Article

Potential and Economic Analysis of Solar-to-Hydrogen Production in the Sultanate of Oman

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Abstract: Hydrogen production using renewable power is becoming an essential pillar for future sustainable energy sector development worldwide. The Sultanate of Oman is presently integrating renewable power generations with a large share of solar photovoltaic (PV) systems. The possibility of using the solar potential of the Sultanate can increase energy security and contribute to the development of the sustainable energy sector not only for the country but also for the international community. This study presents the hydrogen production potential using solar resources available in the Sultanate. About 15 locations throughout the Sultanate are considered to assess the hydrogen production opportunity using a solar PV system. A rank of merit order of the locations for producing hydrogen is identified. It reveals that Thumrait and Marmul are the most suitable locations, whereas Sur is the least qualified. This study also assesses the economic feasibility of hydrogen production, which shows that the levelized cost of hydrogen (LCOH) in the most suitable site, Thumrait, is 6.31 USD/kg. The LCOH in the least convenient location, Sur, is 7.32 USD/kg. Finally, a sensitivity analysis is performed to reveal the most significant influential factor affecting the future's green hydrogen production cost. The findings indicate that green hydrogen production using solar power in the Sultanate is promising, and the LCOH is consistent with other studies worldwide.

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Keywords: green hydrogen; solar photovoltaic; renewable energy; economic feasibility; sensitivity analysis; Sultanate of Oman

1. Introduction

1.1. General and Motivation

Decarbonisation is one of the critical efforts countries worldwide take to reduce the risk of a global threat called climate change. The energy sector plays an essential role in the decarbonisation effort by integrating renewable power generations. By the end of 2020, the aggregated installed capacity of renewable power generation has reached 2799 GW, which has the largest share of hydroelectric, solar, and wind power. In 2020, more than 80% of the new capacity added was from renewable sources, in which solar and wind accounts for about 91% of new renewables [1,2]. Recently, hydrogen fuel from renewable sources has received significant interest because of its broad-spectrum applicability and ability to enhance the decarbonisation mission. The global hydrogen production capacity by the end of 2020 was 2.3 million tons, which is expected to reach 6.7 million tons by the end of 2030 [3]. Table 1 illustrates various hydrogen fuel applications, including transportation, building, industry, and feedstock [4].

The leading renewable energy technologies are hydro, wind, solar photovoltaic, bioenergy, geothermal, solar thermal, and ocean. Hydro technology has the highest, and Ocean technology reveals the least number of contributions in terms of the energy production index worldwide [5]. Among them, hydro technology has topographic restrictions. The availability of solar resources in most parts of the globe is the highest among all kinds of renewable energies. This energy resource is reported as the most appropriate alternative for fossil fuels [6]. Moreover, solar photovoltaics unfolded a profound reduction in cost

over 2010–2019 at 82%, followed by concentrated solar power at 47%, onshore wind at 40%, and offshore wind at 29% [7]. Thus, solar photovoltaic technology has significant potential for hydrogen production, which can accelerate the decarbonisation process.

Table 1. Synopsis of hydrogen fuel applications [4].

Application Sector	Applications
Transportation	Compact vehicle for urban transportation; mid-size vehicle with extended range; lightweight truck/van for urban distribution; medium size vehicle with short-range; medium-duty truck for regional haul; regional transportation, such as passenger train, SUV, ferry, and buses. Heavy-duty truck for long haul transportation; large ferries for vehicles and people; vehicles for commercial uses, such as large passenger vehicles, buses for long-range transport, coaches for long-distance transportation; forklift, and synfuels for aviation.
Heat and power for buildings	Fuel cell-based combined heat and power (CHP) for old hospitals, old flat city centre, and new houses; hydrogen boilers for the new home, old flat city centre, and old hospitals; hybrid heat pump and boiler; and blended application of hydrogen in natural gas boilers.
Heat and power for industry	Fuel cell-based backup and remote power generation; hydrogen furnace for high and medium grade heat; combined cycle hydrogen turbine; and simple cycle hydrogen turbine.
Industry feedstock	Low-carbon ammonia generation; refining; low-carbon steel-hydrogen DRI; and methanol production.
Mobility	Ships for container, motorbikes, tankers, tractors, off-road applications, fuel cells for airplanes
Others	Backup power systems, large-scale CHP for industry, mine apparatus, metals processing (non-DRI steel), etc.

Furthermore, the Sultanate of Oman has considerable potential in generating clean power using renewable sources, such as solar and wind [8–10]. Figure 1 shows the distribution of solar radiation during January and July, respectively [11]. The average wind speed for 28 different locations ranges from 3.0 to 6.3 m/s at 10 m height. Towards decarbonisation, the Sultanate of Oman has set a target to harness 10% of its energy requirement from renewable sources by 2025 [12]. By 2020, the total installed capacity of renewable power generation in the Sultanate was 159 MW [1]. Among these, the solar power share was about 68.56%, and the rest was from wind resources. Apart from electricity production prospects, such renewable energy resources have enormous potential to produce green hydrogen fuel. Presently, more than 95% of hydrogen production worldwide comes from fossil fuels [13], which is not an exception in the case of the Sultanate. Furthermore, the economic diversity, grid-scale energy storage requirement, green transportation, and industrialisation in the Sultanate will demand more hydrogen in the future. Moreover, the Sultanate can utilise the renewable potential for large-scale hydrogen production, which will meet the local demand and prepare the Sultanate as a hydrogen exporter. Thus, it is essential to investigate the potential of producing green hydrogen and the cost of producing hydrogen using renewable resources, particularly solar, in Oman.

Figure 1. Distribution of solar resources in the Sultanate of Oman: (a) 2.375 to 4.078 kW/m²/day in January, (b) 5.587 to 7.34 kW/m²/day in July. Reprinted with permission from ref. [11], ©2009, Elsevier Ltd.

