A novel exergy-based assessment on a multi-production plant of power, heat and hydrogen: integration of solid oxide fuel cell, solid oxide electrolyzer cell and Rankine steam cycle

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Abstract

Multi-production plant is an idea highlighting cost- and energy-saving purposes. However, just integrating different sub-systems is not desired and the output and performance based on evaluation criteria must be assessed. In this study, an integrated energy conversion system composed of solid oxide fuel cell (SOFC), solid oxide electrolyzer cell (SOEC) and Rankine steam cycle is proposed to develop a multi-production system of power, heat and hydrogen to alleviate energy dissipation and to preserve the environment by utilizing and extracting the most possible products from the available energy source. With this regard, natural gas and water are used to drive the SOEC and the Rankine steam cycle, respectively. The required heat and power demand of the electrolyzer are designed to be provided by the fuel cell and the Rankine cycle. The feasibility of the designed integrated system is evaluated through comprehensive exergy-based analysis. The technical performance of the system is evaluated through exergy assessment and it is obtained that the SOFC and the SOEC can achieve to the high exergy efficiency of 84.8% and 63.7%, respectively. The designed system provides 1.79 kg/h of hydrogen at 125 kPa. In addition, the effective designed variables on the performance of the designed integrated system are monitored to optimize the system's performance in terms of technical efficiency, cost-effectivity and environmental considerations. This assessment shows that 59.4 kW of the available exergy is destructed in the combustion chamber. Besides, the techno-economic analysis and exergoenvironmental assessment demonstrate the selected compressors should be re-designed to improve the cost-effectivity and decline the negative environmental impact of the designed integrated energy conversion system. In addition, it is calculated that the SOEC has the highest total cost and also the highest negative impact on the environment compared to other designed units in the proposed integrated energy conversion system.

Keywords: SOEC; SOFC; exergy; techno-economic analysis; life cycle assessment

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1. INTRODUCTION

Various applications have been defined for hydrogen in the industry [1,2]. Currently, refinery units and ammonia production plants are the biggest consumers of hydrogen [3]. Hydrogen is used in the refinery industries to improve the production rate of light distillates out of crude oil [4]. Hydrogen is also utilized in the food industry, metal industry, glass industry and so forth [5]. Hydrogen is also attracted attention to be utilized as fuel and considered as a replacement of conventional fossil fuels [6–8]. It is considered a clean fuel since its combustion does not generate any hazardous pollutants [9]. However, hydrogen production...
cannot be considered as always green and environmentally benign [10,11]. Fuel potential of hydrogen increases the favor in hydrogen power production technologies such as fuel cells [12,13]. Fuel cells can produce power at a higher conversion efficiency in comparison to traditional engines [14]. So, the most important phase into transforming hydrogen as a promising alternative of fossil fuels is to establish a production network to provide hydrogen and supply easily accessed refueling process for hydrogen consumers, i.e. fuel cell cars [15,16].

For small-scale hydrogen production, electricity can be used to split water and generate hydrogen and oxygen, this process is known as water electrolysis [17]. Electricity is mostly produced from conventional power plants that are fed with natural gas (NG) with the maximum conversion efficiency of 53% in the advanced power plants [18]. Other types of electrolyzers have been introduced to produce hydrogen at higher conversion efficiency including proton exchange membrane electrolyzer and solid oxide electrolyzer cell (SOEC) [19]. The latter technology due to its higher working temperature (above 600°C) has this potential to take benefit from other processes by utilizing the available thermal energy and also reduces the electricity consumption of the cell [20]. It should be noted that a high working temperature (around 1000°C) requires expensive materials and it increases the total investment cost of the process [21]. Therefore, it is desired to lower the working temperature in the range of 550–800°C [22]. Hydrogen can also be generated from fossil fuels through other technologies [23]. In most of the fossil-based hydrogen production methods, carbon-containing materials are converted to syngas in the first stage [24]. Among available options, gasification is used when the feedstock is solid [25], when light hydrocarbons are available, then steam reforming (SR) is a better solution [26]. Various approaches can be performed to carry out SR based on the capacity of the plant [27]. It should be mentioned that fossil-based hydrogen production technologies cannot play any contribution to decreasing the emissions of harmful greenhouse gases or in the production of a sustainable energy carrier [28]. Therefore, how the required hydrogen is produced is also a significant issue. As mentioned, fuel cell technology can be the major consumer of hydrogen in the future. In the fuel cells, hydrogen is consumed while electrolyzer cells are developed to generate hydrogen as a result of electrochemical decomposition of water. If the required power of the electrolyzer cell supplied from a clean procedure (i.e. solar, wind, geothermal, etc.), this approach could be named as a solution for the sustainable production of hydrogen toward the green future [29]. Zhang et al. [30] performed a review study and determine the possible approaches that have this potential to be integrated with SOFCs. It was stated that SOFCs can be hybridized with the Bryton cycle, Rankine cycle (RC), CHP unit, absorption refrigeration cycle, thermo-photovoltaic systems and SOEC units. Daneshpour and Mehrpooya [31] investigated the feasibility of combining a thermal photovoltaic system with a SOEC system. An integrated solid oxide electrolyzer and solid oxide fuel cell (SOFC) (CHP process) configuration are introduced and analyzed [32]. The results showed that in the optimum condition SOFC efficiency is ∼50%. Iora et al. [33] coupled SOFC and SOEC and monitored that this integration can increase the overall efficiency of the hydrogen production up to 70%, which is two times more than of conventional water electrolyzers and have this potential to compete with medium-sized reformer plants. Perdikaris et al. [34] presented a tri-generation system of heat, power and hydrogen production through the coupling of SOEC and SOFC. The idea of hybrid SOFC and biodiesel production glycerol SR process is proposed [35]. There is no requirement for extra water in the operation process. In addition, the proposed system was almost carbon-free. Moreover, thermodynamics analysis showed that the system is capable of providing 26.5% of its input energy as hot water and achieved an efficiency of 28.2% and 18.6% for power production stage and hydrogen generation unit, respectively.

