED plant exclusively (to be more economically feasible), while the surplus thermal power is stored.

• A two-stage turbine is used to enhance the cogeneration process efficiency.
APPROACH

A hierarchical design is proposed to efficiently address the water-energy nexus problem. Figure 2 demonstrates the main steps of the approach. The first step is to gather the required data for the system then to select and formulate the appropriate models that describe the major system components. Once the preceding steps are achieved, the computational optimization is applied to the integrated system to maximize annual profit of the system that produces a specific level of desalinated water and electricity. To decompose the optimization problem, the percentage contribution of RO and MED to treating wastewater is iteratively discretized. For each discretization, the thermal and electric loads are calculated, and the energy systems are optimized and designed. The total annualized cost for each discretized iteration is calculated and finally the minimum-cost solution is selected.
Figure 2: Proposed approach

Modeling the Building Blocks

The performance models for MED and RO have been taken from literature [22-26]. For the solar system, a parabolic trough collector was selected. The modeling of the solar system was based on literature models and data [27-30] as described in this section. The solar thermal power (per unit length of a collector) that produced by the solar field when the direct normal irradiance (DNI) strikes collector aperture plane is given by the following expression:

\[ Q_{\text{sun} \rightarrow \text{collector}} (W/m) = DNI \cdot \cos \Theta \cdot W_c \]  

(1)

where DNI (W/m²) is the direct normal irradiance, \( \Theta \) is the solar incidence angle, \( W_c \) (m) is the width of the collector aperture.
For North-South orientation, the incidence angle is calculated as follows:

\[
\cos \theta = \sqrt{\cos^2 \Theta_z + \cos^2 \delta \cdot \sin^2 \omega} \tag{2}
\]

where \(\Theta_z\) is the solar zenith angle, \(\delta\) is the declination, \(\omega\) is the hour angle.

To calculate the thermal power (per unit length of a collector) that absorbed by the receiver tube of a collector loop, the influences of the optical losses can be taken into consideration by inserting four parameters to Eq. is given by the following expression:

\[
Q_{\text{collector\rightarrow receiver}}(W/m) = DNI \cdot \cos \Theta \cdot W_c \cdot \eta_{\text{opt}} \cdot K(\Theta) \cdot F_f \cdot R_{SL} \cdot O_{EL} \tag{3}
\]

Where \(\eta_{\text{opt}}\) is the peak optical efficiency of a collector, \(K(\Theta)\) is the incidence angle modifier, \(F_f\) is the soiling factor (mirror cleanliness), \(R_{SL}\) is the row shadow loss, \(O_{EL}\) is the optical end loss.

The peak optical efficiency of a collector when the incidence angle on the aperture plane is \(0^\circ\) is:

\[
\eta_{\text{opt}} = \rho \cdot \gamma \cdot \tau \cdot \alpha \bigg|_{\theta = 0^\circ} \tag{4}
\]

where \(\rho\) is the reflectivity, \(\gamma\) is the intercept factor, \(\tau\) is the glass transmissivity, \(\alpha\) is the absorptivity of the receiver pipe.

The incidence angle modifier for an LS-3 collector is given by:

\[
K(\Theta) = \begin{cases} 
1 - 2.23073 \times 10^{-4} \times \Theta - 1.1 \times 10^{-4} \times \Theta^2 + 3.18596 \times 10^{-6} \times \Theta^3 & 0^\circ \leq \Theta \leq 80^\circ \\
-4.85509 \times 10^{-8} \times \Theta^4 & \Theta > 80^\circ \\
0 & \Theta < 0^\circ
\end{cases} \tag{5}
\]
The row shadow factor is:

\[ R_{SL} = \min \left[ \max (0, \frac{L_{\text{spacing}}}{W_c} \cdot \frac{\cos \Theta_z}{\cos \Theta}; 1.0) \right] \tag{6} \]

where \( L_{\text{spacing}} \) (m) is length of spacing between troughs.

The optical end loss is:

\[ O_{EL} = 1 - \frac{f \cdot \tan \Theta}{L_{\text{SCA}}} \tag{7} \]

where \( f \) is focal length of the collectors (m), \( L_{\text{SCA}} \) is length of a single collector assembly (m).

The total thermal power (per unit length of a collector) that loss from a collector represents the combination of the radiative heat loss from the receiver pipe to ambient \( (Q_{\text{receiver} \rightarrow \text{ambient}}) \) and convective and conductive heat losses from the receiver pipe to its outer glass pipe \( (Q_{\text{receiver} \rightarrow \text{glass}}) \), and is calculated by the following expression:

\[ Q_{\text{collector} \rightarrow \text{ambient}} (W/m) = U_{\text{rec}} \cdot \pi \cdot d_o \cdot (T_{\text{rec}} - T_{\text{amb}}) \tag{8} \]

where \( U_{\text{rec}} (W/m^2.K) \) is the overall heat transfer coefficient of a receiver pipe, \( d_o \) (m) is the outer diameter of a receiver pipe, \( T_{\text{rec}} \) (K) is the mean receiver pipe temperature, \( T_{\text{amb}} \) (K) is the ambient air temperature.

