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Original Article

Performance Analysis of a Proposed Hybrid Energy Generation and Green Hydrogen Production System for Al Mazunah in Oman

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Abstract *- This paper presents a comprehensive techno-economic study on power generation and hydrogen production for Al Mazunah City, located in the south of Oman. The analysis involved assessing the monthly average solar and wind resources, which showed promising potential for green hydrogen production and power generation at a reasonable cost. To understand the energy demand, we analyzed real load data from 2019, revealing an average daily load of 111.716 kWh/day and a peak demand of 9410 kW. Based on these findings, we explored various techno-economic options for a hybrid power generation system, integrating solar, wind, fuel cells, and battery technologies. Our study determined that the most optimal configuration for power generation and hydrogen production involves employing a 250 kW Fuel Cell, 55,170 kW PV system, 238,856 kWh Lead Acid Battery Storage, and a 1,538 kW Wind Turbine. Remarkably, approximately 90.7% of the required power generation can be met by the solar PV system. The analysis further revealed that implementing such a system would require an investment of $227 million, with a Levelized Cost of Energy of $0.431 per kWh. This indicates an economically viable and sustainable solution for meeting the energy needs of Al Mazunah City. By promoting the integration of renewable energy sources and hydrogen production technologies, these findings offer valuable insights for policymakers and energy stakeholders seeking to enhance energy security, reduce greenhouse gas emissions, and foster sustainable development in the region.*

Keywords *- Hybrid system, Green hydrogen, Clear index, Levelized Cost of Energy, LCOH.*

1. Introduction

Both the environment and the economy face serious threats from the changing climate that is a direct outcome of human-caused global warming [1, 2]. A progressive increase in the average atmospheric temperature [3]-[5] caused by the same factors that cause catastrophic weather events like hurricanes and floods all across the world is known as global warming. The accumulation of greenhouse gases causes global warming, primarily carbon dioxide (CO2) and methane, which are emitted by human activities such as energy generation, agriculture, and transportation [6]-[8]. The majority of the world's energy has come from fossil fuels, which include resources like coal, oil, and natural gas. However, fossil fuels' enormous carbon dioxide emissions have stoked growing fears about their role in accelerating global warming and its subsequent negative effects on the ecosystem (Patel, Nivedita., 2014). Because of this, exploring renewable energy sources such as solar power, wind power, wave power, and hydrogen has become more important. The greatest way to deal with the energy problems we have now is to use renewable, green energy sources. Less pollution and better health for the planet will result from increased use of renewable energy sources. One of the gaps in clean power generation caused by the growing use of renewable energy sources is the requirement for storage systems [10]. A more stable system resistant to intermittency caused by changes in weather conditions can be achieved using green hydrogen as an effective energy carrier, which is crucial in balancing the economical solutions for various power sectors [11]-[13]. Studies on solar hydrogen as a source of energy have been going on for some time now. Several studies and innovations in the last few years have shown the potential of solar-hydrogen synthesis for various uses. The authors of the study [11] investigated the possibility of producing baseload power on a worldwide scale using cost-optimized hybrid PV-wind systems on huge islands. According to the analysis, all continents can achieve baseload power for hydrogen at a cost of 55 €/MWh by 2030. Other research looked at the potential for reducing emissions of Greenhouse Gases (GHG) in chemical synthesis by combining renewable energy with fossil fuels [14]. To export hydrogen from the Atacama Desert to Japan, researchers in northern Chile have investigated cost-effective solar hydrogen production (Gallardo et al., 2021).

Based on the results, PV-supplied systems in Chile can manufacture solar hydrogen at a cost that is competitive with smaller CSP-supplied systems, with LCOH levels as low as 1.9 ppm in 2018 and 2.2 ppm in 2025. By incorporating a hydrogen energy system, the study case reported in [16] was able to reduce its overall annual expenses by 41.6% and its carbon emissions by 67.29% compared to the benchmark scenarios. Techno-economic evaluations of solar and wind energy systems for power generation and optimization in Oman were carried out at a few Saudi Arabian sites with the aim of producing hydrogen [17]. Combining a 2kW PV array, 3kW wind turbines, a 2kW converter, and seven battery storage banks yields the best design with the lowest normalized Cost of Energy (COE) of 0.609 $/kWh for the Yanbu area.

