Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Development and performance assessment of new solar and fuel cell-powered oxygen generators and ventilators for COVID-19 patients

O. Siddiqui*, H. Ishaq**, I. Dincer

Clean Energy Research Laboratory, Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

HIGHLIGHTS

- Solar and fuel cell-based oxygenation system is presented for COVID-19 patients.
- Transient simulations and thermodynamic analyses conducted on the developed system.
- Daily hydrogen production varies between 21.3 kg/day and 76.8 kg/day.
- Maximum energy and exergy efficiencies of the developed system are 14.3% and 13.4%.

ABSTRACT

In this study, a new solar-based fuel cell-powered oxygenation and ventilation system is presented for COVID-19 patients. Solar energy is utilized to operate the developed system through photovoltaic panels. The method of water splitting is utilized to generate the required oxygen through the operation of a proton exchange membrane water electrolyser. Moreover, the hydrogen produced during water splitting is utilized as fuel to operate the fuel cell system during low solar availability or the absence of solar irradiation. Transient simulations and thermodynamic analyses of the developed system are performed by accounting for the changes in solar radiation intensities during the year. The daily oxygen generation is found to vary between 170.4 kg/day and 614.2 kg/day during the year. Furthermore, the amount of daily hydrogen production varies between 21.3 kg/day and 76.8 kg/day. The peak oxygen generation rate attains a value of 18.6 g/s. Moreover, the water electrolysis subsystem entails daily exergy destruction in the range of 139.9 – 529.7 kWh. The maximum efficiencies of the developed system are found to be 14.3% energetically and 13.4% exergetically.

© 2021 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights reserved.

Introduction

The inevitable upsurge in economic development and population that is occurring globally entail critical environmental consequences as processes of energy generation such as production of electricity, cooling, and heating are polluting the environment and are destructive to the ecosystem [1]. Energy is a crucial sector that contributes to wealth generation and economic development making global energy resources tremendously substantial. In the global energy production and consumption, the considerable factors are technological...
developments, population growth, government policies for energy sector, consumer tastes, growth in global energy markets and economic performance. A significant part of this global energy demand is set to be covered by fossil fuels which cause enormous environmental problems [2]. These traditional energy sources (fossil fuels) cover the significant portion of the energy supply but carries some disadvantages such as faster depletion and global warming [3]. The transition of these traditional energy sources with renewable energy sources such as solar [4], wind [5], geothermal [6] and biomass [7] can be a suitable and sustainable solution. Hydrogen provides environmentally benign energy solutions due to the intermittent nature of some renewable energy sources such as wind and solar, and hydrogen can be employed for multiple purposes such as an energy carrier [8], storage medium [9], in fuel combustion [10] and for power generation using fuel cells [11]. The global pandemics such as Ebola and COVID-19 highlighted the need of renewable based stand-alone ventilators, which can be provided with both oxygen and electricity using renewable energy source. This study proposes a new design of oxygen generation and ventilator operation. A solar PV source is employed to generate electrical power, a part of which is supplied to the ventilators directly and remaining is fed to the proton exchange membrane (PEM) electrolyser for hydrogen and oxygen production.

Tani et al. [12] conducted the optimization of solar energy based hydrogen production system. A hydrogen generator was used in this paper for producing hydrogen using a solid polymer electrolyte and photovoltaic (PV) panels were employed to supply the required electrical power at 27.45A and 3.4 V. In the experimental prototype, the power generated by PV module was integrated with hydrogen generator and significant system features namely; hydrogen production flow rate, PV module current/voltage characteristics, and temperature of hydrogen generator and PV module were investigated thoroughly. The results revealed the significance of the photovoltaic module to hydrogen generator cost ratio for optimum experimental solar energy based hydrogen production system. Boudries [13] conducted techno-economic analysis of concentrated solar power (CSP) electrolysis based hydrogen production system. This paper was restricted to the solar parabolic hybrid electrolysis powerplant. They also investigated the significant parameters of hydrogen production system namely; solar fraction and solar irradiance and geographical locations of Southern and Northern Algeria. The results revealed that hydrogen production cost was directly related to the energy production cost.

Barton and Gammon [14] presented a research study on renewable energy based hydrogen production. Three UK based energy-supply pathways were considered in this study that is expected to reduce GHG emissions by 80% in 2050. The first scenario was dependent on significant clean coal amounts with intermittent renewable energy sources, second scenario used twice intermittent renewable energy with no coal and third scenario employs 2.5 times nuclear power than the first scenario with no coal. The results revealed that all three scenarios with zero hydrogen fuel required large energy amount as coal. The designed model also revealed that grid balancing challenge was not adequate motive to limit the intermittent renewable energy amount. Paidar et al. [15] published a comprehensive review study on the membrane electrolysis, history and current status with future perspectives. The aim of this review study is to deliver fundamental material and statistics on membrane electrolysis, its historical background, and current status with future development perspectives. A historical overview of electromembrane processes followed by the review of energy conversion processes for hydrogen production. The review paper was rounded off by combining different small-scale processes that are commercially available.

