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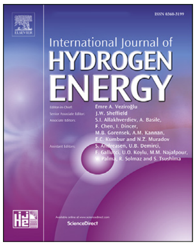

Design and thermodynamic modeling of a renewable energy based plant for hydrogen production and compression

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HIGHLIGHTS

- A solar and wind energy based integrated system is proposed and evaluated.
- Renewable energy-assisted hydrogen and power production is investigated.
- The detailed performance evaluation of the system is done through energetic and exergetic assessment.
- The energy and exergy efficiencies of the whole system are determined as 0.21 and 0.16, respectively.

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ABSTRACT

In the examined paper, a solar and wind energy supported integrated cycle is designed to produce clean power and hydrogen with the basis of a sustainable and environmentally benign. The modeled study mainly comprises of four subsystems; a solar collector cycle which operates with Therminol VP1 working fluid, an organic Rankine cycle which runs with R744 fluid, a wind turbine as well as hydrogen generation and compression unit. The main target of this work is to investigate a thermodynamic evaluation of the integrated system based on the 1st and 2 nd laws of thermodynamics. Energetic and exergetic efficiencies, hydrogen and electricity generation rates, and irreversibility for the planned cycle and subsystems are investigated according to different parameters, for example, solar radiation flux, reference temperature, and wind speed. The obtained results demonstration that the whole energy and exergy performances of the modeled plant are 0.21 and 0.16. Additionally, the hydrogen generation rate is found as 0.001457 kg/s, and the highest irreversibility rate is shown in the heat exchanger subcomponents. Also, the net power production rate found to be 195.9 kW and 326.5 kW, respectively, with organic Rankine cycle and wind turbine. The final consequences obtained from this work show that the examined plant is an environmentally friendly option, which in terms of the system's performance and viable, for electrical power and hydrogen production using renewable energy sources.

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Introduction

Global warming and environmental deteriorations raised by fossil fuels have caused a major negative impact on life throughout the world in recent years. In addition, fossil fuels are thought to have limited supply resources and will not be sufficient to meet the growing energy needs in the future [1]. Therefore, it has been an important motivation for the utilization of clean energy resources for a sustainable environment. In this context, renewable power resources, for example, solar, wind, geothermal, etc., have gained considerable importance in terms of sustainable power production and environment. Among these power resources, solar and wind energies are the most alternatives [2–5].

Solar and wind power production plants are very important to deal with environmental problems. However, in the solar power generation systems, the amount of energy generated is directly influenced by the cloudy sky or when there is insufficient solar radiation at night. This situation can be defined as the disadvantage of these systems. Therefore, incorporating multiple renewable power resources, for example, solar and wind in a combined plant rises the cycle reliability and ensures sustainable energy production [5].

Hydrogen energy is considered a promising solution for environment troubles for example global warming and climate change, and also acceptable as a carbonless and sustainable energy carrier. Hydrogen has the high-density values per mass, if it is generated from renewable powers and water, its production, storing, carrying and final utilization do not damage the environment. Also, produced hydrogen should be stored in different ways (gaseous, liquid, or with metal hydrides, etc.). In consequence of the combustion of renewable hydrogen in a fuel cell, the emission contains only water and in small quantities of NOx [6]. In particular, hydrogen energy produced in combination with renewable energy sources is a promising solution to global warming, environmental issues, and energy-related issues [7]. To achieve sustainable energy generation, hydrogen must be used in a combined power cycle integrated with renewable energy support.

Many researchers have presented numerous studies in the literature on renewable energy (solar, wind, biomass and etc.) based combined power cycles for environmentally benign hydrogen production. Al-Sharafi et al. [5] have investigated a techno-economic evaluation of solar-wind assisted electricity and hydrogen generation in Saudi Arabia. They have examined the production of power and hydrogen in the Saudi Arabia climate conditions with different solar irradiance and wind speeds. The lowest energy cost and hydrogen generation cost are found as 1.208 $/kWh and 43.1$/kg for Abha area. Kalinci [8] has studied a hybrid renewable power based cycle for hydrogen generation in Bozcaada Island, Turkey. The outcomes indicate that although the grid's electricity price is 0.103 $/kWh, the most suitable plant for the grid connecting is the grid/wind with 0.17$/kWh.

Ozlu et al. [9] investigated and compared five specific hybrid systems for electrical, cooling and heating demands for Southern Ontario residence. They have performed thermodynamic, economic and environmental assessments, and their outcomes display that the heat pump plants are the most suitable alternatives among the other plants. According to their study, the wind turbine-fuel cell combined plant is using renewable energy and saving 16.1 tons of CO_2 emissions. Gokcek and Kale [10] proposed a techno-economic evaluation of PV and wind energy supported hybrid cycle based hydrogen refueling station with PEM electrolyzer in Izmir-Çeşme, Turkey. In their study, they used average wind speed and average solar irradiation of 5.72 m/s and 5.08 kWh/m^2/day throughout the year. Their study leveled cost of hydrogen production is 7.526–7.866 $/kg, according to different cycle design solutions.

Ishaq et al. [11] performed a thermodynamic performance assessment of wind turbine combined cycle for hydrogen generation and co-generation. Their proposed study includes a, a PEM electrolyzer, a hydrogen fuel cell and wind turbine. They considered variable wind speeds for thermodynamic calculations. The results of their paper expression that total energetic and exergetic performance are determined as 20.2% and 21.2%, respectively. Zafar and Dincer [12] performed a thermodynamic and exergoeconomic assessment of wind turbine, photovoltaic and fuel cell driven cycle for hydrogen, electricity and hot water generation. Their study outcomes demonstration that the system's energetic and exergetic performances increase by about 14% and 21% respectively. Also, water is heated for domestic utilization aims. Khalid et al. [13] examined a thermodynamic and economic evaluation of renewable energy supported combined cycle. Their planned study includes of solar collector, wind turbine, ORC, heat pump subsystem. The thermodynamic analyses result of their study show that total energy efficiency is 46.1%, while the exergy efficiency is 7.3%.

Ishaq et al. [14] analyzed a thermodynamic examinations of the solar-wind hybrid trigeneration cycle for power, heat and hydrogen generation. The work outputs are hydrogen, electricity, and heat. Also, their examined study comprises of the solar heliostat field, hydrogen generation with copper-chlorine (Cu–Cl) cycle and hydrogen compression plant. The results of their work determined that energetic efficiency is 49% whereas the exergy efficiency is 48.2%. Atiz et al. [15] have investigated the electrical and hydrogen generation performance of vacuum tube solar collectors. Their modeled plant consists of an evacuated solar collector with 300 m^2 area ORC and electrolysis. The total energetic and exergetic efficiencies of their planned work are 5.92% and 18.21%. Nikolaidis and Poullikkas [16] projected a detailed overview of hydrogen generation processes supported by natural gas, coal, solar and wind. They discussed 14 different hydrogen production methods as technically and economically. Luqman et al. [17] have investigated the thermodynamic examination of oxy-hydrogen combustor based wind-solar energy-assisted multigeneration cycle. They designed their suggested work to generate useful products for example clean water, electricity, cooling, hydrogen, oxygen, hot water and drying. The total energetic and exergetic efficiency of the process are 50% and 45%, respectively. Yilmaz et al. [18] have explored a thermodynamic calculation of the solar powered integrated system for hydrogen generation. Their recommended plant comprises of Rankine cycle, heat pump, dryer, ORC, PEM, parabolic solar collector, and double effect cooling cycle. The results

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display that entire energy and exergy efficiencies are 48.19% and 43.57%.