The overall heat transfer coefficient of a collector is found experimentally depending on a receiver pipe temperature, and it can be given in the second-order polynomial equation:

\[ U_{\text{rec}} = a + b \cdot (T_{\text{rec}} - T_{\text{amb}}) + c \cdot (T_{\text{rec}} - T_{\text{amb}})^2 \tag{9} \]

where a, b, and c coefficients have been calculated experimentally for the LS-3 collector have been reported in literature [27].
The thermal power (per unit length of a collector) that transferred from a collector to a fluid is given in the following expression [31]:

\[
Q_{\text{collector→fluid}}(W/m) = Q_{\text{collector→receiver}} - Q_{\text{collector→ambient}}
\] (10)

The thermal power (per unit length of a collector) that loss from the headers (pipes) is given in the following expression [32]:

\[
Q_{\text{LFP}}(W/m) = 0.0583 \cdot W_c \cdot (T_{\text{rec}} - T_{\text{amb}})
\] (11)

The thermal power (per unit length of a collector) that loss from the expansion tank (vessel) is given in the following expression [32]:

\[
Q_{\text{LFV}}(W/m) = 0.0497 \cdot W_c \cdot (T_{\text{rec}} - T_{\text{amb}})
\] (12)

The useful thermal power (per unit length of a collector) that produced by the solar field is given by the following expression, which represents the sum of Equations 10-12:

\[
Q_{\text{solar field→final demand}}(W/m) = Q_{\text{collector→receiver}} - Q_{\text{collector→ambient}} - Q_{\text{LFP}} - Q_{\text{LFV}}
\] (13)

The inlet thermal power of the thermal storage is given in the following expression:

\[
Q_{\text{in}} = m_{\text{ms}} \cdot c_{P,\text{ms}} \cdot (T_{\text{HT}} - T_{\text{CT}}) = \eta_{\text{EX}} \cdot m_{\text{oil}} \cdot c_{P,\text{oil}} \cdot (\Delta T)
\] (14)

And the expression of the discharge process (outlet thermal power) is given by:

\[
Q_{\text{out}} = m_{\text{oil}} \cdot c_{P,\text{oil}} \cdot (\Delta T) = \eta_{\text{EX}} \cdot m_{\text{ms}} \cdot c_{P,\text{ms}} \cdot (T_{\text{HT}} - T_{\text{CT}})
\] (15)

where \( m_{\text{ms}} \) is the molten salt flow rate \((kg/s)\), \((c_{P,\text{ms}} = 1443 + 0.172 T_{\text{ms}})\) is the specific heat of the molten salt \((J/kg \cdot ^\circ C)\), \( T_{\text{ms}} \) is the temperature \((^\circ C)\) of the molten salt, \( T_{\text{HT}} \) is the hot tank.
temperature (°C), $T_{CT}$ is the cold tank temperature (°C), $\eta_{EX}$ is the efficiency of the heat exchanger, $m_{oil}$ is the oil mass flowrate ($Kg/s$), $\Delta T$ is the difference between inlet and outlet of the oil.

The net thermal power inside the tank ($W$) can be calculated by the following expression:

$$Q_{TES} = Q_{acc} + Q_{in} - Q_{out} - Q_{loss}$$  \hspace{1cm} (16)

where $Q_{acc}$ is the accumulated thermal power in the tank from preceding iterations, $Q_{loss}$ is the thermal power loss ($kW/m^2$) of the cold and heat tanks and it is given in the following empirical equation [33]:

$$Q_{loss} = 0.00017.T_{ms} + 0.012$$  \hspace{1cm} (17)

where $T_{ms}$ is the temperature (°C) of the molten salt in the hot and in the cold tanks.

The optimal values of the Rankine cycle parameters of cogeneration process can be satisfied by formulated the entire cycle as an optimization problem. Thus, there is a necessity to obtain suitable correlations of thermodynamic properties that can be used in optimization formulations. In thermodynamic calculations of the Rankine cycle, mathematical equations are used to replace the steam tables because they could incorporate easily into optimization formulations. However, available correlations for steam tables are complicated (e.g., nonlinear, nonconvex function), and it is hard to insert them in optimization task. Consequently, a new set of thermodynamic correlations have been developed in literature [34] to estimate properties of steam and they can be incorporated easily into optimization formulation and cogeneration design. The isentropic efficiency of the steam turbine can be obtained from the turbine hardware model, which developed by Mavromatis and Kokossis [35], to show the efficiency variation with the load, the turbine size, and operating conditions, as in the following correlation:
\[ \eta_\text{ts} = \frac{6}{5} \cdot B \left( 1 - \frac{3.41443 \cdot 10^6 \cdot A}{\Delta h_\text{ts} \cdot m_{\text{max}}} \right) \left( 1 - \frac{m_{\text{max}}}{6 \cdot \dot{m}} \right) \]  

(18)

where \( \dot{m} \) is the inlet turbine steam flowrate (\( lb/hr \)), and \( m_{\text{max}} \) is the maximum mass flowrate of a turbine (\( lb/hr \)). \( A \) and \( B \) are parameters that depend on the inlet saturation temperature (\( ^\circ F \)) and the type of turbine as in the following correlations:

\[ A = a_o + a_1 \cdot T_{\text{sat}} \]  

(19)

\[ B = a_2 + a_3 \cdot T_{\text{sat}} \]  

(20)

where \( a_o, a_1, a_2, a_3 \) the correlation constants and can be found in literature [36].

**OPTIMIZATION FORMULATION**

Because of the diurnal nature of solar energy, a multi-period approach is adopted. The annual operation is discretized in a number of operational periods (e.g., monthly). The index \( m \) refers to the operational period. For each operational period, an average meteorological day is used to represent the solar intensity data. In turn, the meteorological day is discretized into a number of sub-periods (e.g., 24 hours) where the index \( t \) is used to designate a sub-period. Two water-treatment technologies are used: multi-effect distillation (MED) and reverse osmosis (RO). MED consumes mostly thermal energy and some electric energy which are respectively given by the specific requirements: \( q_{\text{MED}} \) (kWh/m\(^3\)) and \( e_{\text{MED}} \) (kWh/m\(^3\)). RO requires electric energy which is represented by the following specific energy consumption term: \( e_{\text{RO}} \) (kWh/m\(^3\)).