Cheng et al. [16] conducted a comprehensive review on the proton exchange membrane fuel cell. They reviewed over 150 papers to enclose the mechanism and operating of PEM fuel cell along with impacts and mitigation. It was revealed that trace impurities present in air or fuel steams or in fuel cell components can poison the electrodes and membrane that results in drastic performance degradation. This study reviewed the progress made to identify the contamination sources in fuel cells and effect of these contaminations on experimental performance of fuel cells. These contaminations usually affect three significant elements of conductivity, electrode kinetics and mass transfer. The significant focus of this review study was on performance measures due to the contamination impacts, mechanism dominated approaches and mitigation development, and future directions were also recommended.

Lamy and Millet [17] published a review study on the water electrolysis (PEM and AEM) energy efficiency coefficients under ambient conditions. After detailed description of the electrode dissociation under different operating conditions, the methods to calculate the energy efficiency coefficient were also mentioned at specific current intensity. It was established that both energy efficiency definitions were consistent. Klemenzson and Perouansky [18] published a research study on the contemporary anesthesia ventilators experiencing substantial oxygen cost. The purpose of this study was the significance of the anesthesia ventilators as they use oxygen gas during controlled ventilation. The consumption of oxygen by Datex-Ohmeda ventilators and AV-2 were found to be (302 ± 17 L/h) and (564 ± 68 to 599 ± 56 L/h) respectively. Rathgeber [19] published a research study on the anesthesia ventilators fundamentals. The functional residual capacity reduction during anesthesia gives rise to the mechanical ventilation required with pressure and volume-controlled modes. Ford and Foale [20] published a study on the conversion of oxygen ventilators to air ventilators. During the preparations for fight with COVID-19 pandemic, they recognized the oxygen gas driven ventilators provided in the GE Healthcare anaesthetic machines. Sadykov et al. [28] designed and investigated an asymmetric supported membrane for oxygen and hydrogen production. Thin deposits of nanocomposite nickel and aluminium foam substrates were utilized. The oxygen separation membranes were investigated in methane selective oxi-dry reforming while the hydrogen separation membrane was tested via steam reforming of ethanol. It was found that increasing temperatures as well as contact times resulted in higher yields of syngas and methane conversion. Zolotarenko et al. [29] investigated the utilization of ultrapure atomic hydrogen enriched molecular hydrogen in artificial lung ventilation for technological advancements related to COVID-19. The study reported that oxygen mixtures enriched with hydrogen to decrease the resistance entailed in
the respiratory tract to ease access to pulmonary alveolus. This was conducted with the objective of enhancing oxygen penetration into the lungs. It was also found that metal hydride hydrogen storage techniques can be employed for safe and portable transport of hydrogen.

This paper presents a unique design for solar PV-powered oxygen generation and ventilator operation. A solar PV source is used to generate electrical power, which is fed to the PEM electrolyser for hydrogen and oxygen production. The produced oxygen is utilized for patient ventilation as well as oxygenation while the hydrogen is used by the PEM fuel cell for electrical power generation. The developed system provides an innovative technique to operate life-saving ventilators and oxygen generators in areas where electricity is not available throughout the day due to insufficient infrastructure. There are several countries across the globe where solar energy is readily available, however, electricity shortage as well as load-shedding are a common phenomena. Hence, the presented system will provide an effective methodology to operate oxygen generators and ventilators without being affected from local electricity problems. The specific objectives are (i) to design a solar PV-powered oxygen generation and ventilator operation system, (ii) to conduct a dynamic analyses to investigate the system performance under different operating conditions, (iii) to investigate the newly proposed solar energy based system by conducting exergetic and energetic assessments, (iv) to determine the overall performance of the developed system through energetic and exergetic efficiencies.

**Analyses**

A transient analysis is performed on the developed solar-based oxygen generator and ventilator system. The solar radiation intensities are evaluated for Toronto, Canada. Moreover, in addition to this, each system component is analysed both energetically and exergetically to determine the overall system performance. The detailed analyses of each subsystem is discussed in the proceeding sections.

**Solar-based power generation**

Transient analyses and simulation is conducted by determining hourly solar irradiation. The direct normal solar radiation is determined from the solar constant \( I_{am} \), eccentricity factor \( E_{fr} \) and scattering transmittances \( r \) according to

\[
\dot{I}_{n} = 0.9715E_{fr}I_{am}T_{at}T_{ch}T_{ch}\text{ on}
\]

Moreover, the day angle \( D_{o} \) is used to find the eccentricity factor as

\[
E_{fr} = 1.00011 + 0.034221\text{Cos}(D_{o}) + 0.00128\text{Sin}(D_{o}) + 0.000719\text{Cos}(2D_{o}) + 0.000077\text{Sin}(2D_{o})
\]

Furthermore, the beam radiation \( \dot{I}_{b} \) is evaluated from the normal radiation intensity and the zenith angle \( \theta_{z} \) as

\[
\dot{I}_{b} = \text{Cos}\theta_{z}\dot{I}_{n}
\]

The cosine of the zenith angle is related to the declination angle \( \delta_{d} \), latitude \( \phi_{l} \) and day angle as

\[
\text{Cos}\theta_{z} = (\text{Cos}\delta_{d})(\text{Cos}\phi_{l})(\text{Cos}D_{o}) + (\text{Sin}\delta_{d})(\text{Sin}\phi_{l})
\]

Also, \( D_{o} \) can be determined from the solar time \( T_{st} \) as

\[
D_{o} = 15(12 - T_{st})
\]

