Performance Analysis of a Green Hydrogen Production System in Several Coastal Locations in Egypt

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1 Introduction

Green hydrogen is produced through electrolysis, a process that uses electricity from renewable sources such as solar and wind to split water molecules into hydrogen and oxygen. This process produces zero emissions and can be used to power vehicles, generate electricity, and store energy for later use [1]. Egypt has abundance of renewable energy resources that could be used to produce green hydrogen. There is an intensive research progress in developing renewable energy systems in the Egyptian environment [2–23]. The country has some of the world's highest levels of solar

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A. M. Negm et al. (eds.), *Engineering Solutions Toward Sustainable Development*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-46491-1_3

radiation as it receives about 3050 h of sunlight annually, making it an ideal location for solar power plants. Also, Egypt has vast deserts with some regions well-suited for wind farms. Furthermore, several Egyptian coastal areas have a good wind potential and are suitable for wind turbine installations that could generate large amounts of electricity for electrolysis [24]. The Egyptian government is already taking significant steps to utilize this potential by investing in green hydrogen production projects. In 2022, the government announced plans to build a $1 billion green hydrogen plant near Cairo that would produce up to 1 gigawatt (GW) of power per year. The plant would use solar and wind energy to produce up to 500 tons of green hydrogen per day, enough to power more than 1 million homes or fuel thousands of cars and buses [25].

Overall, green hydrogen production has great potential in Egypt due to its abundance of renewable resources and strategic location. If properly developed, this technology could help to create new economic opportunities while reducing emissions from traditional energy sources.. With continued investment from both public and private entities, green hydrogen could become a major source of clean energy for Egypt in the near future. Egypt has the vision to produce 42% of its electricity from renewable resources to reduce greenhouse emissions by 10% by 2030–2035 [26].

Jang et al. [27] carried out a techno-economic analysis for the production of green hydrogen. They compared four different methods to find out the most economic technique. The authors compared proton exchange membrane electrolysis, alkaline water electrolysis, and solid oxide electrolysis with a waste heat source and with an electric heater. Results showed that solid oxide electrolysis with a waste heat

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source gave the lowest price for 1 kg of hydrogen production for the price of 7.16 \$/kgH_2. Mastropasqua et al. [28] investigated the economic feasibility of producing green hydrogen using a parabolic dish integrated with a high-temperature electrolysis system. The solar system provided electricity and thermal energy. The system could be operated with a cell efficiency of about 80%, and solar to hydrogen efficiency could reach 30%. Zhang et al. [29] investigated the performance of a solar-driven system for hydrogen production. They investigated the parameters that could affect the system's performance as operating temperature, inlet water rate, and leakage resistance. AlZahrani et al. [30] designed a system to generate hydrogen which has four subsystems: solar tower, thermal energy storage system, supercritical CO_2 Brayton cycle, and solid oxide steam electrolyzer. Results showed the overall efficiency of solar-hydrogen conversion of the integrated system reaching 12.7%. All systems were optimized to provide continuous operation and high overall efficiency. Lin et al. [31] carried out a techno-economic analysis of a solar-driven electrolysis system to produce hydrogen besides synthesis gas. They compared three different configurations to find the most economic one. The three systems had different technologies: solar concentration, photovoltaic, and a combination of both technologies.

Boudries [32] carried out a techno-economic study for hydrogen production using concentrated solar power. The solar system was used to heat the heat transfer fluid for steam production. A Rankine cycle power plant was employed for electricity generation to power the electrolysis unit for hydrogen production. Results showed that the cost of hydrogen depends on the cost of energy production. Normal solar irradiance was an important parameter for hydrogen cost. The system was economically feasible compared to PV based electrolysis system. Rahil et al. [33] investigated the economic feasibility of hydrogen production using a system operated by off-peak electricity. Results showed that the system reliability is low to some extent due to operation by off-peak electricity. Yadav et al. [34] carried out an economic assessment for hydrogen production using solar driven electrolyzer. The authors found that increasing current density improves efficiency. The system was cost-effective for long-term calculations. They depended on the reduction in equipment cost expected in 2030. Mohsin et al. [35] investigated the economic feasibility of producing hydrogen using wind energy in different sites. Air density, turbine size, and wind speed affected hydrogen production. Results showed that the cost of hydrogen varied from 5.30 to 5.80 \$/kg H_2. Abdin et al. [36] presented an economic analysis of hydrogen production using renewable energy. They compared different locations. Optimization was performed for systems sizing depending on load demand as wind speed and solar radiation intensity were different in each location. It was concluded that better wind speed and radiation intensity could lead to reduced cost of energy for the system.

