



Integrating renewable energy sources in desalination: Comparing green hydrogen and solar-powered plants

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ABSTRACT

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The increasing of the global population and climate change in many regions have created a problem of dwindling water resources. Consequently, many countries have turned to desalination technologies, especially Reverse Osmosis (RO) plants. However, the problem with operating desalination plants is their high energy consumption and environmental impact. This study discusses the use of green hydrogen to operate desalination plants. The desalination plant operation sequence begins with a renewable energy system, specifically solar energy, which generates electricity to power an electrolyzer. This electrolyzer splits water into its constituent elements, producing hydrogen gas. The compressed hydrogen is then stored in specialized tanks and fed into fuel cells to generate electricity. This research compares two desalination plants with a capacity of 1 cubic meter of water per hour: the first is powered by solar energy, and the second is powered by green hydrogen. This study found that there are several criteria to ensure the continued operation of desalination plants using green hydrogen.



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1. Introduction

Green hydrogen is considered environmentally friendly and sustainable. (El-Shafie & M, 2023). Hydrogen gas is storable and transportable; fuel cells convert hydrogen gas into electricity. (Rezk et al., 2019; Roselin et al., 2022). The ability to store hydrogen is of great benefit to the continuity of energy supply. (Dincer et al., 2015; Kahil et al., 2025). Competition in the development of fuel cells and electrolyzers will reduce their current high costs (Singh & R, 2008). Integrating green hydrogen with renewable energy sources achieves sustainability (Al-Obaidi et al., 2024; Luu et al., 2019). Therefore, there is competition to design hybrid units in order to improve energy efficiency and reduce costs.

2. Materials and Methods

A desalination unit with a salinity of 5,000 mg/L and a recovery of 70% at 25°C was simulated by using TORAY DS2 software; the energy consumption required was 1.1 kWh/m³. The energy required to produce 1 kg of hydrogen was calculated using Faraday's law, with an efficiency of 70%, the energy is approximately 16–18 kWh per kilogram of hydrogen.

The two systems were evaluated in terms of the number of solar panels required, cost, and operating efficiency. The calculations and assumptions were based on manufacturer data and published researches.

2.1 Design of a RO unit with a capacity of 24 m³/day

Input design data are:

- Product water flow: 24 m³/day
- Feed water salinity: 5,000 mg/l

- Recovery rate: 70%
- Feed water flow: 34.3 m³/day
- Membrane type: TM20D-400 TORAY
- SDI (silt density index): < 3
- Ph: 4 - 10

The TM20D-400 membrane is widely used due to its high efficiency, resistance to pressure, chlorine, and contamination, high water quality, and competitive price.

The outputs were calculated using the TORAY DS2 software, as shown in Figure 1.

Output design data are:

- Operating pressure: 22 bar
- The power required: 1.1 kWh/m³, and for one day it needs 26.4 kWh.

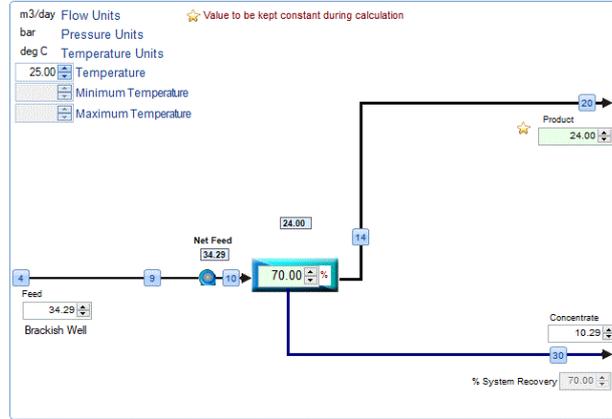


Fig. 1 Toray Software of BW, 20D 5,000 mg/l, 25 C°, RR 70%, 24 m³/day

2.2 Quantification of the hydrogen gas required to operate the desalination unit

Electrolysis is the basis of hydrogen production, where electrical energy is used to split water (H₂O) into hydrogen (H₂) and oxygen (O₂) on the electrodes of an electrolyzer (Li et al., 2024; Ismail et al., 2025; ZOHAIER et al., 2024).