The best locations in the sultanate for solar energy conversion into hydrogen are Thumrait and Marmul, according to a study and economic analysis conducted by [18]. The study showed good economic viability, with a Levelized Cost of Hydrogen (LCOH) of 6.31 USD/kg in Thumrait and 7.32 USD/kg in Sur. The study showed good economic viability, with a Levelized Cost of Hydrogen (LCOH) of 6.31 USD/kg in Thumrait and 7.32 USD/kg in Sur. In order to address the energy needs of the Al Duqum area, a hybrid system comprising wind, photovoltaic, and fuel cells was proposed, with a Cost of Energy (COE) of USD 0.436/kWh (Al-Badi et al., 2022).

According to the data shown above and the outcomes of the green hydrogen project in Oman, additional investment may result in notable synergies between hydrogen and renewable solar electricity, with an efficiency of 74% to 85% [20]. Utilizing surplus energy from renewable sources, green hydrogen storage devices can be constructed. This is particularly helpful in rural areas where electrification is rather expensive.

Improving Oman's power industry through environmentally friendly hydrogen production is the goal of this study. We choose Al Mazunah, a case study in the southern region of Oman. We have covered the current weather conditions as well as the effects of solar and wind variations. In order to plan for the future of the power system sector and make accurate economic predictions, we have also taken energy demand and predicted load growth into account. More realistically, for the purpose of optimally scaling the proposed hybrid power system that combines solar, wind, and fuel cells. This work aims to evaluate the potential for green hydrogen production for power sector enhancement in Oman. A study case in Al Mazunah -south of Oman- is selected. The weather conditions and the impacts of the solar and wind variations have been discussed. Also, the energy demand and expected load growth have been considered for future planning of the power system industry and good economic prediction. More practically for optimum sizing of the proposed hybrid solar-wind- fuel cells power system.

2. Site Details and Proposed Hybrid and Green Hydrogen Production

The selected location for the proposed system in at Al-Mazunah, which is located at 17°50.9N, 52°40.0E south of Oman. Al-Mazunah has a population of 9,000 up to June 2022. The free trade economic zone in Al-Mazunah plays a role in the enhancement of the national economy in Oman by attracting investors from East Africa and other parts of the world. Many industries have developed in recent years and the need for stable, efficient power systems and green hydrogen production is necessary. The proposed hybrid power system is developed to power the local commercial zone in Al-Mazunah and produce green hydrogen for many other applications for zero-emission targets. The system is shown in Figure 1.

It is made up of PV solar, wind turbines, water electrolyzer and hydrogen storage.This research work will focus on the economic evaluation and technical analysis of hybrid systems using HOMER. HOMER is a well-known tool used to carry out different feasibility and cost analyses by considering the available renewable energy resources with the variation of the weather conditions and availability of the storage systems in the same period if needed. HOMER will help to determine the optimum combination of water electrolyzer, fuel cell and hydrogen storage system with the aim to cover the load every hour during one complete year with renewable energy without any deficiency. Tanweer Electrical Company provided 2019 hourly data, and the weather analysis will rely on NASA data, which can be retrieved by HOMER.

3. Analysis of Weather Conditions

Weather conditions must be considered in all techno-economic analyses of hybrid energy systems because any change in the weather may lead to affect the performance of the energy generation of the solar system [21]–[25]. In this section, solar irradiance, temperature, wind, and humidity are considered. The average monthly temperature over a year is presented in Figure 2. The average value of the temperature is 26.48^0C. This range of temperature variation is optimum for solar energy generation in harsh areas like Oman. However, a further increase in the temperature can lead to a further reduction in the performance of the solar panels, as discussed in [26].