Safari and Dincer [19] conducted an evaluation and optimization of a hybrid wind power plant for hydrogen and methane generation. The thermodynamic calculation results of their work show that energy efficiency is 44% and exergy efficiency is 45%. Furthermore, they stated that an increase in wind speed caused drops in exergy performance and an increment in hydrogen and methane generation. Keshtkar and Khaini [20] examined an exergoeconomic assessment and optimization of wind and solar hybrid plant for multigeneration in Iran. Their suggested plant contains of the solar collector cycle, wind turbine, Rankine cycle, absorption cooling cycle, electrolyzer, and desalination system. The results show that exergetic efficiency and operating cost rate of cycle are computed as 32.88% and 8.45 $/h.

The work of Siddiqui and Dincer [21] suggests the design and investigation of a solar and wind-assisted plant for energy storage. Their suggested plant is combined with both solar and wind power sources. They determined that the total energetic and exergetic performance of the considered plant varies between 46.1-53.3% and 34–41.55%. Ozcan and Dincer [22] examined a thermodynamic investigation of the hydrogen generation and compression plant driven by solar energy. The work contains of the supercritical gas turbine cycle, Mg–Cl thermochemical process with four-step and hydrogen compression plant. The whole energy and exergy performances are 6.31% and 39.8%, respectively, for 1 kmol/s hydrogen production rate. Hoffmann [23] investigated a solar thermal hydrogen production plant in South Africa. This study proposed several ways to integrate solar energy technologies into hydrogen production for carbon-free hydrogen in South Africa. Also, the study results show that high-temperature steam electrolysis decreases the energy demands of the hydrogen production plant.

Boudries [24] has performed an evaluation of the solar hydrogen generation cycle for Algeria. The key aim of his work is to assess the potential of hydrogen generation by utilizing electrolysis concentrator photovoltaic plant for distinct regions in Algeria. The results of the study concluded that the hydrogen generation capacity per unit cell area is near 0.19 kg-H_2 m^{-2} during the most appropriate month using the Fresnel reflector. Zhang et al. [25] have conducted an optimization of a solar and wind energy-assisted hybrid reverse osmosis process. The primary contribution of their work is the design optimization method of an integrated desalination process operating with solar and wind power. It concluded that the integrated solar, battery and desalination systems drop the plant cost and increase plant reliability and freshwater availability, according to their study results. Blal et al. [26] have proposed a study on the evaluation of solar and wind power for the potential hydrogen generation of the Algerian and the improvement of a methodology for the use of hydrogen-based fuel cells. In this study, they investigated the evaluation of renewable energy sources in different regions of Algeria, particularly in the Adrar region, where solar radiation is exceeded more than 2300 kWh/m^2. According to their study, they estimated the predictable amount of potential hydrogen generation in different regions of Algeria as 6,477,460,26 m^3, and also concluded that Algeria has significant hydrogen potential from wind and sun.

The study of Alavi et al. [27] investigates the thermal analysis of the stand-alone wind hydrogen power conversion plant. In their study, they examined the reliability assessment aspect of the system, which consists of two main sections which are rectifier and bucket converter. According to the results of the study they proposed, the estimated average downtime of the hybrid cycle is about 7.6 years. Ayodele and Munda [28] have examined the green hydrogen generation by wind power assisted water electrolysis for South Africa in terms of potential and economic applicability. They performed sensitive analyses and concluded that wind speed has an important impact on the cost of hydrogen generation compared to other wind turbine factors. Rabbani et al. [29] have done a performance examination of solar energy-based a new combined plant. They designed the system to produce hydrogen in a maintainable method and to provide 500 MW of electrical power, hot water, and air and also, they observed the energy and exergy losses of the plant components according to the thermodynamic model. As shown from their study results, energy efficiency rises clearly from 60% to 80% with a rise in reference temperature.

Caliskan et al. [30] have observed a renewable energy supported hydrogen generation plant in terms of exergoeconomic and environmental effect evaluations. In their proposed study, which an integrated solar and wind energy system, the energy, exergy, and sustainability assessments are conducted to examine the system, and also conducted a parametric study of different reference temperatures (10-20-30 °C). The overall exergy performance of their suggested model is determined as 5.865%, at 30 °C reference temperature. Kovač et al. [31] have investigated solar energy assisted hydrogen generation through alkaline water electrolysis. In their proposed work, they surveyed the hydrogen production with the solar power system having a capacity of 960 Wp, and also computed the hydrogen production rate as 1.138 g per hour.

Mostafaeipour et al. [32] have worked on a hydrogen generation system with renewable wind energy for different sectors. They have investigated the economic feasibility assessment of hydrogen generation for the agricultural and industrial sectors for the four cities of Ardebil, Iran. They stated that 5253 kg of hydrogen can be generated annually in Ardebil city, according to their examination results. Acar and Dincer [33] have explored the review and assessment of hydrogen generation alternatives for preferable environment. They have studied that diverse hydrogen generation resources and plants, and also some hydrogen storage ways in detail. The consequences of their paper show that the maximum environmental performance (8/10) is seen in solar, while nuclear has the minimum environmental performance (3/10).

When the previous studies presented in the literature are examined, generally, recent publications include energy and exergy efficiencies evaluation of the solar-powered hydrogen generation cycles. In addition, the hydrogen produced by the PEM electrolyzer is in the gas phase, and there is a storage problem due to its high density. The key motivation of this work is to design a small scale solar and wind supported

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hydrogen production cycle and compression of hydrogen at 70000 kPa.

The key scope of this paper is to examine the clean hydrogen and power generation system assisted by renewable energy sources. In this work, a novel small scale solar-wind turbine supported hydrogen production and compression system are investigated by using the thermodynamic viewpoints. In this regard, energy and exergy efficiencies, exergy destruction rate, and hydrogen generation rate of the examined hybrid plant are examined in detail. The planned cycle consists of the solar vacuum tube collector, wind turbine, ORC and hydrogen generation and compression units. In addition, this plant is designed for hydrogen and power generation, and also, the change of thermodynamic performance based on different parameters are examined. The main objectives of this work can be highlighted as given below;

- To design a solar collector and wind turbine supported power and hydrogen generation by using clean and sustainable method.
- To carry out a detailed thermodynamic assessment of the integrated system.
- To investigate the energetic and exergetic efficiency of the combined system.
- To study the impact of some design factors on hybrid plant efficiency.