Hydrogen is considered green if the water source used in the electrolysis process is from a renewable resource such as solar or wind power (Punetha et al., 2024; Jam et al., 2010).

In fuel cells, hydrogen gas undergoes an electrochemical conversion. At the anode, hydrogen molecules are split into protons and electrons. Electrons flow through an external circuit, generating an electric current, while protons travel across a proton exchange membrane to the cathode.

2.2.1 Calculating electrical energy from 1 kg of hydrogen

Fuel cells consist of three main components: an anode, a cathode, and an electrolyte membrane (for proton exchange). Hydrogen is pumped into the anode, while oxygen is pumped into the cathode. At the anode, hydrogen molecules dissociate into protons and electrons. The electrons flow generating an electric current. Fig. 2. (Ren et al., 2024; Islam et al., 2025).

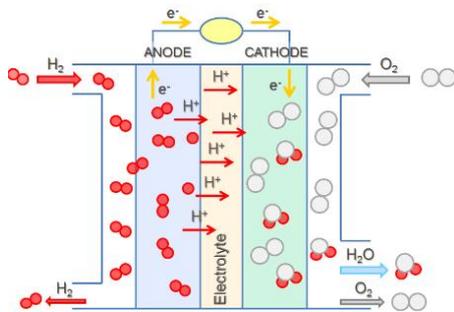


Fig. 2. A fuel cell that leverages the electrochemical reaction of hydrogen and oxygen

At the cathode, the protons, electrons, and oxygen combine to produce water molecules, this reaction is represented by (1):



Where:

EE: Electrical Energy, H: Hydrogen, O: Oxygen, H₂O: Water

Hydrogen has a high energy content of about 33.6 kWh per kilogram (Sahu et al., 2025), making it a promising fuel, especially in fuel cells, where it is converted directly into electricity without combustion, thus reducing energy loss (Sahu et al., 2025; Hamid et al., 2025).

Bloom Energy specializes in solid oxidized fuel cells, generating 300 kWh from 17.3 kg of hydrogen with an efficiency of 52%, consistent with previous calculations.

To calculate the electricity produced from 1 kg of hydrogen (33.6 kWh/kg) at an efficiency of 52% for fuel cells, equation (2) can be used:

$$E1 = H1 \times FC \quad (2)$$

Where: E1: Electrical energy

H1: Hydrogen energy per kilogram

FC: Fuel cell

$$33.6 \text{ kWh} \times 0.52 = 17.472 \text{ kWh}$$

Accordingly, everything from hydrogen produces about 17,472 kilowatt-hours of electrical energy, with typical

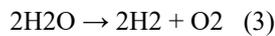
efficiency. However, this value may vary depending on the fuel cell and operation (Sahu et al., 2025).

Hydrogen fuel cells convert the chemical energy of hydrogen into electricity through a highly efficient electrochemical process, producing approximately 17.5 kilowatt-hours per kilogram of hydrogen, with an efficiency of about 52%.

The density of hydrogen gas can be calculated as an ideal gas under standard conditions using the ideal gas law, and its calculated density is approximately 0.0899 g/L (Peng, 2023).

Calculation of Energy Required for 1 kg Hydrogen Production via Electrolysis

To estimate the amount of energy required to produce one kilogram of hydrogen gas using an electrolyzer, key factors must be taken into account, such as the efficiency of the system and the nature of the electrochemical reaction, which is based on the electrolysis of water as shown in equation (3):



