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Simultaneous synthesis of H₂, O₂, and N₂ via an innovatory energy system in Coronavirus pandemic time: Design, techno-economic assessment, and optimization approaches

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HIGHLIGHTS

• An innovative SOEC-based system was designed to generate O₂, H₂ and N₂ in COVID-19 pandemic period.
• The system was scrutinized based on the thermodynamic and economic points of view.
• Effects of the key operation parameters was investigated on the systems performance.
• NSGA-II algorithm was utilized to optimize the designed system.
• The exergy efficiency of the system and pay-back period factor were determined.

ABSTRACT

In this work, an innovative integrated system that is incorporated from solid oxide electrolysis cells and an oxygen separator membrane is assessed and optimized from the techno-economic aspects to respond to oxygen, hydrogen, and nitrogen demands for hospitals and other health care applications. Besides, a parametric comparison is conducted to apprehend the weights of parameters changes on the performance of criteria. Relying on the assessments, from the hydrogen production of 1 kg/s, 23.19 kg/s of oxygen, and 50.22 kg/s of nitrogen are produced. The parametric study shows that by raising the working temperature of the electrolyzer, the cell voltage variation has descending trend and the power consumption of the system is decreased by 19%. Finally, the results of multi-criteria optimization on the Pareto front reveal that in the optimal case, the system payback period is attained at about 5.32 years and the exergy efficiency of 92.47%, which are improved 16.6% and 16.2% compared to the base case, sequentially. Consequently, this system is proposed to consider as a cost-effective and reliable option towards its vital and valuable productions, in the pandemic period and after's.

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In the first quarter of 2020, the world faced a pandemic, strange, and dangerous virus called COVID-19. Emerging this virus changed not only the routine life of people in every corner of the world but also affected industries and manufacturing sectors. Since February of 2020, the world health organization (WHO) and governments motivated citizens to stay at home to reduce the infection curve [1]. This pandemic had a plethora of negative effects on all aspects of life, such as economic, trade phenomenon, demand trends, etc. Moreover, due to the increasing rate of COVID positive cases in most countries of the world, providing some critical chemicals became an external pressure on the shoulders of the hospitals and government. In this regard, any attempt to find reliable, effective, and economical options to produce chemicals in the pandemic period is a valuable effort. O2 is a vital gas that is used in vast amounts in the different sections of hospitals. As mentioned, the COVID-19 pandemic has increased the demand for oxygen in hospitals [2,3]. Several new works have been published in the area of technical [4,5] and thermodynamic [6–10], thermo-economic [11,12], and economic [13–15] simulations and analyses of the integrated energy systems with valuable outputs like hydrogen and multi-objective optimization [16–18] to claim thermodynamic and economic performance improvement of these systems. There are different ways to produce hydrogen [19–21] and other valuable gases like oxygen and nitrogen. Between all traditional and innovative processes for oxygen and other valuable productions, utilizing solid oxide electrolysis cells (SOEC) is a favorable option. Due to the high range of operation temperature (800–1273 K), the overall efficiency of SOEC is higher than other technologies for simultaneous oxygen and hydrogen generation [22]. A typical SOEC includes an electrolyte, an anode, and a cathode. Each section of this unit plays a pivotal role in operating the unit. In the first step, the cathode is fed by steam. After connecting the unit to the

| Nomenclature | Symbols | Greek letters | Subscripts |
|-------------|---------|--------------|-----------|
| **Symbols** | **A** Coefficient of calculation of exchange current density for cathode (mA/cm²) | **η_{ex}** Exergy Efficiency (%) | **a** Anode |
|             | **B** Coefficient of exchange current density calculation for anode (mA/cm²) | **δ** Ratio of the cost (−)/thickness | **at** After Tax |
|             | **C** Purchase cost ($) | **σ** Ionic conductivity (Ω⁻¹·cm⁻¹) | **bt** Before Tax |
|             | **CF** Cash flow ($) | **ρ** Electrical conductivity | **c** Cathode |
|             | **CRF** Capital recovery factor (−) | **τ** Operating hours (h) | **s** Entropy (kJ/kg. K) |
|             | **D** Capital corresponding to depreciation (−) | | **T** Temperature (°C) |
|             | **DGM** Dusty Gas Model | | **t** Tax ($) |
|             | **Dr_j** Effective coefficient of Knudsen diffusion (m²/s) | | **TCI** Total capital investment cost ($) |
|             | **E_0** Standard potential (V) | | **TOC** Total operation cost ($) |
|             | **E_{j-o}** Open-circuit voltage (V) | | **TPB** three-phase region |
|             | **Ex** Total exergy (kJ/kg) | | **TPEC** Total purchase cost of components ($) |
|             | **F** Faraday constant (C/mol) | | **U_{cell}** Cell total voltage (V) |
|             | **FCI** Fixed Capital Investment ($) | | **Ut** Utility costs ($) |
|             | **G** Gibbs free energy (kJ) | | **H_2O_2** Hydrogen peroxide |
|             | **GT** Gas turbine | | **HX** Heat exchanger |
|             | **H** Enthalpy (kJ) | | **JO_2** Oxygen flux (mol/s·m²) |
|             | **H_2O** Water/Steam | | **J** Current density (A/m²) |
|             | **R** Gas constant (kJ/kg. K) | | **L** Membrane thickness (m) |
|             | **r** Average cavity radius | | **LC** Labor cost ($) |
|             | **S** Income from the product’s sale ($) | | **MR** Mass ratio (−) |
|             | **SG** Steam generator | | **N** Particle flux (mol/s·m²) |
|             | **SOEC** Solid oxide electrolyzer cell | | **n** Molar flow rate(mol/s) |
|             | **SOFC** Solid oxide fuel cell | | **np** Number of process |
|             | **T** Temperature (°C) | | **OLC** Operating labor costs ($) |
|             | **t** Tax ($) | | **P** Pressure (kPa) |
|             | **TCI** Total capital investment cost ($) | | **P^0** Oxygen pressure (kPa) |
|             | **TOC** Total operation cost ($) | | **P^00** Oxygen pressure (kPa) |
|             | **TPB** three-phase region | | **PBT** Payback time (year) |
|             | **TPEC** Total purchase cost of components ($) | | **p** Net profit (%) |
|             | **W_{consume.net}** Total consumed power (kW) | | **R_{ohm}** Ohmic voltage (V) |
|             | **WT** Water Tank | | **y** Molar fraction of particles (−) |
electricity supplier, the steam goes to the cathode-electrolyte interface, and it is reduced to form pure oxygen and hydrogen ions. On the other hand, the oxygen ions are oxidized to form pure oxygen gas at the anode surface. Finally, the produced oxygen and hydrogen are transferred to the out of the unit [23].