System description

Undoubtedly, solar power can be described as the most common renewable energy resource. However, in the evenings or in cloudy weather conditions, solar energy systems are directly negative affected. Therefore, it may be possible to eliminate this negative effect if solar-assisted systems are used in integrated with renewable power resources such as wind and geothermal energy. The schematic design of modeled solar and wind-assisted hybrid plant is exhibited in Fig. 1. In this hybrid cycle, solar and wind energy resources are used as energy resources during day and night periods. The designed hybrid system comprises of a solar vacuum tube collector which contains therminol VP-1 molten salt, an ORC which operates with CO_2 refrigerant, a wind turbine, a PEM electrolyzer for hydrogen generation, and also hydrogen compression component. In the examined hybrid plant, the solar collector is utilized to provide the thermal power required for

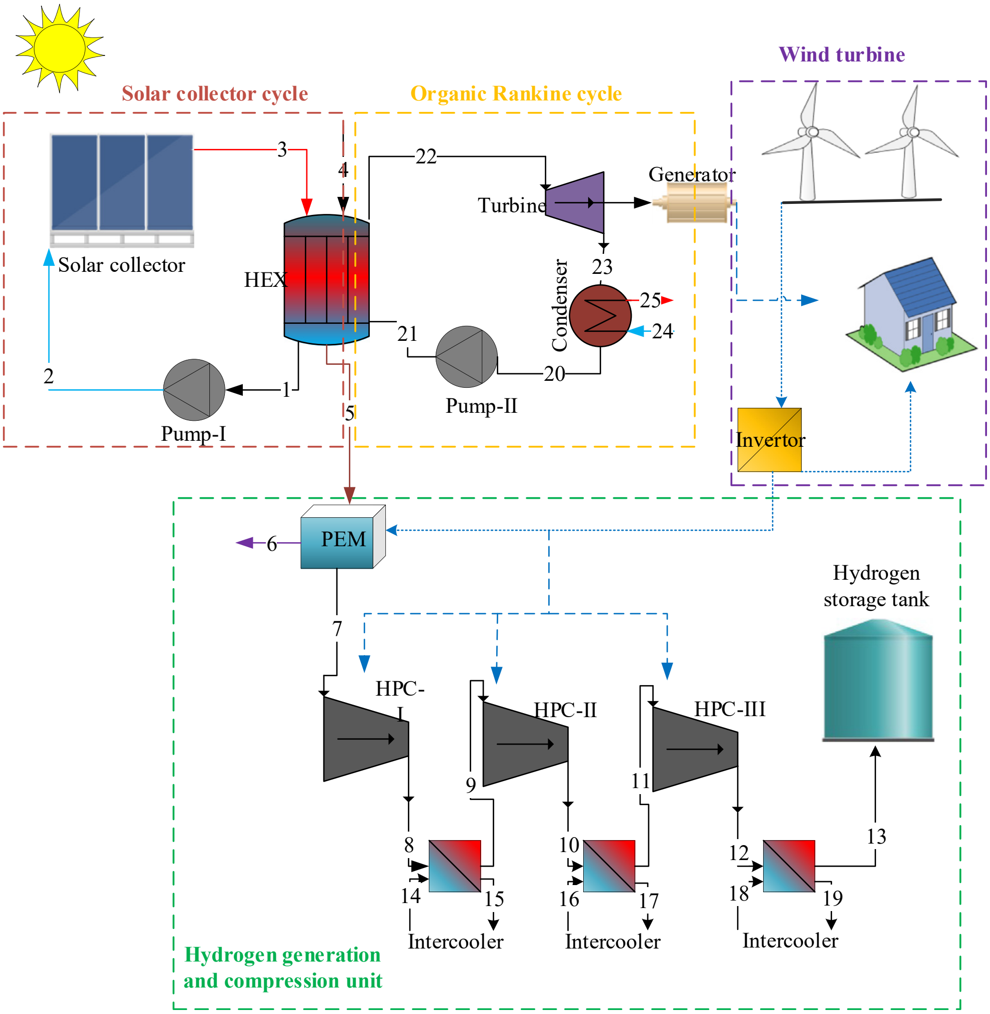

Fig. 1 – Schematic diagram of the examined study.

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the operation of the ORC. Furthermore, power generation is derived from ORC and wind turbine.

In this cycle, the molten salt is heated by the solar collector, and after that, enters the heat exchanger (HEX) at flow 3. The solar collector working fluid temperature is transferred to HEX at point 3 and then it enters the pump-I at flow 1. Subsequently, ORC working fluid CO_2 enters HEX and converts into superheated vapor by absorbing heat through HEX, at point 22. After that, the superheated vapor CO_2 refrigerant at pint 22 enters the ORC turbine for electrical power production. After exiting point 23, the CO_2 refrigerant is condensing in the condenser sub-component outlet state (point 20), and then enters in the ORC pump as the statured liquid phase. The ORC cycle completes the cycle in this way. In addition to this, power is also produced in the wind turbine which mainly depend on the wind speed. Wherein some of the electrical energy obtained is used to meet the electrical need of the compressors in the hydrogen compression unit, while another part of it is sent to PEM electrolysis for hydrogen production.

A part of the produced electricity is passed through to the PEM electrolyzer. Wherein the water molecule from point 5 is separated into hydrogen and oxygen molecules. The hydrogen energy produced in the gas form is sent to the hydrogen compression unit at point 7. The hydrogen enters the hydrogen compression compressors and is pressurized by the passing at points 8-9-10-11-12, respectively. And then it sent to the storage tank as compressed hydrogen at under the 80 °C temperature and 70000 kPa pressure, at 13 points, through a three-stage compression system. After that, the stored hydrogen can be used in cases of insufficient wind speed and solar radiation. Finally, another part of the electrical power can be used for domestic applications. Design parameters of the suggested cycle for thermodynamic calculation are illustrated in Table 1.

Thermodynamic modeling and assessment

Solar collector and wind turbine systems integrated for electricity and hydrogen generation cycle is presented in Fig. 1. In this section, thermodynamic modeling of this proposed hybrid cycle is given according to the energy and exergy performance analyzes. Also, the comprehensive thermodynamic analysis is conducted by Engineering Equation Solver (EES) program [[34]] to investigate suggested system performance, as well as the hydrogen and power production. The impact of some design factors on electricity and hydrogen generation, energy and exergy efficiencies and irreversibility rate of the suggested plant are examined parametrically. The system and its sub-components are handled separately, and then, the whole system is analyzed. To perform thermodynamic evaluation, some reasonable assumptions are considered, and also, these assumptions are presented as below [11,35];

Table 1 – Design parameters of the suggested plant.

