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Research Article

Techno-economic assessment of green hydrogen production using different configurations of wind turbines and PV panels

Mohamed Nasser*
Egypt-Japan University of Science and Technology (E-JUST), Energy Resources Engineering Department, Alexandria, Zagazig University, Mechanical Power Engineering Department, Zagazig, Egypt, mohamed.nafea@ejust.edu.eg
Tamer F. Megahed
Egypt-Japan University of Science and Technology (E-JUST), Energy Resources Engineering Department, Alexandria, Mansoura University, Electrical Engineering Department, Mansoura, Egypt, tamer.megahed@ejust.edu.eg
Shinichi Ookawara
Tokyo Institute of Technology, Tokyo, Japan, ookawara.s.aa@m.titech.ac.jp
Hamdy Hassan
Egypt-Japan University of Science and Technology (E-JUST), Energy Resources Engineering Department, Alexandria, Assiut University, Mechanical Engineering Department, Assiut, Egypt. hamdy.aboali@ejust.edu.eg

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* *Corresponding Author*

Abstract: In this work, a hybrid system is comprised of wind turbines (WT) and photovoltaic (PV) panels to generate green Hydrogen via water electrolysis. Consideration is given to the influence of five electrical power generation scenarios on system performance and Hydrogen production cost. This study adopts the solar radiation, wind speed, and ambient temperature for Mersa-Matruh in Egypt. The system performance is studied using MATLAB-Simulink over one year. The winter months have high wind speed and low sun radiation compared to other months, whereas additional months have high solar radiation and lower wind speed than the winter months. The findings show that the amount of Hydrogen produced for all scenarios varies from 12,340 m3 to 13,748 m3 per year. The system efficiency and LCOH are 7.974% and 3.67$/kg, 9.56%, and 3.97$/kg, 10.7% and 4.12 $/kg, 12.08%, and 4.3$/kg, and 16.23% and 4.69$/kg for scenarios1 to 5, respectively. Finally, the introduced system can reduce CO_2 emissions by 345 tons over the lifetime and gain about 13,806$.

***Keywords**:* *CO_2 emissions, Green hydrogen production, LCOH, Renewable hybrid system, System assessment*

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1. INTRODUCTION

In recent decades, most countries have depended on energy production from fossil fuels. The exponential increase in the required energy and the adverse environmental effect of fossil fuels drove various nations to use alternative clean energy sources [1]. Hydrogen might be a new fuel for the current age that drives economic advancement and avoids existing fuels' problems. It is a sustainable fuel source and is considered one of the potential options for the earth's current energy and environmental challenges. Environmentally friendly Hydrogen production is a better environment and sustainable development features [2].

Renewable energy sources, for instance, wind turbines (WT) and PV panels, can be used to obtain green Hydrogen. One of the most rapidly developing technologies in the world is a hybrid system that combines the power of two or more energy resources, such as PV and wind energy [3]. As a result, a hybrid system has been developed to conquer the intermittent nature of renewable sources [4] and generate pure Hydrogen from water electrolysis. There are various sources to generate Hydrogen, for example, water and hydrocarbons. Several methods, including electrolysis, gasification, and steam reforming, are used to extract Hydrogen from these sources. It is also necessary to have an energy source for electricity production. Hydrogen production from fossil fuels emits Carbon dioxide in the same way as burning fossil fuels for energy production. Wind, sun, and hydropower are ideal for manufacturing Hydrogen in a green manufacturing cycle without unleashing CO_2 into the atmosphere. As a result, the renewable sources driving the water electrolysis process attract worldwide interest since it has the ability to bring the world to a global economy that emits no greenhouse gases [5].

The climatic conditions significantly impact the amount of power generated by the PV system used for Hydrogen generation. Changes in ambient temperature have a considerable influence on the performance of the PV panels. The total system performance generally improves as the temperature drops [6,7]. A ten percent increase in Hydrogen generation and a 0.1% increase in capital investment costs were found when solar power output increased [8]. The PVT Hydrogen production system can produce up to14.15 ml/min with electric efficiency [9]. In addition, wind speed, WT hub height, and WT-rated power considerably impact system performance when used in Hydrogen synthesis utilizing wind power. In general, the cost of hybrid production is lower than that of wind-only production, but it may be higher or lower than that of PV-only output, depending on the weather circumstances [10].

Wind and solar energy are now combined to overcome each technology's shortcomings alone. For example, WT power generation is unstable because of wind speed fluctuations, while solar panels do not produce electricity at night. For Hydrogen production, a hybrid system's performance is evaluated under an average worldwide solar radiation of 200-800 W/m^2 and a wind speed range of 2.0-5.0 m/s. The system's efficiency, which can generate up to 140 ml/min, was found to be 7.78 %. In addition, the system's benefits of superior efficiency, space-saving, and cheap cost [11] make it very commercially viable. Assuming an average worldwide solar radiation of 200-800 W/m^2 and wind speeds ranging from 2.0 to 5.0 m/s, the system's potential for Hydrogen generation was examined by Sopian et al. The system's efficiency was 7.78% at a flow rate of 140 ml/min [12].

The electricity from the grid is supplied to the system to ensure continuous production, as studied in [13]. The study mention that the selling price of Hydrogen ought to be at least 10 €/kg to be economically feasible and recover the initial investment. In case of a surplus of electrical energy produced, it can be sold to reduce the production cost [14]. On the other hand, the hybrid system is mainly used for electricity production, and the excess electricity is used to generate Hydrogen, as stated in [1]. The results showed that Hydrogen production was about 30.4 kg between April and July. The excess electricity can be used to produce Hydrogen, which is collected and provided to a fuel cell for electricity production; when produced, electricity is lower than the demand [4,10]. Studies have been conducted in various climates to determine the potential for Hydrogen generation and the cost per kilogram [15,16]. The price of Hydrogen generation in the United States is 6.2$/kg, whereas in Benin, it is 1.09€/m^3, and in Morocco, it is 4.64$/kg.

