Thermodynamic and economic analyses of hydrogen production system using high temperature solid oxide electrolyzer integrated with parabolic trough collector

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Abstract

In this paper, solar energy is used to produce hydrogen through high temperature electrolysis process. Usually PV modules are used to produce the required electricity. But efficiency of the PV panels is low and it reduces by increasing ambient temperature. To overcome this issue, parabolic trough collector is used in this study to provide both thermal and electrical energy for the electrolyzer. To evaluate performance of the system, energy, exergy and economic analyses are conducted. Finally, sensitivity analysis and multi-objective optimization process are performed to analyze thermodynamic and economic performance of the system simultaneously. The results showed that under design condition, the system is capable of producing 0.003 kg/s hydrogen. Exergy analysis indicated that solar collector and thermal storage tank have the highest rate of exergy destruction with almost 80% of total exergy destruction of the system. Sensitivity analysis showed that the value of current density for the electrolyzer should be selected carefully as it has considerable effect on techno-economic performance of the system. Finally, optimization results showed that the highest achievable exergy efficiency of the system is equal to 26.81%, while the lowest levelized cost of hydrogen is 4.43 $/kg.

1. Introduction

Hydrogen is considered as one of the best alternatives for fossil fuels (Marchenko andSolomin, 2015). It has many advantages over other energy carriers including different forms of storage, higher heating value than the most fossil fuels, high energy conversion efficiency (Dincer and Acar, 2015), near-zero carbon production during the combustion process (Acar and Dincer, 2014), etc. All these benefits encouraged the researchers to focus on hydrogen and its challenges (Ball and Weeda, 2015).

Hydrogen can be produced by different sources of energy (including thermal, electrical, photonic, biochemical, etc.) and different kinds of raw materials (water, biomass, fossil fuels, etc.). A complete review on different hydrogen production methods has been done by (Dincer and Acar, 2015). The problem is that most of these methods are still immature due to their high production cost or their low efficiency. Currently, natural gas steam reforming, oil reforming, coal gasification, and water electrolysis with 48%, 30%, 18% and 4% are the main methods which are used to produce hydrogen (Muradov and Veziroǧlu, 2005). It is supposed that in the second half of the 21st century hydrogen produced from water electrolysis becomes the main energy carrier (Bockris, 2013) as it is the only method of hydrogen production which does not use fossil fuels as the raw material. A comprehensive review on hybrid electrolyzer and renewable energy sources was presented (Mohammadi and Mehrpooya, 2018a).

There are three types of electrolyzers including proton exchange membrane (PEM) electrolyzer, alkaline electrolyzer and solid oxide electrolyzer cell (SOEC). These three types of electrolyzers are different in their operating condition and the electrolyte that they use. As it is known, in electrolysis process, water and electricity are delivered to the cell and hydrogen and oxygen are produced using the following reaction:

\[ H_2O + \text{electricity} \rightarrow H_2 + \frac{1}{2}O_2 \]  

(1)

As mentioned above, utilization of hydrogen can alleviate the environmental problems brought about by fossil fuels consumption. It is proven that the most environmental problems of
Many papers have been published about hydrogen production through electrolysis as related to its electricity supply (Bhandari et al., 2014). Consequently, if electrolyzer systems are powered by renewable energy sources, their environmental footprint would be as low as possible. Solar and wind energy sources are the best candidates to be coupled with electrolysis process (Acar and Dincer, 2014; Mohammadi and Mehrpooya, 2018b). But unlike wind energy, solar energy is available almost everywhere which makes it a better choice. A review on different solar hydrogen processes is performed by (Guo et al., 2010).

Many researchers studied integration between SOEC and solar energy collectors. Integration between parabolic trough collector and SOEC is studied by Seitz et al. (2017) where the solar collector is responsible for providing thermal energy for the electrolyzer, while its electricity is provided by the grid. To enable the system to operate continuously, they added a thermal storage too. The results indicated that using thermal storage in the system has two benefits. First, it decreases levelized cost of hydrogen by 34% and second it increases annual hydrogen production by 50%. Akikur et al. (2014) coupled a reversible solid oxide cell with high temperature solar collectors. Parabolic trough is one of these high temperature solar collectors which could be used (Mehrpooya and Sharifzadeh, 2016; Mehrpooya and Dadak, 2018) and Marefati et al. (2018) studied thermal performance of trough collectors in four different cities in Iran.

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4.6 kWh/Nm³ H₂ for conventional low temperature electrolyzers. Another similar system is also studied by Yadav et al. (Yadav and Banerjee, 2018). They focused on the economic aspect of this system and showed that they are not economically feasible. Ngoh et al. (2014) studied integrated system of SOEC, PV and trough collector too. They found that PV modules occupy more than 93% of total land required for the plant, while this value for trough collector is almost 3%. This is because efficiency of PV modules is much lower than high temperature solar collectors.

Lin et al. (Lin and Haussener, 2017) compared performance of two types of solar collector to be coupled with solid oxide electrolyzer cell. To do this, they defined three scenarios. In the first and second scenarios, solar tower collector and PV module are used alone to provide both thermal and electrical energy for the electrolyzer, while in the third scenario, they were used simultaneously. They concluded that although the lowest levelized cost of hydrogen belongs to the third option where both types of collectors were used simultaneously, the highest efficiency belongs to the first scenario where only solar tower system is used. The idea of using high temperature solar collector coupled with SOEC is studied by other researchers too (AlZahrani and Dincer, 2016; Balta et al., 2016). Optimization processes could be employed to boost performance of energy systems (Li et al., 2018a, 2018b). There are different types of optimization processes which could be used. Selecting the best algorithm to solve a problem is dependent on many factors and it should be done wisely.