Design parameters	Data
Solar collector working fluid	Therminol_VP1
Average solar irradiation	600 (W/m^2)
Number of collectors	2
One vacuum tube solar collector area	1.8 m^2
Pump-I inlet temperature	60.2 °C
Wind turbine diameter	34 m
Average wind speed	5.2 m/s
Wind turbine power coefficient	60%
Number of wind turbines	2
ORC working fluid	Carbon dioxide (R744)
ORC turbine and pump isentropic efficiency	85%
Heat exchanger efficiency	80%
Hydrogen storage tank pressure (P_{13})	70000 kPa
Hydrogen compression stage	3
Hydrogen compression pressure ratio	7.8–8.8
Hydrogen inlet pressure (P_7)	101.325 kPa

- The proposed cycle and components are work under steady-state conditions.
- The dead state conditions which are temperature and pressure are accepted as 25 °C and 101.325 kPa.
- The pressure drops in whole HEX's and the pipelines are disregarded.
- The ORC condenser exit point is statured liquid.
- The total heat losses in HEX's are assumed as %20.
- The wind turbine performance is accepted as 90%.
- The isentropic efficiency of the pumps and ORC turbines are accepted as 85%.
- Intercooling process in the hydrogen compression stages water is used as a cooler [36].
- The ORC pump inlet temperature is the statured liquid temperature corresponding inlet pressure of pump, which is 3000 kPa.

The mass, energy, entropy and exergy balance equalities of thermodynamic plant should be described as in the below equations from 1 to 4 [37–40];

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\sum \dot{m}_i h_i + \dot{Q}_i + \dot{W}_i = \sum \dot{m}_e h_e + \dot{Q}_e + \dot{W}_e \tag{2}$$

$$\sum \dot{m}_i s_i + \frac{\dot{Q}_i}{T} + \dot{S}_{gen} = \sum \dot{m}_e s_e + \frac{\dot{Q}_e}{T} \tag{3}$$

$$\sum \dot{m}_i ex + \dot{Ex}_Q = \sum \dot{m}_e ex + \dot{Ex}_W + \dot{Ex}_{des} \tag{4}$$

here, *ie*, $\dot{Q}$ and $\dot{W}$ are descripted as the inlet, exit, heat transfer rate and work rate, respectively. In addition, $\dot{Ex}_{des}$ are defined as the exergy destruction rate. If the kinetic, potential and chemical exergies are negligible, the physical exergy can be given as;

$$ex_{ph} = h - h_o - T_o(s - s_o) \tag{5}$$

Also, the heat and work exergy are given as below;

$$\dot{Ex}_Q = \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{6}$$

$$\dot{Ex}_W = \dot{W} \tag{7}$$

The general thermodynamic equilibrium equalities, which

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are mass, energy, entropy and exergy, of major sub-systems for the proposed plant are offered in the following sections;

Solar collector;

$$\dot{m}_2 = \dot{m}_3 \tag{8}$$

$$\dot{m}_2 h_2 + \dot{Q}_{solar} = \dot{m}_3 h_3 \tag{9}$$

$$\dot{m}_2 s_2 + \dot{S}_{gen,SC} = \dot{m}_3 s_3 \tag{10}$$

$$\dot{m}_2 ex_2 + \dot{Q}_{solar}\left(1 - \frac{T_0}{T_{SC}}\right) = \dot{m}_3 ex_3 + \dot{E}x_{d,SC} \tag{11}$$

Heat exchanger (HEX);

$$\dot{m}_3 = \dot{m}_1\ ;\ \dot{m}_{21} = \dot{m}_{22}\ ;\ \dot{m}_4 = \dot{m}_5 \tag{12}$$

$$\dot{m}_3 h_3 + \dot{m}_{21} h_{21} + \dot{m}_4 h_4 = \dot{m}_1 h_1 + \dot{m}_5 h_5 + \dot{m}_{22} h_{22} \tag{13}$$

$$\dot{m}_3 s_3 + \dot{m}_{21} s_{21} + \dot{m}_4 s_4 + \dot{S}_{gen,HEX} = \dot{m}_1 s_1 + \dot{m}_5 s_5 + \dot{m}_{22} s_{22} \tag{14}$$

$$\dot{m}_3 ex_3 + \dot{m}_{21} ex_{21} + \dot{m}_4 ex_4 = \dot{m}_1 ex_1 + \dot{m}_5 ex_5 + \dot{m}_{22} ex_{22} + \dot{E}x_{d,HEX} \tag{15}$$

Pump-I;

$$\dot{m}_1 = \dot{m}_2 \tag{16}$$

$$\dot{m}_1 h_1 + \dot{W}_{P\_I} = \dot{m}_2 h_2 \tag{17}$$

$$\dot{m}_1 s_1 + \dot{S}_{gen,P\_I} = \dot{m}_2 s_2 \tag{18}$$

$$\dot{m}_1 ex_1 + \dot{W}_{P\_I} = \dot{m}_2 ex_2 + \dot{E}x_{d,P\_I} \tag{19}$$

Turbine;

$$\dot{m}_{22} = \dot{m}_{23} \tag{16}$$

$$\dot{m}_{22} h_{22} = \dot{m}_{23} h_{23} + \dot{W}_T \tag{17}$$

$$\dot{m}_{22} s_{22} + \dot{S}_{gen,T} = \dot{m}_{23} s_{23} \tag{18}$$

$$\dot{m}_1 ex_1 + \dot{W}_T = \dot{m}_2 ex_2 + \dot{E}x_{d,T} \tag{19}$$

Condenser;

$$\dot{m}_{23} = \dot{m}_{21}\ ;\dot{m}_{24} = \dot{m}_{25} \tag{20}$$

$$\dot{m}_{23} h_{23} + \dot{m}_{24} h_{24} = \dot{m}_{20} h_{20} + \dot{m}_{25} h_{25} \tag{21}$$

$$\dot{m}_{23} s_{23} + \dot{m}_{24} s_{24} + \dot{S}_{gen,con} = \dot{m}_{20} s_{20} + \dot{m}_{25} s_{25} \tag{22}$$

$$\dot{m}_{23} ex_{23} + \dot{m}_{24} ex_{24} = \dot{m}_{20} ex_{20} + \dot{m}_{25} ex_{25} + \dot{E}x_{d,con} \tag{23}$$

Pump-II;

$$\dot{m}_{20} = \dot{m}_{21} \tag{24}$$

$$\dot{m}_{20} h_{20} + \dot{W}_{P\_II} = \dot{m}_{21} h_{21} \tag{25}$$

$$\dot{m}_{20} s_{20} + \dot{S}_{gen,P\_II} = \dot{m}_{21} s_{21} \tag{26}$$

$$\dot{m}_{20} ex_{20} + \dot{W}_{P\_II} = \dot{m}_{21} ex_{21} + \dot{E}x_{d,P\_II} \tag{27}$$