Recently, numerous experimental and theoretical investigations developed around SOEC-based units. These studies generally concentrated on finding the best-operating conditions, improving the efficiency of the unit, integration of the SOEC sub-system with other sub-systems in the integrated and innovative plants [24]. A brief review for both fields of study is needed to delve deeper inside the newest evaluations related to SOEC-based investigations from experimental and theoretical perspectives. From the experimental point of view, some experimental investigations were carried out in the recent decade. For instance, Stoots et al. [25] evaluated the electrolysis process at a high temperature at the Idaho national lab. They found that some structural factors of the system affect the performance of the system to generate hydrogen. They emphasized that using modified high-performance cells can play a pivotal role in reducing economic dependency on fossil fuels in the future. In another investigation [26] an electrochemical concept based on a solid oxide steam electrolyzer (SOSE) was developed for hydrogen production propose. By comparing experimental and obtained simulation data, it has been seen that there was a difference among two SOSE systems in which two different ion-conducting electrolytes were utilized. The finding revealed that in contrast to conventional designs, in the new cathode-supported arrangement, the energy conversion improved. Also, in the experimental test, Cinti et al. [27] introduce an innovative way to integrate a solid oxide electrolyzer by the Fischer–Tropsch process. The input of the introduced system included water and carbon dioxide, and the findings proved that the efficiency of the proposed system was around 57%. The idea related to utilizing a hybrid–ion conductor in the SOEC was examined in the experimental study by Kim et al. [28]. They claimed that using mixed material as an electrolyte boosts the energy efficiency of the unit. To this end, they tested a specific alloy as an electrolyte and showed the mentioned declaration. Moreover, no degradation was seen in the high voltage condition at the tested set up in the continuous operations.

Regarding the importance of theoretical-based investigations, many tries concentrated on this field for electrolyzer-based configurations such as SOEC and SOFC units. Moreover, due to the flexibility of the electrolyzer cells and their capacity to be added to energy systems, theoretical evaluations of these integrated systems have captured scholars' attention. To this end, some research focused on simulation, thermodynamic evaluation, economic investigation, and optimization of SOEC and SOFC based systems. For example, Laurencin et al. [29] researched the modeling of a solid oxide steam electrolyzer. Their investigation aimed to find the impacts of the various operating conditions on hydrogen generation. They utilized a mathematical tool to provide exact data for the modeled system. They mentioned that based on the collected results and the low convective heat transfer condition, the thermal equilibrium of the system was strongly dependent on radiative heat losses. Besides, it has been observed that in the limited polarisation mode, the anode activation overpotential was necessary, while this factor lost its importance in the operating conditions. Also, results revealed that adding diluent materials into hydrogen and water mixture could enhance the concentration overpotential. In another research [30], scholars utilized a SOEC unit to generate methane and dimethyl ether in high-pressure conditions. To find the best operating circumstance, the effective parameters were varied to obtain the best points. Owing to obtained results, for methane synthesis, low temperature and high pressure were desired, while for dimethyl production, setting a high operating temperature was vital to avoid carbon formation. In a similar investigation, Kazempoor and Braun [31] utilized SOECs in high-temperature conditions to generate hydrogen and hydrocarbon-based fuel. They used an intermediate fidelity attitude to anticipate the chemical phenomenon inside the simulated cell. The results confirmed the significant impact of reverse water gas shift on the performance of the cell.

In simulation-based investigations, a different range of analyses has been considered by scholars. One of the viewpoints that have always been one of the challenges of the innovative concepts is the economic feasibility of the proposed framework. To this end, Lin and Hussener [32] with considering economic and technical points, conducted research to simulate, evaluate and optimize a solar-based electrolysis plant. Three different strategies were designed, and the performance and the costs of each one were calculated. The results illustrated that the third strategy, that solar system provided simultaneous power and heat operated efficiently, and the operating costs were lower than other strategies. Finally, to avoid mass transfer limitation in electrodes, the water conversion extent was optimized. Moreover, the thermodynamic analysis and measuring the performance of the proposed cell-based configurations based on the thermodynamic laws have been another issue that captured the attention of researchers. In this regard, scholars [23,33] tried to delve deeper into the performance of the SOEC units by calculating the exergy efficiency of the whole system and the system's exergy destruction. The efficiency of the evaluated SOEC system varied with the operation condition and the input parameters of the unit.

As mentioned above, due to the significant capacity of electrolyzer cells, recent investigations focused on this approach. For instance, Pan et al. [34] introduced a combined plant to generate natural gas. They integrated a SOEC unit with a biomass gasifier and methanation sub-system. The simulation of the proposed plant was done by ASPEN plus software, and the findings demonstrated that the mentioned not only the aimed system was financially feasible, but also the efficiency of the proposed system is favorable. The power to the gas idea was taken into account by Kupecki et al. [35,36]. Scholars developed their concept for a 10kw energy plant. Considering the existing limitations, the efficiency of the aimed system was measured and discussed. Owing to the results, it was revealed that the proposed concept's efficiency was 74%, and this amount of productivity was promising. In Ref. [36], the integration of the SOEC system with a methanation unit to produce natural gas was studied from the
thermodynamic standpoint. The results illustrated that the mentioned integration caused a remarkable energy saving in comparison with other technologies. Besides, from numerical results, it found that the first law and the second law efficiencies of the introduced configuration were 80–85% and 70–78%, respectively. Ali et al. [37] investigated integrating a SOEC unit with a biomass-based gasification process to produce the environmental-friendly methanol. They considered an auto-thermal reformer in which oxygen was available, and due to existing this gas, the rate of synthesized methanol boosted. Based on the results, combining SOEC with the methanol synthesizer unit surged significantly the thermal conversion of the process. Zhang et al. [38] evaluated the conversion of biomass to fuel by designing a state-of-art SOEC plant from technical and economic perspectives. They considered four different fuels to generate and found that the steam electrolysis concept could reach higher energy efficiency. Besides, the founding unfolded that the designed biomass-to-fuel configuration became more economically efficient when it has integrated with the SOEC unit. Mastropasqua et al. [39] conducted a techno-economic assessment of a solar integrated energy system with a SOEC unit. The main purpose of the suggested system was to generate hydrogen supported by the Solar collector. To tackle the variability of solar energy, hybridization with the national gas was carried out. The finding demonstrated that the designed configuration could be operated at a solar to hydrogen efficiency above 30% while integrating the SOEC unit to the proposed system; this factor can be reached around 80%. In another investigation, Giap et al. [40] tested the proposed integrated system's performance by coupling RSOFC with metal hybrid and waste steam. Exergy round-trip efficiencies calculated 45.6% and 48.1%, respectively.

In the current study, an innovative SOEC-based system by setting two important targets (reaching a high efficiency and low pay-back period) is suggested. Which are not taken into account in the previous studies. Moreover, system assessment from an economic point of view is not counted in the past works. Eventually, the techno-economic improvement of the system through multi-objective optimization has not been represented in the previously published works. By solving the optimization problem, scholars and industrial experts will gain a wide prospect of the system and its matured features. The mentioned targets have been taken into account to respond to an urgent demand for oxygen, hydrogen, and nitrogen in healthcare centers in the COVID-19 pandemic circumstance. Accordingly, to bridge up these gaps, different aims are considered in the current study as follows:

- To evaluate mass transfer through electrodes of SOEC unit, Dusty Gas Model (DGM) has been utilized, and for the economic assessment of systems' equipment, all of the economic parameters such as pay-back period, initial investment, tax, etc. have been considered in measurements.
- To improve the preciseness of the calculation and boost the reliability of the developed simulation, the lifetimes of electrolyzer and membrane were adjusted in evaluations.
- To conduct a comprehensive techno-economic assessment and parametric study.