MATLAB/Simulink software simulates and performs a parametric system study for the whole production system [17,18]. The results showed that the system's performance was enhanced due to (I) increasing electrolyzer operation temperature and (II) when PV and WT work simultaneously. The hybrid system is examined under Iran's climatic conditions [19]. This study's results stated that the system produces about 91 kg per day, which provides energy for 91 cars/week and saves about 1347 L of gasoline in the week. A comparison was performed between the hybrid system's Hydrogen production cost and end-user selling price in the Netherlands [20]. The results revealed that the system production is lower than the end-user price by 1.3€/kg. Additionally, the hybrid system can produce urea and Hydrogen. The Hydrogen production reaches up to 518.4 kmol/day of Hydrogen and synthesizes 86.4 kmol/day of urea [21].

Egypt, as with most of Africa, has a lot of sunlight, with an annual average of 3100 hours, or 9–11 hours a day from north to south. In addition, wind speeds of 5 to 10 m/s are typical in several of the country's largest cities. Despite Egypt's availability of renewable energy, the country depends mainly on fossil fuels for its power generation needs. Dependency on fossil fuels releases up to 224 million tons of carbon dioxide into the environment, which severely impacts the environment. According to a government program in Egypt, more than 40% of Egypt's power will come from renewable sources by 2035, with wind power accounting for 14% of that total and solar power accounting for 25% of that total. Because of the fluctuating nature of renewable energy sources, Hydrogen synthesis offers a viable option for energy storage [5,10,22,23].

As mentioned above, the system performance is directly affected by climatic conditions, and the production cost plays a vital role in system assessment. Therefore, the current study focuses on the energy performance and cost analysis of using a hybrid renewable energy system composed of PV and wind turbine systems for clean Hydrogen production using an alkaline electrolyzer. Currently, the study is conducted out of 5 cases of the produced power required for running the electrolyzer, which is: (1) 100% from PV, (2) 70%PV+30%WT, (3) 50%PV and 50%WT, (4) 30%PV+70%WT and (5) 100% from WT. A complete mathematical model is built and solved using MATLAB software and validated. The study is carried out under the climate conditions of Mersa-Matruh city in Egypt, which is rich in solar and wind energy. In contrast to previous studies, this study compares wind and solar power, if available in one place, in terms of Hydrogen production. Additionally, the present research aims to close the knowledge gap in the utilization of Egypt's abundant renewable energy resources (solar and wind) in the area of clean Hydrogen generation.

2. SYSTEM DESCRIPTION AND WEATHER CONDITIONS

The meteorological conditions of Mersa-Matruh, located on Egypt's North Coast (31°20′N 27°13E), are utilized to study the existing stand-alone system employed for Hydrogen generation. Fig. 1 illustrates the hybrid system layout. This system is a hybrid renewable energy source that generates electricity by combining PV and WT. The electricity is sent straight to the alkaline water electrolyzer to produce green Hydrogen using the electricity generated by actual commercial PV panels (100 % PV), wind turbines (100 % wind), or a mix of the two. In reality, the electricity is generated following one of five distinct scenarios: (1) 100 % from the PV; (2) 70 %PV+30 %WT; (3) 50 %PV and 50 %WT; (4) 30 %PV+70 %WT; and (5) 100 %from WT. These scenarios are used to estimate the effectiveness of the system and the cost of producing Hydrogen. The PV panels in scenario.1 have a total rated capacity at a maximum power point of 24 kW, whereas Scenario 5 has three wind turbines, each of which has a rated power of 10 kW. PV and WT are combined with the percentages provided in the remaining scenarios to determine which scenario has the most effective results. In addition, the converter unit is used to modify the needed current for the electrolyzer depending on the estimated voltage. This power regulation is made following the previous scenarios.

The solar radiation values that are incident on the PV panels are computed based on a tilt angle of 31°, considered the PV panels slope angle in Egypt. This angle is chosen to collect a lot of sunlight from the PV panels. Fig. 2 depicts the monthly average solar intensity per unit area (Wh/m^2), showing that July and December have the highest and lowest values, respectively. As a result, it is anticipated that July will have the most significant quantity of power produced from the PV panels, while December will have the opposite effect. Similarly, the values of the monthly average wind speed are depicted in this figure. The chart shows that the maximum value occurs in February, while the lowest value occurs in September.

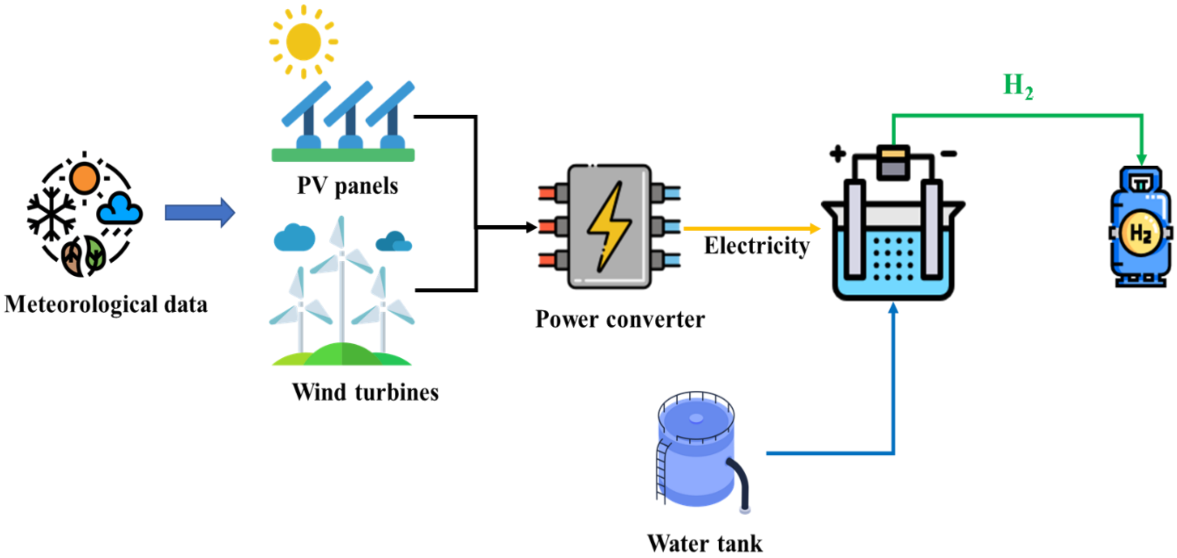

Figure 1. The layout of the hybrid system for Hydrogen production.