For each sub-period \( t \), the thermal power needs for water treatment is obtained directly from the combustion of fossil fuels \( Q_{e,m}^{F\text{ossil}} \), directly from a solar thermal collector \( Q_{e,m}^{D\text{irect,SC}} \),
indirectly from solar energy through thermal storage \(Q_{t,m}^{Out\_Stored\_SC}\), and from steam leaving the cogeneration turbine \(Q_{t,m}^{Turbine}\). Hence,

\[
Q_{t,m}^{Total} = Q_{t,m}^{Fossil} + Q_{t,m}^{Direct\_SC} + Q_{t,m}^{Out\_Stored\_SC} + Q_{t,m}^{Turbine} \quad \forall t, \forall m
\]  

where

\[
Q_{t,m}^{Total} = F_{t,m}^{MED} q_{MED} \quad \forall t, \forall m
\]

The electric power provided by the cogeneration turbine is given by:

\[
E_{t,m}^{Total} = P_{t,m}^{RO} e_{RO} + F_{t,m}^{MED} e_{MED} \quad \forall t, \forall m
\]

The thermal power captured by the solar collector \(Q_{t,m}^{SC}\) is directly used \(Q_{t,m}^{Direct\_SC}\) or is stored \(Q_{t,m}^{In\_Stored\_SC}\) for subsequent usage, i.e.

\[
Q_{t,m}^{SC} = Q_{t,m}^{Direct\_SC} + Q_{t,m}^{In\_Stored\_SC} \quad \forall t, \forall m
\]

Over a sub-period, \(t\), the thermal power balance for the thermal storage unit is given by:

\[
Q_{t,m}^{Stored\_SC} = Q_{t-1,m}^{Stored\_SC} + Q_{t,m}^{In\_Stored\_SC} - Q_{t,m}^{Out\_Stored\_SC} - Q_{t,m}^{Stored\_Loss} \quad \forall t, \forall m
\]

Such collected energy is a function of the solar-radiation intensity \(Solar\_Radiation_{t,m}\) and the effective surface area of the solar collector \(A_{t,m}^{SC}\).

Although each period requires a certain area of the solar collector, the design value (which is also used for capital cost estimation) is the largest of all needed areas, i.e.:

\[
A_{t,m}^{SC} \leq A_{design}^{SC} \quad \forall t, \forall m
\]
The cogeneration turbine is modelled through a performance function (e.g., isentropic expansion with an efficiency) that combines inlet and outlet steam conditions and relates the produced power to heat.

\[ \Omega_{t,m}^{\text{Turbine}} \left( D_{t,m}^{\text{Turbine}}, \Omega_{t,m}^{\text{Turbine}}, \text{Steam}_{t,m}^{\text{In}}, \text{Steam}_{t,m}^{\text{Out}}, \text{Power}_{t,m}^{\text{Out}} \right) = 0 \quad \forall t, \forall m \quad (27) \]

The objective function seeks to maximize the profit for the water-energy nexus system:

Maximize Annual Profit = Annual value of treated water + Annual value of avoided cost of discharging wastewater – Cost of fossil fuels - Total annualized cost of solar collection system – Total annualized cost of solar storage system – Total annualized cost of cogeneration system - Total annualized cost of MED system – Total annualized cost of RO system

Maximum Annual profit =

\[ \sum_m \left( v_{t,m}^{\text{RO}} F_{t,m}^{\text{RO}} + v_{t,m}^{\text{MED}} F_{t,m}^{\text{MED}} \right) + c^{\text{Waste}} W_w - \sum_m \left( c_{t,m}^{\text{Fossil}} F_{t,m}^{\text{Fossil}} \right) - AFC^{\text{SC}} 
- \sum_m \sum_t OPEX_{t,m}^{\text{SC}} - AFC^{\text{SC, Storage}} - \sum_m \sum_t OPEX_{t,m}^{\text{SC, Storage}} - AFC^{\text{Cogen}} 
- \sum_m \sum_t OPEX_{t,m}^{\text{Cogen}} - AFC^{\text{MED}} - \sum_m \sum_t OPEX_{t,m}^{\text{MED}} - AFC^{\text{RO}} - \sum_m \sum_t OPEX_{t,m}^{\text{RO}} \quad (28) \]

**CASE STUDY**

To demonstrate the viability of the proposed approach for solution strategies, a case study will be solved that based on the Eagle Ford shale play, which is located south Texas. A dual-purpose system which integrates solar energy and fossil fuels for producing electricity and fresh water has been considered. The optimal design, operation, and integration of the system will be found through this case study that requires particular input data for each unit of the entire system. As mentioned earlier, this system includes concentrated solar power field, a thermal storage...
system, conventional steam generators, and a cogeneration process into two water treatment plants, a reverse osmosis plant (RO) and a multiple-effect distillation plant (MED).

**Flowback/Produced Water of Shale Gas Play**

In order to supply a specific amount of flow-back and produced water (FPW) from a shale play to a desalination plant, the calculation of an FPW flow average for many years is an appropriate option to avoid the uncertainty in the amount of FPW. Specifically, if we know that wastewater of shale play is typically subjected to heavily regulated and should store in containers so that these containers can be utilized to get a constant flow approximately. Additionally, a large number of wells in a shale play can contribute to making the flow rate of FPW approximately constant because when the FPW production of one well starts declining, another well will start its production and compensate a drop of production in other wells.

Table 1 shows the estimated value of flowback and produced water that returned from shale gas formations to the surface in the Eagle Ford basin. This estimated value is based on the study [37] for 10 plays since the early 2000s until 2015.

