Multi-objective design optimization of a solar based system for electricity, cooling, and hydrogen production

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ABSTRACT

In this research paper, a novel solar-based integrated energy system with a thermoelectric generator (TEG) is proposed to provide cooling and hydrogen production. The energy integration is performed by establishing a TEG unit instead of the condenser of the double effect LiBr-H₂O absorption cooling system. The proposed system is comprehensively investigated and compared with the conventional cogeneration system from energy, exergy, and exergoeconomic point of view. To enhance the understanding of the effect of major design parameters on system exergy efficiency, net output work, total cost rate and hydrogen production, a comprehensive parametric study is carried out. In addition, using a developed MATLAB code, multi-objective optimization method based on genetic algorithm is applied to optimize the proposed model and determine the optimal design parameters. The results of exergy and exergoeconomic analysis show that PVT has the highest exergy destruction rate and the cooling set has the lowest exergoeconomic factor. Results of the parametric study indicate that the proposed system with TEG has higher exergy efficiency, higher hydrogen production rate, lower total cost rate, and lower payback period. Multi-objective optimization results show that, at the optimum point, exergy efficiency and total cost rate of the proposed system are 12.01% and 0.1762 $/h, respectively. Examining scatter distribution, further shows that the high-pressure generator temperature and PV module area are the most sensitive parameters and should be kept at their lowest value. Higher performance indicators and lower economic indices reveal that the proposed integration method is more suitable from the exergy/exergoeconomic standpoints.

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1. Introduction

Considerable reduction in fossil fuel resources, greenhouse gases emission, and environmental issues prompted the researchers to explore carbon free and more environmental benign fuels such as hydrogen. Moreover, designing efficient energy systems for power generation, cooling, and hydrogen production would be favorable especially for domestic applications. In this regard, integrating the energy systems may decrease total cost rate and increase exergy efficiency or optimize both of them.

1.1. Cooling system

An absorption cooling system can be implemented to exploit the waste heat of low grade energy systems [1]. Lerestani and Ardehali [2] proposed the integration of renewable energies for combined heating, cooling, and power generation using absorption chiller for the cooling system. Furthermore, the most cost effective concept can be achieved by implementing PVT panels. Wang et al. [1] investigated a double effect absorption chiller by exploiting the waste heat of the gas engine or solar energy. The results show that coefficients of the performance of the system in the case of using waste heat or utilizing solar energy are 0.91 and 0.6, respectively. Afzali and Mahalec [3] tried to determine the optimal operating modes of an integrated system with heat exchanger, boiler, electric chiller, and an absorption chiller. Lee et al. [4] examined the concept of a compact generator for steam driven H₂O/LiBr absorption chiller. The results show that the minimum volume of the tube was obtained for two tubes and tubes with 12 mm diameter. Ma et al. [5] proposed a novel integrated system with Brayton cycle LiBr absorption chiller. The results show that the energy and exergy...
efficiency of the system are 5.19% and 6.12%. Moreover, the payback period of the system may be 0.67–5.27 years. Energy and exergy assessment of a single effect and a double effect LiBr-H₂O absorption chiller was analyzed and compared by Gomri [6]. He studied the variation of the effective parameters on cooling load and exergy destruction rate of each component. The results show that the COP of the single effect absorption chiller is half the COP of the double effect absorption chiller. The exergoeconomic assessment of a double effect absorption chiller was proposed by Garousi Farshi et al. [7] to optimize the system from an economic standpoint. They further concluded that cooling set has the lowest exergoeconomic factor because of the high value of exergy destruction rate and exergy loss rate.

1.2. Photovoltaic/thermal system

Solar energy is one of the most abundant and cleanest energy sources among the renewable energy resources. Photovoltaic/thermal (PVT) cells are one of the examples of active technologies that convert the sun light into electricity and heating. Using PVT cells is a favorable method to develop energy systems [8]. The effect of waste heat recovery on the overall efficiency of PVT was evaluated by Gaur and Tiwari [9]. They demonstrated that the thermal efficiency and daily average electrical power are increased by
around 7.5% and 4.8%, respectively. Nutton et al. [10] investigated the effect of physical variables of the PV cell material, the module and the climate condition on the performance of PV cell. Exergoeconomic analysis and multi-objective optimization of a concentrated PVT waste heat driven absorption chiller integrated with geothermal cycle was performed by Behzadi et al. [11]. They showed that PVT with 5.72% of total exergy destruction is an important component from exergy viewpoint. The results of parametric study indicated that the variation of total product unit cost and exergy efficiency with module area of PVT is the same as temperature of PVT.

1.3. Hydrogen production

Solid oxide electrolysis (SOEC), Alkaline, and Proton exchange membrane (PEM) electrolysis are the common methods for hydrogen production from electricity that come from renewable sources. The main advantages of PEM electrolyzer are high voltage efficiency, better dynamic operation efficiency, and compact design. Combination of electrolyzers with solar-based system, Rankine and organic Rankine cycles (ORC) has been extensively studied in the literature for hydrogen production [12–16]. Omar and Altimiş [14] examined the rate of hydrogen production of an integrated energy system consisting of solar collectors and PEM electrolyzer. The parametric study was carried out to assess the effect of pressure and temperature on hydrogen production rate and system performance. The results demonstrated that effect of pressure on hydrogen and oxygen production is negligible. Exergy and exergoeconomic assessment of a renewable-based energy system was performed by Khanmohammadi et al. [17] for power/cooling and hydrogen production. They conducted a parametric study to evaluate the effect of major design parameters on hydrogen production rate, exergy efficiency and total cost rate of the system. Penkunh et al. [18] studied a small-scale PEM electrolyzer system for mobile and stationary off-grid applications from exergy and exergoeconomic viewpoints. They ascertained exergoeconomic factor and costs of exergy destruction for each component to compare the investment costs and other economic aspects.