In this paper, integration of parabolic trough collector and solid oxide electrolyzer cell is studied. An organic Rankine cycle converts a part of the thermal energy produced by trough collector into electrical energy. A thermal storage system is also used in the plant to ensure continuous operation of system. 3E analysis (energetic, exergetic and economic analyses) is performed to analyze the system performance. Finally, sensitivity analysis is conducted and optimum solution is found using a multi-objective optimization process. The proposed system could be of huge benefits which lead to a cleaner and low cost method of hydrogen production. The novelties of the paper are listed as follows:

- Using parabolic trough collector to provide both thermal and electrical energy required for the electrolysis process
- Sensitivity analysis of the most important parameters of the system (including solar section, electrolyzer system and power production system)
- Thermodynamic and economic optimizations of the proposed system

2. System description

The proposed system is shown in Fig. 1. Main components of the system are parabolic trough collector, thermal storage system, organic Rankine cycle, heat exchanger network and solid oxide electrolyzer cell.

Solar collector is the main source of energy of the system. It receives heat from the sun to increase temperature of the heat transfer fluid. This energy is stored in a thermal storage tank and enables the system to operate continuously. Thermal storage outlet stream goes into the heat recovery steam generator (HRSG) to provide thermal energy required for the electrolyzer. In this component, water is converted into superheated steam. The remaining required thermal energy for the electrolyzer is provided by energy recovery from electrolyzer outlet streams. This increases efficiency of the system. Finally, an electric heater is used in the system to increase temperature of the steam to the operating temperature of the electrolyzer. Recovering energy from electrolyzer outlet streams reduces the power consumption in the electric heater.

The remaining thermal energy is delivered to the ORC to produce power. To do so, a vapor generator is used which delivers heat to the organic fluid. An auxiliary heater is used in the system prior to the vapor generator. Whenever temperature of the heat transfer fluid decreases, the auxiliary heater begins to operate and increases its temperature by burning some fuel. This is necessary for the system to decrease temperature drop. The power produced in the ORC is used in the electrolyzer cell to produce hydrogen.

3. Mathematical modeling

In this section mathematical modeling of the system is explained. To analyze the system, the following assumptions are made:

- Pumps and turbine have a constant isentropic efficiency.
- Methane is used in the auxiliary heater.
- It is assumed that temperature is constant throughout the electrolyzer cell.
- Temperature and pressure of electrolyzer outlet streams are equal to the operating temperature and pressure of the cell.
- There is no heat transfer to the ambient from components, except for trough collector and thermal storage tank.

3.1. Energy analysis

3.1.1. Solar collector model

Due to good thermo-physical properties of Therminol oil VP-1, it is selected as the heat transfer fluid in this study. Its specific heat capacity is calculated as (Therminol, 2012):

\[
C_p = 0.002414 \frac{\gamma}{2} + 5.9591 \times 10^{-6} \times \left( \frac{\gamma}{2} \right)^2 - 2.9879 \times 10^{-8} \times \left( \frac{\gamma}{2} \right)^3 + 4.4172 \times 10^{-11} \times \left( \frac{\gamma}{2} \right)^4 + 1.498
\]

(2)

It should be noted that the unit of \( T \) in the above equation is in centigrade. Absorbed flux by the collector is obtained as follows (Duffy and Beckman, 2013; Kalogirou, 2013):

\[
S = I_b \rho R_b g \gamma (\tau \alpha)_{\beta} + I_b R_b g (\tau \alpha)_{\beta} \left( \frac{D_0}{W_0 - D_0} \right)
\]

(3)

\[
R_b = \frac{\cos \theta}{\sin \lambda \sin \delta_1 + \cos \lambda \cos \delta_1 \cos \delta_2}
\]

(4)

\[
\sin \delta_1 = 23.45 \cos (0.986(N + 284))
\]

(5)

In equation (3), the first term is the reflected absorbed radiation and the second term is the direct absorbed radiation. In equations (4) and (5), \( \lambda \) is latitude, \( h_1 \) is hour angle, \( \delta_1 \) is the declination angle, \( \theta \) is incident angle and \( N \) is number of days.

Heat received by the collector increases temperature of the oil. Therefore heat gain by the fluid can be calculated as:

\[
\dot{Q}_w = \dot{m}_{HTF} C_p (T_{HTF, out} - T_{HTF, in})
\]

(6)

A trial and error process is needed to find thermodynamic performance of the collector. It is based on energy balance of the absorber tube which is shown in Fig. 2. As can be seen, all kinds of
Heat transfer processes occur in the collector. The equations used to model these heat transfer processes are shown in Table 1.

The trial and error process begins with guessing a value for cover outer temperature. Then heat loss is computed using equation (7). In the next step, cover inner temperature is calculated using equation (8) and finally equation (9) is used to check the first guess for cover outer temperature. This process is repeated until it converges.

In the above equations, $D$ is diameter, $L$ is collector length, $k$ is thermal conductivity and $\varepsilon$ is emissivity. The energy absorbed by the collector is delivered to the thermal storage tank. It is assumed that the tank is a fully mixed one. Therefore both tank outlet streams have the same temperature. To calculate the added and released heat, an hour time interval is used. Meaning that it is assumed that tank temperature remains constant for an hour and then its new temperature is calculated again. The following formula is used to calculate tank temperature:

$$\left( {mC_p} \right)_{\text{water}} \frac{dT}{dt} = \dot{Q}_u - \dot{Q}_l - \dot{Q}_{\text{loss}}$$  \hspace{1cm} (10)