After determining the hourly radiation intensities, the total input solar energy per unit time \( Q_{in, PV} \) is evaluated as

\[
Q_{in, PV} = A_{st, PV}\dot{I}_{n}
\]

Next, the solar PV power output \( W_{PV} \) is determined from \( Q_{in, PV} \) and PV module efficiency \( \eta_{PV} \) as

\[
W_{PV} = Q_{in, PV}\eta_{PV}
\]

The simulation parameters used for system analyses are summarized in *Table 1.*

**System description**

The developed solar-powered oxygen generator and ventilator system is depicted in Fig. 1. The ventilator is supplied with the required oxygen and electricity throughout the day. During the presence of solar irradiation, electricity is generated via solar PV panels that is supplied to both the water electrolyser as well as the ventilator. The water electrolyser splits water molecules into hydrogen and oxygen molecules. The oxygen produced is utilized for the ventilator and the hydrogen generated is used to produce electrical power through the operation of a fuel cell system. During low solar intensities or the absence of solar radiation, the hydrogen produced is utilized as fuel to operate the fuel cell, which generates electricity required by the ventilator. At state 1, water enters the system and mixes with unreacted water (state 4) before entering the water electrolyser state 2. A portion of the electrical power generated by the solar PV panels is sent to the electrolyser where the produced hydrogen exits at state 8 and the produced oxygen exits at state 3 along with unreacted water. At state 5, the produced oxygen is sent to the compressor where it is pressurized to a higher appropriate pressure for storage. Furthermore, at state 7, oxygen is sent to the ventilator as required. In addition to this, the hydrogen exiting the electrolyser at state 8 is compressed to a higher pressure before it is stored for later usage. During unavailability of sufficient solar irradiation, hydrogen is sent to the fuel cell to generate electrical power as required by the ventilator. Thus, through the operational methodology described above, the developed system produces oxygen and operates the ventilator through clean and renewable electricity. Also, the presented system provides an innovative method to operate ventilators and oxygen generators, especially in areas where sufficient electricity infrastructure is not available.
hydrogen exits the subsystem whereas oxygen along with unreacted water exit at state 3. The overall water splitting process occurring in the electrolyser is written as:

$$\text{H}_2\text{O} + \text{W}_{\text{PEM}} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$$  \hspace{1cm} (8)

The Gibbs energy change occurring in the electrolysis process can be written as a function of total enthalpy change ($\Delta H_{\text{PEM,wr}}$), total entropy change ($\Delta S_{\text{PEM,wr}}$) and electrolyser temperature ($T_{\text{PEM}}$) as:

$$\Delta G_{\text{PEM,wr}} = \Delta H_{\text{PEM,wr}} - T_{\text{PEM}} \Delta S_{\text{PEM,wr}}$$  \hspace{1cm} (9)

The total enthalpy change can be evaluated as the difference between the total enthalpy of products and the total enthalpy of reactants as:

$$\Delta H_{\text{PEM,wr}} = \sum_{\text{prod}} N_{\text{p,PEM}} \bar{h}_{\text{p,PEM}} - \sum_{\text{react}} N_{\text{r,PEM}} \bar{h}_{\text{r,PEM}}$$  \hspace{1cm} (10)

where $\bar{h}$ is molar enthalpy, $N$ represents the number of moles, $p$ denotes products and $r$ denotes reactants. Similarly, the total entropy change is determined according to:

$$\Delta S_{\text{PEM,wr}} = \sum_{\text{prod}} N_{\text{p,PEM}} s_{\text{p,PEM}} - \sum_{\text{react}} N_{\text{r,PEM}} s_{\text{r,PEM}}$$  \hspace{1cm} (11)

where $s$ is the molar enthalpy. In addition to this, the molar rate of hydrogen production can be evaluated from the current density ($j_{\text{H}_2, \text{PEM}}$), number of electron moles ($n$) and Faraday’s constant ($F$) as:

$$N_{\text{p, H}_2, \text{PEM}} = \frac{j_{\text{H}_2, \text{PEM}}}{nF}$$  \hspace{1cm} (12)

The molar rate of oxygen generation is found as:

$$N_{\text{p, O}_2, \text{PEM}} = \frac{N_{\text{p, H}_2, \text{PEM}}}{2}$$  \hspace{1cm} (13)

The half-cell electrochemical reaction at the electrolyser anode can be denoted as:

$$\text{H}_2\text{O} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2e^-$$  \hspace{1cm} (14)

Also, at the electrolyser cathode, the occurring half-cell cathodic reaction is expressed as:
Moreover, as the electrolyser is supplied with electrical power, the amount of polarization losses increase with rising current inputs. The actual cell voltage of an electrolyser $V_{\text{PEM}}$ can be written as $V_{\text{PEM}} = V_{\text{PEM,act}} + V_{\text{PEM,at}} + V_{\text{PEM,cn}} + V_{\text{PEM,om}}$ (16)

where the open circuit voltage is written as $V_{\text{PEM,act}}$, the total activation polarization loss is denoted as $V_{\text{PEM,at}}$, the total concentration and Ohmic losses are written as $V_{\text{PEM,cn}}$ and $V_{\text{PEM,om}}$, respectively.