PEM electrolyzer;

$$\dot{m}_5 = \dot{m}_6 + \dot{m}_7 \tag{28}$$

$$\dot{m}_5 h_5 + \dot{W}_{PEM} = \dot{m}_6 h_6 + \dot{m}_7 h_7 \tag{29}$$

$$\dot{m}_5 s_5 + \dot{S}_{gen,PEM} = \dot{m}_6 s_6 + \dot{m}_7 s_7 \tag{30}$$

$$\dot{m}_5 ex_5 + \dot{W}_{PEM} = \dot{m}_6 ex_6 + \dot{m}_7 ex_7 + \dot{E}x_{d,PEM} \tag{31}$$

Hydrogen pressure compressor I (HPC—I);

$$\dot{m}_7 = \dot{m}_8 \tag{32}$$

$$\dot{m}_7 h_7 + \dot{W}_{HPC\_I} = \dot{m}_8 h_8 \tag{33}$$

$$\dot{m}_7 s_7 + \dot{S}_{gen,HPC\_I} = \dot{m}_8 s_8 \tag{34}$$

$$\dot{m}_7 ex_7 + \dot{W}_{HPC\_I} = \dot{m}_8 ex_8 + \dot{E}x_{d,HPC\_I} \tag{35}$$

Hydrogen pressure compressor II (HPC-II);

$$\dot{m}_9 = \dot{m}_{10} \tag{36}$$

$$\dot{m}_9 h_9 + \dot{W}_{HPC\_II} = \dot{m}_{10} h_{10} \tag{37}$$

$$\dot{m}_9 s_9 + \dot{S}_{gen,HPC\_II} = \dot{m}_{10} s_{10} \tag{38}$$

$$\dot{m}_9 ex_9 + \dot{W}_{HPC\_II} = \dot{m}_{10} ex_{10} + \dot{E}x_{d,HPC\_II} \tag{39}$$

Hydrogen pressure compressor III (HPC-III);

$$\dot{m}_{11} = \dot{m}_{12} \tag{40}$$

$$\dot{m}_{11} h_{11} + \dot{W}_{HPC\_III} = \dot{m}_{12} h_{12} \tag{41}$$

$$\dot{m}_{11} s_{11} + \dot{S}_{gen,HPC\_III} = \dot{m}_{12} s_{12} \tag{42}$$

$$\dot{m}_{11} ex_{11} + \dot{W}_{HPC\_III} = \dot{m}_{12} ex_{12} + \dot{E}x_{d,HPC\_III} \tag{43}$$

Wind turbine;

Wind turbine power generation rate can be calculated as [11,25,30];

$$\dot{W}_{wt} = \frac{1}{2}\eta_{wt}\rho_{air}A_{wt}C_{p,wt}V^3 \tag{44}$$

In Eq. (44), $\dot{W}_{wt}$ is the wind turbine electricity, η_{wt} is the efficiency of wind turbine, ρ_{air} is the air density [35]. For the wind turbines, the directly coming energy ($\dot{W}_{wt\_i}$), and the exergy ($\dot{E}x_{wt}$) and exergy destruction rates ($\dot{E}x_{dest,wt}$) can be formulated as below;

$$\dot{W}_{wt\_i} = \frac{1}{2}\rho_{air}A_{wt}C_{p,wt}V^3 \tag{45}$$

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Table 2 – Main outputs of the proposed study.

Systems	Outputs
ORC net power production rate (kW)	195.9
Wind turbine net power production (kW)	326.5
Input of electricity for PEM (kW)	163.25
Input of total electricity for hydrogen compressors (kW)	6.145
Hydrogen production rate (kg/s)	0.001457
Energy efficiency for overall plant	0.21
Exergy efficiency for overall plant	0.16

$$\dot{E}x_{wt} = \frac{1}{2}\rho_{air} A_{wt} V^3 \quad (46)$$

$$\dot{E}x_{dest,wt} = \left(\frac{1}{C_{p,wt}}\right)\dot{W}_{wt} \quad (47)$$

Overall system efficiencies

The main mission of this proposed study is the hydrogen and electrical power generation through solar and wind energy. Firstly, the net electricity generated from integrated system is determined as follows;

$$\dot{W}_{net} = (\dot{W}_{wt} + \dot{W}_T) - \dot{W}_{P\_I} - \dot{W}_{P\_II} - \dot{W}_{HPC\_I} - \dot{W}_{HPC\_II} - \dot{W}_{HPC\_III} \quad (48)$$

While calculating the total energy and exergy performances of the whole plant, the useful outputs obtained from the plant or the exergy outputs are divided by the energy or exergy values entering the plant. The total energy and exergy efficiencies of the suggested system can be computed as;

$$\eta_{system} = \frac{\dot{W}_{net} + \dot{m}_{H2} LHV_{H_2}}{\dot{Q}_{solar} + \dot{W}_{wt\_i}} \quad (49)$$

$$\psi_{system} = \frac{\dot{W}_{net} + \dot{m}_{H2} ex_{H_2}}{\dot{E}x_{Q_{solar}} + \dot{W}_{wt\_i}} \quad (50)$$

Results and discussion

The thermodynamic investigation of examined cycle is conducted using the EES program which is based on mass, energetic, entropy, and exergetic equilibrium equalities as mentioned above section. According to thermodynamic calculation results of the suggested study based on Table 1, the suggested plant main outputs are charted in Table .2. In this paper, one of the wind turbines is designed to meet the electrical need of PEM electrolysis. The net power production rates by the wind turbine and ORC as 326.5 and 195.6 kW, respectively. Subsequently, the general energy and exergy efficiency of the examined system are 0.21 and 0.16. Moreover, the hydrogen production rate is 0.001457 kg/s.

Fig. 2 illustrates the exergy destruction rates of examined hybrid cycle main subcomponents. The HEX sub-component has the maximum irreversibility rate with 2966 kW, while the solar collector has the minimum irreversibility with 1.2525 kW. After that, the second highest irreversibility rate is found to be 1167 kW in the condenser of ORC subsystem. This is due to the high irreversibility rates in the HEX and condenser the fact that the R744 refrigerant is preferred in the ORC system as working fluid. Furthermore, the reason for this situation, the higher irreversibilities occurred in these two subcomponents where mixed two different working fluids at high temperatures.