1.4. Thermoelectric generator

One of the emerging energy technologies is thermoelectric generators (TEGs) due to the capability of converting direct thermal energy to electricity and silent operation since they have not any moving part. A solar-based system consisting of PVT modules integrated with TEG was studied by Chavez-Urbiola et al. [19]. They demonstrated that at operating temperature of 50–200 °C the TEG efficiency would reach 4%. Yang et al. [20] evaluated the performance of a hybrid system containing alkaline fuel cell and a TEG unit. They concluded that reusing waste heat of alkaline fuel cell in the TEG unit can enhance the performance/power generation of the system. They showed that at optimum condition the maximum power from waste heat, energy, and exergy efficiencies are 158 W, 0.51%, and 0.8%, respectively. Performance assessment of an integration of thermoelectric generator with solid oxide fuel cells for power production and cooling generation was investigated by Zhang et al. [22]. They resulted that the integration system has 2.3% more power density and 4.6% more efficiency than the stand-alone solid oxide fuel cells. A comparison between an integration of thermoelectric generator with a Kalina cycle using low-grade geothermal and the conventional Kalina cycle was made by Zare and Palideh [23]. The results of thermodynamic analysis indicated that by integration of thermoelectric generator with the conventional Kalina cycle the net power output and energy and exergy efficiencies are increased about 7.3%. In addition, they concluded that if thermoelectric generator costs lower than 6.4 $/W the proposed integration system would be cost-effective.

1.5. Cogeneration system

To recover waste heat and implement extra power for other purposes, the energy systems combine with each other. Khalid et al. [12] examined and compared two combined renewable energy based systems consisting of PV cells, a PEM electrolyzer, a wind turbine, and a combustion chamber or solid oxide fuel cell. Reportedly, first system has exergy efficiency of 21.0% while 18.9% has been reported for the second system. In addition, they optimized the systems considering total cost rate as the objective function. Nami and Akrami [16] investigated energy, exergy, and exergoeconomic assessment of a power/hydrogen production system, including an ORC and a gas turbine and a PEM electrolyzer unit. Parametric study performed to evaluate the effect of major parameters on the performance of the system. In addition, considering overall exergy efficiency as the objective function, single objective optimization performed by the authors. Accordingly, the optimization results indicate that at optimal operating condition the rate of hydrogen production and exergy efficiency would be 8.723 kg/h and 52.09%, respectively. In a later study, Demir and Dincer [13] proposed and analyzed an integrated system consisting of a gas turbine, PEM, TEG and concentrated solar system for power/hydrogen production. Gas turbine, TEG unit and PEM electrolyzer have been established for power and hydrogen production. The results show that energy, exergy and hydrogen production rate of the system are 42.5% and 40.5%, and 153.4 kg/day, respectively. Akrami et al. [24] investigated exergy and exergoeconomic evaluation of a solar based system consisting of single-effect absorption cooling system, PEM electrolyzer, and PVT modules. The results indicate 80% of total exergy destruction has been triggered by PVT panels. Furthermore, the results of exergoeconomic analysis showed that exergoeconomic factor of condenser would be 0.46%. Exergoeconomic analysis and multi-objective optimization of a solar-based model using flat plate collectors was performed by Hajabdollahi and Hajabdollahi [25]. The results demonstrate that by decreasing the rate of heat transferred to the fluid by the collector the total annual cost decreases which represents a better exergoeconomic evaluation. A multigeneration system, including solar collector, PEM electrolyzer, and ocean thermal energy conversion system was investigated by Ahmadi et al. [26] from exergy/exergoeconomic standpoints. They implemented multi-objective optimization method using genetic algorithm to find the optimal value of major effective parameters and subsequently optimize the system. Accordingly, they concluded that at the optimal solution point, exergy efficiency and total cost rate are 60% and 154$/h, respectively. In a later study, Chen and Dai [27] optimized an integrated PVT collector implementing multi-objective optimization method. Considering life cycle savings and prime energy saving efficiency as conflicting objectives, the system has been optimized. In a recent study, multi-objective optimization of a novel multi-generation system consisting of TEG unit and PEM electrolyzer utilizing geothermal energy for power, and hydrogen generation was proposed by Cholaman et al. [28].

To the best of authors’ knowledge, there is no study which investigates the multi-objective optimization of photovoltaic/thermal (PVT) panels integrated with double effect absorption cooling system, thermoelectric generator (TEG), and proton exchange
membrane (PEM) electrolyzer from exergy and exergoeconomic viewpoints. Hence, in this research study, PVT panels and a TEG as power generation units integrated with a double effect absorption cooling system and a PEM electrolyzer for hydrogen production is proposed. Parametric study of the newly proposed model is carried out to assess the influence of major decision variables on system performance and economic indicator. Eventually, the proposed model is optimized by multi-objective optimization method. Therefore, the main objectives and novelties of this study can be summarized as follow:

- Implementing a TEG unit instead of the condenser to increase the exergy efficiency, power output, hydrogen production rate, and reduce total cost rate and payback period
- Analyzing and comparing energy, exergy and exergoeconomic aspects of the newly proposed model to the conventional condenser based model
- Performing multi-objective optimization technique to determine the best optimal solution points from exergy/exergoeconomic viewpoints
- Gathering optimal solution points as a Pareto frontier and evaluating scatter distribution of the effective parameters