The open circuit voltage denotes the cell voltage in the absence of any current input that can be calculated as

$$V_{\text{PEM,act}} = V_{\text{PEM,act}} = \frac{\Delta G_{\text{PEM,act}}}{nF}$$ (17)

Moreover, the activation polarization loss occurring in the electrolyser can be evaluated in terms of the operating ($J_{\text{H}_2,\text{PEM,op}}$) and exchange current ($J_{\text{ex,PEM}}$) densities as

$$V_{\text{H}_2,\text{PEM,act}} = -\sinh^{-1}\left(\frac{J_{\text{H}_2,\text{PEM,op}}}{2J_{\text{ex,PEM}}}ight)$$ (18)

where $J_{\text{ex,PEM}}$ is evaluated from the activation energy ($E_{\text{H}_2,\text{PEM,act}}$), pre-exponential factor ($\theta_0$) and electrolyser temperature ($T_{\text{PEM}}$) according to

$$J_{\text{ex,PEM}} = \theta_0 \exp\left(-\frac{E_{\text{H}_2,\text{PEM,act}}}{R_{\text{PEM}}}ight)$$ (19)

Further, the Ohmic polarization occurring in the electrolyser is determined from $J_{\text{H}_2,\text{PEM,op}}$ and the Ohmic cell resistances ($\Omega_{\text{om}}$) as

$$V_{\text{H}_2,\text{PEM,om}} = J_{\text{H}_2,\text{PEM,op}} \Omega_{\text{om}}$$ (20)

In addition to this, $\Omega_{\text{om}}$ can be calculated from the ionic conductivity ($cnv(x)$) as

$$\Omega_{\text{om}} = \int_0^L \frac{1}{cnv(M_5(x))} dx$$ (21)
The moisture content \((M_s(x))\) of the membrane is determined from the membrane thickness, moisture content of the interfaces between the membrane and anode \((M_{sa})\), membrane and cathode \((M_{sc})\) as

\[
M_s(x) = \frac{M_{sa} - M_{st}}{L} + M_{st} \tag{22}
\]

Also, the ionic conductivity is written as

\[
cn/(M_s(x)) = (0.5139M_s(x) - 0.326)\exp\left(\frac{1268}{303} - \frac{1}{T}\right) \tag{23}
\]

The relation between the electrolyser power, current, and voltage input is written as

\[
\dot{P}_{H_2, PEM,n} = J_{H_2, PEM, np}V_{PEM, H_2, at}A_{H_2, PEM} \tag{24}
\]

In addition, the energy, entropy and exergy balances are used for electrolyser analysis as

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, PEM, in}dt = \int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} m_{H_2}dt \tag{25}
\]

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, PEM, in}dt = \int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} m_{H_2}dt + \dot{E}_{ex, PEM}dt \tag{26}
\]

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, PEM, in}dt = \int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} m_{H_2}dt + \dot{E}_{ex, PEM}dt \tag{27}
\]

Moreover, the produced hydrogen is compressed to a higher pressure suitable for storage through the hydrogen compressor that is analysed thermodynamically as

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, comp,in}dt = \int_{t=1}^{n} m_{H_2}dt \tag{28}
\]

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, comp,in}dt = \int_{t=1}^{n} m_{H_2}dt + \dot{E}_{ex, comp} \tag{29}
\]

\[
\int_{t=1}^{n} m_{H_2}dt + \int_{t=1}^{n} \dot{p}_{H_2, comp,in}dt = \int_{t=1}^{n} m_{H_2}dt + \dot{E}_{ex, comp} \tag{30}
\]

At state 5, the oxygen produced enters the oxygen compressor that is analysed as

\[
\int_{t=1}^{n} m_{O_2}dt + \int_{t=1}^{n} \dot{p}_{O_2, comp,in}dt = \int_{t=1}^{n} m_{O_2}dt \tag{31}
\]

\[
\int_{t=1}^{n} m_{O_2}dt + \int_{t=1}^{n} \dot{p}_{O_2, comp,in}dt = \int_{t=1}^{n} m_{O_2}dt + \dot{E}_{ex, O_2, comp} \tag{32}
\]

\[
\int_{t=1}^{n} m_{O_2}dt + \int_{t=1}^{n} \dot{p}_{O_2, comp,in}dt = \int_{t=1}^{n} m_{O_2}dt + \dot{E}_{ex, O_2, comp} \tag{33}
\]

**Fuel cell-based power generation**

The hydrogen produced is utilized for power generation during insufficient solar availability or the absence of solar irradiation. The overall process occurring in the fuel cell can be expressed as

\[
H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{34}
\]

where the needed oxygen is obtained through the air input to the fuel cell. Moreover, the reaction occurring in the fuel cell at the anode is written as

\[
2H_2 \rightarrow 4H^+ + 4e^- \tag{35}
\]

The \(H^+\) cations formed at the anode reach the cathodic side of fuel cell through the membrane and the following cathodic reaction occurs:

\[
O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{36}
\]

The actual operating fuel cell voltage is found as

\[
V_{FC, H_2, at} = V_{FC, H_2, at} - V_{FC, H_2, ex} - V_{FC, H_2, oh} \tag{37}
\]

where \(V_{FC, H_2, at}\) denotes the open circuit fuel cell voltage with no applied load that is evaluated as

\[
V_{FC, H_2, at} = \frac{\Delta G_{FC, H_2}}{nF} \tag{38}
\]

where the total Gibbs energy change is found as in Eq. (9). The activation polarization occurring in the fuel cell at the actual cell current density can be determined according to

\[
V_{FC, H_2, at} = \ln \left( \frac{J_{FC, H_2}}{J_{FC, H_2}} \right) \frac{RT_{FC}}{anF} \tag{39}
\]

where \(J_{FC, H_2}\) is the actual fuel cell current density, \(J_{FC, H_2}\) denotes the exchange current density and \(T_{FC}\) is the temperature of the fuel cell.