This paper aims to assess the performance of a solar-powered electrolysis system for green hydrogen production in several coastal locations in Egypt. The system incorporates a PV array with a maximum power point tracking controller, battery storage, and charge controller. A comparative study of the proposed system performance is conducted for a set of 25 different coastal sites considering a year-long dataset for each location.

2 Meteorological Data

In order to obtain a comprehensive assessment of the proposed green hydrogen system in different coastal environments in Egypt, 25 coastal sites have been considered. Figure 1 illustrates the locations of the selected sites on the Egyptian map. The detailed locations of these sites are presented in Table 1 based on the geographic coordinate system. These locations are categorized into three main coastal regions, namely, the Red Sea coast, the Sinai Peninsula coasts, and the Mediterranean Sea coast, as shown in Table 1. Furthermore, the year-averaged Global Horizontal Irradiation (GHI) in [kWh/m^2] for each site is presented in Table 1 based on the data from the Global Solar Atlas [37]. It is observed that Hurghada has the highest GHI among those considered locations with a value of almost 2321.5 [kWh/m^2]. On the other hand, Sidi Barrani possesses the lowest GHI of about 1981.9 [kWh/m^2].

Fig. 1 The map of Egypt with an illustration of the selected coastal cities under investigation. The map is captured from Google Earth Pro Software, with attribution: DATA SIO, NOAA, U.S. Navy, NGA, CEBCO, Image Landsat/Copernicus [38]

Table 1 A list of the selected coastal cities under investigation including their geographic coordinate, year-averaged global horizontal irradiation, and their specific coastal region

No.	City	Latitude	Longitude	Year-averaged global horizontal irradiation [kWh/m^2]	Region
1	Suez	29.97706	32.51149	2133.0	Red Sea coast
2	Ain Sokhna	29.65097	32.31112	2181.8	
3	Zaafarana	29.11065	32.66038	2195.8	
4	Ras Ghareb	28.35084	33.07536	2273.8	
5	Hurghada	27.1925	33.78171	2321.5	
6	Safaga	26.75296	33.93559	2315.5	
7	Marsa Alam	25.06842	34.88419	2312.6	
8	Halayeb	22.22043	36.64124	2237.5	
9	Taba	29.49346	34.89587	2199.8	Sinai Peninsula coast
10	Dahab	28.4956	34.50043	2276.0	
11	Sharm El-Sheikh	27.94671	34.34875	2294.5	
12	Al-Tor	28.23149	33.6375	2286.0	
13	Ras Abu Rudeis	28.90598	33.18981	2194.6	
14	Ras Sedr	29.59099	32.71954	2151.7	
15	Arish	31.11754	33.80462	2073.2	
16	Bir al-Abd	31.0196	33.00792	2114.1	
17	Port Said	31.23868	32.28517	2064.4	Mediterranean Sea coast
18	Gamasa	31.44123	31.53645	2021.9	
19	Rasheed	31.40101	30.41673	2031.1	
20	Alexandria	31.22411	29.95489	2034.1	
21	El-Alamein	30.82247	28.95431	2045.7	
22	El Dabaa	31.02236	28.44776	2063.9	
23	Marsa Matruh	31.33664	27.25533	2045.3	
24	Sidi Barrani	31.61058	25.93	1981.9	
25	El Salloum	31.575	25.15932	2016.5	

The National Solar Radiation Database (NSRDB) [39] is a comprehensive set of meteorological data and solar radiation measurements, including direct normal irradiance, global horizontal irradiance, and diffuse horizontal irradiance, that are available in the hourly form. This investigation utilizes the year-long historical data from the NSRDB to provide the input solar radiation to the system-level model. Spline interpolation is utilized to convert the hourly data from the NSRDB to instantaneous interpolated data which is essential for system-level modeling. More details about the proposed system-level model are available in Sect. 3.