<table>
<thead>
<tr>
<th>Shale gas formations</th>
<th>Number of wells</th>
<th>Total water use $10^6 m^3$</th>
<th>Total gas production $10^{12} ft^3$</th>
<th>Total oil production $10^6 bbl$</th>
<th>Total FPW $10^6 m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eagle ford</td>
<td>5846</td>
<td>80.08</td>
<td>8.01</td>
<td>723.52</td>
<td>151.22</td>
</tr>
</tbody>
</table>
The techno-economic data for RO and MED are reported in Table 2.

**Table 2. Techno-Economic Data for RO and MED [22, 38]**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Thermal energy consumption (kWht/m³ Desalinated water)</th>
<th>Electric energy consumption (kWhe/m³ Desalinated water)</th>
<th>Annualized fixed cost (AFC) ($/year)</th>
<th>Operating cost ($/m³ desalinated water)</th>
<th>Water recovery (m³ desalinated water/m³ feed seawater)</th>
<th>Value of desalinated water ($/m³ desalinated water)</th>
<th>Outlet Salt Content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>-</td>
<td>4</td>
<td>2.0 . 10ª</td>
<td>0.18</td>
<td>0.55</td>
<td>0.88</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ 1.166 . (flowrate of seawater, m³ /day)ªº</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MED</td>
<td>65</td>
<td>2</td>
<td>13.0 . 10ª</td>
<td>0.24</td>
<td>0.65</td>
<td>0.82</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ 2.227 . (flowrate of seawater, m³ /day)ªº</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Solar Energy**

The solar data are summarized in Appendix I. Table 3 summarizes the main cost data for the solar collectors.

**Table 3: The direct capital cost of parabolic trough collector items [39, 40]**

<table>
<thead>
<tr>
<th>Item</th>
<th>Receivers</th>
<th>mirrors</th>
<th>Concentrator Structure</th>
<th>Concentrator Erection</th>
<th>Drive</th>
<th>Piping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost $/m²</td>
<td>43</td>
<td>40</td>
<td>47</td>
<td>14</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Item</td>
<td>Electronic &amp;control</td>
<td>Header piping</td>
<td>Civil works</td>
<td>Spares, HTF, Freight</td>
<td>Contingency</td>
<td>Structures &amp;Improvement</td>
</tr>
<tr>
<td>Cost $/m²</td>
<td>14</td>
<td>7</td>
<td>18</td>
<td>17</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>
The total fixed capital cost of the solar field ($), as follows:

\[ FCI_{SF} = C_{SF} \cdot A_{SF} \]  \hspace{1cm} (29)

where \( C_{SF} \) is the solar field cost per area unit ($241/m^2), \( A_{SF} \) is the solar field aperture area (m^2).

The thermal storage system is assumed an indirect two-tank type which is used the binary solar salt (sodium and potassium nitrate) as a storage material with the following fixed capital cost estimation ($):

\[ FCI_{TES} = C_{TES} \cdot SC \cdot Q_{solar\ field\ to\ final\ demand} \]  \hspace{1cm} (30)

where \( C_{TES} \) is the thermal storage system cost per thermal energy unit ($27.18/kWh), \( SC \) is the number of storage capacity hours (hr), \( Q_{solar\ field\ to\ final\ demand} \) is the useful thermal power that produced by solar field (kW).

The fixed capital cost estimation of a steam generator system ($) is calculated as:

\[ FCI_{SG} = C_{SG} \cdot Q_{solar\ field\ to\ final\ demand} \]  \hspace{1cm} (31)

where \( C_{SG} \) is the steam generator system cost per thermal power unit ($/kW_t).

The fixed capital cost of a boiler ($), which is assumed a water-tube boiler fueled with gas or oil, is estimated as follows [34]:

\[ FCI_B = 3 \cdot N_p \cdot N_T \cdot Q_{Boiler}^{0.77} \]  \hspace{1cm} (32)

where \( Q_{Boiler} \) is the amount of thermal power (BTU/hr) transferred to the steam and equal to \( Q_{Boiler}/\eta_{boiler} \), \( \eta_{boiler} \) is the efficiency of a boiler, \( N_p \) is a factor to account for the operation
pressure and it is given by: \( N_p = 7 \cdot 10^{-4} \cdot P_g + 0.6 \); \( P_g \) is the gauge pressure (psig) of a boiler, \( N_T \) is a factor accounting for the superheat temperature and is given by:

\[
N_T = 1.5 \cdot 10^{-6} \cdot T_{SH}^2 + 1.13 \cdot 10^{-3} \cdot T_{SH} + 1;
\]

\( T_{SH} \) is the superheat temperature (\(^\circ\)F), \( T_{SH} = T^{in} - T_{sat}^{in} \); \( T^{in} \) is the temperature at the inlet of a turbine, \( T_{sat}^{in} \) is the saturation temperature at the inlet of a turbine.

The fixed capital cost of a turbine ($), which is assumed a non-condensing turbine, is estimated as follows [34]:

\[
FCl_T = 475 \cdot E_T
\]  

(33)

where \( E_T \) is the turbine shaft power output (BTU/hr); \( E_T = m \cdot (h^{in} - h^{out}_{act}) \).

Flared Gas

The shale gas production from Eagle Ford wells can be used as a fuel for cogeneration process. Furthermore, the flared gas can be used also as a fuel source for cogeneration process that it will contribute to saving a considerable amount of shale gas along with diminishing CO\(_2\) emissions accompanying to the flared gas. In Eagle Ford fields, 4.4 billion cubic feet of gas was flared in 2013 that represented around 13% of the gas in the formation [41].