2. Cycle description and assumptions

A schematic diagram of the proposed cogeneration cycles is shown in Fig. 1. Both models consist of three main parts: the PVT system, the PEM electrolyzer and the double effect LiBr-H2O absorption chiller. Model (b) is the proposed model in which the condenser of the double effect cooling system is replaced by a TEG unit as cooling and power generation unit. As Fig. 1 shows, in the non-tracking PVT section, the received solar energy is converted into three forms, a portion of the solar energy is utilized by high pressure generator (\(Q_{PV}\)) of double effect absorption cooling system. Another portion is dissipated to the environment in the form of convection and radiation. The rest is transformed into the direct electricity (\(P_{PV}\)) and subsequently is utilized in the PEM for hydrogen production. The required heat of the double effect absorption chiller is provided by exploiting the waste heat of the PVT panels. Water and Li-Br are applied as refrigerant and absorbent, respectively. In the cooling system, the vaporized fluid (state 3) enters the absorber to be mixed with strong solution (state 17) coming from low temperature heat exchanger. The weak solution (state 4) is pumped to the high pressure generator from the absorber through the high and low temperature heat exchangers. In the HPG and LPG, the primary and secondary refrigerant vapor are boiled out from the solution (state 11) and (state 14), respectively and flow into the condenser. The refrigerant, after coming out from the condenser (state 1) and passing through the expansion valve (state 2), enters evaporator to generate cooling load. Noteworthy, evaporator, absorber, condenser and expansion valves are considered as a specific component namely cooling set.

In the PEM electrolyzer unit, the inlet water (state 27) enters the heater to prepare hot water (state 28) for the PEM. Water after passing through the PEM electrolyzer (state 29) is split into hydrogen and oxygen molecules and the remaining water recirculates in the system. In model (a), the required power for hydrogen production is provided from PVT, while in the model (b), PVT and TEG power outputs are transferred into the PEM for hydrogen production.

The following assumptions are considered:

- The proposed system operates under the steady-state condition.
- Changes in potential and kinetic energies are neglected.
3.1. Energy and exergy analysis

In the mathematical modeling part, each component is considered as a control volume in which 1st and 2nd laws of thermodynamics are applied. Mass, energy, and exergy balances can be written as follow [30]:

\[ \sum m_{\text{in}} = \sum m_{\text{out}} \]  
\[ \sum m_{\text{in}}x_i = \sum m_{\text{out}}x_{\text{out}} \]  
\[ Q - W = \sum m_{\text{out}}h_{\text{out}} - \sum m_{\text{in}}h_{\text{in}} \]  
\[ \dot{E}_Q - \dot{E}_W = \sum m_{\text{out}}e_{\text{out}} - \sum m_{\text{in}}e_{\text{in}} + \dot{E}_D \]

where \( m, x, W, \) and \( Q \) are the mass flow rate, the mass fraction of LiBr in solution, the rate of work and heat transfer, respectively. Moreover, the subscript of \( Q, W, \) and \( D \) denote the rate of energy, work, and destruction, respectively. Neglecting the potential and kinetic exergy, the specific exergy is defined, as follow [31]:

\[ e_t = (h_t - h_{0,t}) - T_0(s_t - s_{0,t}) \]  

where \( T_0 \) is the environmental temperature equal to 298.15 K and \( h_{0,t} \) and \( s_{0,t} \) are the specific enthalpy and entropy of ith stream at dead state.

3.1.1. PVT

To simulate PVT, correlated relations and equations are tabulated in Table 1. In Table 1, \( G \) is the concentrated solar radiation equivalence to 1 kW/m² and \( C \) denotes the concentration ratio. Moreover, \( \eta_{\text{PVT}} \) is the power output of PVT and \( Q_{\text{PVT}} \) denotes the rate of heat that is transferred to the HPG. Furthermore, \( \eta_{\text{inv}} \) and \( \eta_{\text{opt}} \) are inverter’s efficiency and optimal efficiency that are assumed to be 0.9 and 0.85 respectively, and \( \beta \) refers to the temperature coefficient [29]. Further details about the PVT simulation method and the corresponding equations can be found in the literature [29].

3.1.2. PEM

The theoretical energy required for electrolysis of water is defined as:

\[ \Delta H = \Delta G + T\Delta S \]  

(6)

where \( \Delta G \) and \( T\Delta S \) are Gibbs free energy and thermal energy, respectively. The rate of hydrogen production is calculated as [32]:

\[ n_{H_2,\text{out}} = \frac{J}{2F} \]  

(7)

where \( J \) is the current density and \( F \) denotes the Faraday constant.

Required electricity for hydrogen production is defined as [26]:

\[ E_{\text{electrical}} = JV \]  

(8)

\[ V = V_0 + \eta_{\text{act,a}} + \eta_{\text{act,c}} + \eta_{\text{ohm}} \]  

(9)

where \( V \) is PEM electrolyzer voltage and \( V_0 \) denotes reversible potential. In addition, \( \eta_{\text{act,a}} \) and \( \eta_{\text{act,c}} \) are activation overpotential of anode and cathode, respectively and \( \eta_{\text{ohm}} \) denotes the ohmic overpotential of the electrolyte. The reversible potential is calculated as [32]:

\[ V_0 = \frac{1}{2}RT_C \ln \left( \frac{p}{p_0} \right) - \frac{RT_C}{2F} \left( \frac{1}{Z_{\text{H}_2}} + \frac{1}{Z_{\text{O}_2}} \right) \]  

(10)

Moreover, the local ionic conductivity of the membrane can be written as [32]:

\[ \sigma(\lambda(x)) = (0.5139\lambda(x) - 0.326) \times \exp \left( \frac{1268 \left( \frac{1}{303} - \frac{1}{T} \right) \lambda(x)}{2} \right) \]  