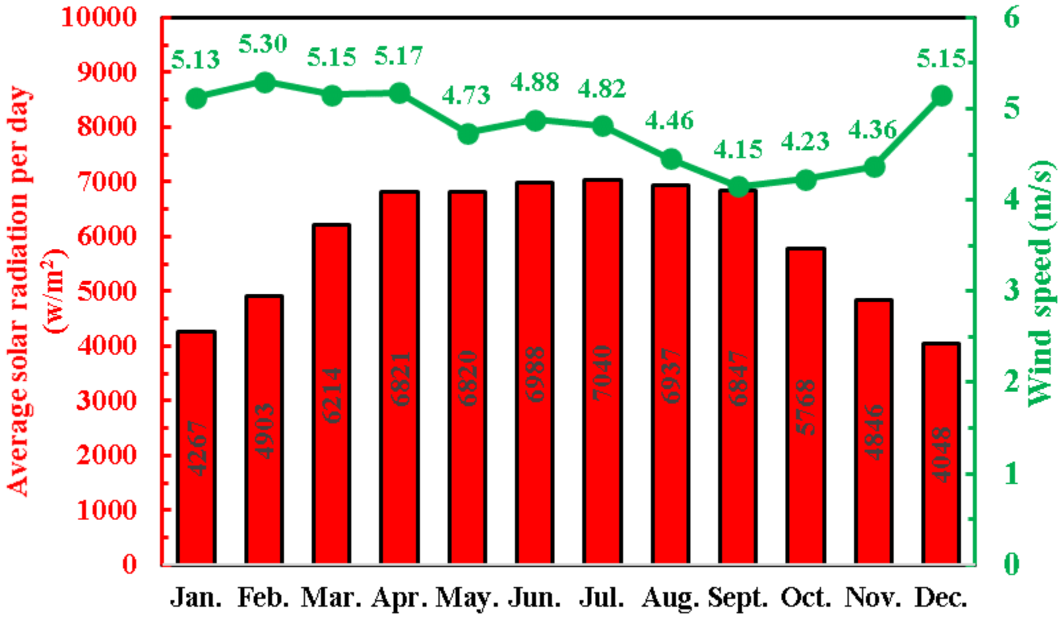

Figure 2. Meteorological data for the current study.

3. MATHEMATICAL MODEL

The current section illustrates the mathematical model for each component of the introduced system.

3.1. Wind Turbine Model

The amount of electricity produced from the WT is calculated based on Eq.1, as described in [24]. It is noted that the WT does not generate any electricity when the wind speed is below the cut-in wind speed (1.85m/s) or above the cut-out wind speed (30 m/s) according to the used Enair E200L wind turbine model specifications.

$$P_{WT} = \begin{cases} Zero & (V < V_{cut-in} \text{ and } V > V_{cut-out}) \\ 10\ kW & (V_{rated} < V \leq V_{cut-out}) \\ 10\ kW \times \dfrac{V^3 - 1.85^3}{V_{rated}^3 - 1.85^3} & (V_{cut-in} \leq V \leq V_{rated}) \end{cases} \tag{1}$$

Where, V_{rated} = 9.55 m/s and the WT generator efficiency (η_{gen}) is taken 95%.

3.2. PV Model

The current PV modules are designed based on Maximum Power Point Tracking (MPPT) to extract the highest existing electricity from the PV panels. The current and voltage at MPP (I_{MPP} and V_{MPP}) depend on the open-circuit voltage, photocurrent, and weather conditions. Then, the equations used to estimate these values are introduced as follows [25-28]. Table.1 shows the used PV panel specifications [10].

$$\begin{cases} I_{\mathrm{MPP}} = \left[I_{\mathrm{MPP_{STC}}} + k_I\,(T_{\mathrm{PV}} - T_{\mathrm{STC}})\right] N_{\mathrm{PVp}}\,\dfrac{\mathrm{G}}{\mathrm{G_{STC}}}, \quad T_{PV} = T_a + \dfrac{T_{NOCT} - 20}{800\ (W/m^2)}\,G \\ V_{\mathrm{MPP}} = \left[V_{\mathrm{MPP_{STC}}} + k_V\,(T_{\mathrm{PV}} - T_{\mathrm{STC}})\right] N_{\mathrm{PVs}} - \left[\left(I_{\mathrm{MPP_{STC}}} - I_{\mathrm{MPP}}\right) R_S\right] \dfrac{N_{\mathrm{PVs}}}{N_{\mathrm{PVp}}} \\ P_{PV} = I_{MPP} \times V_{MPP} \end{cases} \tag{2}$$

Where, the solar radiation in W/m^2 is G.

Table 1. PV panels specifications.

Symbol	Description	Value
G_{STC}	Solar radiation at STC	1000 W/m^2
T_{STC}	Temperature at STC	25℃
k	Boltzmann constant	1.38 ×10^{-23} J/°K
N_s	PV panels cells in series	72
N_{PVp}	Parallel PV panels number.	12
N_{PVs}	Series PV panels number.	2
$I_{SC,\ STC}$	A current of short circuit at STC.	34.72 A
$V_{OC,\ STC}$	A voltage of open circuit at STC.	43.32 V
$I_{MPP,\ STC}$	Current at MPP at STC.	30.86 A
$V_{MPP,\ STC}$	The voltage at MPP at STC.	32.69 V
A_{PV}	Area of PV.	10.78 m^2
T_{NOCT}	Nominal Working Cell Temperature.	40 ℃

STC – Standard Testing Conditions.