The number of moles of hydrogen required to produce 1 kg is calculated using equation (4) (Niaz et al., 2015):

$$(1000 \text{ g}) / (2 \text{ g/mol}) = 500 \text{ moles} \quad (4)$$

From Faraday's law, which states that 237.13 kJ per mole of hydrogen is needed (Jiang, 2024). To produce 500 moles, the energy required is calculated as follows:

$$500 \text{ moles} \times 237.13 \text{ kJ/mol} = 118,565 \text{ kJ}$$

Assuming that 1 kilowatt-hour equals 3600 kilojoules:

$$(118,565 \text{ kJ}) / (3600 \text{ kJ / kWh}) \approx 32.98 \text{ kWh}$$

Consequently, taking into account this efficiency, the actual energy required to produce 1 kilogram of hydrogen is:

$$(32.98 \text{ kWh}) / 0.70 \approx 47.11 \text{ kWh}$$

From the above it can be concluded that to produce 1 Kg of H₂ gas via electrolysis, assuming a system efficiency of 70%, approximately 47.11 KW/h of energy is required. Nel is a prominent, pure-play hydrogen technology company with a global footprint. It specializes in PEM and Alkaline electrolyzer technologies for the production of renewable hydrogen. Fig. 3.



PEM Electrolyser – S Series

0.27 to 1.05 Nm³/h | 0.58 to 2.27kg/day

Producing high purity hydrogen of 99.999+% at up to 1.05 Nm³/h, S Series electrolyzers replace the need for pressurized hydrogen cylinders in a variety of industrial processes.



Fig. 3 Nel. PEM Electrolyzer - Efficiency 70%

Figure 3 shows a product from Nel, the S-series hydrogen analyzer using PEM technology, with a production capacity ranging from 0.58 to 2.27 kg per day. This series is characterized by a low energy consumption in the cells of 4.5 kWh/m³, which represents a new standard for hydrogen production efficiency.

The standard specific gravity of hydrogen (H₂) under normal conditions is approximately 0.0899 g/l, and therefore, one cubic mass of hydrogen is approximately 0.09 kg.

At a consumption rate of 4.5 kWh/Nm³, it is necessary to generate 0.09 kW of hydrogen energy to reach 4.5 kWh, which

means that the energy required to produce 1 kg of H₂ is approximately 50 kWh, consistent with previous estimates. Accordingly, I have shown the energy consumption to produce one hydrogen in the PEM analyzer to be between 47 and 50 kWh.

In summary, calculations indicate that a hydrogen analyzer with a proton exchange membrane requires approximately 47-50 kWh per day to produce 1 kg/day of hydrogen, while one kilogram of hydrogen can generate approximately 16-18 kWh per day of electricity in fuel cells, estimating the efficiency of the two processes at approximately 36%.

2.3 Energy efficiency comparison: Green hydrogen vs. solar-powered desalination for RO 24 m³/day

Energy consumption in water desalination using green hydrogen and solar energy will be compared. This is applied to a 24 m³/day RO desalination system as follows.

2.3.1 Green hydrogen power required for RO 24 m³/day

Green hydrogen desalination requires producing hydrogen via electrolysis, which is energy-intensive but has a low carbon footprint when using renewable sources. The hydrogen is then used as fuel to power the desalination plant, offering a flexible off-grid solution with storage capabilities. However, a hydrogen-based desalination component is being developed that relies less on renewable energy or reduces losses during production, storage, and conversion.

Based on the RO plant design described in Section 1, producing one cubic meter of desalinated water requires 1.1 kWh; therefore, producing 24 m³/d requires 26.4 kWh per day.

Based on that result, 1 kg of hydrogen in the fuel cell produces about 18 kWh of electricity, and therefore, the desalination plant needs about 1.46 kg of hydrogen per day.

Furthermore, the data indicate that the electrolysis process in a PEM analyzer requires approximately 50 kWh to produce one kilogram of hydrogen gas. Accordingly, operating a RO plant requires the use of an electrolyzer with an approximate power of 73.3 kWh per day.

In conclusion, a solar energy system with a daily power load capacity of 73.3 kWh/day must be designed to meet the operational requirements of the desalination plant producing 24 m³/d.