(11)

where \( x \) and \( \lambda(x) \) (Eq. (12)) are the membrane depth measured from cathode interface and content of water at distance of \( x \), respectively.

\[ \lambda(x) = \frac{(\lambda_{an} - \lambda_{ca})x + \lambda_{ca}}{I} \]  

(12)

where \( I \) denotes the thickness of the membrane and \( a \) and \( c \) subscripts denote anode and cathode, respectively. Total ionic resistance and the ohmic overpotential can be calculated as Eq. (13) and Eq. (14) represent, respectively [32]:

\[ R_{\text{PEM}} = \int_0^L \frac{dx}{\sigma(\lambda(x))} \]  

(13)

\[ \eta_{\text{ohm}} = JR_{\text{PEM}} \]  

(14)

The activity of the electrodes is ascertained by activation overpotential as follows [33]:

\[ \eta_{\text{act,i}} = \frac{RT_C}{F} \ln \left( \frac{J}{2J_{0,i}} \right) + \left( \frac{J}{2J_{0,i}} \right)^2 + 1 \]  

(15)

\[ J_{0,i} = \frac{f_i^{\text{ref}}}{R_T} \exp \left( - \frac{E_{\text{act,i}}}{R_T} \right) \]  

(16)

where \( f_i^{\text{ref}} \) is the pre-exponential factor and \( E_{\text{act,i}} \) denotes the activation energy for the anode and cathode, respectively. \( J_{0,i} \) denotes the exchange current density. In the modeling of PEM electrolyzer, the value of constant parameters can be found in the literature [32,34].

3.1.3. TEG

To determine the power output of the TEG unit, the related equations could be found in the literature [19,35]:

\[ \eta_{\text{TEG}} = \eta_{\text{Cerot}} \sqrt{1 + \frac{Z_M}{Z_T} - \frac{1}{2k}} \]  

(17)

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy analysis of the PVT</strong> [29].</td>
</tr>
<tr>
<td><strong>Component</strong></td>
</tr>
<tr>
<td>PVT</td>
</tr>
<tr>
<td>PVT</td>
</tr>
<tr>
<td>Qa</td>
</tr>
<tr>
<td>Qa</td>
</tr>
<tr>
<td>Qa</td>
</tr>
<tr>
<td>Qa</td>
</tr>
</tbody>
</table>
where \( T_c \) and \( T_h \) denote the temperature of the cold and hot side of the TEG unit, respectively. \( ZTM \) (figure of merit) is an important parameter which reveals internal conversion efficiency of the TEG unit. Elegant is an efficient liquid based electricity generation apparatus inside the thermolectric. \( \eta_{\text{Carrot}}Q_{\text{ELEGANT}} \) and \( ZTM \) can be calculated as follow [37]:

\[
\eta_{\text{Carrot}} = 1 - \frac{T_c}{T_h}
\]

\[
Q_{\text{ELEGANT}} = \dot{m}_{20}(h_{21} - h_{20})
\]

\[
ZTM = \frac{\psi^2 T_M}{K R}
\]

where \( K \) and \( R \) denote the thermal conductivity and resistance inside the TEG unit, respectively. \( T_M \) and \( \psi \) can be written as:

\[
T_M = \frac{1}{2} (T_c + T_h)
\]

\[
\psi = \frac{-\Delta V}{\Delta T}
\]

Finding the main source of irreversibility, i.e., determining the component with the highest exergy destruction would be among the most important objectives of exergy assessment. Moreover, to have a better evaluation of exergoeconomic analysis, the exergy of fuel and product are defined and tabulated in Table 2 for each component. In addition, the exergetic efficiency is calculated as [37]:

\[
e_i = \frac{\dot{E}_{P,i}}{\dot{E}_{F,i}}
\]

\[
\eta_{\text{TEG}} = \frac{W_{\text{TEG}}}{Q_{\text{ELEGANT}}}
\]  

\[
\sum \dot{C}_{\text{out},k} + \dot{C}_{\text{w},k} = \sum \dot{C}_{\text{in},k} + \dot{C}_{q,k} + Z_{PV}^{\text{PV}}
\]

\[
Z_{k}^{\text{PV}} = \dot{Z}_k \times \frac{C_{\text{PV}}^{\text{PV}}}{C_{R}^{\text{PV}}}
\]

\[
\dot{Z}_k = Z_k^G + Z_k^{\text{OM}}
\]

\[
\dot{C} = c \cdot \dot{E}
\]

\[
\dot{E}_{\text{out}} = \dot{c}_{\text{out}} \cdot E_{\text{out}}
\]

\[
\dot{C}_q = c_q \cdot \dot{E}_q
\]

\[
\dot{C}_w = c_w \cdot \dot{W}
\]

where \( \dot{C} \) is the cost rate in dollar per hour (\$/h) and \( c_{\text{in}}, c_{\text{out}}, c_q, \) and \( c_w \) denote the inlet, outlet, heat, and power cost per unit of exergy in dollar per gigajoule (\$/GJ), respectively. In Eq. (26), Marshal and Swift equation cost index [39] is applied to convert the value of \( \dot{Z}_k \) from the reference year to the present year (2018). Capital investment and operating and maintenance costs are calculated in Eq. (32) and Eq. (34), respectively [40]:

\[
\dot{Z}_k = \frac{\left(2F^{\text{R}}\right)}{\tau} \dot{Z}_k
\]

\[
\text{CRF} = \frac{\dot{b}(1 + \dot{b})^n}{(1 + \dot{b})^n - 1}
\]

\[
\dot{Z}_k^{\text{OM}} = \frac{\gamma_k}{\tau} \dot{Z}_k
\]