1.2. Related Work

Hydrogen generation depends upon the production process and primary fuels or resources [14,15]. One way to produce hydrogen is to use renewable sources and an electrolysis process called green hydrogen. The hydrogen generated from fossil fuels using a reformer with no carbon dioxide (CO₂) mitigation is grey or black hydrogen. In addition, blue hydrogen is generated using fossil fuels and a reformer, Steam Methane Reforming (SMR), with CO₂ relief, whereas pink hydrogen is produced using nuclear power and the electrolysis process. Grey hydrogen production generates a substantial greenhouse gas released directly into the atmosphere [16]. The blue hydrogen production process captures or stores CO₂ for later use [17]. The CO₂ capture, utilisation, and storage mechanism increase the total capital cost of the process, and hence the hydrogen production cost. However, a high-capacity CO₂ electrolyser and storage CO₂ for formic acid production combined in the blue hydrogen production process can reduce the cost of blue hydrogen [18]. Blue hydrogen can play a vital role as a low-emission (not zero emission because of methane leakage [19]) energy carrier for countries where renewable-based green hydrogen cannot meet the low-carbon hydrogen demand [15]. However, this hydrogen production comes from fossil fuels, such as natural gas, coal, and oil. Moreover, the volatile gas price, lock-in fossil fuel price, depleted fossil fuel reserve, and geopolitical issues may restrict the development of blue hydrogen production.

Green hydrogen production using renewable powers involves three steps: Process primary energy (solar and wind) to produce electricity, ensure compatible and adequate electricity supply to the electrolyser, and generate hydrogen. Figure 2 depicts the renewable-source-based hydrogen production process using water electrolysis. The technologies for water electrolysis are an alkaline electrolyser, a polymer electrolyte membrane (PEM) electrolyser, and a solid oxide electrolyser cell. Alkaline is the earliest and most mature technology; however, it faces challenges, such as losses during operation at the high current densities that result in a rise in operating temperature and lessens efficiency [20,21], and the possibility of mixing hydrogen and oxygen gases while passing through the aqueous electrolyte. The solid oxide electrolyser cell (SOEC) has the highest efficiency; however, this technology market is still in the early stages [22]. The PEM electrolyser can operate at higher-level pressures, resolving the issue of aqueous electrolytes in the alkaline electrolyser [21]. Moreover, the polymer electrolyses can perform with electricity from stochastically varying renewable sources, such as solar and wind [22–26]. This study selects the PEM electrolyser because of its ability to perform under intermittent input power, cost, efficiency, and commercial viability [23,24,27–29].

Figure 2. Hydrogen production stages utilising renewable power sources.

The key drivers for renewable-based hydrogen production are technological readiness, significant potential for decarbonisation, freely available primary energy sources, and broad-spectrum applicability. However, the cost of hydrogen production using renewable sources can be a real obstacle to deploy green hydrogen projects for a country or stakeholder. Therefore, the hydrogen production cost evaluation is an essential element to assess the potential of hydrogen generation from intermittent renewable sources. Several researchers have estimated the green hydrogen generation cost using the notion adopted from the levelized cost of energy (LCOE) [30]. A feasibility study of hydrogen production using wind power is presented in [31–34], which showed the hydrogen production cost using electrolyser technology in the range of 10.15–7.55 USD/kg. A study in [23] reveals that wind power-based hydrogen production costs range from 16.1 to 8.5 USD/kg at 50 and 100 m hub heights. The utilisation of excess wind power for hydrogen production in a grid-connected system is evaluated in [35], and the hydrogen production cost was reported at 10.08 USD/kg. In [36], wind-powered hydrogen production’s economic analysis indicates the price of 10.98 USD/kg. This cost can be reduced by 50% if the electricity from the grid is supplied to the electrolyser. An economic investigation of a wind-hydrogen-battery-based hydrogen production study indicates the price of hydrogen production to be 9.0 USD/kg [37].

Techno-economic analysis of solar hydrogen generation using parabolic dish technology is presented in [38], and the hydrogen production cost was in the range of 7.19 to 11.09 USD/kg. The feasibility of concentrated solar power-based hydrogen production is evaluated. It shows that the cost of hydrogen production is 15.92 USD/kg in the base case, which can be reduced to 8.14 USD/kg in the best-case scenario [39]. A combination of a parabolic trough concentrator and the solar photovoltaic system is analysed for the hydrogen production capacity of the studied system; however, the cost of hydrogen production remains to be determined [40]. In [41], a techno-economic investigation of isolated solar photovoltaic-based hydrogen generation potential is discussed. The cost of hydrogen production is reported at a rate of 3.72 USD/kg, where the capacity factor of the solar photovoltaic system is assumed.

The authors in [42] present a hydrogen production economic analysis using different solar power generation technologies combined with the PEM and alkaline electrolyser. The cost of hydrogen production using solar PV with the PEM electrolyser was at a value of 3.31 USD/kg, lower than the PV and concentrated solar power-based hydrogen generation. In [43], solar photovoltaic-based hydrogen production is discussed, which indicates that the hydrogen generation cost reduction is possible by improving the system efficiency. Hydrogen production using wind and solar for refuelling stations can cost 2.0 USD/kg if the electricity cost is 0.01 USD/kWh [44]. However, the electricity production cost from renewables is yet to reach 0.01 USD/kWh. Hydrogen production using solar power and water electrolysis is evaluated, indicating the prospect of generating green hydrogen; however, the cost of hydrogen production is yet to be determined [45].