Exergy, exergoeconomic and exergoenvironmental analyses have been used for evaluation of the energy systems in various areas [36]. Exergy analysis assesses the process based on the second law of thermodynamics concept. A tri-generation process used for NG liquefaction is analyzed by an exergy method. The results showed that the highest exergy destruction rate is related to the afterburner of the process [37]. Taner and Sivrioglu [38] carried out a techno-economic study to reduce the cost of the power plant in a sugar production unit. Based on the reported result, the payback period was 4.32 years and unit cost for the turbine was estimated to be 3.1425$/kW. Carbon dioxide liquefaction process is investigated and analyzed by energetic and economic methods [39]. A solar dish thermal system used in liquid nitrogen production is evaluated by exergy method [40]. The results showed that in this process overall exergy efficiency is 46%. Exergy method is applied for evaluation of an integrated hydrogen liquefaction, biomass gasification and air separation unit process [41]. Based on the reported results total exergy efficiency of the process is 61.57%.

Exergoeconomic and exergoenvironmental analyse combine the exergy concept with economic and environmental criteria, respectively [42]. An integrated nitrogen rejection process using an absorption refrigeration system is evaluated by the exergoeconomic analysis method [43]. In this study, SOFC, SOEC and RC are integrated to provide heat, power and hydrogen so as to maximize the output and to make the most possible profit from the employed fuel for obtaining a sustainable gain. The considered system is then analyzed through the exergy approach. In addition, exergoeconomic and exergoenvironmental analyses are carried out to evaluate the system’s status with respect to economic and environmental considerations. At last, a sensitivity analysis is carried out to monitor and to compare the effect of key parameters with respect to different criteria including technical output, cost-exergy and environmental costs in order to demonstrate the possible technical enhancement by varying some operational parameters such as temperature, flow rate, working pressure and isentropic efficiency.
2. PROCESS DESCRIPTION

The flow diagram of the integrated system of SOFC, SOEC and RC is illustrated in Figure 1. The main feed of this system is NG at ambient condition and then its pressure is increased by compressor, C-1, to the favorable operational pressure. Before entering the reformer reactor of RE, the pressurized feed is mixed with the extraction of anode gas recycle (AGR) and also with a steam stream from the RC unit. In the reformer reactor of RE, NG is partially converted to the hydrogen. The reformer reactor was designed by a plug flow reactor (PFR) and the conversion rate of NG to the hydrogen is $\sim 20\text{--}30\%$. Since the reactions in the reformer are endothermic, the collected heat from the thermal recovery system is employed. The NG reforming is set through a logical operation dependent on the volume of the PFR. The reformer outlet, stream 4, is then entered into the heat exchanger and heated by means of the hot outlet of the combustion chamber (CC) and form stream 5, which now reaches the operational temperature of the fuel cell. The heated stream, stream 5, is entered into the anode of the fuel cell to participate in the electrochemical reactions. The required oxygen of the electrochemical reactions is provided through ambient air. The anode electrode of the fuel cell is also modeled by a PFR. The produced heat due to the electrochemical reactions is consumed at the cathode to set the temperature of the cell. It should be noted that the anode outlet is divided into two streams; AGR that is used in the reformer and another flow that is entered into the CC. The inlet air before entering the cathode pass through a compressor, C-3, to increase its pressure and set of heat exchangers, HX-4 and HX-2, to reach the fuel cell operational temperature, i.e. $\sim 530\text{--}540^\circ\text{C}$, stream 13. After the occurrence of the electrochemical reactions, the unreacted portion of the air is delivered to the CC for proving the required oxygen of the combustion process.

In the RC, water is entered into the cycle at ambient temperature and pressure. Therefore, it needs to be pressurized and heated up. The main feed-water, stream 23, after pumping is combined with the outlet stream of the condenser, stream 30–31, the combined stream 24 is pumped to the desired pressure of 9000 kPa and then passes through the heat exchanger, HX-3, to heated up and reaches the temperature of $550^\circ\text{C}$, superheated condition. Then, the superheated steam is passing the turbine sets (high pressure, medium pressure and low pressure, respectively). The outlet of the last turbine, low-pressure turbine, is divided into three parts: stream 30, stream 34 and stream 35. Stream 30 is utilized in the RC after passing the condenser and recirculated in the cycle. Stream 34 is mixed with the NG feed and then enters into the reformer reactor. Stream 35 is utilized as the feed stream of the SOEC.

In the SOEC section, the feed stream of 35 is heated through a heat exchanger to obtain the operational temperature of the SOEC, $827^\circ\text{C}$. The feed is then mixed in the mixer with a cathode gas recycle and the formed stream of 37 is entered into the SOEC at a determined temperature and mass composition. The electrolyzer is modeled through a conversion reactor and stoichiometry equations, which are defined to demonstrate the water decomposition. The cell outlet is moved to a splitter to separate hydrogen and water. The required power of the SOEC unit is provided by the generated power of the SOFC section. In this study, a lumped model is employed to simulate the fuel cell and the electrolyzer. Governing mathematical equations are defined in the spreadsheet of HYSYS. The plant is monitored by controlling the imports and exports of the spreadsheet and

Figure 1. Process flow diagram of the integrated system.
components. Overall, the following assumptions are made in the simulation process [44]:

• All of the processes are performed under steady-state conditions (the system’s behavior is fixed as time has progressed).

• SOFC and SOEC are zero-dimensional (there is no fluid mechanic information, therefore, these equipment are zero-dimensional).

• Similar current density is supposed for the SOFC and SOEC.

• The overall heat loss of the whole system is assumed to be 5% of the inlet energy.

• The isentropic efficiency for expanders and compressors are assumed to be 80% and 75%, respectively.

The detailed heat and mass balance (temperature, pressure, flow rate, entropy and enthalpy) of the designed system are expressed in Table 1.