In Eq. (32), \( \text{CRF} \) and \( \tau \) are the capital recovery factor and the annual plant operation hours. In addition, according to Eq. (33) \( \text{CRF} \) is a function of the interest rate \( (\dot{b}) \) and the number of plant operation hours \( (n) \). The values of purchase cost \( (\dot{Z}_k) \) for each component are listed in Table 3. Eventually, cost balance and

### Table 2: Definition of fuel, product and loss exergy flow rates of proposed cogeneration cycle components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Fuel</th>
<th>Product</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT</td>
<td>( E_{18} )</td>
<td>( E_{\text{GVT}} + E_{19} )</td>
<td>–</td>
</tr>
<tr>
<td>HPG</td>
<td>( E_{\text{GVT}} )</td>
<td>( E_{11} + E_{8} - E_{7} )</td>
<td>–</td>
</tr>
<tr>
<td>LPG</td>
<td>( E_{11} + E_{12} )</td>
<td>( E_{14} + E_{15} - E_{10} )</td>
<td>–</td>
</tr>
<tr>
<td>Pump</td>
<td>( W_{p} )</td>
<td>( E_{5} - E_{4} )</td>
<td>–</td>
</tr>
<tr>
<td>HTHEX</td>
<td>( E_{6} + E_{9} )</td>
<td>( E_{7} - E_{6} )</td>
<td>–</td>
</tr>
<tr>
<td>LTHEX</td>
<td>( E_{9} + E_{10} )</td>
<td>( E_{8} - E_{7} )</td>
<td>–</td>
</tr>
<tr>
<td>CS model (a)</td>
<td>( E_{12} + E_{14} + E_{9} + E_{16} - E_{4} - E_{10} )</td>
<td>( E_{21} + E_{22} )</td>
<td>( E_{22} + E_{23} )</td>
</tr>
<tr>
<td>CS model (b)</td>
<td>( E_{11} + E_{12} + E_{9} + E_{16} - E_{4} - E_{10} )</td>
<td>( E_{21} + E_{22} + E_{54} )</td>
<td>( E_{21} + E_{22} + E_{23} + E_{24} )</td>
</tr>
<tr>
<td>PEM model (a)</td>
<td>( E_{15} + E_{27} )</td>
<td>( E_{21} + E_{22} )</td>
<td>–</td>
</tr>
<tr>
<td>PEM model (b)</td>
<td>( E_{15} + E_{27} + E_{16} )</td>
<td>( E_{21} + E_{22} )</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3: Expression of purchase cost \( (\dot{Z}_k) \) [24,41].

<table>
<thead>
<tr>
<th>Component</th>
<th>( \dot{Z}_k ) ($/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT</td>
<td>( \dot{Z}<em>{\text{PVT}} = c_0 \dot{A}</em>{\text{PVT}} )</td>
</tr>
<tr>
<td>HPG</td>
<td>( \dot{Z}<em>{\text{PG}} = c_1 \frac{\dot{A}</em>{\text{PG}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>LPG</td>
<td>( \dot{Z}<em>{\text{LPG}} = c_2 \frac{\dot{A}</em>{\text{LPG}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>Pump</td>
<td>( \dot{Z}_{\text{pump}} = c_3 )</td>
</tr>
<tr>
<td>HTHEX</td>
<td>( \dot{Z}<em>{\text{HTHEX}} = c_4 \frac{\dot{A}</em>{\text{H}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>LTHEX</td>
<td>( \dot{Z}<em>{\text{LTHEX}} = c_5 \frac{\dot{A}</em>{\text{L}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>Evaporator</td>
<td>( \dot{Z}<em>{\text{Evap}} = c_6 \frac{\dot{A}</em>{\text{E}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>Absorber</td>
<td>( \dot{Z}<em>{\text{absorber}} = c_7 \frac{\dot{A}</em>{\text{A}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>Condenser</td>
<td>( \dot{Z}<em>{\text{Condenser}} = c_8 \frac{\dot{A}</em>{\text{C}}}{\dot{A}_0} )</td>
</tr>
<tr>
<td>PEM electrolyzer</td>
<td>( \dot{Z}_{\text{PEM}} = c_9 )</td>
</tr>
<tr>
<td>TEG unit</td>
<td>( \dot{Z}_{\text{TEG}} = c_9 )</td>
</tr>
</tbody>
</table>
3.3. Performance evaluation

To examine and compare proposed models from the thermodynamic and thermo-economic points of view, COP, overall exergy efficiency, and total cost rate are calculated as follow for cogeneration system:

\[
\text{COP_a} = \frac{\dot{Q}_a}{\dot{Q}_{PVT}}
\]  

(40)

\[
\eta_{\text{EE}} = \frac{\dot{E}_{31} + (\dot{E}_{22} - \dot{E}_{23})}{\dot{E}_{18}}
\]  

(42)

\[
\text{PP} = \frac{\sum_{k-1}^{\eta_{i-1}} \dot{Z}_k}{\dot{W}_{\text{net}} \times \tau \times EC}
\]  

(44)

where \(\dot{Q}_a\) is the rate of cooling load which is equal to \(m_2 \times (h_3 - h_2)\). In Eq. (42), \(\dot{E}_{18}\) is the rate of exergy originated from the sun and is determined as follow [41]:

\[
\dot{E}_{18} = \left[ 1 + \frac{1}{3} \left( \frac{T_0}{T_5} \right) \right]^4 - \frac{4}{3} \left( \frac{T_0}{T_5} \right)
\]  

(45)

where \(T_5\) and \(T_0\) are the sun (5778 K) and environment temperatures (298.15 K), respectively. In Eq. (44), \(PP\) (payback period) is defined as the number of years are needed that the capital investment and operating and maintenance costs to be refunded. Furthermore, \(EC\) denotes the electricity cost and assumed to be 0.1 $/kWh in this study [41]. In addition, the power consumption of the pump is neglected.