3.3. Converter

The power converter unit comprises a DC/DC converter and an AC/DC converter coupled to the DC bus, which is used to deliver the electrolyzer with adequate DC. A 95% is believed to represent the constant conversion efficiency of all employed converters. The power of the electrolyzer is described below [5,10]:

$$P_{EZ} = [P_{WT}\eta_{AC/DC}\eta_{gen}] + [P_{PV}\eta_{DC/DC}] \tag{3}$$

Where, P_{EZ} is the electrolyzer power; $\eta_{AC/DC}$ is the efficiency of AC/DC converter and $\eta_{DC/DC}$ is the efficiency of the DC/DC converter.

3.4. Electrolyzer System

Using electricity, an electrolyzer splits water down into Hydrogen and Oxygen. The electrochemical modeling of an alkaline-type electrolyzer in steady-state conditions is used in this study since it is the most widely used [29]. Aqueous Potassium Hydroxide (KOH) with 20-30%wt concentration is the electrolyte of choice in this sort of device. Also, the electrolyzer stack, which comprises many cells, requires a DC power supply to run. Table 2 shows the precise characteristics of the electrolyzer model employed in this investigation.

$$\begin{cases} I = \dfrac{P_{EZ}}{U} \quad and \quad U = V_{cell}.n_c \\ V_{cell} = 1.229 + \left(\dfrac{r_1 + r_2 T_{EZ}}{A_{EZ}} I\right) + s\log(\dfrac{t_1 + t_2/T_{EZ} + t_3/{T_{EZ}}^2}{A} I + 1) \\ \dot{n}_{H_2} = \eta_F (n_c I/2F) \\ \eta_F = \dfrac{(I/A_{EZ})^2}{f_1 + (I/A_{EZ})^2} f_2 \end{cases} \tag{4}$$

where, I is the electrolyzer current, and U is the electrolyzer voltage.

Table 2. Electrolyzer parameters [29].

Symbols		Value
$\mathbf{r_1}$	Ohmic resistance	8.05×10^{-5} Ωm^2
$\mathbf{r_2}$		-2.5×10^{-7} Ωm^2/°C
s	Electrode overvolt Coff.	0.185 V
$\mathbf{t_1}$	Overvoltage Coff.	-0.1002 m^2/A
$\mathbf{t_2}$		8.424 m^2 °C/A
$\mathbf{t_3}$		247.3 m^2 °C^2/A
$\mathbf{n_c}$	Number of cells in the electrolyzer	6
$\mathbf{A_{EZ}}$	Electrolyzer area	0.25 m^2
$\mathbf{T_{EZ}}$	Electrolyzer operation temperature	80 °C
$\boldsymbol{\eta_F}$	Faraday efficiency	-
F	Faraday constant	96,485 C/ mol

3.5. System Performance and Production Cost

The introduced system's efficiency and components are calculated using the following relations to investigate the system's performance [5,10,30].

$$\begin{cases} \eta_{PV} = \dfrac{P_{PV} \times \eta_{\mathrm{DC-DC}}}{I_{\mathrm{T}} \times A_{\mathrm{PV}}} \\ \eta_{WT} = \dfrac{P_{WT} \times \eta_{\mathrm{gen}} \times \eta_{\mathrm{AC-DC}}}{P_{wind}} \\ \eta_{EZ} = \dfrac{m_{H2} \times \mathrm{HHV}_{\mathrm{H_2}}}{\text{Electrolyzer input power}} \\ \eta_{sys} = \dfrac{m_{H2} \times HHV_{\mathrm{H_2}}}{(I_{\mathrm{T}} \times A_{\mathrm{PV}}) + P_{wind}} \end{cases} \tag{5}$$

Where $\dot{m}_{\mathrm{H_2}}$: Hydrogen mass flow rate, HHV_{H2}: the higher heating value of Hydrogen =39 kWh/kg, I_T: solar radiation, A_{PV}: PV area.

3.6. Levelized Cost of Hydrogen

The Levelized cost of Hydrogen (LOCH) is an efficient parameter to determine the system's performance because it indicates its ability to compete with other Hydrogen production methods. As the LCOH decreases, the benefits gained from the system increase. The following equation describes the formula used to predict the LCOH in the current study [31]. Table 3 summarizes the costs of system components.

$$LCOH = \frac{CI + \sum_{t=1}^{n} \dfrac{OM}{(1+i)^t}}{\sum_{t=1}^{n} H_t} \tag{6}$$

Where CI: capital investment, OM: yearly operation and maintenance cost, i: is the Egyptian discount rate (8.75%), H_t: the annual amount of produced Hydrogen, and n: lifetime (20 years).

Table 3. Components capital cost [31,32].

Capital cost.	Cost per unit
PV	1130 $/kW
WT	1,550 $/kW
Power conditioner.	600 $/kW
Electrolyzer.	930 $/kW

3.7. Enviro-economic Analysis

One of our day's most pressing environmental issues is global warming, which results from rising CO_2 concentrations in the atmosphere. Here, an enviro-economic analysis examines the environmental consequences of switching from fossil fuels -generated Hydrogen to a renewable production system. CO_2 mitigation accomplished through renewable energy generation and credit acquired are the basis for this study. Currently, there is no method to sell the CO_2 that the new technology has reduced. This study establishes the quantity of CO_2 that can be taken out of the system, and the credit amount of carbon, if marketed, as introduced in [10].