1.3. Research Gap, Objectives, and Contributions

The previous techno-economic studies of renewable hydrogen production assume the capacity factor of the solar PV or wind plants. Such an assumption influences the cost of energy produced from renewable energy sources, affecting hydrogen production cost. The electricity cost is one of the most sensitive factors in assessing hydrogen production economics [23,25,26,46,47]. Moreover, the energy estimation using a solar PV system, especially in a hot and humid environment, requires derating factor consideration due to temperature variability [48]. This factor remains unaccounted for if the capacity factor is assumed to estimate the energy output of a solar PV plant. Furthermore, using different solar technologies to produce hydrogen is more focused than a solar PV-based system alone. In addition, the prospect of hydrogen production using the significant solar resource available in the Sultanate is yet to be investigated. Therefore, the potential and economic analysis of producing green hydrogen using solar PV renewable power is the main topic of this paper. The objectives of this study are:

1. To examine the potential of green hydrogen production using the solar resources available in the Sultanate of Oman.
2. To analyse the solar photovoltaic-to-hydrogen production process considering site resources and temperature variability for determining the capacity factor of the photovoltaic plant instead of assuming it.
3. To evaluate the cost of green hydrogen production using the idea of levelized cost and identify the influential cost variables in producing hydrogen using solar power in Omani conditions.

Accomplishing these objectives allows making following contributions:

- A pioneering analysis process of solar photovoltaic-to-hydrogen production potential and cost of hydrogen production that considers the capacity factor determined based on the site resources and temperature variability in the Sultanate of Oman.
- Outlining a rank of suitable locations with the potential of dedicated solar photovoltaic-based hydrogen production facilities development and identifying critical variables that significantly impact hydrogen production cost in Omani conditions.

1.4. Paper Structure

The rest of the paper is structured as follows: Section 2 describes the research methodology, i.e., the modelling of PV plant energy output, hydrogen production model, the economic model of the energy cost and hydrogen production cost, and the methodology implementation steps. Then, in Section 3, the results for PV plant energy production, hydrogen production, cost of hydrogen production, and sensitivity analysis are presented and discussed. This section also discusses the technology adoption factors and environmental impact. Finally, Section 4 summarizes the conclusion of the paper that also includes research limitations and future direction.

2. Methodology

The methodology of solar photovoltaic-based hydrogen production potential and cost assessment includes estimating the energy output of the PV plant considering the site data and temperature variability effect, quantifying hydrogen production, and performing an economic analysis. In addition, the financial analysis requires modelling of energy and hydrogen production costs to determine the LCOE and LCOH. Finally, a sensitivity analysis is needed to reveal the factors that significantly impact the LCOH.

2.1. Energy Output Model of a PV Plant

The annual energy output of a solar PV power plant is calculated as [48],

$$E_{PV} = P_{r,pv} D_f P_{sh} N_d \quad (1)$$

where E_{PV} is the energy output of the PV plant in kWh, $P_{r,pv}$ is the rated output power of the PV plant in kW, D_f is the overall derating factor, P_{sh} is the daily average peak sun hour, and N_d is the number of days in a period, such as in a year. The overall derating factor is composed of two components. They are the derating factor due to the temperature variation and other system components that include the PV module nameplate DC rating, the transformer and inverter, diodes and connections, AC and DC wiring, soiling, shading, system availability, sun tracking, and age. The derating factor due to system components can be a fixed value; however, the derating factor due to temperature variation is modelled to reflect the effect of such variations on the PV output. The present study concentrates on the system that can be developed in hot and humid conditions, where the temperature variation occurs in a wide range. The derating factor is calculated by modelling the actual cell temperature as follows [49],

$$T_C = T_a + \left(\frac{T_{NOCT} - 20\text{ }^{\circ}\text{C}}{S_{NOCT}} \right) \times S_S \quad (2)$$

where T_C is the real cell operating temperature in $^{\circ}\text{C}$, T_a is the ambient temperature $^{\circ}\text{C}$, T_{NOCT} is the normal operating cell temperature in $^{\circ}\text{C}$, S_S is the site solar intensity in kW/m^2 , and S_{NOCT} is the solar intensity at the standard testing condition (STC) in kW/m^2 . The amount of reduction in maximum power due to the temperature effect is computed as a percentage as [49],

$$P_{red} = \alpha(T_C - 25\text{ }^{\circ}\text{C}) \quad (3)$$

where P_{red} is the decrease in maximum output power in percentage and α is the reduction in maximum output power due to each $^{\circ}\text{C}$ variation of the cell temperature in $\%/^{\circ}\text{C}$. Therefore, the derating factor due to module temperature alteration is calculated as

$$D_{temp} = 1 - P_{red} \quad (4)$$

Considering the derating factor due to the aforementioned system components as D_{sys} , the overall derating factor can be depicted as

$$D_f = D_{temp} D_{sys} \quad (5)$$

The capacity factor of the PV plant is determined using Equation (6) [49].

$$\text{Capacity factor} = \frac{E_{PV}}{P_{r,pv} \times 8760} \quad (6)$$

2.2. Model of Hydrogen Production

An electrolyser is an essential device to produce hydrogen from electricity. Figure 1 shows a PV-based hydrogen production system, where the energy output from the PV plant is fed to an electrolyser to generate hydrogen. The hydrogen production using an electrolyser provided by PV power is computed using Equation (7) [35].

$$H_{PV} = \frac{\eta_{pc} E_{PV}}{E_{EL}} \quad (7)$$

where H_{PV} is the amount of hydrogen production using PV power in Nm^3 , η_{pc} is the efficiency of the interfacing power converter between the PV plant and the electrolyser as a percentage, and E_{EL} is the energy required by the electrolyser for one unit volume of hydrogen production in kWh/Nm^3 . The hydrogen production in kg is calculated as [13],

$$H_{PV,kg} = \frac{H_{PV} \text{ in } \text{Nm}^3}{11.1} \quad (8)$$

2.3. Economic Model

The economic model of solar-to-hydrogen production requires modelling of solar-to-electricity cost and hydrogen production cost. Unlike if the electrolyser uses electricity from the utility grid, the electricity price is known from the utility company. However, the electricity cost of the renewable source-based power plant is essential to assess in order to utilise it in evaluating hydrogen production cost. The electricity generation cost from renewable sources depends on the resources available on the site and the use of technology [24]. The models of electricity production cost from solar PV and the hydrogen production cost using the electrolyser use the concept of LCOE described in the following subsections.