3 Mathematical Modeling

MATLAB Simulink has been incorporated to build the system-level model. Figure 2 shows a schematic diagram of the Simulink model for the proposed solar-powered green hydrogen system. The solar irradiance data from NSRDB is fed to the model in hourly format. Then, a lookup table is used to provide the instantaneous data to model each second based on the Spline interpolation. The Simulink model consists of blocks, and each block represents an interconnected subsystem to form a system-level model. These subsystems include the PV array, battery storage, and proton exchange membrane (PEM) electrolyzer. The signals between the blocks represent the system variable. While the system input is mainly the meteorological data, the system output is mainly the hydrogen production quantity.

The PV array subsystem is one of the key subsystems. The PV array is represented by a double exponential diodes model that incorporates a current source that provides the highest accuracy. This accurate model is formed by incorporating series resistance, shunt resistance, and recombination into the simplest model. The series resistance reflects the voltage drop that occurs due to the current path through the semiconductor material, metal grid, contacts, and current-collecting bus. The shunt resistance represents the current leakage to the ground at the edges of the cell. The second diode signifies the recombination in the PV cell's depletion regionwhich provides a non-resistive current path in parallel with the intrinsic PV cell [40]. The PV array submodel is constructed with a Maximum Power Point Tracking (MPPT) controller in order to ensure successful tracking of the maximum power under fast changes in solar radiation. Cuckoo Search Algorithm is a bioinspired MPPT algorithm that has been successfully employed in fast changes in solar radiation [41].

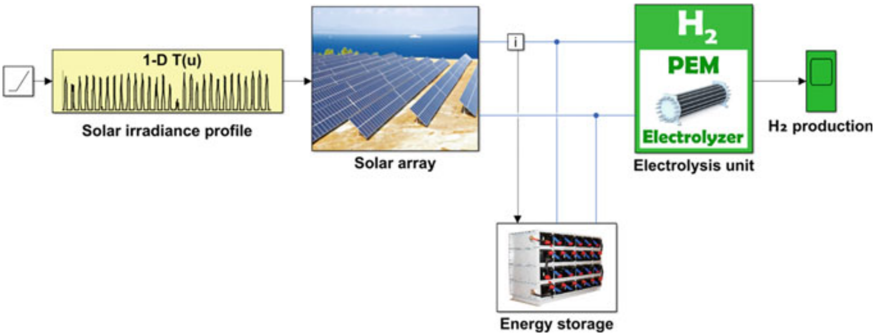

Fig. 2 A schematic diagram of the proposed solar-powered green hydrogen production system for a coastal location

The Buck-boost DC–DC converter is used as a power conditioning unit between the PV source and the electrolyzer [42]. The MPPT controller regulates this Buck-boost converter to adjust its duty cycle.

The battery storage subsystem is implemented to model the storage of excess energy generated by the PV array. Energy management battery storage is important to ensure a stable, reliable, and cost-effective energy supply. The energy management battery storage is regulated by the energy balance based on the instantaneous energy stored in the battery, the initial energy stored in the battery, and the power input/output from the battery. The employed battery charger prevents the battery from overcharging as well as deep discharging. The battery is represented by a combination of a resistor in series and a voltage source that depends on the charge. To make the model more robust, an approximate correlation is employed between voltage and the remaining charge. This correlation mimics the faster decline in voltage as the charge decreases.

The electrolyzer is the key element in any green hydrogen production system. A PEM electrolyzer is one of the promising types of the electrolyzer. It uses a solid polymer electrolyte membrane to split water into hydrogen and oxygen gases. In the proposed system, the PEM electrolyzer is employed. PEM electrolyzers consist of several components, including an anode and a cathode, a proton exchange membrane, and an electrolyte. The Electrolyzer is modeled as an electric load that identifies the amount of hydrogen production based on the electricity provided considering the temperature of water in the tank. The electrolysis stack consists of series-connected individual electrolyzer cells that are modeled considering the ideal state with a constant pH.