Fuel oil power plants have an average CO_2 equivalent intensity of 0.277 kg_{CO2}/kWh. Therefore, the yearly CO_2 reduction for the hybrid system in kilograms of Carbon dioxide (kg_{CO2}) and Carbon credit gained (CCG) are defined as follows [10]:

$$\begin{gathered} CO_2\ reduction\ during\ system\ life\ time = E_{out} \times n \times 0.277 \\ CCG = CO_2\ reduction\ (ton) \times 40\ (\$/ton) \end{gathered} \tag{7}$$

Where, E_{out} annual produced electricity (kWh), and n is the system lifespan (20 years).

4. SOLUTION STEPS AND MODEL VALIDATION

A MATLAB/Simulink code is developed based on the flowchart, as shown in Fig. 3. As this figure demonstrates, the code first reads the metrological data from a separate file. Secondly, the mathematical model is used to calculate the electric power from PV panels and WT; then, the converter model is used to estimate the required current for the electrolyzer. After that, the electrolyzer model calculates the total amount of Hydrogen produced. Finally, the three sub-models (efficiency, LCOH, and CCG) are developed to perform a completer system assessment.

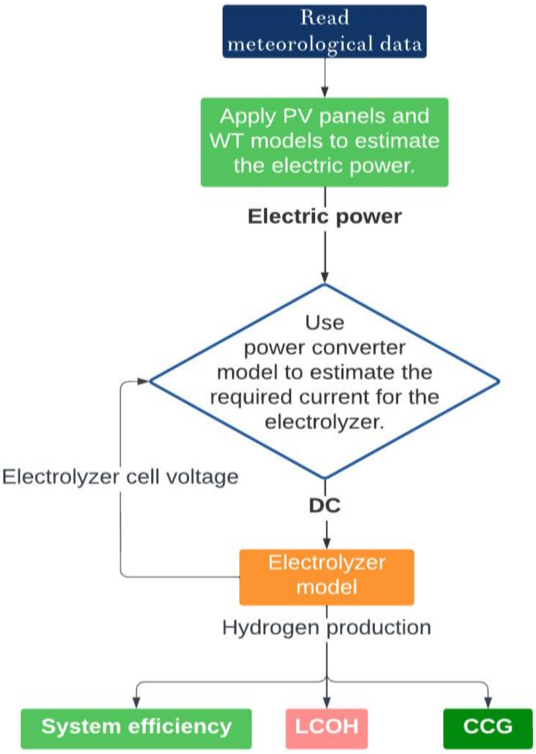

Figure 3. Solution flowchart.

MATLAB/Simulink simulates the previously stated equations over a year (8760 hours) using accurate metrological data. Ulleberg's electrolyzer [33] method gave findings that were compared to the current results. Table.2 shows the operational parameters employed in this study. The obtained results of the current density-voltage curve for one cell of the current model are plotted in Fig. 4 for various electrolyzer temperatures at the same input conditions of Ulleberg. As shown in Fig. 4, the Ulleberg experimental data and the present modeling findings are pretty close in terms of accuracy.

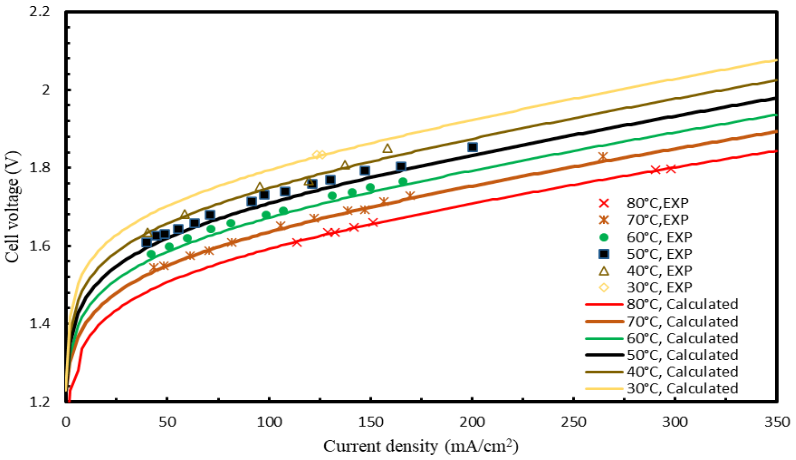

Figure 4. Electrolyzer model validation curve.

5. RESULTS AND DISCUSSION

The present study aims to investigate the performance of the clean Hydrogen generation structure in Egypt under five scenarios (a combination of solar and wind power), as mentioned above. Furthermore, an estimation of the LCOH of each scenario is performed to determine which possible case is more suitable depending on the low production cost. The hybrid system is chosen to provide continuous operation for long hours with high efficiency for the hybrid Hydrogen production system in winter and summer days and nights. For this reason, integration between PV and WT is studied to obtain better operating conditions. Fig. 5 illustrates the monthly average produced electricity from the renewable energy sources for each scenario. It is evident that the power generated from the wind turbine is more than electricity from PV in December, January, and February (winter months), because of the high wind speed. In contrast, the electricity from PV is the highest in other months. Therefore, the annual amount of produced electricity from scenarios with a large PV percentage is higher than WT.

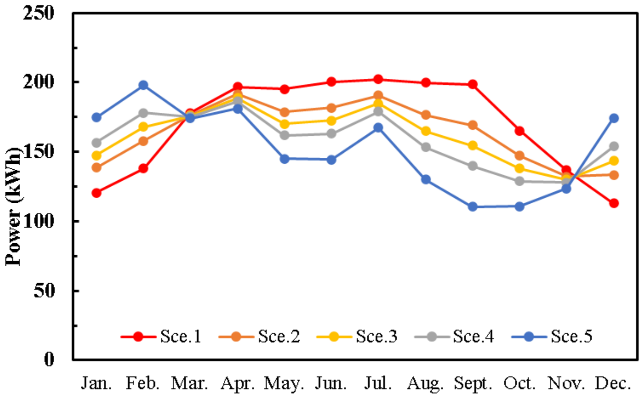

Figure 5. The average produced electricity of each scenario.