Total Cost

The annual fixed cost (AFC) ($/year) of the system is determined as follows:

\[
AFC = [(FCl_{SF} + FCl_{TES} + FCl_{SG} + FCl_B + FCl_T + FCl_{PST})/N] + AFC_{RO} + AFC_{MED}
\]  

(34)
The operation and maintenance cost ($/hr) of solar field, cogeneration process, thermal storage system, administration, and operations is estimated as follows, based on data are given by [39, 40]:

\[
OC_{OM} = C_{OM} \cdot (Q_{solar\ field - final\ demand} + Q_{Boiler})
\] (35)

where \( C_{OM} \) is the operation and maintenance cost per thermal power unit ($0.0203/kWh).

The type and amount of the selected fuel are necessary to estimate the cost of fuel ($/hr) and it is formulated as follows:

\[
OC_F = C_F \cdot Q_B \cdot 3413 \cdot 10^{-6}
\] (36)

where \( C_F \) is the fuel cost ($/MMBTU), \( Q_B \) is the amount of thermal power (BTU/hr) that equals to \( \frac{Q_{Boiler}}{\eta_{boiler}} \), \( \eta_{boiler} \) is the efficiency of a boiler.

The annual operating cost (AOC) ($/year) is determined as follows:

\[
AOC = a_Y \cdot (OC_{OM} + OC_F)
\] (37)

where \( a_Y \) is the annual operation time (hr/year).

The annual income ($/year) is the sum of the total desalinated water production value and the saving value of a reduction in the cost of transportation, fresh water acquisition, and disposal:

\[
Annual\ income = a_Y \cdot \{ (0.88 \cdot flowrate\ of\ desalinated\ water\ from\ RO, m^3/hr + 0.82 \cdot flowrate\ of\ desalinated\ water\ from\ MED, m^3/hr) + [(C_{FW} + C_{DS} + C_{TR}) \cdot total\ flowrate\ of\ desalinated\ water\ from\ (RO,MED)]/0.11924 \}
\] (38)
where $C_{FW}$ is the fresh water cost per volume unit (0.24$/bbl$), $C_{DS}$ is the disposal cost per volume unit (0.05$/bbl$), $C_{TR}$ is the transportation cost per volume unit (0.89$/bbl$).

The net profit represents the sum of the total desalinated water production value and the saving value of a reduction in the cost of transportation, fresh water acquisition, and disposal. The treatment process of flowback and produced water in a shale gas site that can be contributed effectively to save a money for each barrel of flowback and produced water which should be trucked and disposed. Table 4 shows the cost of transportation, fresh water acquisition, primary/secondary treatment, and disposal depending on the characteristics of a water treatment plant with capacity a 2,380 barrel/day in Eagle Ford basin [42].

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water ($/barrel)</td>
<td>0.24</td>
</tr>
<tr>
<td>Disposal (Deep well + Landfill) ($/barrel)</td>
<td>0.05</td>
</tr>
<tr>
<td>Primary &amp; secondary treatment ($/barrel)</td>
<td>0.34</td>
</tr>
<tr>
<td>Transportation ($/barrel)</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**RESULTS & DISCUSSION**

A detailed performance model of the parabolic trough was applied to the case study to determine the useful thermal power (per unit length of a collector) that produced by the solar field. The calculations of the solar field have been carried out depending on the monthly average of hourly direct solar irradiance, hourly ambient temperature, and hourly incidence angle. Moreover, the characteristics of the LS-3 collector were adopted and all types of thermal losses (convection, conduction, radiation) are considered for the entire the solar field. The hourly variations in the useful thermal power for 12 months were obtained, as shown in Figure 3.
Figure 3: Monthly average of hourly DNI and useful thermal power
The obtained results showed that the gained thermal power in the month January, February, November, and December is less than the rest eight months of the year due to low DNI and the high cosine effect. However, the four months, which have the lowest value of useful thermal power still has the significant potential to provide a thermal power to the system. The selecting solar irradiance around \((500 \text{~W/m}^2)\) at design point to calculate the total area of collectors can give a great chance for these four months to contribute efficiently to supply a sufficient thermal power, despite a low value of average direct normal irradiance in the region that selected as a case study. In the same direction, the eight months, which have a higher DNI can be exploited to provide direct thermal power to MED and a surplus thermal power to a thermal storage system. Indeed, the optimal area of collectors and storage system capacity are based on the minimum total annual cost of the entire system that can be obtained through an optimization solution.

The monthly distribution of the optimal thermal power mix for MED plant and the entire system has been determined for the different percentage contribution of RO and MED in the total desalinated water production. The optimal thermal power mix for MED plant includes the direct thermal power of solar field, the indirect thermal power of thermal storage system, the surplus thermal power of cogeneration system, and the direct thermal from the combustion of fossil fuels. The monthly distribution varies over the year due to the availability of DNI and the variability of an incident angle, as shown in Figures 4-6.
Figure 4: Optimal thermal power mix for MED plant and the entire system with (30% RO 70% MED)

Figure 5: Optimal thermal power mix for MED plant and the entire system with (60% RO 40% MED)

Figure 6: Optimal thermal power mix for MED plant and the entire system with (80% RO 20% MED)
The solution of the case study introduces two scenarios to the optimal operation for MED in accordance with the availability of solar energy regardless of the percentage contribution of MED, the first scenario is for the months of January, February, November, and December and shows that it favors the harness of direct solar thermal power during the hours of the diurnal and utilize fossil fuel in the early hours of the day and in the evening. However, stored solar thermal power can be contributed from 1 to 2 hours only because of lacking solar energy in these months, as illustrated in Figure 7, adapted from [43].