The NSRDB's actual historical data from a full year was used to supply solar radiation data to the system-level model. The hourly data from NSRDB was transformed into instantaneously interpolated data using spline interpolation to ensure accurate system-level modeling. Figure 3 illustrates two examples of the annual historical data for two locations, namely Al-Tor and Ain Sokhna, based on the hourly data obtained from NSRDB [39].

4 Results and Discussions

The abovementioned MATLAB Simulink model is implemented to mimic the performance of the green hydrogen production system in the selected coastal locations that are specified in Table 1. The historical data of solar irradiance for each location from the NSRDB is fed to the model as an input. The model is capable to provide instantaneous hydrogen production with a 1-s resolution. However, the hydrogen production is then integrated to provide the annual hydrogen production for each of the considered locations. Figure 4 illustrates the annual output of green hydrogen production in kg for each of the considered coastal locations.

As mentioned before in Table 1, the considered 25 locations are categorized into three regions based on their geographical coastal area, particularly the Red Sea

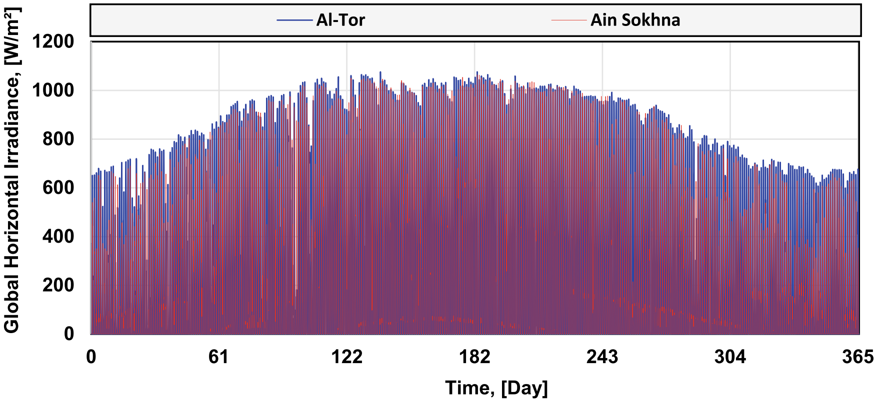

Fig. 3 Examples of the annual historical data for two locations, namely Al-Tor and Ain Sokhna. Data are obtained from NSRDB [39]

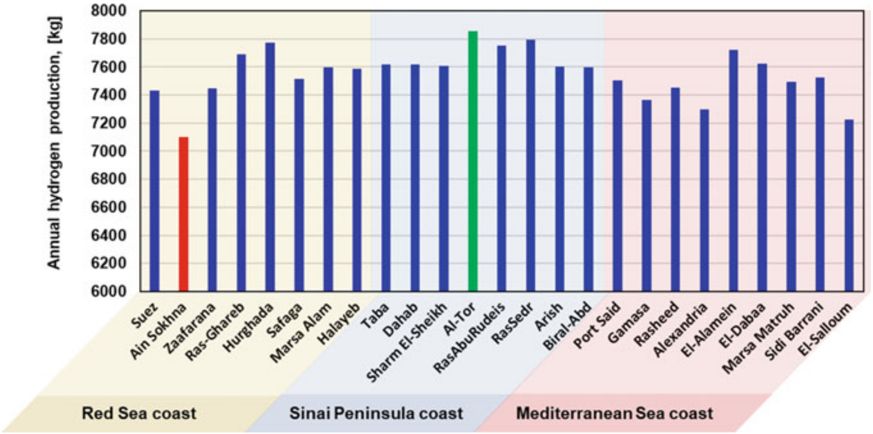

Fig. 4 An illustration of the annual hydrogen production for 25 selected locations over the three coastal regions in Egypt

coast, Sinai Peninsula coast, and Mediterranean Sea coast. These three regions are illustrated in Fig. 4 with different shading colors. Hurghada offers the best annual hydrogen production on the Red Sea coast while Ain Sokhna exhibits the lowest annual hydrogen production. Al-Tor has the highest hydrogen production rate among the other considered locations on the Sinai Peninsula coast. Considering the Mediterranean coast, it can be noticed that El-Alamein has the highest annual hydrogen production rate while El-Salloum is found to exhibit the lowest annual hydrogen production rate. It is well-known that Hurghada and Al-Tor have excellent wind potential which suggests that it would be worth studying the feasibility of green hydrogen production based on a hybrid solar/wind system.