In addition to this, the voltage loss due to concentration polarization is found in terms of limiting current of the fuel cell \((I_{FC, H_2})\) as

\[
V_{FC, H_2, oh} = \ln \left( \frac{I_{FC, H_2}}{I_{FC, H_2}} \right) \frac{RT_{FC}}{anF} \tag{40}
\]

Also, the voltage loss because of Ohmic polarization in the fuel cell is found according to Eq. (20).

The actual power output of the fuel cell system is then found from

\[
W_{FC, H_2} = J_{FC, H_2}V_{FC, H_2}A_{FC, H_2} \tag{41}
\]

The molar rate of hydrogen utilized in the fuel cell is determined according to

\[
N_{FC, H_2} = \frac{J_{FC, H_2}}{nF} \tag{42}
\]

Moreover, the thermodynamic analyses is applied on the fuel cell according to

\[
\int_{i}^{i} m_{H_2}dt + \int_{i}^{i} m_{H_2}dt + \int_{i}^{i} W_{FC, H_2}dt \tag{43}
\]
\[
\int_{t_0}^{t} \dot{m}_{10}\dot{s}_{00}dt + \int_{t_0}^{t} \dot{m}_{11}\dot{s}_{11}dt + \int_{t_0}^{t} \dot{S}_{\text{gen,FC}}dt = \int_{t_0}^{t} \dot{m}_{12}\dot{s}_{12}dt \tag{44}
\]

\[
\int_{t_0}^{t} \dot{m}_{10}\dot{e}_{10}dt + \int_{t_0}^{t} \dot{m}_{11}\dot{e}_{11}dt = \int_{t_0}^{t} \dot{m}_{12}\dot{e}_{12}dt + \int_{t_0}^{t} W_{\text{FC,H}_2}dt + \int_{t_0}^{t} \dot{E}_{\text{dest,FC}}dt \tag{45}
\]

The overall energy efficiency of the system is found according to

\[
\eta_{em} = \frac{\int_{t_0}^{t} N_{\text{Fe,O}_2}M_{\text{Fe}_2}h_{\text{Fe}_2}dt + \int_{t_0}^{t} (N_{\text{Fe,H}_2\text{,PM}} - N_{\text{Fe,H}_2\text{,FC}})M_{\text{H}_2}LHV_{\text{H}_2}dt + \int_{t_0}^{t} W_{\text{FC,H}_2}dt}{\int_{t_0}^{t} Q_{\text{str},i\text{,PV}}dt} \tag{46}
\]

Similarly, the exergy efficiency is calculated according to

\[
\eta_{ex} = \frac{\int_{t_0}^{t} N_{\text{Fe,O}_2}M_{\text{Fe}_2}\dot{e}_{\text{Fe}_2}dt + \int_{t_0}^{t} (N_{\text{Fe,H}_2\text{,PM}} - N_{\text{Fe,H}_2\text{,FC}})M_{\text{H}_2}\dot{e}_{\text{H}_2}dt + \int_{t_0}^{t} W_{\text{FC,H}_2}dt}{\int_{t_0}^{t} Q_{\text{str},i\text{,PV}}\left(1 - \frac{T_i}{T_S}\right)dt} \tag{47}
\]

where \(N_{\text{Fe,O}_2}\) is the molar rate of oxygen generation, the molar mass of oxygen is written as \(M_{\text{O}_2}\), the enthalpy of produced oxygen is denoted as \(h_{\text{O}_2}\), the molar hydrogen production rate in the electrolyser is written as \(N_{\text{Fe,H}_2\text{,PM}}\), the molar hydrogen consumption rate in the fuel cell is written as \(N_{\text{Fe,H}_2\text{,FC}}\), the molar mass of hydrogen is expressed as \(M_{\text{H}_2}\), the lower heating value is expressed as \(LHV_{\text{H}_2}\), the fuel cell power output is written as \(W_{\text{FC,H}_2}\), the total specific exergy of oxygen is \(\dot{e}_{\text{O}_2}\), the total hydrogen specific exergy is denoted as \(\dot{e}_{\text{H}_2}\), the total input solar energy is written as \(Q_{\text{str},i\text{,PV}}\), the ambient temperature is written as \(T_i\) and the sun temperature is denoted as \(T_S\). Table 1 summarizes the parameters utilized for system simulation and analyses.