- Finally, to find the optimal point of operation, the suggested system is optimized by the NSGA-II algorithm, and optimal points in which the thermodynamic and economic performances of the system reach their highest values are determined.

**Description of the proposed system**

The scheme of the proposed system has been depicted in Fig. 1. The suggested plant includes a steam generator (SG), four heat exchangers (HX), a membrane, a gas turbine (GT), a SOEC unit, two electrical heaters (ET), two pumps, three gas storage tanks (GST), a water tank (WT), and a transformer. The liquid water (stream 1) is pumped via pump 1 into the heat exchanger IV (HX-IV). In HX-IV, the input water is heated up by the heat of the generated oxygen (stream 25). This action occurs again in HX-III, and then the high-temperature water goes to the SG, and its phase change from high-temperature liquid to saturated steam (stream 5). In the next step, the saturated steam transfers to HX-I and is pre-heated by the generated high-temperature hydrogen. Moreover, to enhance the temperature of the input stream of the anode, the pre-heated steam (stream 6) mixes with the return current of the SOEC unit (stream 10), and after blending, the mixed stream is heated up in the EH-I, again. The return current has been considered in the proposed system to control the features of the anode's input stream. In the current investigation, the molar fraction of hydrogen and steam in the input stream of the anode (stream 8) has been considered 0.1 and 0.9, respectively. A membrane has been considered in the proposed system to utilize the heat of the cathode's outlet stream and generate oxygen and nitrogen. The outlet stream of the cathode (stream 18) blends with the high-temperature inlet air (stream 17) and goes to the membrane to be separated into oxygen and nitrogen. After the separation of the inlet stream into oxygen and nitrogen, the high-temperature oxygen transfers to the storage tank. To recover the temperature of the generated oxygen and improve the thermal efficiency of the overall system, three heat exchangers (HX-II, HX-III, and HX-IV) have been installed in the flow direction of generated oxygen. On the other hand, the second separated material (nitrogen) discharges by stream 20. From an economic viewpoint and to improve the efficiency of the plant, a GT has been installed in the flow path of generated nitrogen. In fact, due to being in the high temperature and pressure, stream 20 can be considered as an option for the extra power generation from generated nitrogen before being stored. As it was explained, the proposed system has been designed to generate power, oxygen, nitrogen, and hydrogen simultaneously.

**Methodology**

**The model**

Engineering Equation Solver (EES) software [41] is chosen to complete the mathematical modeling of the offered system which comprises thermodynamic and economic notions.
Additionally, it is considered that all processes have occurred under steady-state conditions [42], the reference temperature and pressure are 298 K and 101 kPa [43], and kinetic and potential exergies are negligible [44].

Thermodynamic modeling
Oxygen separator membrane. Oxygen flux on the permeate side of the membrane is assessed by the Wagner equation (assuming that oxygen ionic conductivity is not dependent on partial oxygen pressure) [45]:

\[
J_O = \frac{RT}{16F^2L} \sigma \ln \left( \frac{P'}{P_0} \right)
\]  

(1)

where, R, T, F, L depict the membrane thickness, Faraday constant, temperature, and global gas constant, respectively. \( P' \) and \( P_0 \) depute the oxygen pressure on the permeate side and the membrane feed, respectively. \( \sigma \) stands for ionic conductivity. The characteristics of the oxygen separator membrane are given in Table 1. Also, more details about oxygen separation membranes have been provided in Ref. [46].

Electrolysis process within SOEC. The process of water vapor electrolysis is shown in Eq. (2) [47]:

\[
\text{H}_2\text{O}_{(g)} \rightarrow \text{H}_2_{(g)} + 0.5\text{O}_2{_{(g)}}
\]  

(2)

Apparently, the amount of energy needed for the steam electrolysis process is determined through the following equation [48]:

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

(3)

where, \( \Delta G \) denotes the Gibbs free energy changes throughout the water vapor electrolysis process and is conceptually commensurate to the electricity demand for the electrolysis process. \( T \Delta S \) holds for the energy wanted for the electrolysis process in the form of heat, and \( \Delta H \) is equal to the total energy needed (total electricity and heat required) for the electrolysis process.

In this research, to model the mass transfer inside SOEC electrodes, the powerful Dusty Gas Model method has been established [49].

\[
N_j = \frac{\sum_n y_j N_j}{D^{\text{eff}}_{jj}}
\]  

(4)

In Eq. (4), \( y \) is the molar fraction of particles, \( N \) is the flux of each particle, \( D^{\text{eff}}_{jj} \) outlines the effective coefficient of Knudsen diffusion and \( D^{\text{eff}}_{jj} \) is the effective coefficient of molecular diffusion. More information on how to measure the effective diffusion coefficient and the effective molecular diffusion coefficient and flux of production and consumption of each particle can be found in Ref. [29]. The total voltage of the cell can be calculated.

SOEC voltage. The total voltage of the cell is achieved through Eq. (5) [29]:

\[
U_{\text{cell}} = E_{j=0} + \eta_{\text{anode}} + \eta_{\text{conce}} + \eta_{\text{cathode}} + \eta_{\text{act}} + \eta_{\text{act}} + R_{\text{ohm}}
\]  

(5)

where \( E_{j=0} \) designates the open-circuit voltage and is expressed by the Nerst relation in the form of Eq. (6) [29]:

\[
E_{j=0} = E^0 + \frac{RT}{2F} \ln \frac{y_{\text{H}_2}\text{O}_{j=0}/\text{O}_2}{y_{\text{H}_2}\text{O}_{j=0}/\text{H}_2}
\]  

(6)

| Table 1 – Oxygen Separator Membrane Specifications [45]. |
|---------------------------------|-----------------|------------|
| Parameter          | Value | Unit |
| L                  | 1E-6  | M      |
| \( \sigma \)       | 1     |        |
| \( T \)            | 800 Equal to the output temperature of the electrolyzer | \( ^\circ \text{C} \) |
| \( P' \)           | 20 Equals the inlet pressure to the vacuum pump | kPa |
| Lifetime           | 3     | year  |

Fig. 1 – The scheme of the proposed SOEC-based integrated system for simultaneous production of power, \( \text{H}_2 \), \( \text{O}_2 \), and \( \text{N}_2 \).
Here, $E^0$ indicates the standard potential, and subscripts c and a are used to express the cathode and anode, respectively. Moreover, TPB represents the three-phase region at the electrolyte boundary for each electrode. The voltage drops due to the concentration at the anode and the cathode are shown in Eq. (5) with $\eta^{\text{anode}}_{\text{conc}}$ and $\eta^{\text{cathode}}_{\text{conc}}$, respectively, obtained by Eqs. (7) and (6) [29]:

$$\eta^{\text{anode}}_{\text{conc}} = \frac{RT}{2F} \ln \frac{y_{\text{TPB},j=0}^\text{anode}}{y_{\text{TPB},j=0}^\text{cathode}}$$