Considering the 25 selected locations over the three coastal regions, Al-Tor, marked in green color in Fig. 4, shows the best performance with an annual hydrogen production rate of 7858 [kg/annum] and this is about 11% higher than Ain Sokhna, marked in red color in Fig. 4, that manifested the lowest annual hydrogen production rate about 7102 [kg/annum]. Overall, the locations in the Sinai Peninsula show a relatively close annual hydrogen production rate with relatively low variations in contrast with the other two coastal regions that exhibit considerable variations in the hydrogen production rates even between the close neighboring cities, such as Suez and Ain Sokhna. These considerable variations are due to the different topographic conditions that are expected to influence the clouds and shadings. In conclusion, this suggests that the Sinai Peninsula coast is promising in green hydrogen production based on solar energy.

In order to assess the effect of the seasonal variation of solar irradiance on the performance of the system production of green hydrogen, three coastal locations are considered including Ain Sokhna, Rashed, and Al-Tor. The hydrogen production of each site is illustrated as shown in Fig. 5 for each month over one year. It can be observed that the system hydrogen production in Rasheed in July outperforms the production in Al-Tor even though Al-Tor exhibits the highest annual hydrogen production. Also, in February and April, the production in Ain Sokhna outperforms the production in Rasheed even though Rasheed outperforms Ain Sokhna based on the annual hydrogen production. This illustrates the importance of considering the instantaneous data and the different seasonal conditions rather than the year-averaged solar irradiance in the investigation of green hydrogen production systems.

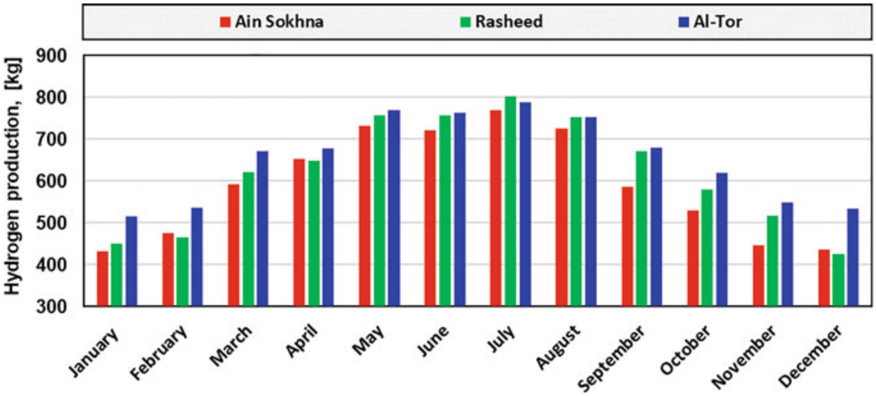

Fig. 5 The monthly hydrogen production of three selected sites over one year

5 Conclusion

This article explores the potential of producing green hydrogen in Egypt, which has ample renewable resources and a strategic location on the Sea. The study evaluates the performance of green hydrogen production in various coastal locations in Egypt, using a MATLAB Simulink simulation that considers 25 locations and their available solar irradiance. The analysis includes an assessment of a solar-powered green hydrogen system, using a historical year-long solar irradiance dataset for each location. The results indicate that the Sinai Peninsula coast is a promising area for green hydrogen production based on solar energy, with Al-Tor showing the best performance and an annual hydrogen production rate of 7858 kg. The study highlights the importance of considering instantaneous data and seasonal conditions for investigating green hydrogen production systems. It is suggested that future work should explore the feasibility of a hybrid solar/wind system for green hydrogen production in locations with high wind potential.

6 Recommendation

Based on the abovementioned findings, it is recommended to implement the proposed green hydrogen production system in Sinai coastal area. Furthermore, it is recommended to investigate the potential of hybrid PV-Wind utilization in green hydrogen production systems.

Acknowledgements The authors acknowledge the British Council for supporting the UK-Egypt Higher Education Climate Change Partnerships project No. 7 (Egyptian Offshore Wind to Produce Green Hydrogen to Mitigate the Effects of Climate Change).

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