### Results and discussion

The engineering equation solver (EES) software is used to perform the simulation and analyses [26]. The hourly solar irradiation and the resulting solar PV power outputs are evaluated for the monthly average days. These are shown in Fig. 2, where the results of PV power outputs are depicted for each hour. The maximum power output is obtained on the average day of June that is found to entail a power output of 346.2 kW at the maximum value. The average day of July is observed to follow June with a maximum power output of 340.4 kW. In addition to this, the amount of available solar energy is also dependent on the total number sunlight hours during the day. As can be observed from Fig. 2, May–July entail 15 h of daylight, which is comparatively higher than other months. The months with less number of daylight hours also entail lower solar intensities. For instance, the solar power output for December is evaluated to have a maximum value of 155.4 kW. Also, December is found to have the lowest daylight hours. Further, January is also found to have comparatively lower power outputs where the peak output power is evaluated to be 168.9 kW. Moreover, the results of oxygen generation rate for each hour on the average days are depicted in Fig. 3. The maximum rate of oxygen generation across all average days is found to be 18.6 g/s, which is observed to occur in June. This is followed by July, which is found to have a maximum oxygen generation rate of 18.3 g/s. The range of oxygen generation rate in June is observed to be 1.77 g/s – 18.6 g/s and the range of oxygen generation rate in July is found to be 0.83 g/s – 18.3 g/s. In addition to this, the range of oxygen generation rate during January and December are found to be 1.18 g/s – 8.65 g/s and 1.29 g/s – 8.05 g/s respectively. Thus, as the oxygen generation rate varies each hour depending on the solar intensity, oxygen is compressed to a higher pressure of 10 bar and stored for later usage. The hourly rates of hydrogen generation are shown in Fig. 4. The maximum rate across the year is found to be 2.32 g/s that occurs in the month of June. This is followed by July, which is associated with a peak hydrogen production rate of 2.28 g/s. Also, the rate of hydrogen production varies between 0.22 g/s – 2.32 g/s in June. Also, July is found to entail hydrogen production rates between 0.10 g/s to 2.28 g/s. However, the least peak hydrogen production rate is observed for December, which has a maximum hydrogen production rate of 1 g/s. Also, January entails a low hydrogen production rate at the peak value, which is found to be 1.08 g/s. Both the rates of hydrogen as well as oxygen production vary with the solar intensities and daylight hours. Thus, the total amount of oxygen and hydrogen produced during the average days is presented in Fig. 5. The maximum amount of oxygen generated during a day is observed to be 614.2 kg,
which is found in June. This is followed by July, which is evaluated to have an oxygen generation of 594.3 kg. Moreover, the least amount of oxygen generated is found for December, which entails a production amount of 170.4 kg. In addition to this, the amount of hydrogen produced on a given day is found to vary between 21.3 kg and 76.8 kg. The lowest and highest production amounts are associated with December and June respectively. Hence, the present system provides an effective technique to generate sufficient oxygen required for ventilators. In addition, sufficient amount of hydrogen is also produced to operate the system in the absence of solar radiation. However, it is suggested to study the present system considering the solar intensities and the daylight hours in different locations.

The total electrolyser energy input results are depicted in Fig. 6 for the average days. The maximum energy input to the
An electrolyser is provided in June where 3058.5 kWh is supplied. Moreover, this is followed by July, which entails an electrolyser energy input of 2951.2 kWh. However, the least energy inputs are provided to the electrolyser in December and January, which entail energy inputs of 841.4 kWh and 949.8 kWh respectively. The energy inputs provided to the electrolyser are a function of the magnitude and length of solar irradiation. Hence, it is recommended to utilize electrolysers considering the highest power inputs that would be provided across the year to ensure maximum rates of hydrogen as well as oxygen can be obtained during high solar availability. As the power input provided to the electrolyser increases, the amount of exergy destroyed also rises as depicted in Fig. 6 (b). The exergy destruction amount reaches its peak value across the year in June that entails a value of 529.7 kWh. Furthermore, average day of July entails an exergy destruction amount of 504.4 kW. The lowest exergy destruction amount is found for December, where 139.9 kWh of exergy is destroyed. Hence, it is suggested to develop electrolysers with lower amounts of irreversibilities, which would aid in attaining higher system performances.

Fig. 3 – Oxygen generation rate results for average monthly days of (a) Jan–Jun and (b) Jul–Dec.
Membranes entailing lower thicknesses and higher conductivities can be implemented to lower the Ohmic voltage losses in the electrolyser. Also, the voltage losses due to activation polarization can be reduced through the usage of higher activity electro-catalysts.

The performance of the hydrogen and oxygen compressors is depicted in Fig. 7. The energy input requirements on average days for each compressor is shown in Fig. 7(a) and the exergy destruction amounts are given in Fig. 7(b). The hydrogen compressor is observed to entail higher energy requirements than the oxygen compressor. For instance, the highest daily energy consumption of the hydrogen compressor is found to be 102.3 kWh while the highest energy consumption of the oxygen compressor is evaluated to be 50.9 kWh. Moreover, the lowest daily energy consumptions of the hydrogen and oxygen compressors are found to be 28.4 kWh and 14.1 kWh respectively. It is also suggested to investigate the system performance considering different storage pressures, where the energy requirements of the compressors will be dependent on the values of compressor outlet pressures. The exergy destructions are also found to be higher in the hydrogen compressor as compared to the
oxygen compressor. This can be attributed to the higher power input requirements of the hydrogen compressor owing to lower density of hydrogen. As the volumetric density of hydrogen entails a comparatively lower value than the volumetric density of oxygen, the power input requirements and thus the exergy destruction rates are higher for the hydrogen compressor. For instance, the highest daily exergy destruction in hydrogen compressor is evaluated to be 96.5 kWh while in the oxygen compressor it is observed to be 24.6 kWh. Moreover, lowest amounts of exergy destruction that are found to occur in the hydrogen and oxygen compressors entail values of 26.8 kWh and 6.84 kWh respectively. Thus, it is suggested to manufacture and utilize compressors with lower irreversibilities and thus lower exergy destruction rates. These will also aid in attaining higher overall system performances.