3.4. The multi-objective optimization method

In thermal design problems, we are accosting with several conflicting objectives where finding the satisfied optimal solutions may be difficult. Unlike single objective optimization, in the multi-objective optimization problems, conflicting objectives should be optimized simultaneously. Therefore, using multi objective optimization as a feasible tool can absolutely help us to determine the optimal solution points. Accordingly, a MATLAB code based on genetic algorithm can be implemented for gathering the optimum solution points as a Pareto frontier. Examining the Pareto frontier can further reveal the optimum points from exergy/avoid-economic viewpoints. Moreover, ascertaining the best final
solution point in which the system operates efficiently and affordably is the main purpose of multi objective optimization. Designing the systems to operate at this point can save the cost considerably and at the same time maintain a favorable performance of the system.

In this regard, overall exergy efficiency (Eq. (42)) as a performance indicator (to be maximized) and total cost rate (Eq. (43)) as an economic indicator (to be minimized) are considered as the conflicting objective functions. In genetic algorithm, stochastic search iteration is applied, so that each point is compared with the next point in terms of overall exergy efficiency and total cost rate, and the optimal point is chosen to be depicted in Pareto frontier. Modeling and optimization procedure of the proposed models are presented in Fig. 2.

4. Results and discussion

4.1. Validation and verification

To verify/validate the results of the present study, the modeling of the PVT, PEM electrolyzer, and TEG unit are validated/verified versus available experimental and theoretical data.

4.1.1. Verification of PVT

To verify the modeling of the PVT, the present model results compared to the Kosmadakis et al. results [29] is shown in Table 5 and a decent agreement between the results is achieved.

<table>
<thead>
<tr>
<th>Concentration ratio</th>
<th>Recovered heat (kW)</th>
<th>Difference (%)</th>
<th>PVT power (kW)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present model</td>
<td>Kosmadakis et al. [29]</td>
<td>Present model</td>
<td>Kosmadakis et al. [29]</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.495</td>
<td>0.513</td>
<td>-3.51</td>
<td>0.121</td>
</tr>
<tr>
<td>5</td>
<td>2.76</td>
<td>2.867</td>
<td>-3.73</td>
<td>0.307</td>
</tr>
<tr>
<td>10</td>
<td>6.57</td>
<td>6.791</td>
<td>-3.25</td>
<td>0.602</td>
</tr>
<tr>
<td>15</td>
<td>10.85</td>
<td>10.72</td>
<td>1.21</td>
<td>0.986</td>
</tr>
<tr>
<td>20</td>
<td>14.92</td>
<td>14.64</td>
<td>2.63</td>
<td>1.306</td>
</tr>
<tr>
<td>40</td>
<td>31.13</td>
<td>30.33</td>
<td>2.63</td>
<td>2.701</td>
</tr>
<tr>
<td>60</td>
<td>46.5</td>
<td>45.99</td>
<td>1.11</td>
<td>4.04</td>
</tr>
<tr>
<td>100</td>
<td>79.18</td>
<td>77.32</td>
<td>2.41</td>
<td>6.68</td>
</tr>
</tbody>
</table>

4.1.2. Validation of PEM electrolyzer

In addition, to validate the modeling of the PEM electrolyzer, experimental results from literature [44] are chosen and shown in Fig. 3(a). The comparison of the present model with the Ioroi et al. [44] results reveals good agreement.

4.1.3. Verification of TEG unit

Moreover, to verify the TEG unit modeling, TEG efficiency and power output of the present model is compared to Ziapour et al. [45] results as shown in Fig. 3(b). A good agreement between the results is achieved.

4.2. Parametric study

A parametric study is performed to examine and compare the effect of decision parameters/variables on overall exergy efficiency, total cost rate, and hydrogen production rate of proposed systems. Module area, cell temperature, solar radiation, HPG temperature, condenser/TEG cooling water temperature difference and figure of merit are considered as major decision parameters.

Influence of the module area on the system performance is shown in Fig. 4. Referring to Fig. 4(a), for both models, the exergy efficiency initially is constant with an increase in module area thereafter decreases. In addition, as module area increases from 0.5 m² to 2.5 m², total cost rate increases about 65% and 75%,
respectively for model (a) and (b). According to Fig. 4(b), larger PVT’s module area, means higher input radiation and so higher power output and rate of hydrogen production are expected. Fig. 4 further shows that in the selected range of PVT aperture area, model (b) would be a more suitable model because of higher exergy efficiency and power output, lower total cost rate, and higher capability of hydrogen production.

Solar radiation can also affect the thermodynamic/economic aspects of the models as depicted in Fig. 5. The results indicate that during the solar radiation from 0.2 kW/m² up to 1.2 kW/m², the exergy efficiency of model (a) increases about 0.23% while the exergy efficiency of model (b) increases 0.25%. In addition, the figure reveals that by raising the solar radiation, total cost rates and hydrogen production rate of the models increase and the rate of the increment in model (b) is even faster in the reasonable range. Moreover, it can be concluded that during shining days, the systems operate efficiently but operation of the systems is not favorable from exergoeconomic viewpoint.