2.3.2 Methodology for determining the number of solar panels in a photovoltaic (PV) system

The RO plant under consideration, it requires 73.3 kW of power. The energy production of solar panels depends on their specifications, such as the 750-watt Huason panel with 24.16% efficiency. This data will be used in the calculations. Solar

irradiance also varies according to location and seasons and is measured in hours of peak sunshine, which typically range between 4 and 7 hours per day depending on the region. It is necessary to determine the average solar irradiance of the location based on reliable data such as global maps and accumulated solar energy resource data (Polo, 2015), as shown in Figure 4.

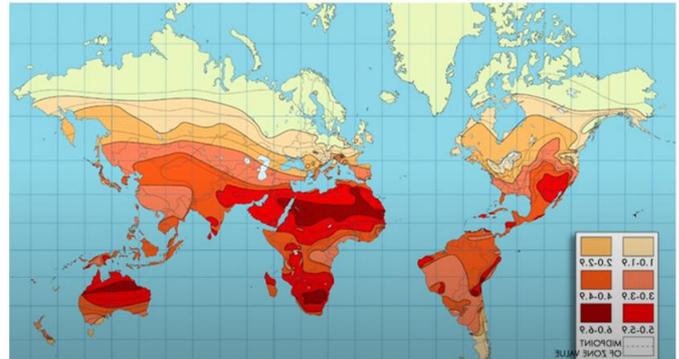


Fig. 4 World Insolation Map (Based on accumulated worldwide solar insolation data)

To compute the required number of panels, equation (5) is employed:

$$PV_n = PVP \times Sh \quad (5)$$

Where:

PV_n: Number of Panels

PVP: Required Capacity Panel Power Rating

Sh: Solar Hours

For RO plant that requires 73.3 KW per day, each panel produces 750 watts, and we will assume the average solar irradiance is 5 hours per day.

$$\text{Power Required} = (73,300W) / 5 = 14,660 W$$

$$\text{Number of Panels} = (14,660 W) / (750 W) = 19.5 \approx 20 \text{ PV Panel}$$

A 20% energy loss in solar systems is consistent with IEC 61724-1:2017, which defines a Performance Ratio (PR) of 75%–85% (i.e., 15%–25% loss) (Ogliari et al., 2023). Regional data from Saudi Arabia, Egypt, and Morocco report total losses of 18%–38% due to high temperatures, soiling, and spectral variation. This compensates for factors such as shading, dust accumulation, and less-than-optimal panel performance. Therefore, the result is multiplied by a factor of 1.2 to account for efficiency losses (Abou Jieb et al., 2022), then the panels with efficiency consideration equal 24 Panels. 24 PV panels would be necessary to meet the energy demands reliably (Fig. 5).

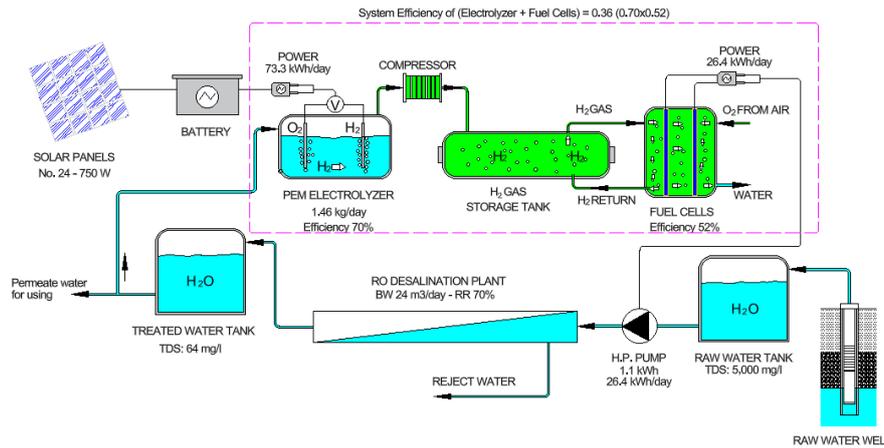


Fig. 5. RO 24 m³/day Powered Green Hydrogen Gas, PEM 1.46 kg/day, Fuel Cells, PV Panel 750 W

Fig. 5 illustrates the design of two integrated units: The first unit, a hydrogen generation station via an electrolyzer with an efficiency of 70%, which is powered by a solar power unit generating 65 kWh. The output of the electrolyzer is hydrogen gas with a capacity of 1.46 kg/day, which is subsequently condensed through a condenser and stored in a hydrogen storage tank. For energy production, the hydrogen gas is utilized in a fuel cell unit with an efficiency of 60%.