(7)

$$\eta^{\text{cathode}}_{\text{conc}} = \frac{RT}{2F} \ln \frac{y_{\text{TPB},j=0}^\text{cathode}}{y_{\text{TPB},j=0}^\text{anode}}$$

(8)

The activation voltage drops due to the appearance of an electrochemical reaction at the electrode-electrolyte boundary. Each electrode of the anode and the cathode in Eq. (5) was shown as $\eta^{\text{act}}_{\text{anode}}$ and $\eta^{\text{act}}_{\text{cathode}}$, respectively, calculated by the following equations [48].

$$\eta^{\text{anode}}_{\text{act}} = \frac{RT}{F} \sinh^{-1} \left( \frac{j}{j_0^{\text{anode}}} \right)$$

(9)

$$\eta^{\text{cathode}}_{\text{act}} = \frac{RT}{F} \sinh^{-1} \left( \frac{j}{j_0^{\text{cathode}}} \right)$$

(10)

$j_0$ registers the density of the exchange current for each of the electrodes, and its value for the anode and cathode electrodes is taken through Eqs. (11) and (12), respectively [29].

$$j_0^{\text{anode}} = B^* \left( \frac{y_{\text{TPB},j=0}^\text{anode}}{y_{\text{TPB},j=0}^\text{cathode}} \right)^p e^{-\frac{E_{\text{act}}^{\text{anode}}}{RT}}$$

(11)

$$j_0^{\text{cathode}} = A^* \left( \frac{y_{\text{TPB},j=0}^\text{cathode}}{y_{\text{TPB},j=0}^\text{anode}} \right)^m e^{-\frac{E_{\text{act}}^{\text{cathode}}}{RT}}$$

(12)

Here, $E_a$ describes the activation energy for the electrode. The coefficients $A$ and $B$, $p$, $m$, and $n$ depend on the material of the electrodes. $R_{\text{ohm}}$, $R_{\text{LSM}}$, $R_{\text{8YSZ}}$, and $R_c$ represent the ionic resistance of the electrolyte, the ohmic drop, and the general resistance due to the connection of the electrodes to the Interconnect ($R_c$) [29]:

$$R_{\text{ohm}} = R_{\text{LSM}} + R_{\text{8YSZ}} + R_a + R_c$$

(13)

$$R_{\text{LSM}} = \frac{\delta_a}{\rho_{\text{LSM}}}$$

(14)

$$R_{\text{8YSZ}} = \frac{\delta_c}{\rho_{\text{8YSZ}}}$$

(15)

where, $\delta$ and $\rho$ represent the thickness and electrical conductivity of the material, sequentially. The parameters obliged to determine the solid oxide electrolyzer cell voltage are itemized in Table 2.

Input data of SOEC performance, cost, and service life are recorded in Table 3. In this study, the total capital investment expected to purchase power plant equipment is concerned with the total cost of each component of the system [56].

$$\text{TPEC} = \sum C_i$$

(16)

Where TPEC describes the total purchase cost of all system components and $C$ denotes the purchase cost of each component. Since the total capital investment is included in the purchase of components and ancillary costs, these ancillary costs can be signified as a part of TPEC. Fig. 1 displays the presuppositions and procedure for the total capital investment estimation of the power plant.

According to Fig. 2, the total capital investment cost of a power plant (TCI) can be reached as follows [32,56]:

$$\text{TCI} = 4.991 \times \text{TPEC}$$

(17)

Costs related to the annual operation of a power plant (Total Operation Cost) are accomplished through the following equation [32,56]:

$$\text{TOC} = 1.25(U_t + R_n) + 2.70 \times \text{OLC} + 0.2 \times \text{FCI}$$

(18)

where $U_t$ and $R_n$ signify the costs related to Raw material and Utility, sequentially. (In this study, since the raw material does not enter the power plant, the cost associated with $R_n$ is recognized to be 0) OLC attains for Operating Labor Cost and FCI stands for the total fixed capital investment [32,56].

$$\text{FCI} = 4.347 \times \text{TPEC}$$

(19)

OLC is received in bellow equation [32,56]:

$$\text{OLC} = \frac{h}{\text{year}} \times \text{LC}$$

(20)

Here, LC is labor cost, $h_{\text{labo}}$ is the total working hours of the labor during one year of operation of the power plant and is taken through the next equation [57]:

$$h_{\text{labo}} = 2.13 \times \text{Plant capacity}^{0.242} \times \eta_p \times \frac{\tau}{3600}$$

(21)

Here, Plant capacity is the production capacity of a power plant and its unit is based on kilograms of fuel produced per unit hour. $\eta_p$ designates the number of process steps of the power plant and $\tau$ symbolizes the operating hours of a power plant per year. Utility costs are realized within the subsequent equation [57]:

$$U_t = \text{Electricity price} \frac{S}{\text{kW}} \times \text{Plant consumption[kW]} \times \tau \times 3600$$

(22)

$$\text{GP} = S - \text{TOC}$$

(23)

$S$ denotes the income from the product's sale. Net profit before tax is determined through the following equation [57].

$$\text{P}_{\text{net}} = \text{GP} - D$$

(24)

$D$ symbolizes the amount of capital corresponding to depreciation. This parameter is measured by the latter equation [57]:

$$D = \delta \times \text{FCI}$$

(25)

$\delta$ is the ratio of the cost corresponding to the depreciation to the total fixed cost of the FCI gained through Eq. (19). Net profit after tax is estimated as follows [57].

Economic modeling

Economic calculations and the estimation of time of return on investment are chief indicators in establishing power plants.
\[ P_{at} = P_{et}(1 - t) \]  

(26)

t is tax. Cash flow is accomplished through the following relation [57]:

\[ CF = P_{at} + D = GP(1 - t) + D \times t \]  

(27)

where \( D \times t \) is usually assigned as the tax credit on depreciation of capital. Finally, the payback time is calculated by the following equation, assuming that the CF does not change during the plant start-up until the end of the plant lifetime and is a fixed value [58]:

\[ PBT = \frac{TCI}{CF} \]  

(28)

To control the input mass flow rate of the membrane, the Mass Ratio (MR) is defined based on Eq. (29). This factor demonstrates the ratio of the molar flow rate of the input air in the compressor (state 12) to the molar flow rate of the required air in the electrolyzer (state 16).

Fig. 2 – The total capital investment presuppositions and procedure of a power plant [32].
The efficiency of the proposed system is calculated by the following formula:

\[
\eta_{\text{ex}} = \frac{\text{Ex}_{\text{H}_2} + \text{Ex}_{\text{O}_2} + \text{Ex}_{\text{N}_2}}{W_{\text{Consume,net}}}
\]

Where \(\text{Ex}\) denotes the total exergy (chemical and physical) and \(W_{\text{Consume,net}}\) shows the total consumed power in the proposed plant.