In this equation, $T$ is the tank temperature, $\dot{Q}_u$ is the amount of heat received by the tank from the collector, $\dot{Q}_l$ is the heat delivered to the ORC section and HRSG unit and $\dot{Q}_{\text{loss}}$ is the heat released to the ambient from the tank. Equation (10) can be rewritten as:

$$\dot{q}_{\text{loss}} = \pi D_{co} L h_w (T_{co} - T_a) + \varepsilon_c \pi D_{co} L \sigma \left( T_{co}^4 - T_{\text{sky}}^4 \right)$$ \hspace{1cm} (7)

$$\dot{q}_{\text{loss}} = \frac{2 \pi k_c L}{m(D_{co}/D_{cl})} (T_{cl} - T_{co})$$ \hspace{1cm} (8)

$$\dot{q}_{\text{loss}} = \frac{2 \pi k_{cl} L}{m(D_{cl}/D_r)} (T_r - T_{cl}) + \frac{\pi D_{cl} L \sigma (T_r^4 - T_{cl}^4)}{1/\varepsilon_r + \frac{1-\varepsilon_c}{\varepsilon_c} \left( \frac{R_c}{R_s} \right)}$$ \hspace{1cm} (9)
Table 1
Heat transfer equations to model solar collector (Ashouri et al., 2015).

| 1-2 | Convection | \( \dot{q}_{\text{conv}} - h_d(T_s - T_1) \) |
| 3-2 | Conduction | \( \dot{q}_{\text{cond}} = \frac{2k_{\text{eff}}}{\ln(D_2/D_1)}(T_2 - T_1) \) |
| 3-4 | Radiation | \( \dot{q}_{\text{rad}} = \frac{\pi d_1^4}{16 \varepsilon_1} \left( T_1^4 - T_2^4 \right) \) |
| 3-4 | Convection | \( \dot{q}_{\text{conv}} - h_d(T_s - T_3) \) |
| 4-5 | Conduction | \( \dot{q}_{\text{cond}} = \frac{2k_{\text{eff}}}{\ln(D_3/D_4)}(T_4 - T_3) \) |
| 5-6 | Convection | \( \dot{q}_{\text{conv}} - h_d(T_s - T_6) \) |
| 5-7 | Radiation | \( \dot{q}_{\text{rad}} = \frac{\pi d_1^4}{16 \varepsilon_1} \left( T_1^4 - T_2^4 \right) \) |

\( T_{s,\text{new}} = T_s + \frac{\Delta t}{(mC_p)_w} [\dot{Q}_d - \dot{Q}_l - \dot{Q}_{\text{loss}}] \) (11)

Also \( \dot{Q}_{\text{loss}} \) is computed as:

\( \dot{Q}_{\text{loss}} = (UA)_l(T_s - T_{\text{amb}}) \) (12)

In the above equation, \( (UA)_l \) indicates heat transfer coefficient and surface area of the tank. Its value is a function of tank geometry and its insulation material.

3.1.2. ORC section
Isopentane is selected as the organic fluid. Since it is a dry working fluid, it is better to enter it to the turbine in saturated condition (Chen et al., 2010). Therefore the vapor generator only consists of an economizer and an evaporator. Energy balance for these two heat exchangers is written as:

\[ \dot{m}_{\text{HTF}}(h_2 - h_3) = \dot{m}_{\text{ORC}}(h_9 - h_8) \] (13)

\[ \dot{m}_{\text{HTF}}(h_3 - h_4) = \dot{m}_{\text{ORC}}(h_8 - h_7) \] (14)

where \( m \) and \( h \) are mass flow rate and specific enthalpy, respectively. Power produced by ORC turbine, power consumed by ORC pump and net output power are obtained as follows:

\[ W_{\text{tur}} = \dot{m}_{\text{ORC}}(h_9 - h_{10}) \] (15)

\[ W_{\text{pump}} = \dot{m}_{\text{ORC}}(h_6 - h_5) \] (16)

\[ W_{\text{net}} = W_{\text{tur}} - W_{\text{pump}} \] (17)

3.1.3. Electrolyzer cell
To calculate cell voltage, Nernst voltage, activation, Ohmic and concentration overpotentials should be calculated first (Ni et al., 2007):

\[ V_{\text{SOEC}} = E_{\text{Nernst}} + V_{\text{act.,i}} + V_{\text{ohm}} + V_{\text{conc.,i}} \] (18)

Nernst voltage is computed using the following equation:

\[ E_{\text{Nernst}} = E^0 - \frac{RT}{2F} \ln \left( \frac{p_0^1 p_0^2}{p_0^0} \right) \] (19)

In this equation, \( p_0^0 \) is partial pressure of hydrogen, oxygen and water and \( E^0 \) is the standard potential of the cell. The value of standard potential is calculated based on its temperature as (Barelli et al., 2013):

\[ E^0 = 1.253 - 2.4516 \times 10^{-4}T \] (20)

Activation overpotential for both electrodes is computed by:

\[ V_{\text{act.i}} = \frac{RT}{F} \sinh^{-1} \left( \frac{J}{J_{0,i}} \right) \] (21)

\[ J_{0,i} = \gamma_i \exp \left( -\frac{E_{\text{act.i}}}{RT} \right) \] (22)

where \( F \) is faraday constant, \( T \) is cell temperature and \( J \) is current density. Ohmic overpotential is a function of temperature, current density and thickness which is calculated as:

\[ V_{\text{ohm}} = 2.99 \times 10^{-5} \exp \left( \frac{10300}{T} \right) J L \] (23)

And concentration overpotential is defined as:

\[ V_{\text{conc.,c}} = \frac{RT}{2F} \ln \left( \frac{1 + \left( JRTd_c/2FD_{\text{H}_2O}^0 p_0^0 / p_0^c \right)}{1 - \left( JRTd_c/2FD_{\text{H}_2O}^0 p_0^0 / p_0^c \right)} \right) \] (24)

\[ V_{\text{conc.,a}} = \frac{RT}{4F} \ln \left( \frac{p_0^a}{p_0^0} \left[ 1 + \frac{\sqrt{JRT\dot{z}}d_a/2FB_0}{p_0^a} \right] \right) \] (25)