2.3.1. Model of Energy Production Cost

The LCOE approach uses different cost factors, such as a discount rate, capital cost, installation and operation, and maintenance costs, to determine the energy cost. The LCOE for a PV plant is determined by the ratio of the aggregated annualized cost of the PV plant to yearly energy produced from the PV plant, which can be expressed as [23],

$$LCOE = \frac{C_{PV}CRF_{PV} + C_{pc}CRF_{pc} + C_{ins}CRF_{ins} + C_{mis}CRF_{mis} + C_{OM}}{E_{PV}} \quad (9)$$

where C_{PV} , C_{pc} , C_{ins} , and C_{mis} are the cost of PV panel, interfacing power converter, installation and civil works, and miscellaneous, respectively. CRF_{PV} , CRF_{pc} , CRF_{ins} , and CRF_{mis} are the cost recovery factors of the PV panel, the interfacing power converter, installation and civil works, and miscellaneous cost, respectively. Equation (9) can be formulated as Equation (10), where C_{plant} is the total installed cost of the PV plant and CRF_{plant} is the cost recovery factor for the total installed PV plant cost.

$$LCOE = \frac{C_{plant}CRF_{plant} + C_{OM}}{E_{PV}} \quad (10)$$

The accepted total installed cost of a PV plant can be obtained based on the per kW installed cost ($C_{ins/kW}$) basis from [7], and it can be expressed as,

$$C_{plant} = C_{ins/kW}P_{r,pv} \quad (11)$$

The cost recovery factor can be computed using Equation (12) [23],

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

where i is the discount rate and n is the system lifetime. The operation and maintenance cost can be computed by employing the escalation ratio in Equation (13) [23].

$$C_{OM-S} = \frac{C_{OM}}{i - \lambda_{om}} \left[\frac{1 - (1 + \lambda_{om})^n}{(1 + i)^n} \right] \quad (13)$$

where C_{OM-S} is the operation and maintenance cost employing the escalation ratio, where λ_{om} denotes the escalation ratio. As per Ref. [7], the accepted operation and maintenance cost is obtained 10 USD/kW.

2.3.2. Model of Hydrogen Production Cost

For a solar photovoltaic-hydrogen system, the LCOH can be determined based on the total annualized cost of the electrolyser, cost of electricity, and operation and maintenance cost of the electrolyser. The LCOH is computed as [23,24],

$$LOCH = \frac{C_{EL}CRF_{EL} + C_{electricity} + C_{HS} + C_{OM_EL}}{H_{PV,kg}} \quad (14)$$

where C_{EL} , $C_{electricity}$, C_{HS} and C_{OM_EL} are the capital cost of the electrolyser, electricity cost, hydrogen storage cost, and the operation and maintenance cost of the electrolyser and hydrogen storage system, respectively. CRF_{EL} is the cost recovery factor of the electrolyser, and the cost recovery factor is determined using Equation (12). However, the lifetime of an electrolyser system is considered to be 20 years, which is different from the lifespan of the PV system, which is 25 years. The electrolyser capital cost is determined as [24]

$$C_{EL} = P_{EL}C_{EL/kW} \quad (15)$$

where P_{EL} is the electrolyser capacity in kW, and $C_{EL/kW}$ is the per kW cost of a specific electrolyser that is obtained from [13]. The required capacity of an electrolyser is found using Equation (16) as given in [50].

$$P_{EL} = \frac{\text{Annual energy input to the electrolyser in kWh}}{8760U_f} \quad (16)$$

where U_f is the utilisation factor. The operation and maintenance cost of the electrolyser can be manifested as [35],

$$C_{OM_EL} = 8760m_wC_WU_F + 0.03C_{EL}CRF_{EL} \quad (17)$$

where m_w is the required water flow for the electrolyser in m^3/h , and C_W is the cost of water in USD/m^3 . The accepted operation and maintenance cost of a water electrolyser system is obtained from [13,35], which is 5% of the annualized capital cost of the electrolyser. The hydrogen storage cost is taken 0.5 USD/kg [50].

2.4. Implementation of the Methodology

The process of evaluating hydrogen production potential and the unit cost of hydrogen involves energy output estimation from the renewable-based generation, quantifying the hydrogen production, calculating the cost of electricity from the renewable sources, and assessing the cost of hydrogen production. Figure 3 shows the implementation flow of the methodology described earlier. Site selection and renewable resource assessment are essential since hydrogen production depends on renewable sources, such as solar radiation. The temperature effect in PV power generation requires derating factors, which is critical for hot and humid locations. The large PV plant is selected to produce a large quantity of green hydrogen to reduce the hydrogen production cost. The energy output of the PV plant is determined that is used to calculate the LCOE, electrolyser size, and capacity factor. The capacity factor is used as a utilisation factor to determine the electrolyser size since hydrogen production is only based on solar power. Equation (7) uses the efficiency of the power electronic converter and the specific energy consumption by the electrolyser to calculate the per unit volume of hydrogen production. In order to be consistent with the literature and to present a better comparison, the per-unit hydrogen cost is converted into USD/kg using Equation (8). The LCOE is calculated for the energy generated by the PV plant using the economic model and data related to financial analysis. This cost is used as the electricity cost to determine LCOH. The LCOH also requires the size and utilisation factor of the electrolyser, which is determined using the energy available from the PV plant. Table 2 presents the data necessary to accomplish the implementation of the evaluation process.

Figure 3. A process of evaluating hydrogen production potential and cost using renewable power generations.

Table 2. Data to implement evaluation process of hydrogen production potential and the LCOH.