3. MATHEMATICAL MODELING

3.1. SOFC system

Subtracting voltage losses from the ideal thermodynamic voltage yields the SOFC operating voltage as follows [45]:

\[ V_{SOFC} = E_{thermo} - \eta_{activation} - \eta_{ohmic} - \eta_{concentration} \] (1)

The output cell voltage is represented by \( V_{SOFC} \), \( E_{thermo} \), \( \eta_{activation} \), \( \eta_{ohmic} \) and \( \eta_{concentration} \), which denote the ideal voltage, activation loss, ohmic loss and concentration overpotentials loss, respectively. The ideal voltage is calculated as follows:

\[ E_{thermo} = 1.18 - 0.06855(\tau - 1) - 0.0165(\ln(\tau) - \tau) \]

\[ -\frac{RT}{n_{e}F} \ln \left( \frac{P_{H_{2}O}^{0}}{P_{H_{2}}^{0} \sqrt{P_{O_{2}}^{0}}} \right) \] (2)

\[ \tau = \frac{T}{298} \] (3)

where \( T \), \( n_{e} \), \( P_{H_{2}O}^{0} \), \( P_{H_{2}}^{0} \) and \( P_{O_{2}}^{0} \) indicate cell working temperature (K), amount of transferred electrons, partial pressure of water, partial pressure of hydrogen and partial pressure of oxygen, respectively. Butler–Volmer equation is used to calculate the activation loss, i.e. summation of activation losses in anode and cathode [46]:

\[ \eta_{activation} = \frac{RT}{F} \left( \sinh^{-1} \left( \frac{i}{2i_{0,c}} \right) + \sinh^{-1} \left( \frac{i}{2i_{0,a}} \right) \right) \] (4)

\[ i_{0,c} = \gamma_{c} \frac{RT}{2F} \exp \left( -\frac{E_{act,c}}{RT} \right) \] (5)

Table 1. Heat and material balance of the integrated system.

| 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| T   | °C  |     |     |     |     |     |     |     |
| P   | kPa |     |     |     |     |     |     |     |
| M   | kg/h|     |     |     |     |     |     |     |
| S   | kJ/kg°C |     |     |     |     |     |     |     |
| H   | kJ/kg |     |     |     |     |     |     |     |
| h   | kJ/kg |     |     |     |     |     |     |     |
| T   | °C  |     |     |     |     |     |     |     |
| P   | kPa |     |     |     |     |     |     |     |
| m   | kg/h|     |     |     |     |     |     |     |
| S   | kJ/kg°C |     |     |     |     |     |     |     |
| h   | kJ/kg |     |     |     |     |     |     |     |

The detailed heat and mass balance (temperature, pressure, flow rate, entropy and enthalpy) of the designed system are expressed in Table 1.
where \( i_{0,c}, i_{0,a}, \gamma_i \) and \( E_{act,i} \) represent cathode exchange current density, anode exchange current density, pre-exponential factor and activation energy, respectively.

Ohmic loss is occurred due to the over-potentials resulted in by flows of electrons and ions and calculated as follows [47]:

\[
\eta_{ohmic} = i \times \sum_j \left( \sigma_j \right)^{-1} \times \delta_j
\]

Here, \( \sigma_j \) and \( \delta_j \) are electronic or ionic conductivity and thickness of the component, respectively.

The resistance between the bulk concentration and the surface of the electrodes causes concentration loss and calculated as follows:

\[
\eta_{concentration} = \frac{RT}{2F} \left( \ln \left( \frac{P_{H_2}^{a}P_{H_2}^{o}}{P_{H_2}^{a}P_{H_2}^{o}} \right) + \frac{1}{2} \left( \ln \left( \frac{P_{O_2}^{a}P_{O_2}^{o}}{P_{O_2}^{a}P_{O_2}^{o}} \right) \right) \right)
\]

\( P_{H_2}^{a} = P_{H_2}^{o} - \frac{i \times \delta_a \times R \times T}{n_e \times F \times D_{H_2}^{eff}} \)

\( P_{O_2}^{a} = P_{O_2}^{o} - \frac{2 \times n_o \times F \times D_{O_2}^{eff}}{i \times \delta_o \times R \times T} \)

\( P_{H_2O}^{a} = P_{H_2O}^{o} + \frac{i \times \delta_a \times R \times T}{n_e \times F \times D_{H_2O}^{eff}} \)

\( D_{i}^{eff} = \frac{\varepsilon}{\tau} \left[ \frac{1}{D_{i,M}} + \frac{1}{D_{i,K}} \right]^{-1} \)

Here, \( \varepsilon, \tau, D_{i,M} \) and \( D_{i,K} \) indicate porosity, tortuosity of the electrodes, Knudsen diffusion and diffusivity in multi-component gaseous materials, respectively.

The electrical power of the SOFC unit can be obtained as follows [44]:

\[
P_{w,SOFC} = N_{SOFC} \times P_{SOFC} \times \delta_{SOFC}
\]

3.2. SOEC system

The performance of the SOEC system is completely in a reverse mode of the SOFC unit. Nernst equation is a basic equation that is used to calculate the reversible cell voltage [49]:

\[
E_{reversible} = -\frac{1}{2F} \left( \Delta G(T) + RT \ln \left( \frac{y_{H_2O}}{y_{H_2}y_{O_2}^{1/2}} \right) \right)^{1/2}
\]

Here, \( \Delta G \) represents the Gibbs free energy, \( F \) is the Faraday constant, \( \gamma_i \) states the molar fraction of different species at electrodes and \( P \) expresses the standard state pressure. \( \Delta G \) is calculated as follows [50]:

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

\( \Delta H, T \) and \( \Delta S \) denote enthalpy, absolute temperature and entropy, respectively.