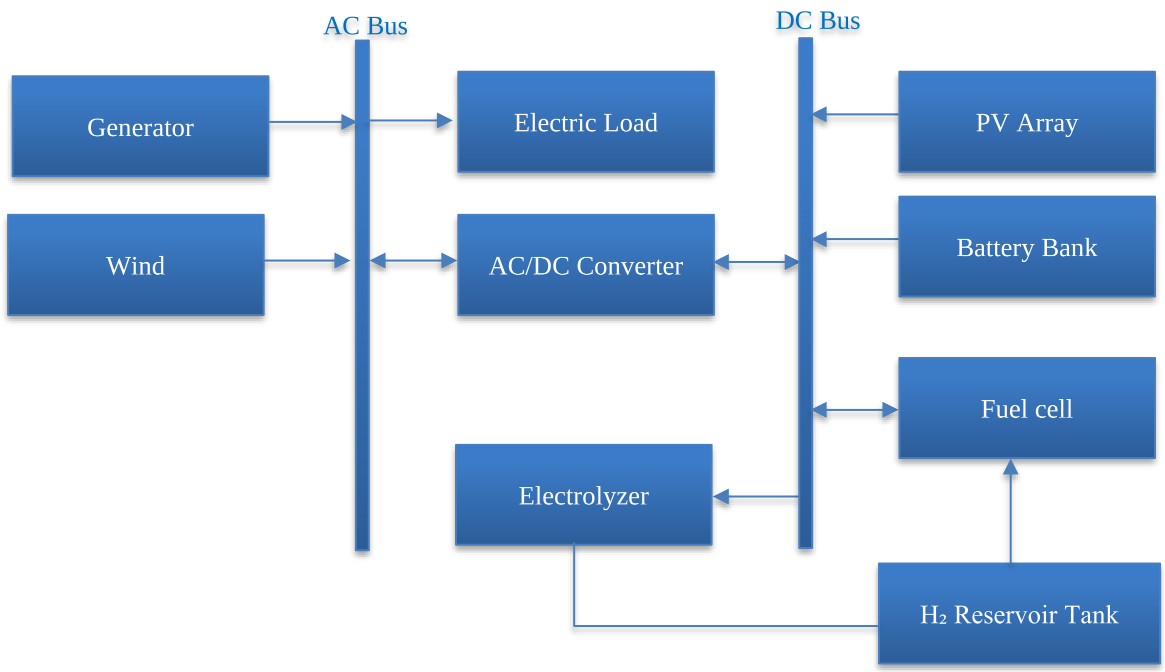

Fig. 1 Block diagram of the proposed hybrid system for Al-Mazunah

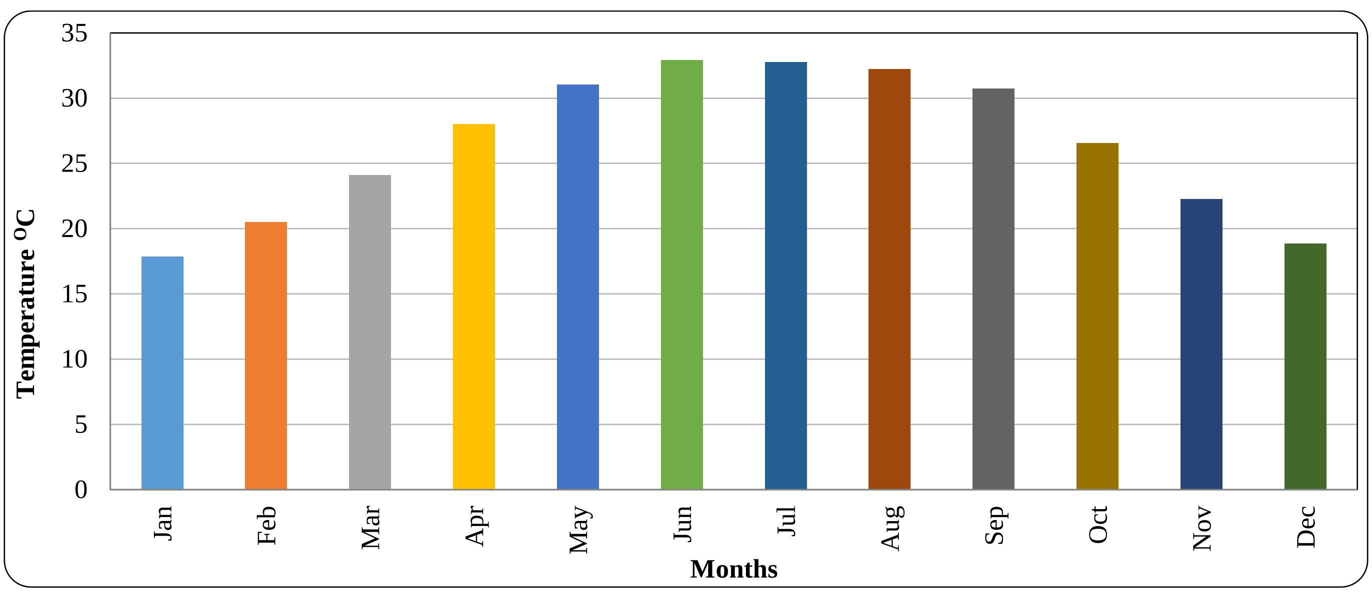

Fig. 2 Monthly average temperature variation in Al-Mazunah

The average monthly solar radiation and the clearance level are presented in Figure 3. The solar radiation is slightly dropped in the summer period due to the rainy session in the south of Oman. The monthly average of solar radiation is 6.45kWh/m^2. The clearance index is also shown in the same Figure. The higher the clearance index the better the performance of the solar panels [27], and it is measured between 0-1, and it reveals the quality of sun shining. The average value of the clearance level is 0.68. A noticeable drop in the clearness level is observed in the months of July and August due to the rain in the selected area. The monthly average wind speed is presented in Figure 4 and it shows higher wind speed in July and August, and the monthly average wind speed is 5.84m/s. This value shows a very good potential to utilize wind energy in the south of Oman. The complementary impacts of solar irradiation and wind speed in some areas have been reported in many [28]. Wind and solar energy complementary leads to many advantages of interconnecting spatially distributed generators, dispatchable generators in hybrid systems, assessing some applications of demand-response and flexible loads and deploying energy storage[29].