The second unit, a RO desalination unit, where water is sourced from a well and stored in a raw water tank. The raw water tank feeds a high-pressure pump 1.1 kWh, which compresses the water and directs it into the RO membrane unit 24 m³/d, where salt is separated. The produced freshwater is then stored in a product water tank.

The purified water required for the electrolyzer process is supplied from the freshwater produced by the RO system, which has an extremely low salinity of 65 mg/L. In this way, a closed-loop system is established, starting from the electrolyzer, passing through the fuel cells, then to the desalination unit, and returning to the electrolyzer.

2.3.3. The estimated cost of the solar system, electrolyzer, and fuel cells

The cost depends on the country, type of panels, efficiency, battery storage, and installation method. For a total capacity required of 73.3 kWh/day, 750W per panel type, Huasun Himalaya G12, PV panel requires 24 panels. Table 1 shows the approximate cost for only the solar PV system to produce the power requirement for the PEM electrolyzer, which produces 146 kg/day of H₂ gas.

The capital expenditure for an electrolyzer with a hydrogen production capacity of 1–2 kg per day typically ranges from \$2,000 to \$3,000.

The cost of a hydrogen fuel cell system with a power output between 1 and 2 kilowatts (kW) varies from \$6,000 to \$8,000, contingent upon the fuel cell technology employed (e.g., PEM or Solid Oxide Fuel Cell (SOFC)), the manufacturer, and the

degree of system integration. Table 1 shows the estimated cost of solar, electrolyzer, and fuel cells.

Table 1. Estimated Cost of Solar, Electrolyzer, and Fuel Cells

System Requirements	Qty	Unit Cost (\$)	Total
Huasun G12 Panel – 750W	24	80	1,920
Inverter (12 kW capacity)	1	1,500	1,500
Mounting system	-	600	600
Wiring, combiner box, etc.	-	400	400
Installation labor (varies)	-	1,600	1,600
Battery storage	-	3,500	3,500
Electrolyzer	-	2,500	2,500
Hydrogen Fuel Cell	-	7,000	7,000
Accessories	-	1,500	1,500
Total Estimated Cost (\$)			20,520

It is anticipated that these costs will decline over time as advancements in technology and economies of scale drive greater commercialization and efficiency improvements.

2.4. The operation of RO 24 m³/day desalination with direct solar system utilizing

Solar-powered desalination harnesses solar energy, typically through photovoltaic (PV) systems, to directly supply power to desalination facilities. The use of solar energy in desalination is considered an effective option in sunny regions, where the Electric Finance Corporation directly converts modern energy into electricity to power desalination plants without the need for production processes such as oxygen production, with low energy consumption and seamless integration into the dinosaurs. The dynamics of finance have contributed to this and increased its suitability. However, it depends on the continuity of sunlight and requires the use of Brent for storage or the use of a hybrid to operate.

2.4.1 Methodology for determining the number of solar panels in a PV system

The first step is to determine the amount of power required to cover the expected load, usually measured in kilowatts. For a RO plant that needs 26.4 kilowatts, this figure is used as the basis for calculations. The power output from solar panels depends on their specifications, such as Huasun panels with a power of 750 watts and an efficiency of 24.16%, and solar radiation also varies depending on the location and the time of year.

In certain regions, the average daily solar irradiance might range from 4 to 6 hours, while in others, it may be as high as 5 to 7 hours.