![Figure 7: Optimal operation for MED during January, February, November, and December](image)

The second scenario is for the months of April, March, May, June, July, August, December, and October and shows sharply diminishing in using fossil fuel up to 2 hours only. Typically, direct solar thermal power is exploited in the middle of the day while stored solar thermal power is dispatched in the early hours and in the evening, as shown in Figure 8, adapted from [43]. In the future work, the previous two scenarios can be applied to the entire system in the case of integrating solar energy to cogeneration process.
It is observed that the total annual cost of the system as mentioned in the previous section can be reduced by increasing the percentage contribution of RO over MED, but it requires consuming much amount of fossil fuel. More consumption of fossil fuel causes serious environmental impacts due to emitting a massive amount of $CO_2$. From the case study, the sustaining of fossil fuel resources and diminishing the emissions of greenhouse gas requires enhancing the percentage contribution of MED in the system that based on solar energy as a provider for a high percentage of thermal power. Figure 9 offers an obvious comparison between the economic and environmental aspects of the system through the different percentage contribution of RO and MED in the total desalinated water production. Reconciliation of economic and environmental objective can be achieved using a sustainability weighted return on investment calculation [44, 45].
The case study shows that in Eagle Ford fields, 4.4 billion cubic feet of gas was flared in 2013 that represented around 13% of the gas in the formation [41]. Therefore, this significant amount of flared gas can be exploited as a major source of energy for the system or sharing shale gas in a specific percentage as a minor source of energy, the results of the different percentage contribution of flared gas are shown in Table 5:

Table 5: Technical and economic results for the system

<table>
<thead>
<tr>
<th>Percentage of Contribution * (%)</th>
<th>Percentage of Contribution ** (%)</th>
<th>Total annual cost (MM$/year)</th>
<th>Annual Net (After – Tax)profit (MM$/year)</th>
<th>ROI (%)</th>
<th>Payback period (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 RO 70 MED</td>
<td>0.0</td>
<td>35.3</td>
<td>50.4</td>
<td>14.9</td>
<td>5.9</td>
</tr>
<tr>
<td>30 RO 70 MED</td>
<td>50</td>
<td>35.1</td>
<td>50.6</td>
<td>14.96</td>
<td>5.6</td>
</tr>
<tr>
<td>30 RO 70 MED</td>
<td>100</td>
<td>34.8</td>
<td>50.8</td>
<td>15</td>
<td>5.5</td>
</tr>
<tr>
<td>60 RO 40 MED</td>
<td>0.0</td>
<td>28.1</td>
<td>48.8</td>
<td>17.2</td>
<td>4.9</td>
</tr>
<tr>
<td>60 RO 40 MED</td>
<td>50</td>
<td>27.8</td>
<td>49</td>
<td>17</td>
<td>4.8</td>
</tr>
<tr>
<td>60 RO 40 MED</td>
<td>100</td>
<td>27.5</td>
<td>49.2</td>
<td>17.3</td>
<td>4.8</td>
</tr>
<tr>
<td>80 RO 20 MED</td>
<td>0.0</td>
<td>23.5</td>
<td>47.7</td>
<td>19.1</td>
<td>4.4</td>
</tr>
<tr>
<td>80 RO 20 MED</td>
<td>50</td>
<td>23.2</td>
<td>47.9</td>
<td>19.2</td>
<td>4.3</td>
</tr>
<tr>
<td>80 RO 20 MED</td>
<td>100</td>
<td>22.8</td>
<td>48.1</td>
<td>19.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>
CONCLUSIONS

A water-energy nexus framework has been used to address water management in shale gas production. The following key elements have been integrated: solar energy, fossil fuel, cogeneration process, MED and RO. A hierarchical approach and a multi-period MINLP have been developed and solved to find the optimal mix of solar energy, thermal storage, and fossil fuel and the optimal usage of water treatment technologies. A case study for Eagle Ford Basin in Texas has been solved to show the applicability of the proposed approach. The system has been analyzed according to technical, economic, and environmental aspects. The multi-period method has been applied to discretize the operational period to track the diurnal fluctuations of solar energy. The percentage utilization of water treatment technologies has been iteratively discretized. Once the solution of the mixed integer nonlinear program (MINLP) was applied to each discretization, the optimal mix of solar energy, thermal storage, and fossil fuel, the optimal values of the design and operating variables of the system (e.g., minimum area of a solar collector, maximum capacity of a thermal storage system, etc.) have been determined. The results show that the system the economic and environmental merits of using a water-energy nexus framework and enabling effective water management strategies while incorporating renewable energy.
NOMENCLATURE

\(a_0, a_1, a_2, a_3\)  
Correlation constants

\(a, b,\) and \(c\)  
Coefficients for the LS-3 collector

\(AFC_{\text{MED}}\)  
Annualized fixed capital cost of the multi-effect desalination

\(AFC_{\text{RO}}\)  
Annualized fixed capital cost of the reverse osmosis

\(AFC_{\text{SC}}\)  
Annualized fixed capital cost of the solar collector

\(AFC_{\text{cogen}}\)  
Annualized fixed capital cost of the cogeneration system