Furthermore, to simplify calculations and develop the proposed model, the following assumptions are considered:

- The price of used network electricity is set based on the network electricity in the USA in 2019. This price is equal to 0.15$/kWh, and this amount is considered in calculations [60].
- The interest rate (2.2%) for determining the CRF factor is considered based on the USA interest rate in 2019 [61].
- In this study, the amount of \(\delta\) parameter is considered 0.1 [58].
- The selling price of the generated hydrogen, oxygen and nitrogen have been considered 3$/kg, 2 $/kg, and 2 $/kg, respectively.
- The tax rate parameter \((t)\) is taken into account at about 40% in the current investigation [58].
- The operating hours and the lifelong of the proposed plant are considered 8760 h and 25 years.
- The production capacity of the suggested configuration for hydrogen generation has been considered equal to 1 kg/s, and the MR factor has been set on 1.2.
- The price of skilled and non-skilled workers is considered 33.67$/h, 25.58$/h [62], and the average of mentioned amounts are taken into account for each workforce’s fee of 1-h work.

### Optimization

The main application of the multi-objective optimization problems is in to set of optimal non-dominated answers and to present in the Pareto front [63]. In this work, to attain the most desirable working point of the offered system concerning thermodynamic and economic aspects, multi-objective optimization is conducted. Variables with higher influence on system operation and their upper and lower limits through parametric study presented in Section Results and discussions are given as decision variables and listed in Table 4.

To help from the accuracy of EES in thermodynamic simulation and MATLAB [64] in resolving the optimization problems concurrently, Artificial Neural Network (ANN) as a medium means has been applied to derive a correlation between inlet and outlet of the system investigation in this work. Multiple runs from EES have been ordered by ANN and the collected objective functions are imported to MATLAB to complete the optimization [65,66].

### Results and discussions

The model accuracy can be judged as good considering it is deep-seated on usual physics for the investigated SOEC utilization. Moreover, the simulation derived from a SOFC one [29] that had been previously verified.

The thermodynamics specs of the prescribed system are detailed in Table 5 recognizing the table, for the hydrogen production of 1 kg s\(^{-1}\), 23.19 kg s\(^{-1}\) of oxygen, and 50.22 kg s\(^{-1}\) of nitrogen are produced. The minimum mass flow rate is linked to the returned stream from the electrolyzer outlet joining the electrolyzer anode. The largest amount of mass flow rate is relevant to the air penetrating the compressor.

The importance of SOEC current density on the cell voltage and cell voltage drop is exposed in Fig. 3. According to the figure, it is explicit that while the current density raises, both the cell voltage and the voltage drop inside the cell increase. Moreover, the concentration voltage drop is the smallest in terms of quantity. When the cell current density reconstructions from 3000 A.m\(^{-2}\) to 20000 A.m\(^{-2}\), the total cell voltage, the activation voltage drop, the Ohmic voltage drop, and the concentration voltage drop vary about 58%, 86%, 500%, and 513% from their original value, individually. From the current density of 0 A.m\(^{-2}\) to 18367 A.m\(^{-2}\), the largest voltage drop is nominated to the activation voltage drop. After the current density of 18367 A.m\(^{-2}\), the largest voltage drop is affiliated to the Ohmic voltage drop.

The force of electrolysis process temperature on the total cell voltage and the drop in cell voltages is presented in Fig. 4. It is obvious that improving the temperature of the electrolysis process points to a contraction in Activation and Ohmic voltages, and an increment in Concentration voltage drop, however, due to the share of Concentration voltage drop corresponded to Activation and Ohmic voltages is very scanty, the total cell voltage decreases. By changing the temperature of the electrolysis process from 700°C to 950°C, the decrement of total cell voltage is 33% from its initial state.

The impression of the operating temperature of the SOEC on the power consumed in the cell and the whole system as well as the surface area of the oxygen separator membrane is presented in Fig. 5. Since increasing the temperature of the electrolysis process leads to a decrease in the overall voltage of the cell, it is expected a reduction in power consumed in the electrolyzer. The dominant fraction of power employed in the electrolysis process points to a contraction in Activation and Ohmic voltages, and the power consumption of the cell diminishes. On the other hand, with expanding the temperature range of the electrolyzer, the membrane inlet temperature jumps, and according to the Wagner equation, the hydrogen flux improves. Since the mass flow rate of the gaseous compound inserting the membrane is

### Table 4 – Decision variables limits for the optimization.

| Decision variables          | Limits       |
|----------------------------|--------------|
| Electrolyser temperature (°C) | 700–1000    |
| Electrolyser pressure (kPa)    | 1300–2100    |
| Current density (A/m\(^2\))  | 0–20000      |

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constant, the surface area of the oxygen separator membrane is reduced. Meanwhile, the temperature of the electrolysis process shifts from 70°C to 95°C, the power consumption of the system and the electrolyzer and the overall surface of the membrane are lessened by 19%, 33%, and 20%, sequentially.

The influence of the SOEC working pressure and vacuum pump pressure (membrane permeate pressure) on the membrane surface area is exhibited in Fig. 6. In this figure, developing the electrolyzer pressure leads to a decrease in the membrane surface area. Based on the Wagner equation, increasing the electrolyzer pressure leads to a slight increase in the pressure of oxygen accessing the membrane, and causes the flux of oxygen production to increase, due to the constant amount of mass flow rate of oxygen accessing the membrane, the surface area of the membrane is decreased. On the other hand, increasing the vacuum pump pressure (Permeate pressure) according to the Wagner equation directs to a contraction in oxygen production flux, as well as the constant mass flow of oxygen accessing the membrane, which drives to an escalation in membrane surface area. During the permeate pressure of the membrane is 20 kPa, turning the electrolyzer pressure from 1350 kPa to 2000 kPa decreases the membrane surface area by 11%.

The effect of the utilization factor on the cell number and power consumption of SOEC is revealed in Fig. 7. The utilization factor betokens that the percentage of the steam enrolling the electrolyzer participates in the electrolysis process and is reformed to hydrogen, in other words, the high utilization factor means the purity of hydrogen in the electrolyzer output. Enhancing the utilization factor guides to raising the number of cells and the power consumed by the cell. A higher utilization factor means more cells must be used to convert steam into hydrogen. When the utilization factor moves from 60% to 100%, the power consumption of the cell and the number of cells progress 5 and 4.8 times, each.