\( V_{op,SOEC} \) is the operating voltage of the SOEC unit and obtained as follows:

\[
V_{op,SOEC} = E_{reversible} + \eta_{activation} + \eta_{ohmic} + \eta_{concentration}
\]

Here, \( \eta_{activation}, \eta_{ohmic} \) and \( \eta_{concentration} \) represent the voltage losses due to activation, ohmic and concentration, respectively, and obtained as follows:

\[
\eta_{activation} = \frac{2RT}{nF} \sinh^{-1} \left( \frac{i}{2i_{0,a}} \right) + \frac{2RT}{nF} \sinh^{-1} \left( \frac{i}{2i_{0,c}} \right)
\]

\[
\eta_{ohmic} = i \times \sum_j \left( \sigma_j \right)^{-1} \times \delta_j
\]

\[
\eta_{concentration} = \frac{RT}{2F} \times \ln \left( \frac{P_{H_2}^{o}P_{H_2}^{o}}{P_{H_2}^{a}P_{H_2}^{o}} \right) + \frac{RT}{4F} \times \ln \left( \frac{P_{O_2}^{o}P_{O_2}^{o}}{P_{O_2}^{a}P_{O_2}^{o}} \right)
\]

\( T \) represents the working temperature of the SOEC unit, \( i \) denotes the current density of the SOEC and \( \delta \) indicates the thickness. \( P_{H_2}^{o} \) and \( P_{O_2}^{o} \) are the partial pressure at electrode–electrolyte interface and inlet, respectively, and calculated as follows:

\[
P_{H_2}^{o} = P_{H_2}^{o} + \frac{i \times \delta_e \times R \times T}{n_e \times F \times D_{H_2}^{eff}}
\]

\[
P_{O_2}^{o} = P_{O_2}^{o} + \frac{i \times \delta_o \times R \times T}{2 \times n_o \times F \times D_{O_2}^{eff}}
\]

In the above equations, \( D^{eff} \) indicates the effective diffusion coefficient, which is formerly discussed in the SOFC section. The average value of the steam utilization factor is reported in the range of 75–90% in the literature. Hence, the steam utilization factor is considered at 0.85 [51]. The electrical power that is required for the electrolysis process at the SOEC unit is calculated as follows:

\[
P_{w,SOEC} = i_{SOEC} \times A_{SOEC} \times \delta_{SOEC} \times V_{op,SOEC}
\]

4. DESIGN CONSIDERATIONS

Prior to the process simulation, it is necessary to define a process model. Model definition, i.e. state equation, is very influential and has a significant role in the modeling process and also in
the solving procedure of the system’s equation sets. An appropriate selection of state equations leads to a beneficial and also practical simulation with high accuracy. After the determination of the process model, any conventional and available simulation software can be employed. Here, the most powerful simulation software of Aspen-HYSYS is utilized to simulate the proposed integration of SOFC-SOEC-RC. Typical state equations that are mostly utilized in the process plants are Peng Robinson (PR), Peng–Robinson–StryjekVera (PRS V) and Soave–Redlich–Kwong (SRK), respectively [52]. These three equations express high precision in process development in plants. Thus, SRK thermodynamic equation set is employed in the simulation of the proposed integrated system.

The design parameters of the heat exchangers are stated in Table 2. The other components’ specification such as compressors, pumps and turbines are defined in Table 3. The input data of SOFC and SOEC models are listed in Table 4.

### 5. ASSESSMENT METHOD

#### 5.1. Exergy assessment

The highest amount of achievable work in theory from a certain flow due to its interaction with the surrounding is called ‘Exergy flow’ [53,54]. As a result of this interaction, the flow has reached an equilibrium with the environment and its pressure and temperature are matched with the ambient condition [55,56]. Exergy can be transformed in four ways, including physical exergy, chemical exergy, kinetic exergy and potential exergy, respectively [57,58].

Since there is no velocity and height in the process, the main factor for the production of kinetic and potential exergies, respectively, these terms of exergy can be neglected in the calculation of the exergy flow. Therefore, the total exergy flow can be calculated as follows [59]:

\[
e_{\text{tot}} = e_{\text{ph}} + e_{\text{ch}}
\]

where \( e_{\text{ph}} \) and \( e_{\text{ch}} \) represent the physical and chemical exergy flows, respectively.

Physical exergy of a flow can be calculated from the following equation [60]:

\[
e_{\text{ph}} = (h - h_0) - T_0 (s - s_0)
\]

where \( h, T \) and \( s \) represent the flow’s enthalpy, flow’s Temperature and flow’s entropy, respectively. The subscript ‘\( 0 \)’ shows the ambient status.

#### 5.2. Exergoeconomic analysis

The first law of thermodynamics is not able to determine the quality of energy or the effectiveness of a specific process, therefore, the second law of thermodynamics is developed to supplement it [66]. In order to compare the operational status of the system with its performance in an ideal condition, the concept of exergy efficiency is developed to specify the exergy destruction of a component, process or system. A very potent approach for performance evaluation and also optimization process of energy systems can be obtained by combining the second law of thermodynamics with economic considerations. This combined method creates additional capacity in engineering known as the exergoeconomic analysis. The exergoeconomic evaluation mixes economic basics with the exergy analysis method and is equipped to specify the

### Table 2. Specifications of the heat exchangers of the integrated system.

| Heat exchanger | HX-1 | HX-2 | HX-3 | HX-4 | HX-5 |
|---------------|------|------|------|------|------|
| LMTD (°C)     | 335.2| 490.9| 293.8| 215.1| 40.6 |
| Min approach (°C) | 311.8| 485.8| 243.1| 201.0| 20.2 |
| Heat duty (kW) | 26.2 | 136.3| 189.7| 85.6 | 123.7|

The Eq. (22) can be employed to obtain the chemical exergy of a flow when combustion process is existed [61,62]:

\[
e_{\text{ch}} = \sum_{i=1}^{N} y_i d_i^0 + G - \sum_{i=1}^{N} y_i G_i
\]

where \( y \) indicates the mass molar fraction, \( d_i^0 \) expresses the standard chemical exergy and \( G \) is the Gibbs free energy.