To compute the required number of panels, the following equation is employed:

$$\text{Number of Panels} = \frac{\text{Required Capacity}}{\text{Panel Power Rating} \times \text{Solar Hours}}$$

For our RO plant that required 64.4 KW per day, each panel produces 750 watts, and the average solar irradiance in the region is 5 hours per day.

$$\text{Power Required} = \frac{26,400 \text{ W}}{5} = 5,280 \text{ W}$$

$$\text{Number of Panels} = \frac{5,280 \text{ W}}{750 \text{ W}} = 7 \text{ PV Panel}$$

Therefore, the result is multiplied by a factor of 1.2 to account for efficiency losses:

Thus, 9 panels would be necessary to meet the energy demands reliably (Fig. 6).

The estimated cost of a 26.4 kWh/day solar energy system:

The cost depends on the country, type of panels, efficiency, battery storage, and installation method. For a total capacity required of 26.4 kWh/day, 750W per panel type, Huasun Himalaya G12, PV panel requires 9 panels. Table 2 shows the approximate cost of the solar PV system to produce the power requirement for the RO system that produces 1 m³/hr.

Table 2. Cost of Solar System 26.4 kWh/day

System Requirements	Qty	Unit Cost (\$)	Total
Huasun G12 Panel – 750W	9	80	720
Inverter (6 kW capacity)	1	1,000	1,000
Mounting system	-	300	300
Wiring, combiner box, etc.	-	300	300
Installation labor (varies)	-	1,200	1,200
Battery storage	-	1,500	1,500
		Total Estimated Cost (\$)	5,020

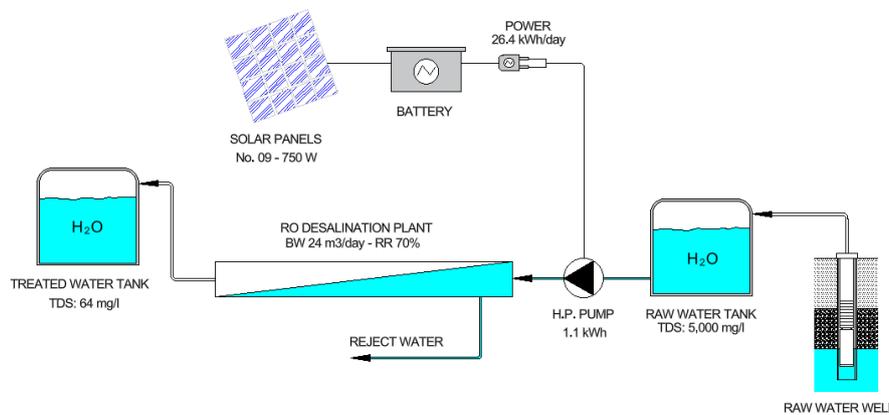


Fig. 6 RO 24 m³/day powered by solar system – PV panel 750 W

Fig. 6 illustrates the design of a RO desalination unit powered directly by a solar energy system. The desalination unit has a production capacity of 24 m³/d.

2.5. Comparison between a 24 m³/day RO desalination system powered by green hydrogen and powered by solar energy

In terms of energy consumption and operational costs, the operation of a 24 m³/day desalination plant powered by green hydrogen and fuel cells necessitates an energy input of 73.3

kWh per day, due to energy losses in the electrolyzer and fuel cell systems. This is equivalent to the output of 24 photovoltaic (PV) panels, each generating 750 W, with an initial cost of \$10,000 for only the solar system, excluding costs of the electrolyzer and fuel cell units. With electrolyzer units and fuel cells, the cost becomes high, reaching about \$ 20,000. In contrast, operating the same desalination plant directly via a solar power system requires 26.4 kWh per day, corresponding to the output of 9 PV panels, with an initial cost of \$6,000 for the solar system. A summary of the comparative analysis between the 24 m³/day RO desalination unit powered by green hydrogen and the solar-powered desalination plant is presented in Table 3.