A complete description of parameters used to calculate concentration overpotential is presented in (Ni et al., 2007). Using equations (18)–(25), cell potential can be computed. Having the cell potential and its current density, power consumed by the electrolyzer cell can be easily computed:

\[ W_{\text{SOEC}} = J_{\text{cell}} N_{\text{cell}} V_{\text{SOEC}} \] (26)

Also molar flow rate of products and reactants at the electrolyzer outlet can be obtained by the following equations:

\[ N_{\text{H}_2,\text{out}} = \frac{J}{2F} N_{\text{H}_2,\text{used}} \] (27)
3.2. Exergy analysis

Exergy is defined as the maximum obtainable work from a given form of energy using the environmental parameters as the reference state (Kotas, 2013). Exergy balance for a control volume is defined as:

$$\dot{E}^{x}_h + \sum m_{in} \dot{E}_{in}^{x} = \dot{E}^{w}_h + \sum m_{out} \dot{E}_{out}^{x} + \dot{E}^{D}_h$$

(34)

where $\dot{E}^{x}_h$ and $\dot{E}^{w}_h$ are exergy of heat and exergy of power which are defined as:

$$\dot{E}^{x}_h = \frac{(1 - \frac{T_0}{T_f}) \dot{Q}}{C_0}$$

(35)

$$\dot{E}^{w}_h = \dot{W}_{exh}$$

(36)

In equation (35), $T_f$ is the temperature in which heat transfer is occurred. Specific exergy is the sum of physical and chemical exergy which are expressed as:

$$\dot{E}_{ph}^x = (h - h_0) - T_0(s - s_0)$$

(37)

$$\dot{E}_{ch}^x = \sum_{i=1}^{N} y_i \dot{E}_{ch, i} + RT_0 \left( \sum_{i=1}^{N} y_i \ln(y_i) \right)$$

(38)

Since fuel is used in the combustion process, its chemical exergy should be calculated (Dincer and Cengel, 2001):

$$\xi = \frac{\dot{E}_{ch}^{fuel}}{LHV_{fuel}}$$

(39)

The value of $\xi$ is constant and for methane and hydrogen, it is equal to 1.06 and 0.985, respectively (Ahmadi et al., 2011).

The objective of exergy analysis is to find exergy destruction of each equipment. The required formulas for this are shown in Table 2.

Another parameter which is very important is exergy efficiency of the solid oxide electrolyzer cell. It is calculated as:

$$\psi_{SOEC} = \frac{m_{in} \xi LHV}{W_{SOEC} + \dot{E}_{SOEC} + \dot{E}_{in}^{Q, SOEC}}$$

(40)

The term in the numerator shows exergy of the produced hydrogen. As mentioned before in equation (39), the value of $\xi$ for hydrogen is equal to 0.985. Also lower heating value of hydrogen is 120067 kJ/kg. In the denominator, there are three terms including power consumed by the electrolyzer cells, exergy of heat in the electrolyzer and exergy of heat to increase temperature of water from ambient condition to the operating condition of electrolyzer.

Finally, total exergy efficiency of the plant is defined as:

$$\psi_{plant} = \frac{M_{daily} H_2 \xi LHV + \sum (W_{excess})}{\sum (\dot{E}_{sun}) + \sum (\dot{E}_{ex})}$$

(41)

In this equation, the unit of all parameters are in kWh. The first term in the numerator is like the numerator in equation (40), except that mass flow rate of hydrogen is for a complete 24 h. The second term in numerator is sum of the excess power produced during a complete 24 h. Number of electrolyzer cells is selected in a way that power consumed by electrolyzer is lower than minimum power produced by ORC section in design condition. Therefore, the surplus power is sold to the grid. In the denominator, both energy sources of the system should be considered which are the solar energy and the fuel used in the auxiliary heater.

3.3. Economic analysis

Levelized cost of hydrogen is calculated using equation (42):

$$LCOH = \frac{\dot{Z}_{CapitalCost} + \dot{Z}_{O&M} + \dot{Z}_{Fuel} + \dot{Z}_{electricity}}{M_{annual} H_2}$$

(42)

In this equation, $\dot{Z}_{CapitalCost}$ is investment cost rate which is obtained by the following equation:

Table 2
The required formulas to calculate exergy destruction for all components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Exergy destruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector</td>
<td>$\dot{E}<em>{Collector}^{0} = \dot{E}</em>{in} + \dot{E}<em>{sun} - \dot{E}</em>{out} + \dot{A}<em>{Op} \left[ 1 + \frac{1}{3} \left( \frac{T_0}{T</em>{sun}} \right)^4 - \frac{4}{3} \left( \frac{T_0}{T_{sun}} \right)^2 \right] + \dot{A}<em>{Op} \left[ 1 + \frac{1}{3} \left( \frac{T_0}{T</em>{sun}} \right)^4 - \frac{4}{3} \left( \frac{T_0}{T_{sun}} \right)^2 \right] \right]$</td>
</tr>
<tr>
<td>Thermal storage</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Auxiliary heater</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Turbine</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Condenser</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Pump</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Electric heater</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>$\dot{E}<em>{in}^{0} = \sum \dot{E}</em>{in} - \sum \dot{E}_{out}$</td>
</tr>
</tbody>
</table>

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are exergy of input and output, respectively.
Table 3
Investment cost of each component (Akikur et al., 2014; Boyaghchi and Heidarnejad, 2015; Mehrpooya et al., 2017).