Parameter	Value	Reference/Data Obtained
Solar radiation	Refer to Figure 4	[51]
Site temperature	Refer to Figure 5	[51]
Derating factor due to system components. PV module nameplate DC rating, transformer and inverter, diodes and connections, AC and DC wiring, soiling, shading, system availability, sun tracking, and age.	0.7895	[52]
PV plant capacity	2000 kW	Assumed
Power converter efficiency	95%	[35]
Average power consumption	4.53 kWh/Nm ³	[53]
PV capital cost per kW	996 USD	[7]
Discount rate	6.5%	[48]
PV system lifetime	25 years	[48]
Operation and maintenance cost of PV plant in per kW	10 USD	[7]
Electrolyser capital cost	1010 USD/kW	[13]
Electrolyser's operation and maintenance cost	5% of the annualized capital cost	[13,35]
Utilisation factor	20%	[50]
Hydrogen storage cost	0.5 USD/kg	[50]

Figure 4. Annual average solar radiation in 15 different locations throughout the Sultanate of Oman.

Figure 5. Annual average ambient temperature in 15 different locations and the photovoltaic cell operating temperature of these locations.

3. Results and Discussion

For the purpose of evaluating the hydrogen production potential using solar PV in the Sultanate of Oman, energy production from solar PV and hydrogen generation from solar energy is estimated for the selected locations in the Sultanate of Oman. The LCOE is assessed to determine the cost of electricity that is used by the electrolyser. With the concept of levelized cost, the LCOH is then calculated to investigate the economics of hydrogen production in the country. Finally, cost reduction scenarios and sensitivity analysis are carried out to reveal variables that significantly influence hydrogen production costs.

3.1. Energy Output of the Solar PV Plant

There are 15 different locations selected throughout the country. These locations have a solar radiation profile such that the hydrogen production potential of these locations can be compared with any other sites in the Sultanate. The selected areas are Ibri, Al Mudybi, Buraimi, Fahud, Khasab, Marmul, Masirah, Nizwa, Salalah, Muscat, Sohar, Sur, Thumrait, As-Suwayq, and Duqm. Figure 4 shows the annual average solar radiation for 15 different locations, and the range of solar radiation is from 4.53 kWh/m²/day to 6.13 kWh/m²/day. The highest solar radiation was found for Thumrait (6.13 kWh/m²/day) and Marmul

(6.09 kWh/m²/day), whereas the lowest solar radiation was found in Salalah (4.8 kWh/m²/day) and Sur (4.53 kWh/m²/day). The peak sun hour for these locations is calculated using the one-sun of insolation (1 kW/m²) approach [52]. For example, Thumrait has solar radiation of 6.13 kWh/m²/day. With the one-sun insolation approach, the peak sun hour for Thumrait was calculated as 6.13 h. Table 3 shows the peak sun hour for the selected locations.

Table 3. Peak sun hour for 15 different locations in Oman.

Site Name	Peak Sun Hour (hours)
Ibri	5.68
Al Mudaybi	5.72
Buraimi	5.37
Fahud	5.69
Khasab	5.75
Marmul	6.09
Masirah	5.65
Nizwa	5.8
Salalah	4.8
Muscat	5.45
Sohar	5.51
Sur	4.53
Thumrait	6.13
As-Suwayq	5.66
Duqm	5.76

Figure 5 captures the effect of ambient temperature on the PV cell operating temperature. The annual average temperature varies between 26.3 °C and 29.46 °C. Fahud represents the highest temperature, 29.46 °C, and Salalah means the lowest temperature, which is 26.3 °C. Thumrait and Marmul possess the most increased solar radiation compared to Fahud; however, the temperatures in Thumrait and Marmul are lower compared to Fahud. On the other hand, Fahud has lower annual average solar radiation than in Thumrait and Marmul. The yearly average ambient temperature in Salalah (26.3 °C) and Thumrait (26.2 °C) are almost identical. However, the annual average solar radiations in Salalah and Thumrait are 4.8 kWh/m²/day and 6.13 kWh/m²/day, respectively. The higher ambient temperature results in a higher PV cell operating temperature that degrades the conversion efficiency of the PV system. Fahud has shown the highest PV cell operating temperature, whereas Salalah has revealed the lowest PV cell operating temperature. As a result, the highest percentage reduction in maximum power was noticed in the case of Fahud, which was about 7.1%, as can be seen from Figure 6. The minimum percentage reduction from the maximum output power was found in the case of Salalah, which was about 5.05%. It can be attributed to the low ambient temperature in the Salalah. Regarding Thumrait and Marmul, Thumrait (6.27%) has a lower percentage reduction in maximum output power than Marmul (6.7%). The ambient temperature difference between Thumrait (26.2 °C) and Marmul (27.4 °C) is 1.2 °C, which causes a 0.43% reduction in the maximum power of the PV system. Ibri, Al Mudaybi, Khasab, Muscat, As-Suwayq, and Duqm have a similar temperature profile, which causes an almost identical amount of percentage reduction in maximum power. Nizwa has close characteristics to Marmul, while Buraimi and Thumrait have similar features.

Figure 6. Percentage reduction in maximum power due to the temperature derating factor at 15 different locations.

A 2000 kW PV plant is considered for all the selected locations in the Sultanate of Oman to evaluate energy production. Figure 7 shows the annual energy production with and without considering the temperature effect for the chosen sites. The maximum annual energy production was found in Thumrait, whereas the yearly minimum energy generation was found in Sur. In Thumrait, the annual energy production with and without the temperature effect are 3311 MWh and 3533 MWh, respectively. It indicates that about 6.27% of the yearly energy reduction in this location is due to temperature. In Sur, the yearly energy productions with and without the temperature effect are 2461 MWh and 2611 MWh. This unveils that about 5.75% of the reduction in annual energy production for this location is due to temperature development. The temperature effect also reveals that Marmul can produce 3275 MWh of energy in a year, the second highest among all sites. Although Fahud has a slightly higher annual average solar radiation than Ibri, the annual energy production in Fahud (3046 MWh) is lower than Ibri (3064 MWh) because of the higher ambient temperature. This difference in annual energy production can be significant over the plant lifetime, which will impact the cost of electricity from the PV plant.