\(A^{\text{SC}}\)  
Effective surface area of the solar collector

\(A_{\text{SF}}\)  
Solar field aperture area

\(AFC\)  
Total annual fixed cost

\(AOC\)  
Total annual operating cost

\(A\) and \(B\)  
Parameters that depend on the type of the turbine

\(bbl\)  
Barrel

\(c^{\text{Waste}}\)  
Value of avoided cost of discharging wastewater

\(c_{\text{Fossil}}\)  
Value of fossil fuel

\(C_{\text{DS}}\)  
Disposal cost per volume unit

\(C_F\)  
Fuel cost per thermal power unit

\(C_{\text{FW}}\)  
Fresh water cost per volume unit

\(C_{\text{OM}}\)  
Operation and maintenance cost per thermal power unit

\(C_{\text{PST}}\)  
Primary and secondary treatment cost per volume unit

\(C_{\text{SF}}\)  
Solar field cost per area unit

\(C_{\text{SG}}\)  
Steam generator system cost per thermal power unit

\(C_{\text{TES}}\)  
Thermal storage system cost per thermal power unit

\(C_{\text{TR}}\)  
Transportation cost per volume unit

\(C_{\text{Pms}}\)  
Specific heat of the molten salt

\(C_{\text{Poil}}\)  
Specific heat of oil

\(d_{\text{o}}\)  
Outer diameter of the receiver pipe

\(D_{\text{turbine}}\)  
Design variable of the turbine

\(DNI\)  
Direct normal irradiance
\( e_{\text{MED}} \)

Electric energy requirements of MED

\( e_{\text{RO}} \)

Electric energy requirements of RO

\( E_T \)

Turbine shaft power output

\( E_{T,\text{Total}} \)

Electric energy provided by the cogeneration turbine

\( ft^3 \)

Cubic feet

\( f \)

Focal length of the collectors

\( FC_{B} \)

Fixed capital cost of a boiler

\( FC_{\text{PST}} \)

Fixed capital cost of the primary and secondary treatment

\( FC_{\text{SF}} \)

Total fixed capital cost of the solar field

\( FC_{SG} \)

Fixed capital cost estimation of the steam generator system

\( FC_{T} \)

Fixed capital cost of the turbine

\( FC_{\text{TES}} \)

Fixed capital cost of the thermal storage system

\( FC_{\text{Total}} \)

Total fixed capital cost

\( F_f \)

Soiling factor (mirror cleanliness)

\( FPW \)

Flowback and produced water

\( F_{\text{Fossil}} \)

Volumetric flow rate of fossil fuel

\( F_{\text{MED}} \)

Volumetric flow rate of desalinated water from MED

\( F_{\text{RO}} \)

Volumetric flow rate of desalinated water from RO

\( h_{\text{act}}^\text{out} \)

Actual outlet enthalpy of the turbine

\( h_{\text{in}}^\text{in} \)

Inlet enthalpy of the steam

\( h_{\text{is}}^\text{out} \)

Outlet isentropic enthalpy

\( HCE \)

Sum of heat collection element

\( K(\Theta) \)

Incidence angle modifier

\( L_{\text{SCA}} \)

Length of a single collector assembly

\( L_{\text{spacing}} \)

Length of spacing between troughs

\( m \)

Inlet turbine steam flowrate

\( m_{\text{max}} \)

Maximum mass flowrate of the turbine

\( m_{\text{ms}} \)

Mass flow rate of molten salt

\( m_{\text{oil}} \)

Mass flowrate of oil
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED</td>
<td>Multi-effect distillation plant</td>
</tr>
<tr>
<td>MINLP</td>
<td>Mixed integer nonlinear program</td>
</tr>
<tr>
<td>MM</td>
<td>Million</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Factor to account for the operation pressure of the boiler</td>
</tr>
<tr>
<td>$N_t$</td>
<td>Factor accounting for the superheat temperature of the boiler</td>
</tr>
<tr>
<td>$N$</td>
<td>Service life of the property in years</td>
</tr>
<tr>
<td>NSRDB</td>
<td>National Solar Radiation Data Base</td>
</tr>
<tr>
<td>$OC_{OM}$</td>
<td>Operation and maintenance cost</td>
</tr>
<tr>
<td>$O_{EL}$</td>
<td>Optical end loss</td>
</tr>
<tr>
<td>$OC_F$</td>
<td>Cost of fuel</td>
</tr>
<tr>
<td>$O_T^{turbine}$</td>
<td>Operation variable of the turbine</td>
</tr>
<tr>
<td>$OPEX_{t,m}^{MED}$</td>
<td>Annualized operational expenditure of MED</td>
</tr>
<tr>
<td>$OPEX_{t,m}^{RO}$</td>
<td>Annualized operational expenditure of RO</td>
</tr>
<tr>
<td>$OPEX_{t,m}^{SC}$</td>
<td>Annualized operational expenditure of the solar collector</td>
</tr>
<tr>
<td>$OPEX_{t,m}^{SC-storage}$</td>
<td>Annualized operational expenditure of the thermal storage system</td>
</tr>
<tr>
<td>$OPEX_{t,m}^{cogen}$</td>
<td>Annualized operational expenditure of the cogeneration system</td>
</tr>
<tr>
<td>$P_g$</td>
<td>Gauge pressure of the boiler</td>
</tr>
<tr>
<td>PTC</td>
<td>Parabolic trough collector</td>
</tr>
<tr>
<td>$q_{MED}$</td>
<td>Thermal energy requirements of MED</td>
</tr>
<tr>
<td>$Q_{Boiler}$</td>
<td>Thermal power output of the boiler rate</td>
</tr>
<tr>
<td>$Q_{LFP}$</td>
<td>Thermal power that loss from the headers (pipes)</td>
</tr>
<tr>
<td>$Q_{LFV}$</td>
<td>Thermal power that loss from the expansion tank (vessel)</td>
</tr>
<tr>
<td>$Q_{TES}$</td>
<td>Net thermal power inside the tank</td>
</tr>
<tr>
<td>$Q_{in}$</td>
<td>Inlet thermal power</td>
</tr>
<tr>
<td>$Q_B$</td>
<td>Amount of thermal power that produced by the boiler</td>
</tr>
<tr>
<td>$Q_{acc}$</td>
<td>Accumulated thermal power in the tank from preceding iterations</td>
</tr>
<tr>
<td>$Q_{collector→ambient}$</td>
<td>Total thermal power that loss from a collector to ambient</td>
</tr>
<tr>
<td>$Q_{collector→fluid}$</td>
<td>Thermal power that transferred from a collector to a fluid</td>
</tr>
</tbody>
</table>
The thermal power absorbed by the receiver tube of a collector loop is denoted by $Q_{\text{collector-reciever}}$. The outlet thermal power is given by $Q_{\text{out}}$. The useful thermal power produced by the solar field is $Q_{\text{sol-field-final demand}}$. The solar thermal power produced by the solar field is $Q_{\text{sun-collector}}$. The thermal power loss is $Q_{\text{loss}}$. The direct solar thermal power from the solar thermal collector is $Q_{\text{Direct, SC}}$. The direct thermal power from the combustion of fossil fuels is $Q_{\text{Fossil}}$. The inlet thermal power of the thermal storage system is $Q_{\text{In, Stored -SC}}$. The indirect thermal from solar energy through the thermal storage system is $Q_{\text{Out, Stored_SC}}$. The thermal power captured by the solar collector is $Q_{\text{SC}}$. The loss thermal power of the thermal storage system is $Q_{\text{Stored-Loss}}$. The thermal power stored in the thermal storage system is $Q_{\text{Stored-SC}}$. The total thermal power needs for water treatment is $Q_{\text{Total}}$. The thermal power from steam leaving the cogeneration turbine is $Q_{\text{Turbine}}$. The thermal power stored from previous iterations is $Q_{\text{T-1, Stored SC}}$. The row shadow loss is $R_{\text{SL}}$. The reverse osmosis plant is $RO$. The return on investment is $ROI$. The number of storage capacity hours is $SC$. The cold tank temperature is $T_{\text{CT}}$. The hot tank temperature is $T_{\text{HR}}$. The superheat temperature is $T_{\text{SH}}$. The ambient air temperature is $T_{\text{amb}}$. The temperature at the inlet of the turbine is $T_{\text{in}}$. The temperature of the molten salt is $T_{\text{ms}}$. The mean receiver pipe temperature is $T_{\text{rec}}$. The saturation temperature at the inlet of a turbine is $T_{\text{sat}}$. The overall heat transfer coefficient of the receiver pipe is $U_{\text{rec}}$. 
Subscript and superscript symbols