Table 3. Comparison between the 24 m³/day RO desalination unit powered by green hydrogen and the solar system

Description	RO powered by H ₂ Gas	RO powered by Solar Energy
Power required	73.3 kWh/d	26.4 kWh/d
Power efficiency	Electrolyzer 70% Fuel cells 52%	PV panel 80%
PV panels required	24 pcs – 750 W	9 pcs – 750 W
Estimated cost for the solar system	9,000 – 11,000 \$ Excluding Electrolyzer & Fuel cell units	5,000 – 7,000 \$
Continuity of Operation Geographically constrained	Continuous Low	Intermittent High
Future scalability	Required a complex infrastructure	Solar panels can be seamlessly integrated
Power Storage Capacity	Relatively limited, depends on battery size and energy density (150–250 Wh/kg)	Very high, hydrogen can be stored as fuel with an energy density up to 30,000 Wh/kg
Power Storage Duration	Effective for short-term storage from minutes to several hours	Suitable for long-term storage from days to months or even years

Table 3 shows the results of the design calculations under specific geographical constraints, noting that these estimates may vary depending on the configuration of the hydrogen infrastructure or variations in solar radiation.

3. Results and Discussion

The study indicates that using hydrogen gas to power RO water disposal units allows operation to continue even in the absence of sunlight, but it leads to increased energy consumption compared to solar power operation. These results are consistent with what (Arunachalam et al., 2024) stated, where they indicated that hydrogen provides the possibility of long-term energy storage, but it is accompanied by a large loss in conversion through energy reduction processes and fuel cells, and what (Sarker, 2023) also emphasized.

Although direct solar power is more energy-efficient (26.4 kWh per day versus 73.3 kWh when using green hydrogen), it does not guarantee continuous operation without relying on expensive batteries with a limited lifespan. On the other hand, green hydrogen provides large storage capacity for long periods, which was confirmed by (Buonomano et al., 2025) as a key advantage of long-term energy storage.

From an environmental perspective, both systems can significantly reduce carbon emissions if the consistent electricity used is derived entirely from renewable sources (Al-Obaidi et al., 2024) indicate that the environmental benefits of green hydrogen depend mainly on the use of clean energy (Wang, 2025; Muhammad et al., 2025).

However, the future technical challenge is to improve the efficiency of electrolyzers and fuel cells, this is what the author indicated (Cai et al., 2024; Jam et al., 2025).

Furthermore, the continued high cost of electrolyzers and fuel cells has resulted in green hydrogen systems costing up to three times that of solar systems.

In this study, several limitations were considered, including considering the stability of the electrolytic analyzer and fuel

cell, analyzing the cost without going into details, considering the average solar radiation, which may vary depending on dust levels and temperatures, and finally assuming stable daily demand. Therefore, as a result of the above, it is recommended that more accurate field tests be conducted.

This study contributes to the field of water desalination by comparing solar-powered desalination plants with those powered by hydrogen gas, determining the actual energy requirements of both types of plants to operate the same desalination plant, and highlighting the balance between operational reliability and energy efficiency.

Overall, the study showed that green hydrogen gas could be viable for long-term, sustainable water desalination projects, considering the economic challenges and low efficiency, compared to solar energy, but solar energy does not have the advantage of continuous operation and storability.

4. Conclusion

- Energy losses in green hydrogen systems are higher than in solar power systems. However, both are environmentally friendly and contribute to reducing carbon emissions.
- Green hydrogen is best suited to areas with low or unusual exposure to sunlight. The appropriate system depends on local conditions, available scientific infrastructure, and the operational needs of the desalination plant.
- Solar energy is easy to expand and maintain, but it depends on daylight and requires a large area, while it produces a long-term hydrogen system and requires a large infrastructure, but it provides storage and then stable production, which is promising for future water desalination.
- Actual performance may vary due to location, climate, water demand, equipment efficiency, and operational practices.

- Finally, integrating water desalination with hydrogen production is promising for enhancing sustainability and energy efficiency, but it faces technical and economic challenges, such as heat management and recovery of wasted energy, which require more detailed technical and economic studies.

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