Fig. 6 demonstrates the annual electricity production for each studied scenario. It is noted that the produced electricity increases with a reduction in the share of WT in electricity production. The most significant amount of produced electricity is 62.3 MWh when the system operates on PV only. Still, this amount reduces until it reaches 55.77 MWh when the system uses WT only for electricity production. Therefore, using PV panels for electricity production is beneficial under Egypt's climatic conditions.

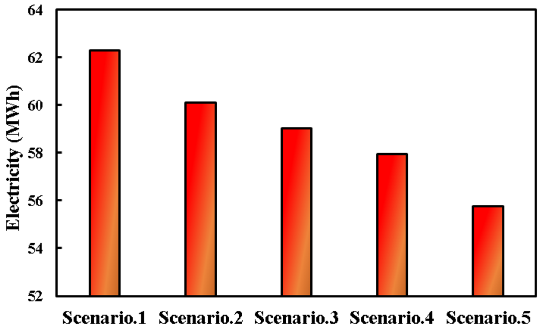

Figure 6. Annual electricity production.

The main concern of the current study, as mentioned before, is to get as high much Hydrogen as possible to get the lowest LCOH. When the LCOH decreases, the ability of the green production system to compete with other production methods increases. From the yearly Hydrogen production for the different studied scenarios, as shown in Fig. 7, the amount of produced Hydrogen also reduces as the produced electricity decreases. This figure revealed that the highest amount of yearly Hydrogen production is 1,153 kg in Scenario 1. In comparison, the lowest amount is 1,035 kg for Scenario 5 (PV only) when the hybrid system uses only WT. Also, the WT has a negative impact on Hydrogen production.

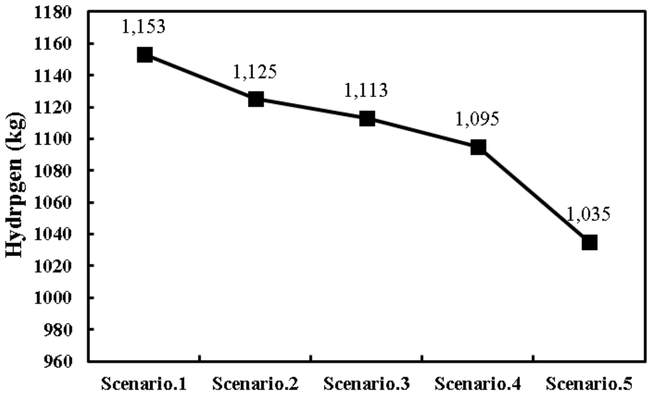

Figure 7. Annual Hydrogen production.

In each scenario, the characteristics of WT, PV panels, and alkaline electrolyzer are constant, but the portion of PV and WT in electricity production changes. The PV and WT efficiencies were assumed constant during the study and equal to 11.1% and 22.4%, respectively. Although WT has a higher efficiency than PV, electricity produced from PV is higher. This is because the wind speed in the studied area is not abundant and constant. Furthermore, higher WT efficiency leads to the higher efficiency of the system containing more electricity produced from WT. The opposite is true for systems with more electricity produced from PV. Additionally, the electrolyzer efficiency is 76% for all scenarios.

Fig. 8 shows the variation in the system efficiency of each scenario. To sum up, higher system efficiency implies making optimal use of the energy that has been introduced into the system but does not mean high Hydrogen production. Scenario 5 has the highest efficiency, 16.23%, and lowest yearly Hydrogen production, 1,035 kg, while Scenario 1 has the lowest efficiency, 7.974%, and most increased Hydrogen production, 1,153 kg.

Besides efficiency and Hydrogen production, the other concept used to judge the system is LCOH. During the calculation of this value, the project's lifetime is assumed to be 20 years, and each component's operation and maintenance cost is taken at 2% of the capital cost. In addition, the land cost of 50\$/m^2 is considered when estimating the capital cost. The LCOH for different scenarios is shown in Fig. 9. Hydrogen produced using Scenario 5 is the most expensive scenario. The cost is reduced as the percentage of WT share in electricity production decreases. The best-case scenario, considering the LCOH, is scenario one because of the abundance of solar radiation and the ability of PV to harvest solar radiation and convert it to valuable electricity. The results clearly show that the idea of running the electrolyzer during sun time is more economically feasible than operating it 24 h a day. This is because the wind turbines do not produce enough electricity during the night, so a lower amount of Hydrogen is produced while spending more money on constructing wind turbines. However, the results of this study may change if the sharing of the wind increases compared to the PV output power.

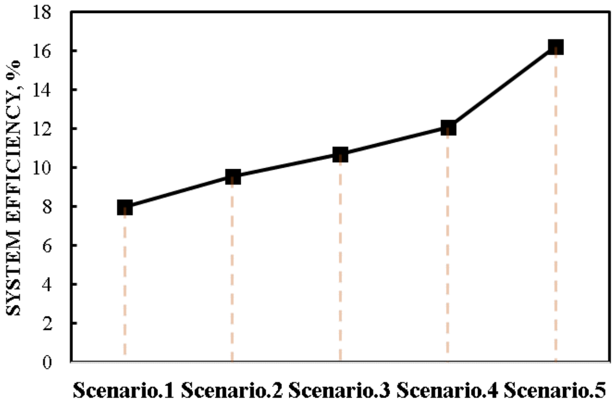

Figure 8. Total system efficiency for each scenario.

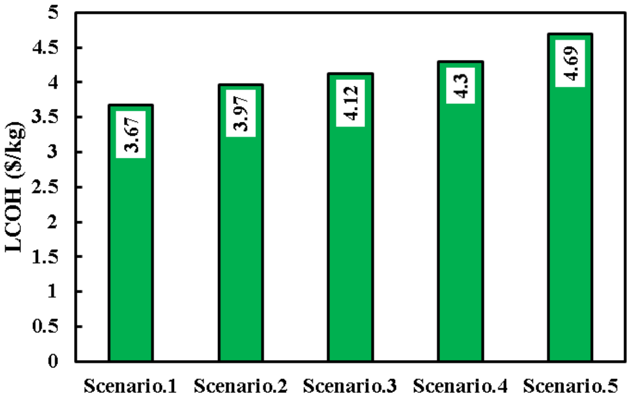

Figure 9. LCOH for each scenario.