The varying of environment temperature is an important parameter for thermal system design. Figs. 3–5 represent the effect of environment temperature on the plant performance, hydrogen and net power generation rates and irreversibility rate, for the examined plant. In Fig. 3, it is clearly shown that, the thermodynamic performance of the overall plant reduction with the rising reference temperature from 0 to 40 °C. Also, the examined study results demonstrated that the reference temperature is inversely proportional to the system performance. The main reason for this situation is that the decrease in power generation from the wind turbine by means of the increase in the reference temperature. A similar

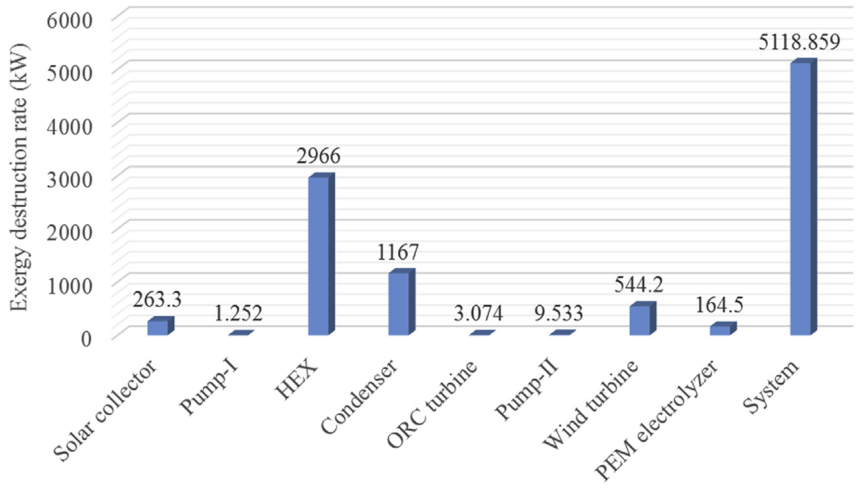

Fig. 2 – Exergy destruction rate of the main components of the studied plant.

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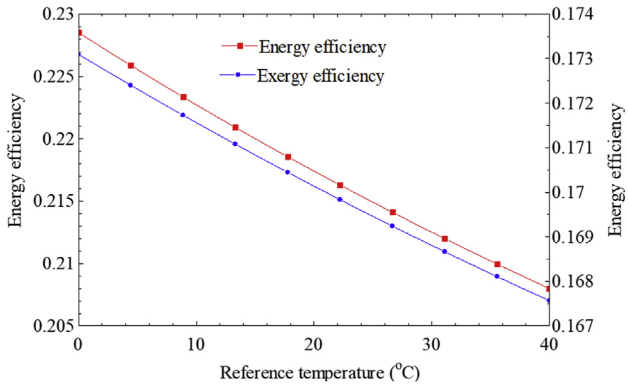

Fig. 3 – Variations of energy and exergy efficiency of the overall system with reference temperature.

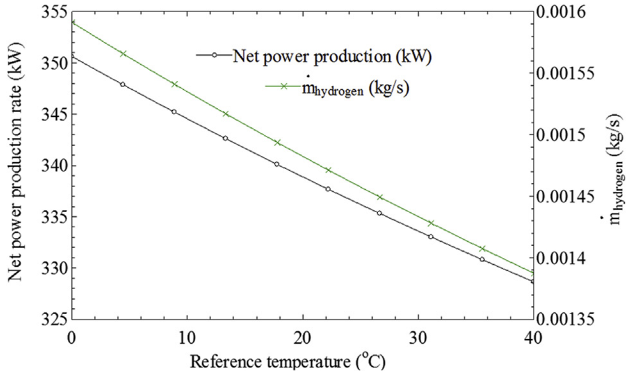

Fig. 4 – Variations of power and hydrogen generation with reference temperature.

situation as in Fig. 3, the decreases net power generation as well as hydrogen generation with rising the reference temperature demonstrated in Fig. 4. Increment in the dead state temperature from 0 °C to 40 °C, the hydrogen generation rate drops in from 0.0016 to approximately 0.0014 kg/s. In short, for the above specified both figures, it can be said that, as the reference temperature rises, the density of air reduces and then based on Eq. (44) produced electrical power through wind turbine decreases.

The variation of irreversibility rates of the whole cycle and subsystems due to increasing reference temperature is exhibited in Fig. 5. While the increase in the dead state temperature from 0 to 40 °C, the irreversibility rate of the overall plant and major subcomponents drops except for solar collector. The reason for this trend in the solar collector is the rise in the reference temperature give rise to increases the irreversibility of solar collector at high temperature. Among the subsystems, the ORC subsystem has a maximum irreversibility rate due to the inclusion of HEX. Because the HEX subcomponent has two different working fluids (Therminol VP-1 and CO_2), the exergy destruction rate is high.

Another important parameter in this work is varying of the solar irradiation because solar power is used as a thermal energy reservoir, which the required to works of ORC subsystem and heating of water. Fig. 6 displays the impact of solar irradiation on the examined plant performances. As can be understood in Fig. 6, the energetic and exegetic efficiency of the suggested plant reduce with rise in the solar energy intensity from 500 to 1000 W/m^2. Also, it can be specified that the rising solar irradiation has a negative impact on the energetic and exergetic efficiencies of the suggested system that is inversely proportional with solar radiation to system performance. The main reason for this is the increase in the solar collector temperature with an increase in solar radiation and then occurs in high irreversibility in the plant. The effect of solar irradiation on the performance of the examined system shown in this figure has the same tendency within the study of Ozlu and Dincer [35].

The net electricity generation rate from the plant rises with the increasing solar radiation as illustrated in Fig. 7. It is shown that the net power generation of suggested plant increased with the rising solar radiation at the constant reference temperature. However, at constant solar radiation, while reference temperature increase, the net power production rate of plant drops. The reason for this increment trend that the solar collector working fluid temperature entering the HEX rise with the increment in the solar radiation, and then the power generation from the ORC turbine increase linearly. Fig. 8 illustrates the impact of solar collector mass flow rate on

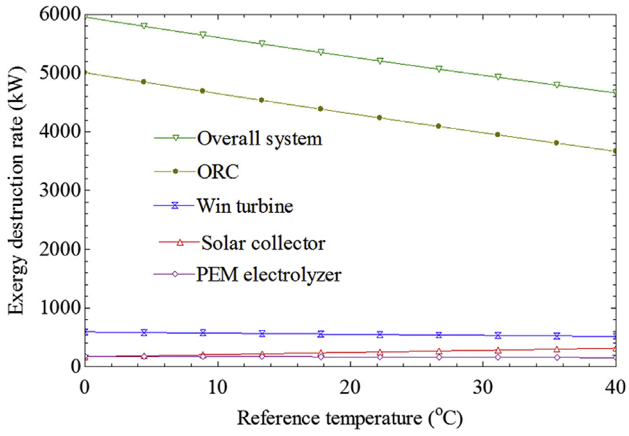

Fig. 5 – Variations of exergy destruction rate of proposed study and major components with reference temperature.

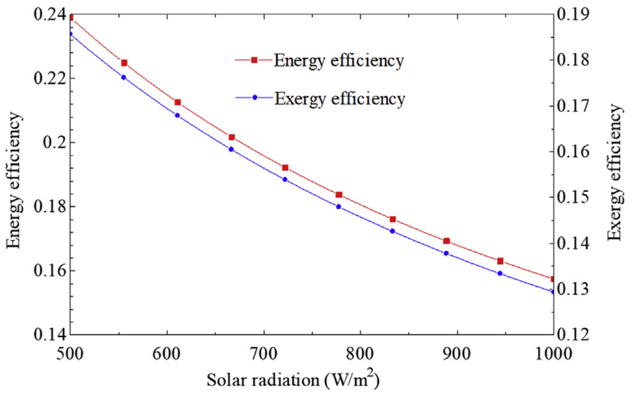

Fig. 6 – Impact of the solar radiation on energy and exergy efficiency of the examined plant.