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic trough collector</td>
<td>$Z_{\text{total}} = (150 + 90)A_{\text{col}}$</td>
</tr>
<tr>
<td>Thermal storage tank</td>
<td>$Z_{\text{TS}} = 35 \text{$/kWh}$</td>
</tr>
<tr>
<td>Auxiliary Heater</td>
<td>$Z_{\text{Aux}} = 28 \text{$/kWh}$</td>
</tr>
<tr>
<td>Vapor generator</td>
<td>$Z_{\text{VG}} = 45.7A_{\text{ev}} + 34.9A_{\text{fl}}$</td>
</tr>
<tr>
<td>ORC turbine</td>
<td>$Z_{\text{Turbine}} = 10A_{\text{SOEC}} + 4.498 \log(W) - 0.1776(\log(W))^2$</td>
</tr>
<tr>
<td>Recuperator</td>
<td>$Z_{\text{Rec}} = (A_{\text{Rec}}/0.093)^{0.78}$</td>
</tr>
<tr>
<td>Condenser</td>
<td>$Z_{\text{cond}} = 1773h_{\text{ev}}/C_0$</td>
</tr>
<tr>
<td>Pump</td>
<td>$Z_{\text{Pump}} = 3540W_{\text{Pump}}$</td>
</tr>
<tr>
<td>HRSG</td>
<td>$Z_{\text{HRSG}} = 45.7A_{\text{ev}} + 34.9A_{\text{fl}} + 96.2A_{\text{Aux}}$</td>
</tr>
<tr>
<td>SOEC</td>
<td>$Z_{\text{SOEC}} = 1000W_{\text{SOEC}}$</td>
</tr>
</tbody>
</table>

Where $Z_{\text{total}}$ is the total capital cost of the system.

\[ Z_{\text{CapitalCost}} = \frac{Z_{\text{total}}}{H} \left( \frac{(1+i)^N}{(1+i)^N - 1} \right) \]  
(43)

In equation (43), $Z_{\text{total}}$ is the capital cost of the system. Its value for each equipment is shown in Table 3.

Other economic parameters are shown in Table 4.

It should be mentioned that chemical engineering plant cost index is used to update the estimated cost for each equipment. More information about how to use this index is available in (Boyaghchi and Heidarnejad, 2015).

The second term in the numerator of equation (42) is the operation and maintenance cost of the equipment. Its value is defined as:

\[ Z_{\text{O&M}} = aZ_{\text{CapitalCost}} \]  
(44)

where $a$ is a constant and its value for all components is equal to 0.06 (Bejan et al., 1996), except for SOEC which is equal to 0.04 (Akikur et al., 2014).

The third term in the numerator of equation (42) is $Z_{\text{fuel}}$. This is the cost of fuel (methane) which is used in auxiliary heater to increase temperature of the heat transfer fluid. It should be mentioned that cost of fuel is assumed to be equal to 0.2825 $/\text{kg}$ based on data published by EIA.

As mentioned before, required power of the electrolyzer is provided by ORC section. If power produced in ORC section is higher than power required by electrolyzer and electric heater, then the excess power is sold to the grid. But if produced power is lower than the required power, then power should be bought from the grid. Cost of this electricity should be considered in the economic analysis ($Z_{\text{electricity}}$ in equation (42)). It should be mentioned that cost of electricity is assumed to be equal to 0.043452 $/\text{kWh}$ (Nezamoddini and Wang, 2017).

Finally, the parameter in the denominator ($M_{\text{annual,}\text{H}_2}$) is annual hydrogen production (its unit is kg/year) which can be easily calculated using equation (27).

4. Optimization

Engineering problems could be optimized by different evolutionary algorithms such as Particle swarm optimization (Shayeghi et al., 2009), genetic algorithm (GA) (Moharam et al., 2017), Ant colony optimization (Zohal and Soleimani, 2016), etc. A comparison between genetic algorithm, PSO and ant colony optimization algorithms is shown in Table 5.

Among different methods to perform optimization process, GA has gained researchers attention due to its simplicity, robustness and the ability to solve nonlinear problems. Darwin's theory is used to develop this algorithm. To solve the problem, GA first produces some random numbers. In the next step, the value of objective function is evaluated for each set of the produced numbers. The new generation is produced by using crossover and mutation processes. These steps are continued until the optimum solution is found. More explanation about GA could be found in (Simon, 2013).

5. Results and discussion

The results of the analysis are presented in this section. Matlab software is used to perform the analyses. Also thermodynamic properties of all the working fluids were calculated using REFPROP (Lemmon et al., 2007). Assumed values for design condition of the system are shown in Table 6. It should be mentioned that the analysis is performed in a typical day of June in Eshtehard city in Iran.

Using data provided in Table 6 and mathematical model provided in section 3, the system can be analyzed. Performance of solar collector and thermal storage tank is shown in Fig. 3. As can be seen, collector outlet temperature is exactly equal to thermal storage tank temperature till 5:00 a.m. This is because during this period there is no solar radiation. Also during this period temperature of storage tank decreases because no heat is added to the tank and on the other hand, organic cycle is utilizing the heat stored in the storage tank. From 6:00 a.m., the sun rises and due to absorbed radiation, collector outlet temperature increases and therefore heat is added to the storage tank. Consequently, temperature of storage tank increases. This process continues till 16:00 p.m. and after that storage tank temperature begins to fall again. It should be mentioned that at 19:00 p.m., the sun sets again and collector outlet temperature equals to the storage tank temperature begins to fall again. It should be mentioned that at 19:00 p.m., the sun sets again and collector outlet temperature equals to the storage tank temperature.

As shown in Fig. 3, temperature of thermal storage tank varies during the day. Therefore, heat delivered to the ORC section changes too. As a result, power produced by ORC is not constant. From Fig. 3 it can be seen that temperature of thermal storage tank is lower than 200°C till 10:00 AM. During this period, auxiliary heater operates and increases heat transfer fluid’s temperature to 200°C. Therefore power produced by ORC section during this period of time is constant and it is equal to 341 kW. After that, since temperature of storage tank is higher than 200°C, the auxiliaries
heater bypassed and power produced by ORC turbine increases due to higher heat delivered to the ORC section. Variation of power produced by ORC section and mass flow rate of fuel consumed in the auxiliary heater are shown in Fig. 4. It can be seen that maximum mass flow rate of fuel is consumed when temperature of storage tank is at its minimum value (7:00 a.m.).