The exergy balance for each component by combining the first and second laws of thermodynamics can be written as follows [63,64]:

\[
\dot{E}_Q + \sum_i \dot{m}_i e_i = \sum_e \dot{m}_e e_e + \dot{E}_W + \dot{E}_D
\]

where \( \dot{E}_Q \) and \( \dot{E}_W \) are related to the exergy of output/input heat and work to the component, respectively. \( i \) and \( e \) are representing the inlet flow and outlet flow to the component. \( \dot{E}_D \) indicates the amount of exergy destruction in the component. Eq. (23) can be expressed in another way by considering the product and the fuel rule, P and F rule, as follows:

\[
\dot{E}_{x_p,k} - \dot{E}_{x_f,k} - \dot{E}_{x_d,k} = 0
\]
The main target of exergoeconomic analysis is the cost effects on the exergy inefficiencies in the overall cost. These assessments enable the energy systems engineer to monitor the procedure of the cost formation. An exergoeconomic method is also a great tool for the optimization of the energy systems since it leads to an emphasis on decreasing the total costs of the system [67]. The main target of exergoeconomic analysis is the calculation of exergy destruction cost of all components in the first phase, and at last obtaining the total capital cost of components, products and input fuels. Cost equations of each component and the considered economic constants and assumptions are provided in Table 5. These equations are obtained by considering the total manufacturing cost of equipment and plotting the cost figure based on the major influential physical specifications such as capacity, total surface area, efficiency, etc.

| Component name | C-1 | C-2 | C-3 | P-1 | P-2 | T-HP | T-MP | T-LP |
|----------------|-----|-----|-----|-----|-----|------|------|------|
| Pressure ratio  | 1.34| 1.08| 1.33| 1.33| 66.52| 0.22 | 0.22 | 0.30 |
| Pressure inlet (kPa) | 101.3 | 125.3 | 101.3 | 101.3 | 135.3 | 9000 | 2000 | 450 |
| Temperature inlet (°C) | 25 | 827 | 25 | 25 | 98.8 | 550 | 358.8 | 214 |
| Power (kW) | 0.99 | 6.067 | 15.49 | 0.0003 | 0.77 | 20.98 | 16.38 | 10.68 |

Table 4. SOFC and SOEC models input data.

| Parameter | Value for SOFC | Value for SOEC | Unit |
|-----------|----------------|----------------|------|
| Electrolyte | | | | |
| Thickness (δE) | 8 | 20 | μm |
| Anode | | | | |
| Thickness (δA) | 500 | 50 | μm |
| Average pore radius (rp) | 0.5 | 1.07 | μm |
| Average particle diameter (dp) | 2.5 | 1.5 | μm |
| Porosity (ε) | 0.35 | 0.48 | Dimensionless |
| Tortuosity (τ) | 3.8 | 5.4 | Dimensionless |
| Charge-transfer coefficient (α) | 0.5 | 0.5 | Dimensionless |
| Cathode | | | | |
| Thickness (δC) | 50 | 500 | μm |
| Average pore radius (rp) | 0.5 | 1.07 | μm |
| Average particle diameter (dp) | 2.5 | 1.5 | μm |
| Porosity (ε) | 0.48 | 0.48 | Dimensionless |
| Tortuosity (τ) | 5.4 | 5.4 | Dimensionless |
| Charge-transfer coefficient (α) | 0.5 | 0.5 | Dimensionless |
| Condition | | | | |
| Current density | 0.35 | 0.35 | A/cm² |
| Cell area | 250 | 250 | cm² |
| Voltage | 0.863 | 0.898 | V |
| Fuel/steam utilization | 0.85 | 0.85 | Dimensionless |
| Power | 544.60 | 50.91 | kW |

The total cost of a component (\(\dot{C}_{T,k}\)) is obtained by summing the exergy destruction rate (\(\dot{C}_{D,k}\)) and investment cost (\(\dot{Z}_k\)):

\[
\dot{C}_{T,k} = \dot{C}_{D,k} + \dot{Z}_k
\]
Exergy destruction cost of a component is calculated as:

\[ \dot{C}_{D,k} = \dot{C}_{F,k} \dot{E}_{D,k} \]  \hspace{1cm} (32)

Cost balance equation and the required auxiliary equations of all components are listed in Table 6 based on P and F rule:

F equations: These equations composed of exergy streams that are supplied by a component and the output stream is still worthy in terms of exergy value. The amount of exergy that is decreased is related to the component. However, the specific cost balance and environmental impact of these streams remain constant between input and output of the component's control volume.

P equations: These streams are those that their exergy increase after passing the component or exergy content, which is generated in the component. This exergy augmentation or exergy generation is related to the product output of the component. In the next step, an exergy unit is provided all of the exergy streams that have similar cost balance or environmental impact.

At last, two assessing factors of \( f_k \) and \( r_k \), i.e. exergoeconomic factor and relative cost difference, respectively, are the final results of an exergoeconomic analysis and calculated as:

\[ f_k = \frac{Z_k}{Z_k + \dot{C}_{D,k}} \]  \hspace{1cm} (33)

\[ r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{c_{F,k} \dot{E}_{P,k}} \]  \hspace{1cm} (34)

The values of exergy, exergy cost and exergoenvironmental impact are listed and fully described in Table 7.

5.3. Exergoenvironmental analysis

The concept of exergoenvironmental analysis is similar to exergoeconomic methodology and is developed to provide an assessment that considered exergy theory in addition to the environmental issues based on life cycle assessment (LCA) to identify the environmental impacts of an energy conversion system [69].

The LCA methodology evaluates the environmental impact of the studied system over its defined lifetime [70]. This approach is globally established and monitors the strategies of ISO 14004. In order to obtain the environmental impacts for LCA, the total environmental impact equation can be written as follows [69]:

\[ \dot{B}_{P,k} = \dot{B}_{F,k} + (\dot{Y}_k + \dot{B}_{k,PP}) \]  \hspace{1cm} (35)

\( \dot{Y}_k \) indicates the environmental impact of the equipment in the total considered life cycle.