Effect of PVT’s module temperature is shown in Fig. 6. Fig. 6(a) reveals that a higher PVT’s cell temperature leads to a lower overall exergy efficiency and lower total cost rates. By increasing the cell’s temperature from 100 °C to 160 °C the hydrogen production rate and net output work decrease around 0.102 kg/day and 0.22 kW, respectively. Similar to the previous graphs, in the whole range of cell’s temperature, model (b) has higher exergy efficiency/power output and lower total cost rate. Furthermore, rate of hydrogen production of model (b) is considerably higher compared to model (a).

As demonstrated in Fig. 7(a), by increasing temperature of the high-pressure generator, total cost rate of model (a) remains constant while little increment is observed for total cost rate of model (b). Furthermore, increasing the temperature of the high-pressure generator can decrease the cooling load, therefore value of the coefficient of performance and exergy efficiencies will decrease. Moreover, by examining the right hand side of the graph it can be seen that temperature of the high-pressure generator cannot affect...
the performance or economic aspects of the models by much.

Cold end temperature difference affects the results notably. As shown in Fig. 8, by increasing this parameter, the exergy efficiency and net output work of model (b) decrease while the corresponding variables of model (a) remain constant. This is justified because raising the parameter increases the temperature of the cold side of the TEG unit; so the TEG efficiency decreases and, thereafter, the total exergy efficiency and net output work of model (b) decrease. Moreover, by increasing the parameter from 3 °C to 28 °C, total cost rate and hydrogen production rate of model (a) remain constant while the corresponding variables of model (b) continually decrease.

In Fig. 9, the influence of figure of merit as a key design parameter is illustrated which directly relates to the efficiency of the TEG. Raising the figure of merit increases the TEG efficiency, which leads to an increase in the net output work and exergy efficiency of the model (b). Moreover, by increasing the figure of merit from 0.2 to 1.6 the value of $Z_{TEG}$ increases about 0.00276$/GJ, therefore the total cost rate of the system (b) rises from 0.2025 $/h to 0.2077 $/h, which can be neglected. As the TEG unit is not implemented in the model (a), the thermodynamic and economic indicators of the model (a) are reported just for a better comparison to model (b).

4.3. Results of exergy and exergoeconomic analysis

Side by side comparison of exergy efficiency, total cost rate, net output power, the hydrogen production rate, and the payback period of the models are presented in Fig. 10. Referring to this figure, model (b) has 0.49 kW higher net output work, 0.39% higher exergy efficiency, 23 g/day higher rate of hydrogen production, and 2.4 years lower payback period compared to the model (a). In this regard, establishing the TEG unit instead of the condenser can definitely enhance the performance, increase the rate of hydrogen production and reduce total cost rate and refunding period. Therefore, the proposed system and the integration method is a promising technique to optimize the conventional system from exergy/exergoeconomic viewpoints.

Exergy destruction rate of each component of the models is calculated and illustrated in Fig. 11. LPG has the lowest exergy destruction rate with the rate of 0.0882 kW. In the cooling system, HPG and CS with the sum of 60% portion of the total exergy

Fig. 7. Influence of high-pressure generator temperature on the performance and economic indicators of the proposed models.

Fig. 8. Influence of the cooling water temperature difference in the condenser/TEG on the performance and economic indicators of the proposed models.

Fig. 9. Influence of the figure of merit on the performance and economic indicators of the proposed models.
destruction rate are considered as the main source of irreversibility. Moreover, PVT panels are the major source of irreversibility and destruction in both models (5.246 kW).

Values of exergy and exergoeconomic parameters are summarized in Table 6 for each component. Exergoeconomic factor, which is one of the most important parameters from an economic perspective, is calculated as follows:

\[
\text{Exergoeconomic factor} = \frac{C_D}{W_{net}}
\]

Table 6

<table>
<thead>
<tr>
<th>Component</th>
<th>( E_f ) (kW)</th>
<th>( E_r ) (kW)</th>
<th>( E_0 ) (kW)</th>
<th>( E_L ) (kW)</th>
<th>( \varepsilon ) (%)</th>
<th>( C_D ) ($/h) )</th>
<th>( C_L ) ($/h) )</th>
<th>( Z ) ($/h) )</th>
<th>( f ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT</td>
<td>7.915</td>
<td>2.669</td>
<td>5.246</td>
<td>0</td>
<td>33.73</td>
<td>0</td>
<td>0</td>
<td>0.04064</td>
<td>100</td>
</tr>
<tr>
<td>HPG</td>
<td>2.174</td>
<td>1.901</td>
<td>0.2725</td>
<td>0</td>
<td>87.46</td>
<td>0.002858</td>
<td>0</td>
<td>0.00862</td>
<td>75.11</td>
</tr>
<tr>
<td>LPG</td>
<td>0.8038</td>
<td>0.7156</td>
<td>0.0882</td>
<td>0</td>
<td>89.02</td>
<td>0.003173</td>
<td>0</td>
<td>0.00558</td>
<td>63.76</td>
</tr>
<tr>
<td>Pump</td>
<td>0.01</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0.01802</td>
<td>100</td>
</tr>
<tr>
<td>HTHEX</td>
<td>0.9337</td>
<td>0.7464</td>
<td>0.1873</td>
<td>0</td>
<td>79.94</td>
<td>0.02385</td>
<td>0</td>
<td>0.04305</td>
<td>64.35</td>
</tr>
<tr>
<td>LTHEX</td>
<td>0.3565</td>
<td>0.2491</td>
<td>0.1074</td>
<td>0</td>
<td>69.87</td>
<td>0.01202</td>
<td>0</td>
<td>0.03001</td>
<td>71.4</td>
</tr>
<tr>
<td>CS (model (a))</td>
<td>1.518</td>
<td>0.5132</td>
<td>0.7502</td>
<td>0.2548</td>
<td>33.8</td>
<td>0.07593</td>
<td>0.02579</td>
<td>0.04882</td>
<td>32.43</td>
</tr>
<tr>
<td>CS (model (b))</td>
<td>1.518</td>
<td>0.5622</td>
<td>0.702</td>
<td>0.2541</td>
<td>37.03</td>
<td>0.07104</td>
<td>0.02571</td>
<td>0.03827</td>
<td>28.34</td>
</tr>
<tr>
<td>PEM (model (a))</td>
<td>0.4957</td>
<td>0.3257</td>
<td>0.17</td>
<td>0</td>
<td>65.71</td>
<td>0.00612</td>
<td>0</td>
<td>0.01917</td>
<td>75.8</td>
</tr>
<tr>
<td>PEM (model (b))</td>
<td>0.5447</td>
<td>0.3568</td>
<td>0.1879</td>
<td>0</td>
<td>65.51</td>
<td>0.006764</td>
<td>0</td>
<td>0.02106</td>
<td>75.69</td>
</tr>
</tbody>
</table>