Table 7 shows the most important indicators of the system. The first three rows are related to the power cycle. The power cycle includes solar collector, thermal storage and ORC section. Energy efficiency, exergy efficiency and solar fraction of the power cycle are defined as:

\[
\eta_{\text{power cycle}} = \frac{\text{sum}(W)}{\text{sum}(Q_{\text{cathode}}) + \text{sum}(Q_{\text{aux}})}
\]  
\[
\psi_{\text{power cycle}} = \frac{\text{sum}(W)}{\text{sum}(E_{\text{sun}}) + \text{sum}(E_{\text{aux}})}
\]  
\[
SF = \frac{\text{sum}(Q_{\text{load}} - Q_{\text{aux}})}{\text{sum}(Q_{\text{load}})}
\]

As shown in the table, energy and exergy efficiency of the power cycle are 22.94% and 16.29%, respectively. The main reason for low exergy efficiency of the power cycle is huge exergy loss in the solar collector. Solar fraction of the system shows how much of input energy to the system is from solar energy. A solar energy equal to 91% indicates that more than 90% of the input energy is provided by solar energy and share of auxiliary heater in input energy is only 9%.

The results show that cell voltage is equal to 1.035V. Among the three overpotentials, the highest value belongs to the activation overpotential. Also concentration overpotential has the lowest value. Under design condition, the electrolyzer stack can produce 0.003 kg/s hydrogen with 62.60% energy efficiency. Also its exergy efficiency is equal to 70.45%. Although exergy efficiency of electrolyzer system is high, total cycle exergy efficiency is 17.076%. This is because exergy efficiency of power cycle is very low. But its efficiency is still higher than PV modules. At last, leveled cost of hydrogen is calculated to be 6.9636 $/kg which is lower than values reported by (Lin and Haussener, 2017; Sayedin et al., 2016).

To gain a better insight, exergy destruction of each equipment is shown in Fig. 5 at 13:00 p.m. As can be seen, trough collector and storage tank have the highest share in total exergy destruction of the system, in a way that share of these two equipment in total exergy destruction of the system is higher than 80%. On the other hand, solid oxide electrolyzer cell is only responsible for 3.59% of total exergy destruction. This is the reason why total exergy efficiency of the system is low, while exergy efficiency of the electrolyzer is high. As shown in Fig. 5, exergy destruction of all the other components are negligible except for vapor generator, condenser and heat exchanger.

5.1. Sensitivity analysis

5.1.1. Number of collectors

As shown in Table 6, total number of collectors was equal to 1000. To analyze its effect on the system, number of collectors is changed. The results are shown in Fig. 6 and Fig. 7. As can be seen, system performance deteriorates with increasing collector number as LCOH increases and total exergy efficiency of the system decreases.

When collector number increases, more energy is absorbed by the solar collector and therefore both collector outlet temperature and thermal storage tank temperature increase. This leads to higher solar fraction ratio. Also, the amount of energy delivered to the ORC section increases which results in higher power production by ORC turbine (Fig. 7). On the other hand, exergy loss increases in the collector when more collectors are used in the system. All these effects lead to lower exergy efficiency of the system. It should be mentioned that exergy efficiency of the electrolyzer remains constant and decreasing exergy efficiency of the system is due to decreasing exergy efficiency of the power cycle. Also higher collector number increases capital cost of the system while mass flow rate of produced hydrogen is constant. Consequently, leveled cost of hydrogen increases.

### Table 5
Advantages and disadvantages of different optimization algorithms (Adrian et al., 2015; Moradi and Mehrpooya, 2017).

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic algorithm</td>
<td>Exchange information (crossover and mutation)</td>
<td>No memory</td>
</tr>
<tr>
<td></td>
<td>Efficient to solve continuous problems</td>
<td>Weal local search ability</td>
</tr>
<tr>
<td>Particle swarm</td>
<td>Has a memory</td>
<td>Premature convergence</td>
</tr>
<tr>
<td>optimization</td>
<td>Easy implementation</td>
<td>Weak local search ability</td>
</tr>
<tr>
<td>And colony optimization</td>
<td>Rapid discovery of good solutions</td>
<td>Not effective in solving the continuous problems</td>
</tr>
</tbody>
</table>

### Table 6
Assumed values for design condition of the system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trough collector</strong></td>
<td></td>
</tr>
<tr>
<td>Outer diameter of absorber tube (cm)</td>
<td>5</td>
</tr>
<tr>
<td>Inner diameter of absorber tube (cm)</td>
<td>5</td>
</tr>
<tr>
<td>Outer diameter of Envelope (cm)</td>
<td>9</td>
</tr>
<tr>
<td>Inner diameter of Envelope (cm)</td>
<td>8.2</td>
</tr>
<tr>
<td>Aperture (m)</td>
<td>2.5</td>
</tr>
<tr>
<td>Number of collector</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Storage tank</strong></td>
<td></td>
</tr>
<tr>
<td>Number of storage tank</td>
<td>6</td>
</tr>
<tr>
<td>Tank diameter (m)</td>
<td>5</td>
</tr>
<tr>
<td>Tank height (m)</td>
<td>4.2</td>
</tr>
<tr>
<td>Storage tank insulation thickness (cm)</td>
<td>20</td>
</tr>
<tr>
<td><strong>ORC section</strong></td>
<td></td>
</tr>
<tr>
<td>Turbine inlet pressure (bar)</td>
<td>25</td>
</tr>
<tr>
<td>Condenser pressure (bar)</td>
<td>2</td>
</tr>
<tr>
<td>Pinch temperature in vapor generator (C)</td>
<td>10</td>
</tr>
<tr>
<td>Isentropic efficiency of pump (%)</td>
<td>75</td>
</tr>
<tr>
<td>Isentropic efficiency of turbine (%)</td>
<td>85</td>
</tr>
<tr>
<td>Minimum temperature for auxiliary heater outlet temperature (C)</td>
<td>200</td>
</tr>
</tbody>
</table>