The effect of the MR parameter on exergy efficiency and payback time is displayed in Fig. 8. When the MR parameter is zero means that the mass flow rate of stream#17 is equal to zero. In other words, this parameter designates that the air entering the compressor (Stream#12) is more than the required air of the electrolyzer. Rising this parameter, as shown in Fig. 8, demotes the payback time and exergy efficiency. By increasing this parameter, the size of devices such as compressor, membranes, Heat exchangers 2, 3, and 4, gas turbines, and electric heater 2 increases, thus leading to an increment in total system capital cost investment (TCI), besides, the mass flow rates of oxygen and nitrogen increase, and the revenue from their sales increases at a higher rate than the total cost of the system, so reduces the payback time. Moreover, increased oxygen and nitrogen production

| Stream | T (°C) | P (kPa) | Mass flow rate (kg/s) | Working fluid |
|--------|--------|---------|----------------------|---------------|
| 1      | 25     | 101.3   | 8.937                | H₂O           |
| 2      | 25.12  | 1350    | 8.937                | H₂O           |
| 3      | 193.4  | 1350    | 8.937                | H₂O           |
| 4      | 193.4  | 1350    | 8.937                | H₂O           |
| 5      | 193.4  | 1350    | 8.937                | H₂O           |
| 6      | 654.1  | 1350    | 8.937                | H₂O           |
| 7      | 665.3  | 1350    | 9.048                | H₂O,H₂       |
| 8      | 800    | 1350    | 9.048                | H₂O,H₂       |
| 9      | 800    | 1350    | 1.111                | H₂O,H₂       |
| 10     | 800    | 1350    | 0.111                | H₂O,H₂       |
| 11     | 800    | 1350    | 1                    | H₂O,H₂       |
| 12     | 25     | 101     | 65.69                | N₂O₂         |
| 13     | 377.1  | 1350    | 65.69                | N₂O₂         |
| 14     | 514.4  | 1350    | 65.69                | N₂O₂         |
| 15     | 800    | 1350    | 54.74                | N₂O₂         |
| 16     | 800    | 1350    | 10.95                | N₂O₂         |
| 17     | 800    | 1350    | 62.46                | N₂O₂         |
| 18     | 800    | 1350    | 73.41                | N₂O₂         |
| 19     | 800    | 1350    | 50.22                | N₂         |
| 20     | 800    | 20      | 23.19                | O₂           |
| 21     | 800    | 20      | 23.19                | O₂           |
| 22     | 402.1  | 20      | 23.19                | O₂           |
| 23     | 218.4  | 20      | 23.19                | O₂           |
| 24     | 556    | 101.3   | 23.19                | O₂           |
| 25     | 50.12  | 101.3   | 23.19                | O₂           |
| 26     | 349.1  | 110     | 50.22                | N₂         |
| 27     | 218.4  | 1350    | 1                    | H₂           |

**Table 5** - The thermodynamics specifications of the system.

![Fig. 3](image_url) - The importance of SOEC current density on the cell voltages.
commences to increased product exergy, but the fuel exergy of the system (total system power) grows at a higher rate, which causes to decrease in the system exergy efficiency. By changing the MR from 0 to 1, the exergy efficiency and payback time shrinkage by 7% and 28%, severally.

Cumulative cash flow over the years of the system operation is shown in Fig. 9. It is expected that it will take two years to raise the capital obliged to purchase land, equipment, and working capital. In assessing the total system capital investment cost (TCI), the life of the oxygen separator membrane and the electrolyzer cell is considered from the beginning. It takes about 6 years and 138 days after the start-up of the system for the cumulative cash flow to be equal to zero, during this period all the required capital investment of the system (TCI) is recovered and this period is called: time to return the investment. Initially, two years before the system start-up, the costs related to land, building, and space are paid, then during two years, the fixed cost of the system is paid and all the equipment is installed and ready to use, and before the start-up of the system, a cost is paid as working costs and finally the

Fig. 4 – The force of electrolysis process temperature on the cell voltages.

Fig. 5 – The impression of the operating temperature of the SOEC on the power consumed in the cell and the whole system as well as the surface area of the oxygen separator membrane.

Fig. 6 – The influence of the SOEC working pressure and vacuum pump pressure (membrane permeate pressure) on the membrane surface area.
system starts. At the time of commissioning, the plant has a cumulative cash flow of about $12 billion, and as shown in the figure, it will take about 6 years and 138 days for the system to recover this amount, and profitability arrives. At the end of the system life, cash flow, including system operating capital, is $34.7 billion.

The economic circumstances of the system are itemized in Table 6. According to the table, the capital investment cost ordered to purchase system equipment is $2 billion, the direct and indirect costs of the system are $8.16 billion and $2.52 billion dollars, each. Of these two, the fixed cost is $10.6 billion dollars. The total capital investment cost required by the system, including working capital, is $12 billion. The annual cost of labor is $2 million and the cost of electricity required by the system based on the price of electricity in the US network in 2019 is equal to $216 million. The system generates $4.72 billion in annual revenue from the sale of oxygen, nitrogen, and hydrogen. Net profit before tax, including capital lost due to depreciation, is $1.24 billion. After deducting tax, the net profit of the system is $808 million, and finally, after tax credit is calculated on depreciation, the net cash flow is $1.87 billion annually.

The meaning of taxes and electricity prices on payback time is manifested in Fig. 10. According to this figure, the minimum payback time is 4.8 years, which transpires when the price of electricity is equal to $0.05/kWh and the amount of tax is 50%. Also, the payback time when the tax is 50% and the fuel price is $0.35/kWh is in its maximum amount, about 8 years. Totally, by increasing the tax percent and electricity price, from 0.05 $/kWh to 0.35 $/kWh, the payback time is increased.

The effect of using different sources on the payback time is reported in Table 7. Among the technologies that are associated with emissions, the use of electricity obtained from geothermal energy leads to the shortest payback time (5.95 years), and the use of biomass works to the longest payback time of 6.17 years. Among the technologies that do not emit
pollutants, the use of solar cells to provide electricity reaches the shortest payback time (5.94 years).

The Pareto frontier related to the optimization of payback time and exergy efficiency is drawn in Fig. 11. According to the figure, the minimum and maximum amount of payback time are equal to 4.7 and 8 years, severally, and the exergy efficiency reaches 95% at its maximum and 91% at its lowest. It should be noted that all points on the frontier are acquainted as the optimal point, but the choice of each of them depends on the policy of the system operators. In this study, it is preferred that the payback time is always less than 6 years, so the selection range refers to points on the frontier that have a payback time of fewer than 6 years. To select a point from the remaining points, an ideal point is reached that is unattainable and out of the frontier, at which point both the payback time and the exergy efficiency are at their lowest and highest values, each. The point that has the shortest distance from the ideal point is selected as the optimal point (point B).