The fuel cell energy output provided to the ventilators and the operation time for the average days is shown in Fig. 8. The operation time when low solar availability exists, such as January and December reaches 15 h. Moreover, when high solar intensities are present such as in June and July, the fuel cell energy outputs entail comparatively lower values of 270 kWh. Also, the operation times during these months are found to be 9 h. The results for the overall system efficiencies are depicted in Fig. 9. The range of energy efficiency is found to be 13.2%–14.3% during the year.

Fig. 5 – Total daily hydrogen and oxygen production results.

Fig. 6 – Total daily electrolyser energy input and exergy destruction results.
Similarly, the exergy efficiency range is evaluated to be 12.3%–13.4%. Comparatively higher efficiencies are found for December, entailing exergetic and energetic efficiencies of 13.4% and 14.3% respectively. Moreover, the lowest efficiencies of 12.3% and 13.2% are found exergetically and energetically for October. The efficiencies of the developed system can be enhanced with the usage of higher efficiency solar PV panels. The primary process entailing highest energy losses in the present system can be identified as the energy conversion process from thermal to electrical energy in the PV panels. Moreover, it is suggested to study the proposed system with integration with other renewable energy resources. In the present study, the effects of air pollutants and impurities have been considered negligible. However, such contaminants in air may deteriorate the fuel cell performance over time. The air filters are then required to capture these contaminants from air before utilizing it as an oxidant for the fuel cell. Hence, it is recommended to investigate the present system by incorporating the effects of air contaminants and the energy requirements for their treatment [27]. Also, other externalities can affect the system performance such as the actual temperature, altitude, sky clarity, etc. It is hence recommended to investigate the effects of such parameters on the performance of the overall system as well as subsystems.

The capital costs of major system components are evaluated according to the cost functions provided in Table 1. The capital cost of the solar PV panels is evaluated to be $970000. This is determined according to the capital cost function for solar PV systems provided in Table 1 and the

![Fig. 7 – Oxygen and hydrogen compressor energy inputs and exergy destruction results.](image-url)
corresponding power output capacity ($W_{PV}$) considered in the present study that entails a value of 485 kW. In addition to this, the electrolysis and fuel cell subsystems are considered to have capacities of 350 kW that entails individual capital costs of $350000. Moreover, the capital cost functions of the compression subsystems are also provided in Table 1 that are evaluated to be $8186. Furthermore, the total capital cost of the ventilators considering the maximum operational capacity of 20 ventilators is determined to be $200000. However, an economic feasibility analysis of the present system should be considered in future studies where the transient operation is incorporated with corresponding power control strategies.

Conclusions

A new renewable energy-based system is presented for oxygen generation and ventilator operation utilizing solar energy. The latest pandemic outbreak requires the development of such systems that can operate without dependency on the local electricity infrastructure. Solar powered water splitting is implemented for oxygen generation as well hydrogen production through a proton exchange membrane water electrolyser. The produced hydrogen is used for electric power generation during insufficient solar irradiation. Both energetic and exergetic analyses are
conducted dynamically to investigate the performance of the system. The peak amount of oxygen production is found to be 614.2 kg/day. Also, peak hydrogen production reaches 76.8 kg/day. The highest amount of exergy destruction of 529.7 kWh is found to occur in the electrolyser. The peak overall exergy efficiency reaches 13.4% whereas the peak energy efficiency is found to be 14.3%. It is suggested to study the proposed system with other sources of renewable energy such as wind energy. Also, economic feasibility of the proposed system should be investigated.

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.

Nomenclature

A area (m²)
cnv conductivity (S/m)
ex specific exergy (kJ/kg)
F Faradays constant (96,500 C/mol)
G Gibbs free energy (kJ)
h specific enthalpy (kJ/kg)
l solar intensity (kW/m²)
J current density (A/m²)
m mass flow rate (kg/s)
Ms moisture content
n number of moles of electrons
N mole flow rate (mol/s)
P power (kW)
Q thermal energy transfer (kW)
R universal gas constant (8.314 J/molK)
s specific entropy (kJ/kgK)
t time (s)
T temperature (°C)
V voltage (V)

Greek letters

Ω resistance (Ohm.cm²)
η efficiency
α charge transfer coefficient

Subscripts

act actual
at activation
be beam
cn concentration
dest destroyed
en energy
ex exergy
i input
L limiting
p product
no normal
o output
om Ohmic
ot open circuit
PV photovoltaic
sr solar
st solar constant
s sun
zh zenith

Acronyms

C compressor
FC fuel cell
LHV lower heating value
PEM proton exchange membrane
PV photovoltaic
SEP separator