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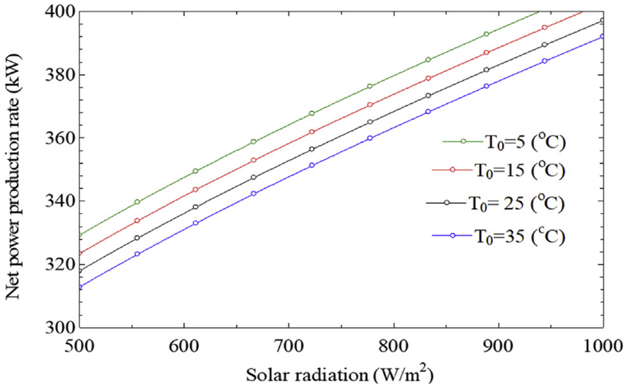

Fig. 7 – **Effect of solar radiation on the net power generation rate with various reference temperature.**

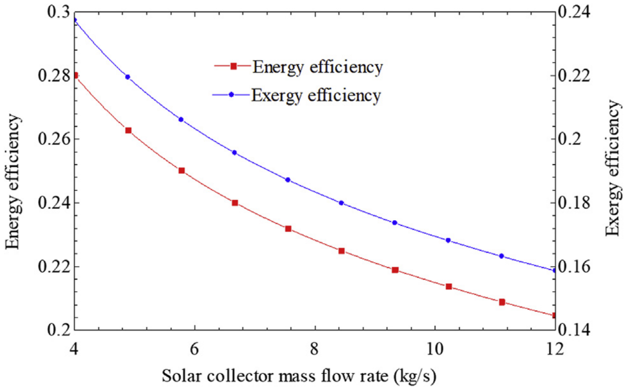

Fig. 8 – **Impact of solar collector mass flow rate on the energy and exergy efficiency of the plant.**

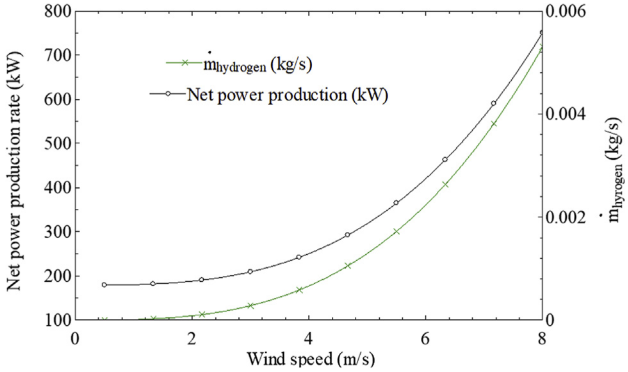

Fig. 10 – **Net power and hydrogen generation rates of the examined system with wind speed.**

the examined system performance. Mass flow rate increment in the solar collector from 4 to 12 kg/s give a rise to drops in the examined system performance. The proposed system efficiency drops, since the pump-I in the solar collector cycle must more work to pump the working fluid. The cause for this reduction in the cycle performance is that the work entering the system increases, and the outputs of the system, such as work and heat, do not increase with escalation in the mass flow rate of solar collector.

Another energy factor in the examined cycle is the wind speed that is directly proportional to the change of wind energy. As expected, in Fig. 9, it is noted that the overall plant's performance increase with the rising wind speed. According to Eq. (44), the wind speed is direct proportion with the wind turbine power generation rate, that is as the higher wind speed the higher the power generated from the wind turbine as up to a certain wind speed ratio. It can be concluded that the wind speed is not only proportional to the energy and exergy efficiencies of the proposed plant, but that the rate of efficiency drop is large at low speeds. Likewise, the influence of wind speed on the hydrogen and net electricity production rate of suggested plant is depicted in Fig. 10. As above mentioned in Fig. 9 that it clearly increases the power generation rate with the rise in the wind speed. That is the wind speed rises from 0.5 to 8 m/s, the net power generation rate rises from 150 kW about to 700 kW and due to this increase, the hydrogen generation rate increases. Consequently, it should be stated that the average wind speed should be more than 3.5 m/s in order to efficiently work a wind turbine, based on our study results.

In the wind turbine power systems, air temperature is an important indicator as it directly affects the air density. The

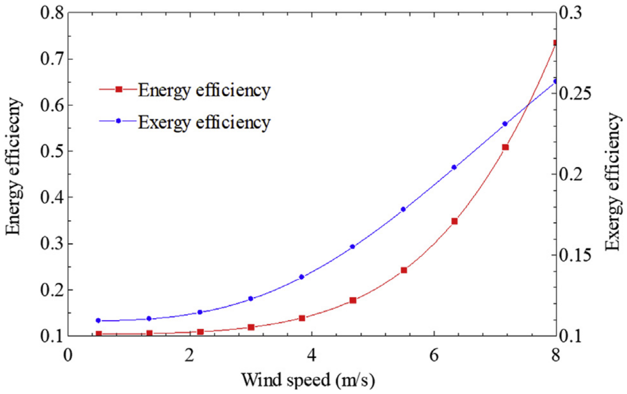

Fig. 9 – **Variations of energy and exergy efficiency of the examined plant with wind speed.**

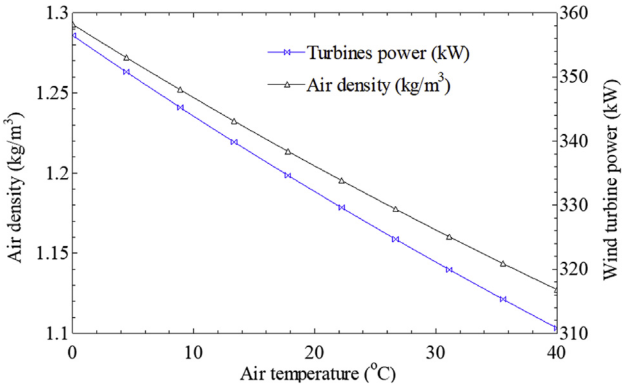

Fig. 11 – **Changes of the turbine power and air density with wind speed.**

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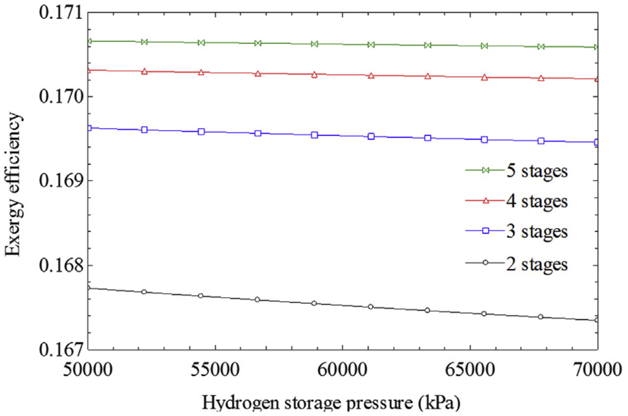

Fig. 12 – Impact of hydrogen compression stages on the exergy efficiency of the overall system in different storage pressures.