Table 4 details the CO_2 reduction and carbon credit gains during 20 years of the hybrid system lifetime. It can be concluded that the growth in electricity production leads to an increase in the amount of CO_2 mitigation and an increase in credit gain. Scenario 1 can reduce the amount of CO_2 by 345 tons over the system's lifetime, and the system may gain up to 13,806 $ due to this reduction in CO_2.

Table 4. CO_2 mitigation and CCG over the system lifetime.

Scenario No	CO_2 mitigation (Ton)	CCG ($)
1	345	13,806
2	333	13,323
3	327	13,081
4	321	12,842
5	309	12,360

6. CONCLUSION

The performance and LCOH of a green hybrid Hydrogen generation system in Mersa-Matruh in Egypt, are depicted. This study is performed under identical climatic situations but with different proportions of power generated from PV and WT for five distinct scenarios: (1) 100 % from PV, (2) 70 %PV+30 % WT, (3) 50% PV, and 50% WT, (4) 30% PV+70% WT, and (5) 100% from WT. MatLab/Simulink code is given hourly yearly environmental variables (solar radiation, wind speed, and ambient temperature) to simulate PV and WT models for electricity production. The electricity is then linked with an electrolyzer model confirmed by Ulleberg's experimental data to produce Hydrogen. The following are some of the study's concluding observations:

In winter (December, January and February) have high wind speed and low solar radiation yielding high power from WT and low power from PV, while the opposite is obtained for other months.
Scenario 1 has the highest amount of produced electricity and Hydrogen, and Scenario 5 has the lowest amount of both values.
The total system efficiency for each scenario from 1 to 5 is 7.974%, 9.56%, 10.7%, 12.08%, and 16.23%, respectively.
The LCOH for each scenario from 1 to 5 is 3.67$/kg, 3.97$/kg, 4.12$/kg, 4.3$/kg, and 4.69$/kg, respectively.
The best configuration of the system for Hydrogen production based on LCOH is Scenario 1.
The system can reduce CO2 emissions by 345 tons over the lifetime and gain about 13,806$.

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REFERENCES

[1] Nasser, M, Megahed, TF, Ookawara, S, Hassan, H. A review of water electrolysis–based systems for hydrogen production using hybrid/solar/wind energy systems, *Environmental Science and Pollution Research* 2022; *1* (2022): 1–25, DOI: 10.1007/S11356-022-23323-Y.

[2] Kyuz, E, Oktay, Z, Dincer, I. Performance investigation of hydrogen production from a hybrid wind-PV system. *International Journal of Hydrogen Energy* 2012; *37*: 16623-30. DOI: 10.1016/j.ijhydene.2012.02.149.

[3] Devrim, Y, Bilir, L. Performance investigation of a wind turbine–solar photovoltaic panels–fuel cell hybrid system installed at İncek region – Ankara, Turkey. *Energy Conversion and Management* 2016; *126*: 759–66. DOI: 10.1016/j.enconman.2016.08.062.

[4] Devrim, Y, Bilir, L. Performance investigation of a wind turbine–solar photovoltaic panels–fuel cell hybrid system installed at İncek region – Ankara, Turkey. *Energy Conversion and Management* 2016; *126*: 759–66. DOI: 10.1016/j.enconman.2016.08.062.

[5] Nasser, M, Megahed, TF, Ookawara, S, Hassan, H. Techno-economic assessment of clean hydrogen production and storage using hybrid renewable energy system of PV/Wind under different climatic conditions. Sustainable *Energy Technologies and Assessments* 2022; *52*: 102195. DOI: 10.1016/J.SETA.2022.102195.

[6] Soliman, AMA, Hassan, H. An experimental work on the performance of solar cell cooled by flat heat pipe. *Journal of Thermal Analysis and Calorimetry* 2021; *146*: 1883–92. DOI: 10.1007/s10973-020-10102-5.

[7] Gad, R, Mahmoud, H, Ookawara, S, Hassan, H. Energy, exergy, and economic assessment of thermal regulation of PV panel using hybrid heat pipe-phase change material cooling system. *Journal of Cleaner Production* 2022; *364*: 132489. DOI: 10.1016/j.jclepro.2022.132489.

[8] Mraoui, A, Khellaf, A. Optimization of the design of hydrogen production systems based on product cost. *Journal of Solar Energy Engineering ASME* 2020; *142*. DOI: 10.1115/1.4046085/1073675.

[9] Senthilraja, S, Gangadevi, R, Koten, H, Marimuthu, R. Performance assessment of a solar powered hydrogen production system and its ANFIS model. *Heliyon 2020*; *6*: DOI: 10.1016/j.heliyon. 2020.e05271.

[10] Nasser, M, Megahed, TF, Ookawara, S, Hassan, H. Performance evaluation of PV panels / wind turbines hybrid system for green hydrogen generation and storage: Energy, exergy, economic, and enviroeconomic. *Energy Conversion and Management* 2022; *267*: 115870. DOI: 10.1016/j.enconman.2022.115870.

[11] Armijo, J, Philibert, C. Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. *International Journal of Hydrogen Energy* 2020; *45*: 1541–58. DOI: 10.1016/j.ijhydene.2019.11.028.

[12] Sopian, K, Ibrahim, MZ, Wan Daud, WR, Othman, MY, Yatim, B, Amin, N. Performance of a PV-wind hybrid system for hydrogen production. *Renewable Energy* 2009; *34*: 1973–8. DOI: 10.1016/j.renene.2008.12.010.