Figure 7. Annual energy production by a 2000 kW PV plant at 15 different locations in Oman.

For the purpose of estimating the utilisation factor required to determine the electrolyser size, the capacity factor of a 2000 kW PV plant is calculated for the selected locations. Figure 8 captures the capacity factors with and without considering the temperature effect

for a 2000 kW PV plant for the designated areas. With the temperature effect, the study reveals that the capacity factor of the PV plant in Thumrait is 0.19, while it is 0.14 in Sur. In Marmul, the capacity factor of the plant with temperature development was found to be 0.187. With the temperature effect, the study also indicates that the capacity factor of the PV plant in Fahud is 0.165, while it is 0.175 in Ibri. Thus, for all selected locations, the capacity factors of a 2000 kW PV were found to be in a range of 0.14 to 0.19. Such a range of capacity factors is identical to that reported in [54], indicating that the annual average capacity factor is 0.15 in the Muscat area, Oman. The current study found the capacity factor in the Muscat area to be 0.168. Moreover, a typical PV plant's yearly average capacity factors in Brazil, Morocco, and India were reported as 0.192, 0.1484, and 0.1569, respectively [55–57].

Figure 8. Capacity factors of a 2000 kW PV plant at 15 different locations in Oman with and without considering the temperature effect.

3.2. Hydrogen Production Using Solar PV Power

The solar PV plant's hydrogen production at the selected locations was computed using Equation (7). The energy output of the PV plant presented in Figure 7 is used as input to the electrolyser. Moreover, the hydrogen production calculation requires the efficiency of the power electronic converter and the amount of energy consumption by the selected electrolyser (PEM). The power electronic converter efficiency was considered to be 95% [35], and the electrolyser energy consumption was obtained at 4.53 kWh/Nm³ [53]. Figure 9 reveals the annual hydrogen production at 15 different locations in the Sultanate of Oman. The highest yearly hydrogen yield was found to be 694,377 Nm³ (62,557 kg) at Thumrait. Sur has revealed the hydrogen production of 516,050 Nm³/year (46,491 kg/year), which is the lowest among the selected locations. Such a difference in hydrogen quantity comes from Thumrait and Sur's distinct solar radiation and temperature pattern. The Marmul site presents the second-highest hydrogen production potential, 686,769 Nm³/year (61,871 kg/year). The prospect of hydrogen production in Fahud and Masirah was estimated at 57,558 kg/year and 57,892 kg/year, respectively. Regarding solar radiation, Fahud is expected to produce a higher amount of hydrogen per year; however, the study reveals a lower production of hydrogen in Fahud because of the elevated operating cell temperature of the PV system or ambient temperature. It indicates that the locations with high ambient temperature may lead to lower hydrogen production, hence less suitable to develop hydrogen production facilities. It is evident from Table 4 that Fahud is ranked 10th even though the solar radiation is higher than Masirah, which is ranked 7th.

Figure 9. Annual hydrogen production at 15 different locations for a 2000 kW PV plant.

Table 4. Rank of potential locations based on yearly green hydrogen production by a 2000 kW solar PV plant in the Sultanate of Oman.

Rank	Locations	Solar Radiation (kW/m ² /day)	Ambient Temperature (°C)	Solar PV Energy Production (MWh/year)	Green Hydrogen Production (kg/year)
1	Thumrait	6.13	26.2	3311	62,557
2	Marmul	6.09	27.4	3275	61,871
3	Nizwa	5.8	27.9	3122	58,979
4	Duqm	5.76	27.56	3106	58,677
5	Khasab	5.75	27.6	3100	58,572
6	Al Mudaybi	5.72	27.8	3082	58,236
7	Masirah	5.65	26.4	3064	57,892
8	Ibri	5.68	27.7	3064	57,876
9	As-Suwayq	5.66	27.9	3050	57,637
10	Fahud	5.69	29.46	3046	57,558
11	Sohar	5.51	26.8	2987	56,446
12	Muscat	5.45	28.3	2939	55,527
13	Buraimi	5.37	28.3	2898	54,756
14	Salalah	4.8	26.3	2626	49,624
15	Sur	4.53	28.8	2461	46,491

Moreover, Masirah (57,892 kg/year), Ibri (57,876 kg/year), Al Mudaybi (58,236 kg/year), As-Suwayq (57,637 kg/year), and Fahud (57,558 kg/year) have similar potential to produce green hydrogen. On the other hand, Nizwa (58,979 kg/year), Duqm (58,677 kg/year), and Khasab (58,572 kg/year) have identical prospects of producing green hydrogen. Table 4 presents the ranking of potential locations indicating the most to least suitable for green hydrogen production in the Sultanate of Oman. The position is ordered based on the merit of green hydrogen and solar PV energy production in a year. It shows that Sur is the least convenient location because it has the lowest annual average solar radiation and higher ambient temperature compared to the top-ranked sites.

The electrolyser capacity required to produce green hydrogen is determined using Equation (16). The electrolyser's energy for green hydrogen production is the same as the energy produced by the selected solar PV plant for all designated locations. Therefore, the utilisation factor is required to determine the capacity of the electrolyser. The utilisation

factor is 20% since the hydrogen production facility solely depends on an intermittent solar PV plant. Figure 10 presents the electrolyser capacity required for the selected locations. The largest capacity electrolyser was 1890 kW, which was necessary for the top-ranked site, Thumrait. On the other hand, the smallest capacity electrolyser was 1404 kW, needed for the lowest-ranked location, Sur. The electrolyser capacity rating is used for computing the capital cost of the electrolyser.

Figure 10. Electrolyser capacity required for hydrogen production at 15 different locations.