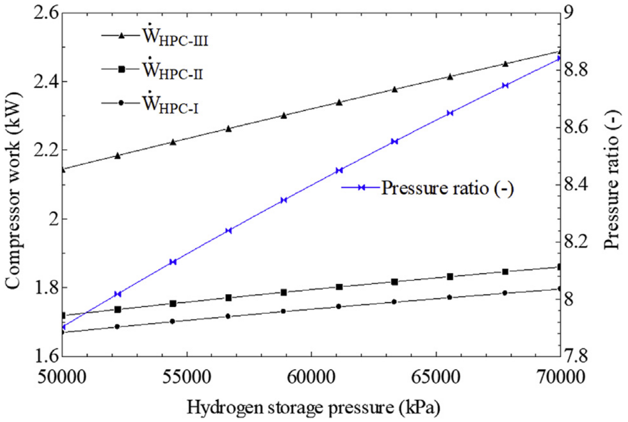

Fig. 13 – Impact of hydrogen storage pressure on the required compressors work and pressure ratio.

air density and wind turbine power production drop with the increasing air temperature as given in Fig. 11. As the air temperature increases by about 40 °C, the air density decreases from 1.3 kg/m^3 to about 1.1 kg/m^3 and as well as the wind turbine power generation also falls according to Eq. (44). It can be concluded that the increment in the air temperature has an adverse impact on the wind turbine power generation rate.

Fig. 12 displays the impact of hydrogen compression stages on the exergetic efficiency of the suggested plant under the different storage pressure values. In this study, the input pressure of hydrogen to the hydrogen compression unit is accepted as 101.325 kPa. While the increase the storage pressure from 50000 kPa to 70000 kPa, the slightly drops in the exergetic efficiency of examined plant. However, the exergetic efficiency of the same system increases with the rising hydrogen compression stages. Nevertheless, although this exergy efficiency is low, higher pressure storage is suggested for higher hydrogen density. The result of this study shown in this figure has a similar inclination with the study of Ozcan and Dincer [22]. The required work of compressors and pressure ratio of hydrogen compression system rise with the increasing hydrogen storage pressure as it can be indicated in Fig. 13. The required compressor work increases linearly by increasing the hydrogen storage pressure from 50000 kPa to 70000 kPa. This increment trend is due to the fact that compressors must have higher compression rates in order to achieve high hydrogen storage pressures. The maximum required compressor work is seen in $\dot{W}_{HPC-III}$ which is the last compressor before storage tank. The reason for this is that the $\dot{W}_{HPC-III}$ compressor reaches higher pressure levels. It can be stated that by increasing the compression stages, compressors can be used for less work with lower pressure ratios.

Finally, a summary of some proposed studies in literature for comparison of results which depends on the energetic and exergetic efficiencies are tabulated in Table 3. It is clear that there are many studies with different designs to develop the performance of integrated cycles with renewable energy support. The aim of these studies is to integrate with different systems with single or two different energy inputs in general and produce more useful outputs. In addition, as it is clearly seen in Table 3, the system performances vary according to the design of combined systems. Energy and exergy performances of our suggested study are partially low because it is a smaller scale compared to other works and in that works at low temperature. It may be possible to improve the performance of this proposed study by rising the wind speed and the number of wind turbines. Additionally, the performance of the system can be improved by using to heating application in

Table 3 – Summary of some proposed studies for comparison of results.

Authors	System	Sources	Energy efficiency	Exergy efficiency
Ishaq et al. [11]	Co-generation	Wind	20.2	21.2
Siddiqui and Dincer [21]	Integrated system	Solar-wind	46.61–53.3%	34–41.5%
Ozlu and Dincer [35]	Multigeneration system	Solar-wind	65%	43%
Luqman et al. [17]	Polygeneration system	Solar-wind	51%	33%
Sorgulu and Dincer [7]	Integrated system	Solar-wind	33–45%	–
Khalid et al. [41]	Integrated system	Solar-wind	26%	26.8%
Khalid et al. [13]	Integrated system	Solar-wind	46.1%	7.3%
Zafar and Dincer [12]	Integrated system	Solar-wind	14%	21%
Sezer and Koc [42]	Integrated system	Solar-wind-osmotic power	73.3%	30.6
This study	Integrated system	Solar- wind	21%	16%

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the condenser part of the ORC cycle or by using thermoelectric power generation.

Conclusion

The proposed cycle is supported by solar and wind energy which produce useful outcomes such as electricity and hydrogen. The examined system comprises of four subsystems; a solar collector cycle, an ORC, a wind turbine power and hydrogen production and compression systems. A detailed thermodynamic performance assessment is performed to determine energetic and exergetic performances besides exergy destruction rates of this system. Also, in this study, hydrogen in the gaseous phase obtained from PEM electrolysis is compressed under 70000 kPa pressure. The outputs show that an increase in air temperature reduces the air density, thus adversely affecting wind turbine electricity generation rate. Increment in the reference temperature has an adverse effect on the examined study's performance. The important conclusions that can be summarized according to the results of the analysis can be written as;

- The wind turbine net power production rate is 326.5 kW, also producing net power rate from ORC is 195.9 kW. Additionally, the hydrogen production rate is 0.001457 kgs^{-1} with PEM electrolyzer.
- The whole energy and exergy efficiencies of the planned plant are 0.21 and 0.16.
- The rise in the reference temperature reduces the examined plant performance, net electricity and hydrogen generation rates.
- It can be concluded that increment in the wind speed has a constructive effect on the system efficiency and hydrogen generation rate.
- It can be determined that the impact of wind speed on the cycle performance and hydrogen generation rate has a favorable. The increases in wind speed, the cycle performance and hydrogen generation curves are the same trend.

Consequently, it can be stated that in order to cope with global warming and environmental problems, energy needs to be used efficiently and interest in renewable energy-supported systems should be increased. Solar and wind power can be defined as the most widely used energy sources among renewable energy sources. When solar radiation is insufficient or nights, hybrid use in combination with wind turbines provides many advantages. Moreover, the excess electrical power generated in such hybrid systems can also be used in the production of hydrogen with the PEM electrolyzer, for a clean and sustainable future. In this sense, the proposed study emphasizes the importance of clean hydrogen production for environmentally benign.

Nomenclature

ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
s	specific entropy (kJ/Kg-K)
T	temperature (K, °C)
V	wind speed (m/s)
$\dot{W}$	work rate (kW)
$\dot{Q}$	heat transfer rate (kW)

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

0	dead state
P	pump
T	turbine
e	output
gen	generation
i	input
wt	wind turbine

Abbreviations

EES	engineering equation solver
HEX	heat exchanger
LHV	lower heating value
PEM	proton exchange membrane
SC	solar collector
HPC	hydrogen production and compression
ORC	organic Rankine cycle

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