---

Table 6. Cost balance and environmental impact balance equations of the components.

| Component | Cost balance equations | Environmental impact balance equations |
|-----------|------------------------|----------------------------------------|
| CC       | \( C_1 + C_{WCl} + Z_{C1} = C_2 \) | \( B_1 + B_{WCl} + Y_{C1} = B_2 \) |
| T-HP     | \( C_25 + Z_{T-HP} = C_{27} + C_{WTHP} \) | None |
| SOFC     | \( C_6 = C_{CW-SCFC} + C_{CW-SCOF} \) | None |
| RE       | \( C_3 + C_{Q-RE} + Z_{Q-RE} = C_4 \) | None |
| HX-1     | \( C_16 = C_{Q-01} + Z_{Q-HX,1} = C_{17} \) | None |
| Mix-1    | \( C_2 + C_{34} + C_{M-1} = C_3 \) | None |
| Mix-2    | \( C_{14} + C_{15} = C_{15} \) | None |
| Mix-3    | \( C_{33} + C_{34} = C_{3} \) | None |
| Mix-4    | \( C_{37} + C_{5} = C_{37} \) | None |
| TEE-1    | \( C_{38} = C_{38} \) | None |
| TEE-2    | \( C_{39} + C_{34} + C_{35} = C_{39} \) | None |
| TEE-3    | \( C_{41} + C_{40} + C_{41} = C_{40} \) | None |

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In equation (35), \( \dot{b}_{F,k}^{FF} \) denotes the environmental impact of pollutants. In cases that there is no chemical reaction involved, \( \dot{b}_{F,k}^{FF} = 0 \).

The used environmental impact equations for all of the employed equipment are listed in Table 6 based on P and F rule. The environmental parameters that are utilized are expressed as follows [69]:

\[
\dot{b}_{F,k} = \frac{\dot{b}_{P,k}}{\dot{E}_{P,k}} \quad (36)
\]

\[
\dot{b}_{P,k} = \frac{\dot{b}_{P,k}}{\dot{E}_{P,k}} \quad (37)
\]

\( \dot{b}_{F} \) indicates the fuel's environmental impact per unit of exergy and \( \dot{b}_{P} \) denotes the product's environmental impact per unit of exergy of a component.

\[
\dot{B}_{D,k} = \dot{b}_{F,k} \dot{E}_{D,k} \quad (38)
\]

\( \dot{B}_{D} \) states the environmental effect of the exergy destruction. Finally, the exergoenvironmental factor (f) and the relative environmental impact difference (\( r_{b} \)) are defined [69]:

\[
f_{b,k} = \frac{\dot{Y}_{k}}{\dot{Y}_{k} + \dot{B}_{D,k}} \quad (39)
\]

\[
r_{b} = \frac{\dot{b}_{F,k} - \dot{b}_{P,k}}{\dot{b}_{F,k}} \quad (40)
\]

5.4. Sensitivity Analysis

In this study, a 3-axis sensitivity analysis method is carried out to determine the mutual effect of exergy destruction (\( \dot{E}_{D,k} \)), investment cost (\( \dot{Z}_{k} \)) and environmental impact (\( \dot{Y}_{k} \)) of a component on each other, as it is illustrated in Figure 2. The product exergy rate (\( \dot{E}_{P,k} \)) at different working conditions and design variables is obtained to link the exergy, exergoeconomic and exergoenvironmental analyses in order to monitor the size effect of a component. A broad zone is represented in Figure 2 in which for an exergy destruction value of a component, the other factors of \( \dot{Z}_{k} / \dot{E}_{P,k} \) and \( \dot{Y}_{k} / \dot{E}_{P,k} \) can vary in the plotted range [71].

Monitoring Figure 2 brings about possibilities for the first and second quarters of the plotted zone as follows [72]:

- \( \dot{E}_{D,k} / \dot{E}_{P,k} \) of a component can be lowered by augmentation of \( \dot{Z}_{k} / \dot{E}_{P,k} \) (line 1) or by a reduction in the terms of \( \dot{Y}_{k} / \dot{E}_{P,k} \) (line 3),
- \( \dot{E}_{D,k} / \dot{E}_{P,k} \) has a positive linear relationship with \( \dot{Z}_{k} / \dot{E}_{P,k} \) and has a negative linear relationship with \( \dot{Y}_{k} / \dot{E}_{P,k} \). Hence, 2 possibilities can be defined for the third quarter:
  - \( \dot{Z}_{k} / \dot{E}_{P,k} \) has a direct relationship with \( \dot{Y}_{k} / \dot{E}_{P,k} \) (lines 1–3 and 2–4).
Figure 2. Triple monitoring of investment cost, construction-of-component related environmental impact and exergy destruction for the kth component.

• \( \dot{Z}_k / \dot{E}_{P,k} \) is inversely proportional to \( \dot{Y}_k / \dot{E}_{P,k} \) (lines 1–4 and 2–3).

Now, how should this information be utilized to optimize a process based on criteria of exergoeconomic (first quarter), exergoenvironmental (second quarter) or in overall analyses (third quarter)?

The performance of a component is improved when ‘the lower . . . the lower’ condition is achieved. A component needs a major change when the case is ‘the lower . . . the higher’.

6. RESULTS AND DISCUSSION

6.1. Exergy assessment

Exergy analysis is applied on the proposed integrated system of SOFC-SOEC-RC. The obtained results from the exergy analysis report of each component are listed in Table 8. The exergy efficiency of each section, namely the SOFC unit and the SOEC section, are calculated by 84.81% and 63.68%, respectively. In the RC unit, the three stages of turbines obtain the exergy efficiency of 85.89%, 82.37% and 79.43%, T-HP, T-MP and T-LP, respectively. The exergy analysis demonstrates that heat exchangers are the most exergy destructive component in the proposed process. On the other hand, compressors are the least exergy destructive component. In terms of heat exchangers, HX-3 and HX-2 are the two most destructive employed heat exchangers, respectively. The highest exergy destruction rate of the process is calculated for the SOFC unit, whereas its exergy efficiency is not the least. Hence, it should be noted that the evaluation of either exergy efficiency or exergy destruction rate is not sufficient for establishing a practical assessment. Therefore, both factors should be monitored simultaneously.