Separate system performance at each of points A, B, and C concerning the reference state of the system is reported in Table 8. It is clear that in all points, including point B (selected point), the temperature of the electrolysis process is at its maximum. When the temperature of the electrolysis process is higher, the surface area of the membrane and the power consumption of the system are reduced, exergy efficiency and capital cost reductions lead to reducing the payback time. At point B opposed to the reference state of the system, the exergy efficiency improves by about 16.2%, and the payback time improves by about 16.6% compared to the reference state. At point C, which has the highest exergy efficiency, as well as the longest payback time, the exergy efficiency improves by 19.3% compared to the reference state of the system, and the payback time increases by about 25.5%. At point

![Image](image-url)

**Fig. 10** – The meaning of taxes and electricity prices on payback time.

| Parameter                          | Value       | Unit       |
|------------------------------------|-------------|------------|
| The purchase cost of equipment     | 2.00 × 10^8 | $          |
| Total direct costs                 | 8.16 × 10^8 | $          |
| Total indirect costs               | 2.52 × 10^8 | $          |
| Fixed capital                      | 1.06 × 10^10| $         |
| Working capital                    | 1.30 × 10^5 | $         |
| Total capital investment           | 1.20 × 10^10| $         |
| Labor cost                         | 2.00 × 10^6 | $/year    |
| Electricity cost                   | 2.16 × 10^6 | $/year    |
| Revenue                            | 4.72 × 10^7 | $/year    |
| Gross profit                       | 2.31 × 10^7 | $/year    |
| Net profit before tax              | 1.24 × 10^7 | $/year    |
| Net profit after tax               | 8.08 × 10^6 | $/year    |
| Net cash flow                      | 1.87 × 10^6 | $/year    |
| Pay-back time                      | 6.38        | year      |

**Table 7 – Different sources and the payback time [67].**

| Source                          | Power plant          | Cost ($/kWh) | Pay-back time (year) |
|---------------------------------|----------------------|--------------|----------------------|
| Dispatchable technologies       | Ultra-supercritical coal | 0.076        | 6.10                 |
|                                 | Combined cycle        | 0.038        | 5.96                 |
|                                 | Combustion turbine    | 0.066        | 6.06                 |
|                                 | Advanced nuclear      | 0.074        | 6.09                 |
|                                 | Geothermal            | 0.035        | 5.95                 |
|                                 | Biomass               | 0.094        | 6.17                 |
| Non-dispatchable technologies   | Wind (onshore)        | 0.039        | 5.97                 |
|                                 | Wind (offshore)       | 0.122        | 6.27                 |
|                                 | Solar PV              | 0.033        | 5.94                 |
|                                 | Hydroelectric         | 0.052        | 6.01                 |
A, the exergy efficiency and payback time increase by 14.7% and decrease by 25.8%, sequentially, corresponding to the initial state of the system.

Conclusions

In this research, a new configuration consisting of a solid oxide electrolyzer cell and an oxygen separator membrane were welded to produce hydrogen, oxygen, and pure nitrogen. The system was designed to respond to surging demand for mentioned materials in healthcare centers during the COVID-19 pandemic period. Due to the economic perspective, the proposed system was scrutinized from a wide range of economic-based factors. Since the output of the electrolyzer is at a high temperature, it presents the most fitting substrate for the oxygen separating membrane to separate the oxygen from the cathode air. The system was reviewed thermodynamically and economically, and finally, through multi-objective optimization, the exergy efficiency and payback time were improved. The following are the several practical consequences of this research:

- By changing the temperature of the electrolysis process from 700°C to 950°C, the decrement of total cell voltage is 33% from its initial state.
- By changing the MR from 0 to 1, the exergy efficiency and payback time shrinkage, severally.
- By increasing the working temperature of the electrolyzer from 700°C to 950°C, the cell voltage, the power consumption of the system, and the surface area of the membrane lowered by 33%, 19%, and 20%, apiece, compared to their original state.
- Low permeate pressure and high cell working pressure humble the surface area of the oxygen separator membrane. When the permeate pressure of the membrane is 20 kPa, enhancing the electrolyzer pressure from 1350 kPa to 2000 kPa diminishes the membrane surface area by 11%.
- Expanding the utilization factor guides to growing the number of cells and the power consumption of cells, when the utilization factor switches from 60% to 100%, the power consumed by the cell and the number of cells rise 5 and 4.8 times, severally.
- The expected total capital investment cost was estimated at $12 billion, and the payback time was estimated at 6 years and 138 days. It also generated about $1.87 billion in annual net cash flow.
- In the optimal case, the payback time is 5.32 years and the exergy efficiency is 92.47%, which are improved 16.6% and 16.2% contrasted to the beginning state of the system, respectively.

Table 8 – System performance at each of points of A, B, and C.

| Parameters                  | Reference | A         | B         | C         |
|-----------------------------|-----------|-----------|-----------|-----------|
| Electrolyser temperature (°C) | 800       | 898.93    | 899.71    | 899.6     |
| Electrolyser pressure (kPa) | 1350      | 1978.70   | 1975.55   | 1781.17   |
| Permeate pressure (kPa)     | 20        | 20.23     | 22.84     | 59.28     |
| Current density (A/m²)      | 4000      | 3041.25   | 3011.95   | 3007.9    |
| Exergy efficiency           | 79.58     | 91.27 (-14.7%) | 92.47 (-16.2%) | 95.00 (-19.3%) |
| Pay-back time               | 6.38      | 4.73 (-25.8%) | 5.32 (-16.6%) | 8.01 (-25.5%) |

Fig. 11 – Pareto frontier related to the optimization of payback time and exergy efficiency.
To provide some suggestions for future works, some suggestions are recommended as follows:

- Since the proposed plant generates hydrogen and oxygen, simultaneously, adjusting a unit to convert a part of the generated hydrogen and oxygen into hydrogen-peroxide ($\text{H}_2\text{O}_2$) can be considered as an alluring option. The mentioned material has a high demand in the hospitals and healthcare centers and mentioned method can provide an economic way to respond to the mentioned need.
- The suggested plant in the current study has enough flexibility to operate with other energy sources such as solar energy and biomass. Developing this idea (utilizing the energy of biomass and sun radiation to provide the required power of the SOEC unit) can improve the reliability and independence of the proposed configuration.
- There is a plethora of tools for deep evaluation of innovative energy systems. On top of methods, the energy evaluation and advanced exergy assessment are suggested for the scholar in future works. Mentioned methods consider deeper features to test energy systems and can provide further information for researchers.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**References**