- \( W_c \): Width of the collector aperture
- \( W_w \): Volumetric flow rate of discharging wastewater
- \( W \): Watt

- \( \text{ac} \): Actual
- \( \text{acc} \): Accumulated
- \( \text{amb} \): Ambient
- \( \text{B} \): Boiler
- \( \text{c} \): Collector aperture
- \( \text{Cogen} \): Cogeneration process
- \( \text{CT} \): Cold tank
- \( \text{DS} \): Disposal
- \( \text{EL} \): End loss
- \( \text{f} \): Factor
- \( \text{F} \): Fuel
- \( \text{FW} \): Freshwater
- \( \text{g} \): Gauge
- \( \text{HT} \): Hot tank
- \( \text{is} \): Isentropic
- \( \text{LFP} \): Loss from pipes
- \( \text{LFV} \): Loss from vessel
- \( \text{m} \): Time period (month)
- \( \text{MED} \): Multi-effect distillation plant
- \( \text{ms} \): Molten salt
- \( \text{OM} \): Operation and maintenance
- \( \text{P} \): Pressure
- \( \text{PST} \): Primary and secondary treatment
- \( \text{rec} \): Receiver
RO  Reverse Osmosis plant
sat  Saturation
SC   Solar collector
SCA  Single collector assembly
SF   Solar field
SG   Steam generator
SH   Superheat
SL   Shadow loss
t   Time period (hr)
T    Turbine
TES  Thermal energy storage
TR   Transportation
w    wastewater

Greek symbols

$\eta_{boiler}$  Efficiency of the boiler
$\eta_{is}$  Isentropic efficiency of the steam turbine
$a_f$  Annual operation time
$\Omega_{Turbine}$  Vector set of the turbine
$v_{MED}$  Value of produced water from MED
$v_{RO}$  Value of produced water from RO
$v_{m}$  For every month (operational period)
$v_{t}$  For every hour (sub-period)
$\Delta h_{is}$  Isentropic enthalpy change
$\eta_{opt}$  Peak optical efficiency of a collector
$\Theta$  Solar incidence angle
$\Theta_z$  Solar zenith angle
$\gamma$  Intercept factor
$\delta$  Declination
ΔT \quad \text{Difference between inlet and outlet of the oil}

ρ \quad \text{Reflectivity}

τ \quad \text{Glass transmissivity}

ω \quad \text{Hour angle}

α \quad \text{Absorptivity of the receiver pipe}

**REFERENCES**


APPENDIX I: SOLAR DATA FOR THE CASE STUDY

The solar data for Eagle Ford Shale Play as extracted from National Solar Radiation Data Base (NSRDB) are shown by Tables I.1-I.4 to represent:

- Average hourly dry bulb temperature (°C)
- Average hourly wet bulb temperature (°C)
- Average hourly direct solar irradiance (W/m²)
- Average hourly solar incidence angle (degree)

The solar beam radiation is 500 (W/m²) at a design point.

<table>
<thead>
<tr>
<th>Hour</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>7.1</td>
<td>8.1</td>
<td>13.4</td>
<td>17.3</td>
<td>20.9</td>
<td>23.6</td>
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<tr>
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<td>5.9</td>
<td>6.49</td>
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Table I.3: Average hourly direct solar irradiance (W/m²)
Table I.4: Average hourly solar incidence angle (degree)

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doi:10.20944/preprints201804.0235.v1

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