Fig. 10. The comparison of payback period, exergy efficiency, total cost rate, net output work and the hydrogen production rate for both model (without or with thermoelectric generator).

Fig. 11. Exergy destruction rate of each component of the proposed models.
Oppositely, the lower value of component is owing to capital and operating and maintenance cost. Higher values of f indicate that the main part of the cost rate for the component is owing to capital and operating and maintenance cost. Oppositely, the lower value of f shows the major effect of irreversibility cost on the component cost rate. Lower values of f (such as CS) is due to the higher exergy destruction rate/loss that can increase the cost of irreversibility hence, trying to reduce exergy destruction rate by purchasing efficient components would be favorable. For the PEM electrolyzer with an exergoeconomic factor of over 75%, replacing with the low efficient device may be a better choice for reducing total cost rate of the system. The exergoeconomic factor of LPG reveals that 63.76% relative cost difference is caused by the operating and maintenance cost and the remaining 36.24% is triggered by the cost of irreversibility. Establishing a TEG unit instead of the condenser of the cooling system improves the overall system performance from 2nd law analysis by decreasing exergy destruction of cooling system about 6.5%. Moreover, implementing TEG unit results in a decrease of cost rate of exergy destruction and exergy loss and Z of cooling set, therefore the system operation from exergoeconomic viewpoint is modified.

4.4. Multi-objective optimization

A multi-objective optimization method based on genetic algorithm is applied to optimize the newly proposed system. Optimum solution points of the system are gathered as a Pareto frontier, which is depicted in Fig. 12. In Pareto frontier, for each optimization data point, the total cost rate and exergy efficiency are the optimization functions. Major effective parameters and their reasonable ranges are tabulated in Table 7 for optimization purpose.

Examining the Pareto frontier shows that similar trends for exergy efficiency and total cost rate are expected so this similarity reveals the importance of multi objective optimization. In this regard, the system should be optimized to operate efficiently and affordability. Considering exergy efficiency as a better indicator, point A has the potential to be considered as the best solution point if total cost rate is important, point C would be the most suitable spot. Moreover, as shown in the figure, the intersection of the highest exergy efficiency and the lowest total cost rate refers to the ideal point which is definitely unimaginable to reach. Consequently, the closest point to the ideal point (which is located on Pareto frontier) is selected as the best optimal solution point. The system is expected to operate at a satisfactory and decent condition on point B. Eventually, the optimal values of the major design parameters and objective functions are listed in Table 8 at point A, B, and C.

To have a better outlook of the optimum ranges of decision parameters, scatter distribution of the parameters is illustrated in Fig. 13. In scatter distribution, the total cost rate and exergy efficiency are considered as optimization functions for each data point. As Fig. 13(a) shows, the optimal points are dispersed in a wide range of PVT’s cell temperature while a considerable amount of solution points are located near 100 °C. Fig. 13(b and c) reveals that module surface area and temperature of the high-pressure generator are sensitive parameters and they should be held at their lowest value (0.5 m², 120 °C). Higher values of these parameters keep away the system from the optimized condition. Moreover, as shown in Fig. 13(d), there are a few optimal points lower than ZTM=0.35 while many optimal points are located between 0.35< ZTM <1.6; most of them being near ZTM=0.38.

5. Conclusion

In this research paper, an integrated novel solar-based cogeneration system is proposed to enhance the exergy efficiency and reduce total cost rate of the system. The integration is conducted by establishing a TEG unit instead of the condenser of the cooling system. Energy, exergy, and exergoeconomic aspects of the models are investigated and compared through a parametric study. Results of the parametric study show that the newly proposed model is more suitable compared to the conventional condenser-based since
it has higher net output work/hydrogen production rate and lower payback period/total cost rate. In addition, considering the total cost rate and exergy efficiency as the objective functions, multi-objective optimization method based on genetic algorithm is implemented to optimize the proposed system. Moreover, to have a better overview of the optimal ranges of important decision parameters, scatter distribution of the parameters are presented. Other main conclusions of this study can be described as:

- In both models, PVT with exergy destruction rate of 5.246 kW is the main source of irreversibility.
- Cooling set, as a dissipative component, has the lowest exergoeconomic factor.
- Establishing a TEG unit instead of the condenser of the cooling system improves the overall system performance by decreasing exergy destruction, cost rate of exergy destruction and exergy loss and $Z$ of cooling set.
- Results of multi-objective optimization indicate that at the optimal operating condition, exergy efficiency and total cost rate of the proposed model would be 12.01% and 0.1762 $/GJ$, respectively.
- Examining Scatter distribution reveals that the high-pressure generator temperature and PVT module area are the most sensitive parameters, which should be kept at their lowest value.

References