References

[1] Dincer I, Zamfirescu C. Sustainable energy systems and applications. New York: Springer; 2011. https://doi.org/10.1007/978-0-387-95861-3.
[2] Capell An-P Erez I, Mediavilla M, De Castro C, Carpintero O, Miguel UJ. Fossil fuel depletion and socio-economic scenarios: an integrated approach. Energy 2014;77:641–66.
[3] Dincer I. Global warming : engineering solutions. London, New York: Springer; 2010.
[4] Kalinci Y, Hepbasli A. Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. Int J Hydrogen Energy 2015;40:7652–64.
[5] Ishaq H, Dincer I, Naterer GF. Performance investigation of an integrated wind energy system for co-generation of power and hydrogen. Int J Hydrogen Energy 2018;43:9153–64.
[6] Balta MT, Dincer I, Hepbasli A. Potential methods for geothermal-based hydrogen production. Int J Hydrogen Energy 2010;35:4949–61.
[7] Iribarren D, Susmozas A, Petrakopoulou F, Dufour J. Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification. J Clean Prod 2014;69:165–75.
[8] Briguglio N, Andaloro L, Ferraro M, Di Blasi A, Dispensa G, Matteucci F, Breedveld L, Antonucci V. Renewable energy for hydrogen production and sustainable urban mobility. Int J Hydrogen Energy 2010;35:9996–10003.
[9] Turner John, George Sverdrup, Margaret K, Mann, Pin-Ching Maness BK, Maria Ghirardi RJE and DB, Turner J, Sverdrup G, Mann MK, Maness P-C, Kroposki B, Ghirardi M, Evans RJ, Blake D. Renewable hydrogen production. Int J energy Res 2008;33:23–40.
[10] Fan B, Zhang Y, Fan J, Liu Y, Chen W, Otchere P, Wei A, He R. The influence of hydrogen injection strategy on mixture formation and combustion process in a port injection (PI) rotary engine fueled with natural gas/hydrogen blends. Energy Convers Manag 2018;173:527–38.
[11] Hemmes K. Innovative membrane induced functionalities of fuel cells. Int J Hydrogen Energy 2016;41:18837–45.
[12] Tani T, Sekiguchi N, Sakai M, Ohta D. Optimization of solar hydrogen systems based on hydrogen production cost. Sol Energy 2000;68:143–9.
[13] Boudries R. Techno-economic study of hydrogen production using CSP technology. Int J Hydrogen Energy 2018;43:3406–17.
[14] Barton J, Gammon R. The production of hydrogen fuel from renewable sources and its role in grid operations. J Power Sources 2010;195:8222–35.
[15] Paidar M, Fateev V, Bouzek K. Membrane electrolysis—history, current status and perspective. Electrochim Acta 2016;209:737–56.
[16] Cheng X, Shi Z, Glass N, Zhang L, Zhang J, Song D, Liu Z-S, Wang H, Shen J. A review of PEM hydrogen fuel cell contamination: impacts, mechanisms, and mitigation. J Power Sources 2007;165:739–56.

[17] Lamy C, Millet P. A critical review on the definitions used to calculate the energy efficiency coefficients of water electrolysis cells working under near ambient temperature conditions. J Power Sources 2020;447:227350.

[18] Klemenzson GK, Perouansky M. Contemporary anesthesia ventilators incur a significant ‘oxygen cost’. Can J Anesth 2004;51:616–20.

[19] Rathgeber J. Fundamentals of anaesthesia machines and ventilators. Anaesthesist 1993;42:885–909.

[20] Ford P, Foale M. Converting gas-driven ventilators from oxygen to air. Assoc. Anaesth. 2020. https://doi.org/10.1111/anae.15064.

[21] Siddiqui O, Dincer I. Experimental investigation and assessment of direct ammonia fuel cells utilizing alkaline molten and solid electrolytes. Energy 2019;169:914–23.

[22] Ni M, Leung MKH, Leung DYC. Energy and exergy analysis of hydrogen production by a proton exchange membrane (PEM) electrolyzer plant. Energy 2008;49:2748–56.

[23] Amore-Domenech R, Leo TJ. Sustainable hydrogen production from offshore marine renewable farms: techno-energetic insight on seawater electrolysis technologies. ACS Sustainable Chem Eng 2019;7:8006–22.

[24] Villagra A, Millet P. An analysis of PEM water electrolysis cells operating at elevated current densities. Int J Hydrogen Energy 2019;44:9708–17.

[25] World Health Organization. Oxygen sources and distribution for COVID-19 treatment centres. 2020.

[26] Klein SA. Engineering equation solver, V10.462. 2019. Available from, http://www.fchart.com.

[27] Cheng X, Shi Z, Glass N, Zhang L, Zhang J, Song D, Liu Z, Wang H, Shen J. A review of PEM hydrogen fuel cell contamination: impacts, mechanisms, and mitigation. J Power Sources 2007;165:739–56.

[28] Sadykov VA, Eremeev NF, Fedorova YE, Krasnov AV, Bobrova LN, Bespalko YN, Lukashevich AI, Skriabin PI, ol Smorygo, Veen AC. Design and performance of asymmetric supported membranes for oxygen and hydrogen separation. Int J Hydrogen Energy 2021;46:20222–39.

[29] Zolotarenko AD, Zolotarenko AD, Veziroglu A, Veziroglu A, Shvachko NA, Pomytkin AP, Gavrylyuk NA, Schur DV, Ramazanov TS, Gabdullin MT. The use of ultrapure molecular hydrogen enriched with atomic hydrogen in apparatuses of artificial lung ventilation in the fight against virus COVID-19. Int J Hydrogen Energy 2021. https://doi.org/10.1016/j.ijhydene.2021.03.025. In Press. (Online ahead of print).