### Table 7
The most important indicators of the system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid oxide electrolyzer cell</strong></td>
<td></td>
</tr>
<tr>
<td>Cell operating temperature (C)</td>
<td>1100</td>
</tr>
<tr>
<td>Cell operating pressure (bar)</td>
<td>10</td>
</tr>
<tr>
<td>Current density (A/m²)</td>
<td>4000</td>
</tr>
<tr>
<td>Anode thickness (µm)</td>
<td>17.5</td>
</tr>
<tr>
<td>Cathode thickness (µm)</td>
<td>12.5</td>
</tr>
<tr>
<td>Electrolyte thickness (µm)</td>
<td>12.5</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.48</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>5.4</td>
</tr>
<tr>
<td>Cell area (m²)</td>
<td>0.04</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1800</td>
</tr>
<tr>
<td>Inverter efficiency (%)</td>
<td>95</td>
</tr>
</tbody>
</table>
**Fig. 3.** Collector and thermal storage performance during a complete 24 h.

**Table 7**  
Results of simulation in design condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency of power cycle (%)</td>
<td>22.94</td>
</tr>
<tr>
<td>Exergy efficiency of power cycle (%)</td>
<td>16.29</td>
</tr>
<tr>
<td>Solar fraction for power cycle (%)</td>
<td>91.02</td>
</tr>
<tr>
<td>Electrolyzer voltage (V)</td>
<td>1.035</td>
</tr>
<tr>
<td>Activation overpotential (V)</td>
<td>0.0453</td>
</tr>
<tr>
<td>Ohmic overpotential (V)</td>
<td>0.0174</td>
</tr>
<tr>
<td>Concentration overpotential (V)</td>
<td>0.0014</td>
</tr>
<tr>
<td>Mass flow rate of produced hydrogen (kg/s)</td>
<td>0.003</td>
</tr>
<tr>
<td>Mass flow rate of produced oxygen (kg/s)</td>
<td>0.0241</td>
</tr>
<tr>
<td>Energy efficiency of electrolyzer (%)</td>
<td>62.60</td>
</tr>
<tr>
<td>Exergy efficiency of electrolyzer (%)</td>
<td>70.45</td>
</tr>
<tr>
<td>Total cycle exergy efficiency (%)</td>
<td>17.0769</td>
</tr>
<tr>
<td>LCOH ($/kg)</td>
<td>6.9636</td>
</tr>
</tbody>
</table>

**Fig. 4.** Variation of system performance during a complete 24 h.

**Fig. 5.** Exergy destruction of each component at 13:00 p.m.

**Fig. 6.** Variation of exergy efficiency and LCOH of the system with changing collector number.
5.1.2. Mass flow rate of thermal storage tank
The effect of mass flow rate of thermal storage tank is shown in Fig. 8. This parameter shows mass flow rate of stream 1. Increasing mass flow rate of thermal storage tank increases the amount of energy extracted from the tank and the energy delivered to the ORC section. This means that with constant absorbed solar energy, more power is generated in ORC section which increases efficiency of the power cycle and total exergy efficiency of the plant.

In terms of economic, increasing mass flow rate of thermal storage tank affects both annual cost of fuel and annual cost of electricity. On one hand, when more energy is extracted from the tank by increasing mass flow rate of heat transfer fluid, temperature of storage tank drops and therefore more fuel is consumed in the auxiliary heater. Therefore annual cost of fuel increases. On the other hand, since more energy is delivered to the ORC section, power produced by turbine increases and therefore more electricity could be sold to the grid. As a result, cost of annual electricity decreases. In general, by increasing mass flow rate of thermal storage tank levelized cost of hydrogen increases slightly and from 6.93 $/kg reaches to 7.02 $/kg.

5.1.3. Minimum outlet temperature of auxiliary heater
As explained before, this parameter shows the minimum temperature of heat transfer fluid in which auxiliary heater starts to operate to increase its temperature. The effect of this parameter is shown in Fig. 9. Increasing minimum outlet temperature of auxiliary heater increases the amount of energy delivered to the ORC section. But unlike the case for increasing collector number, it leads to higher efficiency of the plant. This is because energy loss in auxiliary heater is smaller compared with the energy loss in the collector.
On the other hand, when minimum temperature of auxiliary heater increases it means that more fossil fuel is consumed in the auxiliary heater. This reduces the solar fraction in the system. In a way that when minimum temperature of auxiliary heater from 190 °C reaches to 250 °C, solar fraction decreases from 95.12% to 69.79%. It also increases annual cost of fuel which results in higher levelized cost of hydrogen.

5.1.4. ORC turbine inlet pressure
The effect of ORC turbine inlet pressure on the system performance is shown in Fig. 10. This parameter only affects ORC section and it does not have anything to do with solar collector or electrolyzer cell. Therefore its effect on the system performance is lower than other parameters. As can be seen, increasing turbine inlet pressure increases exergy efficiency of the plant which is due to lower exergy destruction in the vapor generator. As it is known, temperature difference is one of the main sources of exergy destruction. Saturation temperature of the organic fluid increases with increasing ORC turbine inlet pressure. Consequently when turbine inlet pressure increases, exergy destruction in vapor generator decreases due to lower temperature difference between hot and cold streams. This leads to higher power production in ORC section. In terms of economic, increasing power produced by ORC turbine decreases annual cost of electricity which results in small reduction in levelized cost of hydrogen.