Table 8. Results of exergy analysis of the integrated system.

| Component | \( \dot{E}_F \) (kW) | \( \dot{E}_P \) (kW) | \( \dot{E}_D \) (kW) | \( Y_D \) (%) | \( \varepsilon \) (%) |
|-----------|----------------|----------------|----------------|-------------|-------------|
| C-1       | 0.99           | 0.76           | 0.23           | 0.31        | 76.83       |
| C-2       | 6.07           | 5.34           | 0.72           | 0.98        | 88.05       |
| C-3       | 15.49          | 11.27          | 4.22           | 5.68        | 72.76       |
| T-HP      | 24.43          | 20.98          | 3.45           | 4.64        | 85.89       |
| T-MP      | 19.88          | 16.38          | 3.51           | 4.72        | 82.37       |
| T-LP      | 13.45          | 10.68          | 2.77           | 3.73        | 79.43       |
| CC        | 412.12         | 352.73         | 59.40          | 80.03       | 85.59       |
| SOFC      | 642.17         | 544.60         | 97.57          | 131.45      | 84.81       |
| SOEC      | 100.14         | 63.76          | 36.37          | 49.01       | 63.68       |
| HX-1      | 21.33          | 17.94          | 3.39           | 4.57        | 84.09       |
| HX-2      | 103.97         | 72.95          | 31.02          | 41.79       | 70.17       |
| HX-3      | 127.33         | 88.09          | 39.24          | 52.88       | 69.18       |
| HX-4      | 46.40          | 23.71          | 22.69          | 30.57       | 51.10       |
| HX-5      | 27.04          | 23.40          | 3.64           | 4.90        | 86.55       |

6.2. Exergoeconomic analysis

A logical evaluation can be made by means of exergoeconomic analysis between initial capital cost and current operational cost of the system based on the system failure. In addition, the practicality of the system can be demonstrated by the exergoeconomic analysis. The report of exergoeconomic analysis of the proposed system of SOFC-SOEC-RC is presented in Table 9. As it is discussed in the methodology section, \( r \), relative cost difference, illustrates the relationship between the exergy cost of product flows and the exergy cost of fuel flows. The parameter of \( f \), exergoeconomic factor, expresses useful evidence about investment cost in addition to exergy efficiency. The high exergoeconomic factor states that the cost of the component should be decreased to make lower the total cost of the system. However, the low exergoeconomic factor indicates that the studied component or system is not operating efficiently and in order to lower the cost of the system enhancement in the operation of the component or system is necessary. Based on the exergoeconomic report, the highest value of \( f \) is for firstly the compressors and after that the SOFC and SOEC units due to their relative expensiveness and higher investment cost. On the other hand, heat exchangers and the CC obtain the least exergoeconomic factor among other components. Thus, the operational condition, i.e. efficiency, of these equipment needs to be significantly upgraded to make lower the system’s cost. The largest and the smallest value of exergoeconomic factor is obtained for the compressor of C-1 and the heat exchanger of HX-5 at 97.49% and 1.08%, respectively. Analyzing the relative cost difference factor illustrates that the compressor of C-1 obtains the highest value of 1201.9% and the heat exchanger of HX-5 obtains the least value of 16.1%. The value of the exergy cost rate of fuel and product flows designate the exergy cost of a specific component. Based on the exergoeconomic analysis, the highest exergy cost rate of fuel is calculated for the heat exchanger of HX-5 at 93.61$/Gj. The highest exergy cost rate of products is obtained for the compressor C-1 at 256.74$/Gj. Exergy destruction cost, \( \dot{C}_D \), is another important factor in the exergoeconomic analysis. It is monitored that the largest exergy destruction cost is calculated for the CC at 7.03$/h and the lowest amount is obtained for
A novel exergy-based assessment on a multi-production plant of power, heat and hydrogen

6.3. Exergoenvironmental analysis

The exergoenvironmental report of the proposed system is fully listed in Table 10. The largest value of the environmental impact of the exergy destruction rate, \( \dot{B}_D \), is obtained for the CC at 4.74 Pts/h and the least value is calculated for the compressor of C-1 at 0.01 Pts/h. Components with larger values of \( \dot{B}_D \) should be re-designed to make lower the destructive effects on its surroundings. Furthermore, the exergoenvironmental report stated that the compressor C-2 and the heat exchanger HX-3 have the highest (93.29%) and the least (23.54%) values of exergoenvironmental factor, respectively. Hence, the construction process of the compressor and the heat exchanger should be changed to make lower its hazardous effect on the environment. Overall, total environmental impact (\( \dot{Y} + \dot{B}_D \)) values of the components in the integrated system illustrate that the SOFC and SOEC units have priority on possible future re-design processes to decrease the negative environmental impact of the total integrated system.

6.4. Improvement techniques

The major factors that lead to inefficiencies in the CC are mostly triggered by chemical reactions, heat transfer, mixing and friction. Unfortunately, there is no determined technical approach to minimize most of the destructions that occurred. However, by focusing on avoidable endogenous and exogenous exergy destructions some amount of inefficiencies would be reduced through some changes in the combustion process or by optimizing other plant components such as heat exchangers, compressors, etc. This means that in order to achieve an optimum state, there is no need to isolate the CC and perform optimization. Overall, the mutual interactions and the whole system performance must be considered to yield a practical optimization [73].

In the case of heat exchangers improvement must be focused on increasing the heat transfer area for a fixed amount of cost, or decreasing the allowable minimum temperature approach, or installing heat exchangers with higher heat transfer performance such as plate heat exchangers instead of conventional shell and
of product exergy, considerably by 4.5–16.64%. The results indicate that the ratio of energy efficiency can be increased based on the rolling piston type rotary investigated. The variation of the rotor tip gap.

In the case of shell and tube heat exchangers techniques discussed in [75,76]. Usage of the nano-fluid has been considered for currently in operation shell and tube heat exchangers because of their operating temperature range (60°C to 160°C).