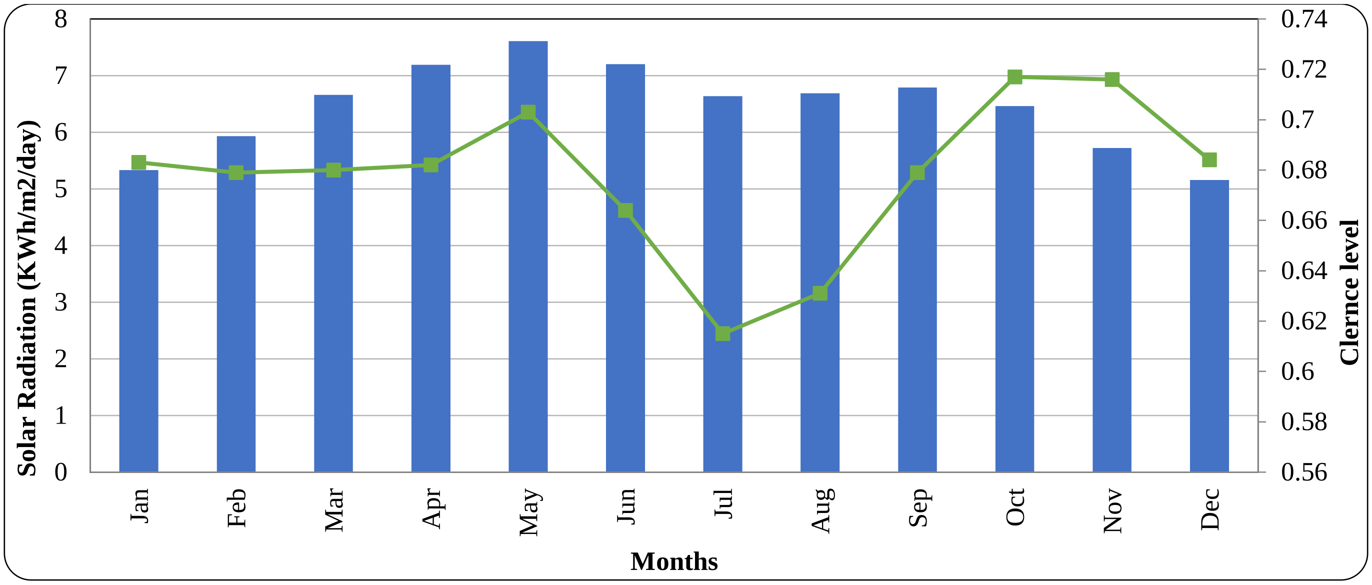

Fig. 3 Monthly average solar radiation and clearness Index

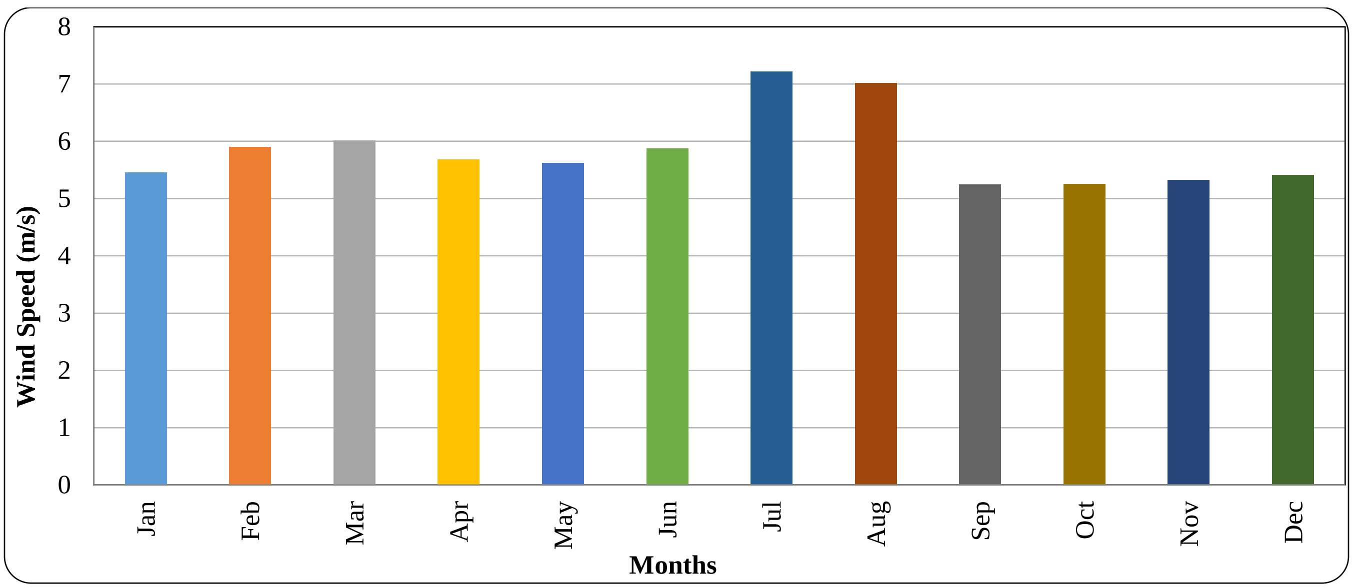

Fig. 4 Monthly average wind speed for Al-Mazunah