[13] Dufo-López, R, Bernal-Agustín, JL, Mendoza, F. Design and economical analysis of hybrid PV-wind systems connected to the grid for the intermittent production of hydrogen. *Energy Policy* 2009; *37*: 3082–95. DOI: 10.1016/j.enpol.2009.03.059.

[14] Bernal-Agustín, JL, Dufo-López, R. Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. *Renewable Energy* 2010; *35*: 747–58. DOI: 10.1016/j.renene.2009.10.004.

[15] Fopah-Lele, A, Kabore-Kere, A, Tamba, JG, Yaya-Nadjo, I. Solar electricity storage through green hydrogen production: A case study. *International Journal of Energy Research* 2021: 1–15. DOI: 10.1002/er.6630.

[16] Touili, S, Alami Merrouni, A, Azouzoute, A, El Hassouani, Y, Amrani, A. A technical and economical assessment of hydrogen production potential from solar energy in Morocco. *International Journal of Hydrogen Energy* 2018; *43*:22777–96, DOI: 10.1016/j.ijhydene.2018.10.136.

[17] Huang, PH, Kuo, JK, Wu, ZD. Applying small wind turbines and a photovoltaic system to facilitate electrolysis hydrogen production. *International Journal of Hydrogen Energy* 2016; *41*: 8514–24. DOI: 10.1016/j.ijhydene.2016.02.051.

[18] Ursúa, A, Barrios, EL, Pascual, J, San Martín, I, Sanchis, P. Integration of commercial alkaline water electrolysers with renewable energies: Limitations and improvements. International Journal of Hydrogen *Energy* 2016; *41*: 12852–61. DOI: 10.1016/j.ijhydene.2016.06.071.

[19] Rezaei, M, Mostafaeipour, A, Qolipour, M, Momeni, M. Energy supply for water electrolysis systems using wind and solar energy to produce hydrogen: a case study of Iran. *Frontiers in Energy Research* 2019; *13*: 539–50. DOI: 10.1007/s11708-019-0635-x.

[20] Van der Roest, E, Snip, L, Fens, T, Van Wijk, A. Introducing Power-to-H3: Combining renewable electricity with heat, water and hydrogen production and storage in a neighbourhood. *Applied Energy* 2020; *257*: 114024. DOI: 10.1016/j.apenergy.2019.114024.

[21] Ishaq, H, Siddiqui, O, Chehade, G, Dincer, I. A solar and wind driven energy system for hydrogen and urea production with CO2 capturing. *International Journal of Hydrogen Energy* 2021; *46*: 4749–60. DOI: 10.1016/j.ijhydene.2020.01.208.

[22] El-Emam, RS, Ezzat, MF, Khalid, F. Assessment of hydrogen as a potential energy storage for urban areas' PV-assisted energy systems – Case study. *International Journal of Hydrogen Energy* 2022. DOI: 10.1016/J.IJHYDENE.2022.01.107.

[23] Ismail, M, Zahra, WK, Ookawara, S, Hassan, H. Boosting the air conditioning unit performance using phase change material: Impact of system configuration. *Journal of Energy Storage* 2022; *56*: 105864. DOI: 10.1016/j.est.2022.105864.

[24] Wang, Z, Zhang, X, Rezazadeh, A. Hydrogen fuel and electricity generation from a new hybrid energy system based on wind and solar energies and alkaline fuel cell. *Energy Reports* 2021; *7*: 2594–604. DOI: 10.1016/j.egyr.2021.04.060.

[25] Soliman, AMA, Hassan, H. Effect of heat spreader size, microchannel configuration and nanoparticles on the performance of PV-heat spreader-microchannels system. *Solar Energy* 2019; *182*: 286–97. DOI: 10.1016/J.SOLENER.2019.02.059.

[26] Toumi, D, Benattous, D, Ibrahim, A, Abdul-Ghaffar, HI, Obukhov, S, Aboelsaud, R, et al. Optimal design and analysis of DC–DC converter with maximum power controller for stand-alone PV system. *Energy Reports* 2021; *7*: 4951–60. DOI: 10.1016/j.egyr.2021.07.040.

[27] Hassan, AA, Elwardany, AE, Ookawara, S, Sekiguchi, H, Hassan, H. Energy, exergy, economic and environmental (4E) assessment of hybrid solar system powering adsorption-parallel/series ORC multigeneration system. *Process Safety and Environmental Protection* 2022; *164*: 761-780. DOI: 10.1016/j.psep.2022.06.024.

[28] Gado, MG, Ookawara, S, Nada, S, Hassan, H. Performance investigation of hybrid adsorption-compression refrigeration system accompanied with phase change materials − Intermittent characteristics. International Journal of Refrigeration 2022; *142*: 66-81. DOI: 10.1016/j.ijrefrig.2022.06.007

[29] Contreras Bilbao, D. Valorization of the waste heat given off in a system alkaline electrolyzer-photovoltaic array to improve hydrogen production performance: Case study Antofagasta, Chile. International Journal of Hydrogen Energy 2021; *46*:31108–21, DOI: 10.1016/j.ijhydene.2021.07.016.

[30] Soliman, AMA, Hassan, H, Ookawara, S. An experimental study of the performance of the solar cell with heat sink cooling system. *Energy Procedia* 2019; *162*: 127–35. DOI: 10.1016/j.egypro.2019.04.014.

[31] Bhandari, R, Shah, RR. Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. *Renew Energy* 2021; *177*: 915–31. DOI: 10.1016/j.renene.2021.05.149.

[32] Tebibel, H. Methodology for multi-objective optimization of wind turbine/battery/electrolyzer system for decentralized clean hydrogen production using an adapted power management strategy for low wind speed conditions. *Energy Conversion and Management* 2021; *238*: 114125. DOI: 10.1016/j.enconman.2021.114125.

[33] Ulleberg, Ø. Modeling of advanced alkaline electrolyzers: A system simulation approach. *International Journal of Hydrogen Energy* 2003; *28*: 21–33. DOI: 10.1016/S0360-3199(02)00033-2.