3.3. Economic Analysis

To calculate the production cost of hydrogen for the selected locations, the cost of energy using a solar PV plant in those locations is determined first. Then, this electricity cost is input to compute the LCOH hydrogen. In calculating the LCOE, the capital cost of the PV system is determined based on the cost of per kW installed capacity, as presented in Table 2. In addition, the discount rate, PV plant lifetime, and operation and maintenance cost are also outlined in Table 2. Figure 11 explains the LCOE if a 2000 kW PV plant is located in the selected sites. The LCOE was found to be the lowest in Thumrait, and it was 0.0554 USD/kWh. The LCOE in Marmul was 0.0560 USD/kWh, which is the following economic site. It can be attributed to the fact that these sites have the best solar radiation and moderate temperature profile. The study also indicates that Sur and Salalah are the least suitable sites, revealing an LCOE of about 0.0745 USD/kWh and 0.0698 USD/kWh, respectively. It can be associated that these two locations have the lowest solar radiation, whereas Sur has the higher temperature profile; however, Salalah has a moderate temperature profile. The LCOEs for the PV plants in Nizwa, Duqm, Khasab, Al Mudaybi, Masirah, Ibri, As-Suwayq, and Fahud are 0.0587, 0.0590, 0.0591, 0.0595, 0.0598, 0.0598, 0.0601, and 0.0602 USD/kWh, respectively. Masirah and Ibri indicate an identical LCOE, although the solar radiation in Ibri is higher. However, Ibri is the hotter site compared to Masirah.

Figure 11. Levelized cost of energy produced from the solar PV plant at 15 different locations.

Further, some of the sites, namely Nizwa, Duqm, and Khasab, reveal a slight difference in LCOE; however, this can influence the total revenue of the project owner in consideration of the entire project lifetime. The LCOEs for the solar PV plants in Sohar, Muscat, and Buraimi are 0.0614, 0.0624, and 0.0632 USD/kWh. Therefore, the range of LCOE for the selected PV plant in the designated locations is 0.0554 to 0.0745 USD/kWh. This range of the LCOE is consistent with the LCOE for solar photovoltaic technology, as indicated in [7].

For evaluating the production cost of hydrogen for the selected locations, the cost of energy consumed by the electrolyser is obtained as per the LOCE determined in the preceding section. In calculating the LCOH, the capital cost of the water electrolyser is obtained as the per kW capacity cost that includes power supply and installation costs, as given in Table 2. In addition, the discount rate, electrolyser lifetime, and costs of operation and maintenance are also presented in Table 2. Figure 12 unveils the cost of hydrogen production using a 2000 kW solar PV plant for the selected location in the Sultanate of Oman. The LCOH in Thumrait was found to be the lowest, and it was 6.31 USD/kg. The LCOH was found to be 6.34 USD/kg in Marmul, the second-best economic site. It can be connected to the lowest-cost electricity availability in Thumrait and Marmul, which comes from the rich solar radiation and moderate temperature profile. The investigation also shows that Sur and Salalah are the least suitable sites, revealing an LCOH of about 7.32 USD/kg and 7.07 USD/kg, respectively. It can be understood that Sur and Salalah require a high cost to generate solar PV-based electricity, which comes from the low-level solar radiation profile. In addition, Sur has a higher temperature profile; however, Salalah has a moderate temperature profile.

The LCOHs for the solar PV-based systems in Nizwa, Duqm, Khasab, Al Mudaybi, Masirah, Ibri, As-Suwayq, and Fahud are 6.49, 6.50, 6.51, 6.53, 6.55, 6.55, 6.56, and 6.56 USD/kg, respectively. Masirah and Ibri indicate an identical LCOH, although the solar radiation in Ibri is higher. However, Ibri is the hotter site compared to the Masirah. Moreover, some of the sites, namely Nizwa, Duqm, and Khasab, reveal a slight difference in LCOH; however, this can influence the total revenue of the project owner in consideration of the entire project lifetime. The LCOHs for the solar PV-based systems in Sohar, Muscat, and Buraimi are 6.63, 6.68, and 6.73 USD/kg. Therefore, this research finds the range of LCOH for the designated locations to be from 6.31 to 7.32 USD/kg with the selected solar PV-based hydrogen production system. Such a range of the LCOH is lower than reported in [13], indicating that the LCOH at a 25% utilisation factor is about 12.12 USD/kg (≈ 10 €/kg). The current study has observed the range of the LCOH 6.31 to 7.32 USD/kg for a 20% utilisation factor. Moreover, the LCOH was found in recent studies, such as 6.02 USD/kg [50], 8.14 USD/kg [39], 11.09 USD/kg [38], and 10.08 USD/kg [35]. The low

value of the LCOH was reported at 6.02 USD/kg [50], which has used a utilisation factor of 85%. It is worth mentioning that the LCOH found in this study (considering the low utilisation factor) is almost identical to those obtained at the higher utilisation factor. This can be attributed to the high solar radiation available in the sites.

Figure 12. Cost of hydrogen production using the solar PV plant at 15 different locations.

3.4. Sensitivity Analysis

For the purpose of identifying significantly influential variables to hydrogen production cost, a sensitivity analysis is performed. This analysis considers hydrogen production cost at Thumrait as the base case cost, which is 6.31 USD/kg. Thumrait has been shown as the best potential location for producing hydrogen in the Sultanate of Oman. In the base case, LCOH computation, the inputs to the hydrogen production cost, such as capital cost of the electrolyser, electricity cost, and utilisation factor, were considered as 1010 USD/kW, 0.0554 USD/kWh (or 55.4 USD/MWh), and 20% utilisation factor. These inputs are modified by a 10% increase and decrease in a range of -50% to 50% . Figure 13 captures the sensitivity results of green hydrogen production costs for the best suitable location, Thumrait. It indicates that the electricity cost is the primary influential cost input to the LCOH. In addition, the capital cost is the second most significant factor that can change the LCOH. With the higher utilisation factor, the LCOH can reduce as can be seen from Figure 13. However, electricity and capital costs are the most influential variables contributing to cost-effective hydrogen production in Oman.