In the case of the compressor, improving its efficiency must be highlighted. In fact, decreasing the required power for reaching a specific pressure in the outlet should be the technical improvement result. In [77], efficiency improvement is investigated by variation of the rotor tip gap. In [78], a novel compressor structure based on the rolling piston type rotary is investigated. The results indicated that the ratio of energy efficiency can be increased considerably by 4.5–16.64%.

6.5. Sensitivity analysis

In this work, sensitivity analysis is carried out to illustrate a possible approach that can be beneficial in obtaining a maximized output from each introduced cycle by altering some influential and key parameters such as temperature, mass flow rate and isentropic efficiency. In addition, this sensitivity analysis is performed based on an exergy-based approach. Therefore, sensitivity analysis is implemented to probe if there is any mutual interaction effect between the exergy destruction, investment cost and environmental effect of a component by changing of some design parameters such as isentropic efficiency, pressure ratio, minimum temperature difference, inlet pressure, current density and efficiency of the electrolyzer. For this aim, a sensitivity graph is generated with three axes: exergy destruction, \( \frac{\dot{E}_D}{\dot{E}_P} \), cost of product exergy, \( \frac{\dot{Z}}{\dot{Y}} \), and environmental effect, \( \frac{\dot{Y}}{\dot{Z}} \), respectively. Variation of investment cost and environmental effect are always proportional, \( \dot{Y} \) and \( \dot{Z} \) are simultaneously decreased or increased.

So, two possibilities may be presented: (I) both parameters of \( \dot{Y} \) and \( \dot{Z} \) are also proportional to the exergy destruction rate, this mode is so-called ‘the lower … the lower’. It states that lowering the exergy destruction led to lower the cost and the environmental impact. In the second status, an inverse relation is established between \( \dot{Y} \) and \( \dot{Z} \), which is named as ‘the lower … the higher’. It expresses that reducing the exergy destruction rate boost up the values of \( \dot{Y} \) and \( \dot{Z} \). Based on Figure 3a, it is monitored that increasing the isentropic efficiency of the compressor of C-2 decreases the exergy destruction, increases the total cost and also increases the environmental impact. This case is known as ‘the lower … the higher’. Hence, to perform optimization and find out an optimum status where all three parameters of exergy destruction, total cost and environmental impact have a logical optimum value, the isentropic efficiency should be varied. It is understood from Figure 3b that increasing the pressure ratio of the compressor C-2 causes to form the case of ‘the lower … the lower’. Thus, it is favorable to increase the pressure ratio in the re-design procedure of the compressor.

Figure 3a illustrates the effect of the minimum temperature difference between inlet/outlet of the heat exchanger of HX-4 on the exergy destruction, total cost and environmental impact so the case is ‘the lower … the lower’. Therefore, it is stated that the utilization of a turbine with higher isentropic efficiency is favorable. On the other hand, Figure 4b, increasing the pressure ratio caused to form the status of ‘the lower … the higher’, which is not favorable, and try and error procedure is required to find out an optimal point where all of the factors meet the desired values.

Figure 5a illustrates the effect of the minimum temperature difference between inlet/outlet of the heat exchanger of HX-4 and the effect of inlet pressure on the performance of the heat exchanger of HX-4 is shown in Figure 5b. It is monitored that either decreasing the minimum temperature difference between inlet flow and outlet flow or increasing the inlet pressure led to the desired case of ‘the lower … the lower’.

In order to perform the sensitivity analysis for the SOEC unit, the variation of current density, Figure 6a and the variation of...
the electrolyzer efficiency, Figure 6b, are assessed. It is declared that in lower current density, the value of exergy destruction, total cost and environmental impact are following a decreasing trend, ‘the lower . . . the lower’. In addition, although utilization of an electrolyzer with higher efficiency decreased the exergy destruction, on the other hand, it increases the investment cost and also the environmental impact, so this case is ‘the lower . . . the higher’.

7. CONCLUSIONS

Exergy-based assessment illustrates that the presented system can be an appropriate choice for the tri-production of hydrogen, heat and power. Based on the exergy evaluation, the SOFC and SOEC units obtain the exergy efficiency of 84.8% and 63.7%, in this proposed layout, respectively. Three-axes sensitivity analysis reveals the following conclusions:
• CCs and heat exchangers are predominant components from consideration of exergy destruction cost in this specific case of integrating the RC, SOFC and SOEC. It is shown that the CC in this presented integrated system obtains the exergy efficiency of 85.59%.

• The exergoeconomic factor of compressors is relatively large. Therefore, in order to reduce the cost of the system, these components should be re-designed to be improved.

• Due to large values of exergy destruction cost, heat exchangers have the lowest values of the exergoeconomic factor in comparison to others. This negative issue would be addressed by increasing the heat transfer area, decreasing the allowable minimum temperature approach and employing nanofluids.

• The overall exergoeconomic analysis demonstrates that due to the higher values of the total cost ($Z + C_D$) for the SOFC and SOEC units, improvements in the operation of these units are vital. In order to decrease this cost, changing the mass flow rate, operational voltage and current would be practical to reduce the operational and maintenance costs, or by analyzing the feasibility of manufacturing with cheaper materials.

• Exergoenvironmental analysis illustrates that the utilized compressors of the system obtain the highest values of the exergoenvironmental factor.

• The SOEC unit has the highest total environmental impact ($\dot{Y} + B_D$). Therefore, to ease the environmental threats, changing the status and design parameters of the SOEC unit may be beneficial, for example by altering the thickness of the cathode and anode, or by measuring the effect of possible materials that can be used to have the least environmental impact.

The only matter that challenges the feasibility of multi-production plants is reliability since these system are complex and it should be considered that performance of each sub-system affect the whole plant and they cannot considered as individual system that its output product is combined and integrated. An optimization study sounds to be an interesting approach for further investigations in this field to determine the efficient values of working conditions in order to obtain an efficient cycle with the highest exergy efficiency, the least exergy destruction cost and also the least environmental impact on its surroundings.

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