[1] Steffen B, et al. Navigating the clean energy transition in the COVID-19 crisis. Joule 2020;4(6):1137–41.
[2] Hauser P, et al. The impact of the COVID-19 crisis on energy prices in comparison to the 2008 financial crisis. In: IAEE energy forum/Covid-19 issue; 2020.
[3] Siddiqui O, Ishaq H, Dincer I. Development and performance assessment of new solar and fuel cell-powered oxygen generators and ventilators for COVID-19 patients. Int J Hydrogen Energy 2021;46(66):33053–67.
[4] Ghasemi A, et al. Thermodynamic and exergy analysis of a novel trigeneration energy system based on solar energy and MSW gasification using energy and exergy concept. J Therm Eng 2021;7(1):349–66.
[5] Salehi A, et al. Simulation process of biodiesel production plant. Environ Prog Sustain Energy 2019;38(6):e13264.
[6] Ghasemi A, Heidarnejad P, Noorpoor A. A novel solar-biomass based multi-generation energy system including water desalination and liquefaction of natural gas system: thermodynamic and thermoeconomic optimization. J Clean Prod 2018;196:424–37.
[7] Montazerinejad H, Ahmadi P, Montazerinejad Z. Advanced exergy, exergo-economic and exergo-environmental analyses of a solar based trigeneration energy system. Appl Therm Eng 2019;152:666–85.
[8] Alirahmi SM, et al. A comprehensive techno-economic analysis and multi-criteria optimization of a compressed air energy storage (CAES) hybridized with solar and desalination units. Energy Convers Manag 2021;236:114053.
[9] Heidarnejad P. Exergy based optimization of a biomass and solar fuelled CCHP seawater desalination plant. J Therm Eng 2017;3(1):1034–43.
[10] Minaeir PK, et al. Chance-constrained programming for optimal scheduling of combined cooling, heating, and power-based microgrid coupled with flexible technologies. Sustainable Cities and Society; 2021. p. 103502.
[11] Manesh MHK, et al. Techno-economic, environmental and energy analysis and optimization of integrated solar parabolic trough collector and multi effect distillation systems with a combined cycle power plant. Energy 2021;122499.
[12] Karim SHT, et al. 4E analyses and multi-objective optimization of a solar-based combined cooling, heating, and power system for residential applications. Energy Rep 2021;7:1780–97.
[13] Sani MM, et al. Optimal energy hub development to supply heating, cooling, electricity and freshwater for a coastal urban area taking into account economic and environmental factors. Energy 2022;238:121743.
[14] Syah R, et al. The economic evaluation of methanol and propylene production from natural gas at petrochemical industries in Iran. Sustainability 2021;13(17):9990.
[15] Cao Y, et al. The economic evaluation of establishing a plant for producing biodiesel from edible oil wastes in oil-rich countries: case study Iran. Energy 2020;213:118760.
[16] Cao Y, et al. Multi-objective bat optimization for a biomass gasifier integrated energy system based on 4E analyses. Appl Therm Eng 2019;166:114739.
[17] Heidarnejad P, Hashemian N, Noorpoor AR. Multi objective exergy based optimization of a solar micro CHP system based on organic Rankine cycle. J Sol Energy Res 2017;2(2):41–7.
[18] Golkar B, et al. Determination of optimum hybrid cooling wet/dry parameters and control system in off design condition: case study. Appl Therm Eng 2019;149:132–50.
[19] Hashemian N, Noorpoor A, Heidarnejad P. Thermodynamic diagnosis of a novel solar-biomass based multi-generation system including potable water and hydrogen production. Energy Equip Syst 2019;7(1):81–98.
[20] Vojdani M, Fakhari I, Ahmadi P. A novel triple pressure HRSG system including potable water and hydrogen production. Environ Prod 2018;196:424–37.
[21] Hasanzadeh A, et al. Flowsheet-based model and exergy analysis of a solar-based combined cooling, heating, and freshwater: techno-economic-environmental assessment, and multi-objective optimization. Energy Convers Manag 2021;233:113876.
[22] Hasanazadeh A, et al. Stand-alone gas turbine and hybrid MCFC and SOFC-gas turbine systems: comparative life cycle cost, environmental, and energy assessments. Energy Rep 2021;7:4659–80.
[23] Stempien JP, Sun Q, Chan SH. Performance of power generation extension system based on solid-oxide electrolyzer cells under various design conditions. Energy 2013;55:647–57.
[24] Im-orb K, et al. Flowsheet-based model and exergy analysis of solid oxide electrolysis cells for clean hydrogen production. J Clean Prod 2018;170:1–13.
[25] Pandiyan A, et al. Review of solid oxide electrolysis cells: a clean energy strategy for hydrogen generation. Nanomater Energy 2019;8(1):2–22.
Syngas production via high-temperature co-electrolysis of steam and carbon dioxide. 2009.

Ni M, Leung MK, Leung DY. Electrochemical modeling of hydrogen production by proton-conducting solid oxide steam electrolyzer. Int J Hydrogen Energy 2008;33(15):4040–7.

Cinti G, et al. Integration of solid oxide electrolyzer and Fischer-Tropsch: a sustainable pathway for synthetic fuel. Appl Energy 2016;162:308–20.

Kim J, et al. Hybrid-solid oxide electrolysis cell: a new strategy for efficient hydrogen production. Nanomater Energy 2018;44:121–6.

Laurencin J, et al. Modelling of solid oxide steam electrolyser: impact of the operating conditions on hydrogen production. J Power Sources 2011;196(4):2080–93.

Sun X, et al. Thermodynamic analysis of synthetic hydrocarbon fuel production in pressurized solid oxide electrolysis cells. Int J Hydrogen Energy 2012;37(22):17101–10.

Kazempoor P, Braun R. Hydrogen and synthetic fuel production using high temperature solid oxide electrolysis cells (SOECs). Int J Hydrogen Energy 2015;40(9):3599–612.

Lin M, Haussener S. Techno-economic modeling and optimization of solar-driven high-temperature electrolysis systems. Sol Energy 2017;155:1389–402.

AlZahrani AA, Dincer I. Thermodynamic and electrochemical analyses of a solid oxide electrolyzer for hydrogen production. Int J Hydrogen Energy 2017;42(33):21404–13.

Pan Z, et al. Thermodynamic analyses of synthetic natural gas production via municipal solid waste gasification, high-temperature water electrolysis and methanation. Energy Convers Manag 2019;202:112160.

Kupecki J, et al. Energy analysis of a 10 kW-class power-to-gas system based on a solid oxide electrolyzer (SOE). Energy Convers Manag 2019;199:111934.

Ancona M, et al. Thermal integration of a high-temperature co-electrolyzer and experimental methanator for Power-to-Gas energy storage system. Energy Convers Manag 2019;186:340–55.

Ali S, Sørensen K, Nielsen MP. Modeling a novel combined solid oxide electrolyssis cell (SOEC)-Biomass gasification renewable methanol production system. Renew Energy 2020;154:1025–34.

Zhang H, et al. Techno-economic evaluation of biomass-to-fuels with solid-oxide electrolyzer. Appl Energy 2020;270:115133.

Mastropasqua L, et al. Solar hydrogen production: techno-economic analysis of a parabolic dish-supported high-temperature electrolysis system. Appl Energy 2020;261:114392.

Giap V-T, et al. A novel electrical energy storage system based on a reversible solid oxide fuel cell coupled with metal hydrides and waste steam. Appl Energy 2020;262:114522.

Klein S. Engineering equation solver (EES) V9. Madison, USA: F-chart software; 2015.

Ghasemi A, Moghaddam M. Thermodynamic and environmental comparative investigation and optimization of landfill vs. Incineration for municipal solid waste: a case study in Varamin, Iran. J Therm Eng 2020;6(6):226–46.

Taleizadehsardari P, et al. Energy, exergy, economic, exergoeconomic, and exergoenvironmental (EE) analyses of a triple cycle with carbon capture. J CO2 Util 2020;41:101258.

Shayesteh A, et al. Determination of the ORC-RO system optimum parameters based on 4E analysis: Water–Energy–Environment nexus. Energy Convers Manag 2019;183:772–90.

Burggraaf AJ, Cot L. Fundamentals of inorganic membrane science and technology. Elsevier; 1996.