Furthermore, three cost reduction cases were analysed for 20 years to estimate the production cost of hydrogen in the future. The cost reduction cases include: (1) Reducing the electrolyser capital cost only; (2) reducing the electricity cost only; (3) reducing both the electrolyser capital cost and electricity cost. This analysis applies a 3% capital cost reduction of the electrolyser and a 4% electricity cost reduction [4,50] yearly. Figure 14 reveals the hydrogen production cost profile over 20 years for three different cost reduction scenarios. With the electrolyser capital cost reduction only, the LCOH can be reduced from 6.31 to 5.05 USD/kg, which is about a 19.96% cost reduction at the end of 20 years. With the electricity cost reduction only, the LCOH can decrease from 6.31 to 4.68 USD/kg, which is about a 25.58% cost reduction at the end of 20 years. For both the electrolyser capital cost and electricity cost decrease, the LCOH shows a significant decline, from 6.31 to 3.41 USD/kg, and it is about a 45.96% downturn in the LCOH.

Figure 13. Sensitivity of the hydrogen production cost with a change in cost variables from -50% to 50% .

Figure 14. Hydrogen production cost profile over 20 years for three different cost reduction cases.

3.5. Technology Adoption Factors and Environmental Impact

It is worth mentioning that this study focused on PEM electrolyser technology-based hydrogen production. The cost of the technology is one of the significant factors to consider when adopting technology. The cost reduction of PEM technology is substantial with the system scale-up [58]. The cost reduction rate of the PEM electrolyser is faster than the other technologies. The flexibility and shorter response time of the PEM electrolyser are other driving factors of this technology. They allow supplying hydrogen to various clients, i.e., industry, mobility, or injection into the gas network, simultaneously [13]. These features can enhance overall hydrogen production economics by earning revenues from multiple stakeholders and help in compensating the higher capital cost of PEM compared to alkaline electrolyzers. Moreover, the PEM electrolyser is the most energy-efficient and clean technology, as indicated in [59].

Solar photovoltaic-to-hydrogen production can reduce greenhouse gas emissions significantly. The greenhouse gas emission reduction for the study system in this research is estimated based on the emission factors given in [60]. It reveals that about 2346 metric tons of greenhouse gas emissions can be reduced per annum upon operating a system presented in this study.

4. Conclusions

This paper has presented a techno-economic analysis of producing green hydrogen using solar photovoltaic power in the Sultanate of Oman. The analysis process includes energy production evaluation of a photovoltaic power plant, hydrogen generation quantification, and assessing electricity cost, green hydrogen production cost, and environmental impact. The study is conducted for 15 different locations in Oman with a large-size (2000 kW) photovoltaic plant. The inclusion of intermittent solar radiation and varying temperature conditions into the energy production evaluation process of the solar photovoltaic plant ensures accurate energy determination. Such accuracy is confirmed by comparing the photovoltaic plant capacity factor found in this study with those available in the literature. The produced hydrogen quantification process has used this calculated energy amount instead of the estimated energy based on assuming a capacity factor.

Thumrait has been revealed as the most suitable green hydrogen generation location, producing 62,557 kg/year for the selected photovoltaic power plant. On the contrary, Sur has been unveiled as the least qualified site of green hydrogen production with 46,491 kg/year for the same photovoltaic power plant. Based on the amount of annual hydrogen production, a ranking of suitable locations is provided in this study. It is indicated that a location with higher solar radiation may not produce more green hydrogen fuel because of the higher ambient temperature in the site that causes a decline in the plant energy production, hence, hydrogen production. In addition, factors that may influence hydrogen production, cost, and emission are dust, cloud, shadow, and solar eclipse, which directly affect solar power production.

Furthermore, the analysis process has evaluated the cost of energy production from a solar photovoltaic plant instead of assuming the electricity cost for the electrolyser. The levelized cost of energy from the photovoltaic plant has been found to be 0.0554 to 0.0745 USD/kWh. The economic analysis of hydrogen production has utilised this electricity cost to determine the production cost of green hydrogen based on solar photovoltaic power. It was shown that the hydrogen production cost for the selected locations in Oman is in the range of 6.31 to 7.32 USD/kg. The obtained range of hydrogen production costs shows consistency with the hydrogen production costs reported in the other studies. Thumrait has the highest potential of producing green hydrogen fuel with a cost of 6.31 USD/kg, and Sur has the least potential with a cost of 7.32 USD/kg. Similar solar radiation and temperature profiles of any other candidate locations in Oman are comparable with the presented sites in this study to find their potentiality of producing green hydrogen. Otherwise, the illustrated analysis process can be applied to identify the potentiality of any other candidate locations in Oman and beyond, given that the source of electricity is based on a solar photovoltaic plant.

In addition, a sensitivity analysis has been performed on hydrogen production cost as the last step of the analysis process in this study. The sensitivity analysis has revealed that the electricity cost has a notable influence in calculating the production cost of hydrogen followed by the capital cost of the electrolyser. A consolidated yearly cost decline rate of 3% in capital cost and 4% in electricity cost unveils a hydrogen production cost decline of 45.96% in 20 years. The fruitful cognisance obtained through this study provides an assessment process for researchers, industry, energy stakeholders, and energy policymakers on solar photovoltaic-to-hydrogen potential, cost of hydrogen production, and cost variables to identify critical ones for a hot and humid condition, like the Sultanate of Oman.

The life cycle costing approach is a holistic and comprehensive method utilised to evaluate the economics of hydrogen production in this study. However, the methodology uses future estimated data since the electrolysis-based hydrogen production technology is yet to be in the expansion stage. As a result, uncertain assumptions on some of the fundamental cost data were unavoidable.

Only a solar-based hydrogen production system is limited to a low utilisation factor, which requires an increased size of the electrolyser. A hydrogen production system may need to be designed with a higher utilisation factor of the electrolyser; thus, the size and

cost of the hydrogen production system can be reduced, which will be further investigated in general and specifically in Omani conditions.

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