5.1.5. Condenser pressure in ORC section
This parameter only affects the ORC section too. Its effect is shown in Fig. 11. As it is known, power production in turbine increases when condenser pressure decreases. This is because when condenser pressure decreases, pressure ratio of the turbine increases which results in higher power production. Consequently lower condenser pressure leads to higher exergy efficiency of the system. Also decreasing condenser pressure benefits the system economically by reducing levelized cost of hydrogen.

5.1.6. Operating temperature of the electrolyzer
Fig. 12 and Fig. 13 show how variation of electrolyzer temperature affects the system performance. When electrolyzer temperature increases, overpotential voltages decrease which benefits the system, because total cell voltage decreases and therefore lower amount of electricity is needed in the electrolyzer. This is shown in Fig. 13. As can be seen, concentration overpotential is very small compared with Ohmic and activation overpotentials. On the other hand, increasing electrolyzer temperature means that temperature of water should be increased and therefore power consumed by electric heater increases. In general, consumption power decreases and exergy efficiency of the system increases by increasing electrolyzer temperature. It also benefits the system economically. Since lower electricity is consumed in the electrolyzer, annual cost of electricity decreases which results in lower levelized cost of hydrogen.

5.1.7. Current density of the electrolyzer cell
Current density has a considerable effect on the electrolyzer performance. Based on equation (27), if current density increases, rate of hydrogen production increases too. This is shown in Fig. 14. On the other hand, power consumed by electrolyzer and electric heater also increases considerably. In a way that when current density is higher than 4000 A/m² power produced by ORC section is not enough and power from grid should be used in the system. This can be explained by increasing all the overpotentials and consequently the cell voltage (Fig. 15). But in general, electrolyzer efficiency rises. This is because the increase in hydrogen production rate dominates the increase in energy consumption of the electrolyzer.

Variation of total exergy efficiency and levelized cost of hydrogen by changing current density are shown in Fig. 16. As can be seen, levelized cost is highly dependent on the current density, in a way that when current density is set to be equal to 1500 A/m², levelized cost is 15.47 $/kg, but when current density decreases to 7500 A/m², levelized cost reaches to 4.7 $/kg which shows 69% reduction.

On the other hand, there is an optimum value for current density in which electrolyzer efficiency is maximal. As shown in Fig. 16,
when current density is equal to 3500 A/m$^2$, plant's exergy efficiency is almost 17%.

5.2. Optimization results

In this section, optimization process is performed on the system. To do so, levelized cost of hydrogen and total exergy efficiency of the plant were selected as the two objective functions. Seven

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of collector</td>
<td>800</td>
<td>1500</td>
</tr>
<tr>
<td>Mass flow rate of thermal storage (kg/s)</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>Minimum temperature of auxiliary heater (°C)</td>
<td>190</td>
<td>250</td>
</tr>
<tr>
<td>ORC turbine inlet pressure (bar)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>ORC condenser pressure (bar)</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Operating temperature of electrolyzer (K)</td>
<td>1000</td>
<td>1150</td>
</tr>
<tr>
<td>Current density (A/m$^2$)</td>
<td>1500</td>
<td>7500</td>
</tr>
</tbody>
</table>

Fig. 14. Effect of current density on hydrogen production rate and electrolyzer efficiency.

Fig. 15. Effect of current density on overpotentials and cell voltage.

Fig. 16. Variation of exergy efficiency and LCOH of the system with changing current density.

Table 8

Range of each decision variable.
parameters which are used in the sensitivity analysis were selected as the decision variables. These parameters are shown in Table 8 along with their lower and upper limits.

The result is shown in Fig. 17. As can be seen, both objective functions were improved considerably compared with design condition. This is because all the decision variables are at their optimum value. Fig. 17 shows that the highest achievable exergy efficiency is equal to 26.81% and the lowest possible levelized cost equals to 4.43 $/kg. It can be concluded that exergy efficiency of the plant could be improved with the cost of increasing levelized cost of hydrogen.

6. Conclusion

In this paper, parabolic rough collector is coupled with solid oxide electrolyzer cell to produce hydrogen. In this respect, trough collectors are integrated with a thermal storage tank so that the system could operate continuously. The main findings are listed as follows:

- The proposed system is capable of producing around 260 kg/day hydrogen. The ability to operate even in remote areas makes the system very special.
- Performance of solar thermal collectors are better than PV modules in producing electricity which leads to higher system efficiency.
- Although the proposed system in this paper could reach to higher efficiency compared with previous studies, its efficiency is still lower than conventional hydrogen production systems such as steam reforming, gasification, etc. To solve this, the highest energy and exergy losses of the system should be identified.
- Exergy analysis showed that exergy destruction of electrolyzer is very small compared with exergy destruction of solar collector and thermal storage tank. Therefore to improve total system performance, it should be focused on improving efficiency of solar collector and thermal storage system.
- Between different parameters considered in the sensitivity analysis, current density has the highest effect on the system performance. This is because this parameter directly changes the amount of produced hydrogen.
- Optimization process showed that the highest achievable exergy efficiency is 26.81% and minimum levelized cost of hydrogen is 4.435 $/kg. This shows that system performance can be improved a lot by the optimization process.
- For future studies, the system could be analyzed using advanced exergy analysis. Performing advanced exergy analysis would be very helpful to identify the true amount of exergy destruction in each component as it splits the exergy destruction of each component into avoidable/unavoidable and endogenous/exogenous exergy destructions. Also using life cycle assessment process, one can find the environmental burden of hydrogen production through high temperature electrolysis system and compare it with other hydrogen production systems.

References