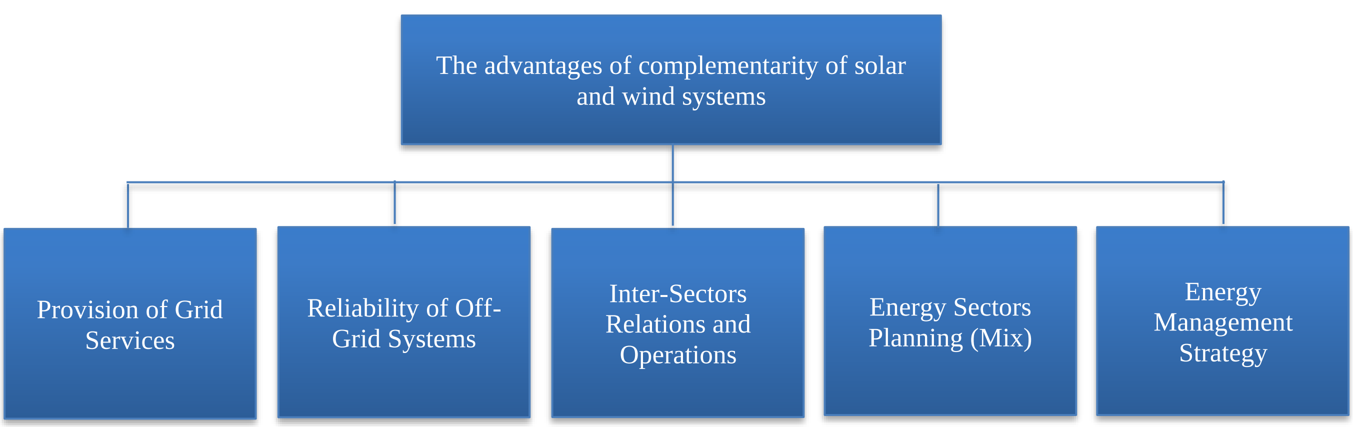

Fig. 5 Advantages of complementarity wind and solar systems

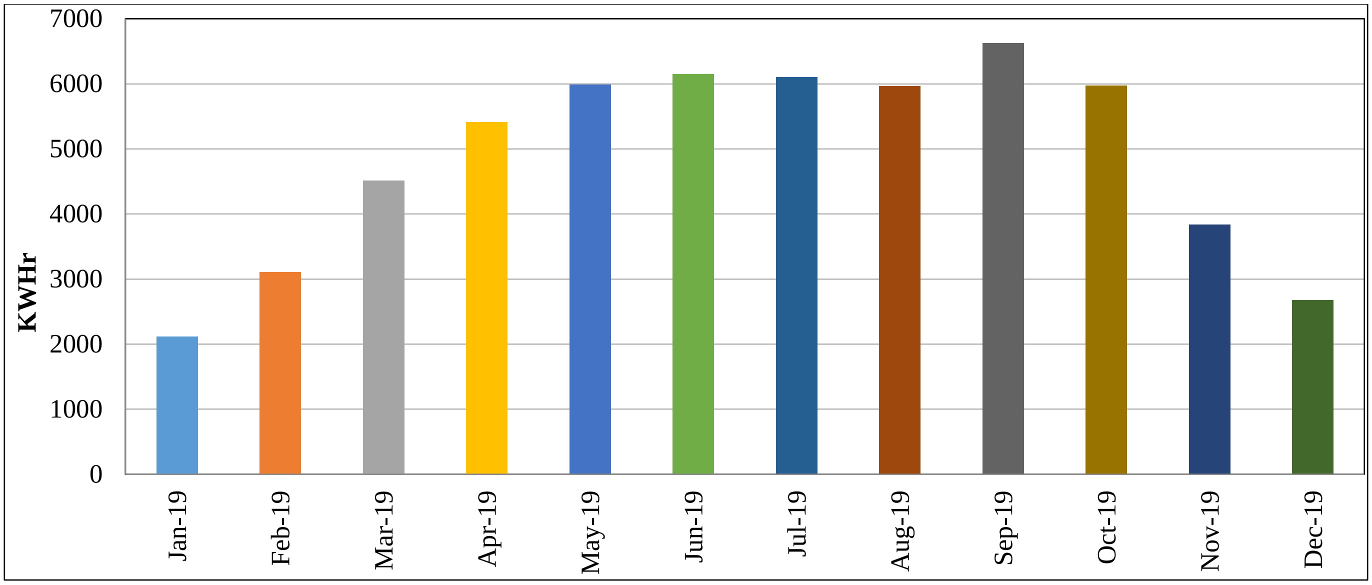

Fig. 6 Monthly average load variation demand in 2019

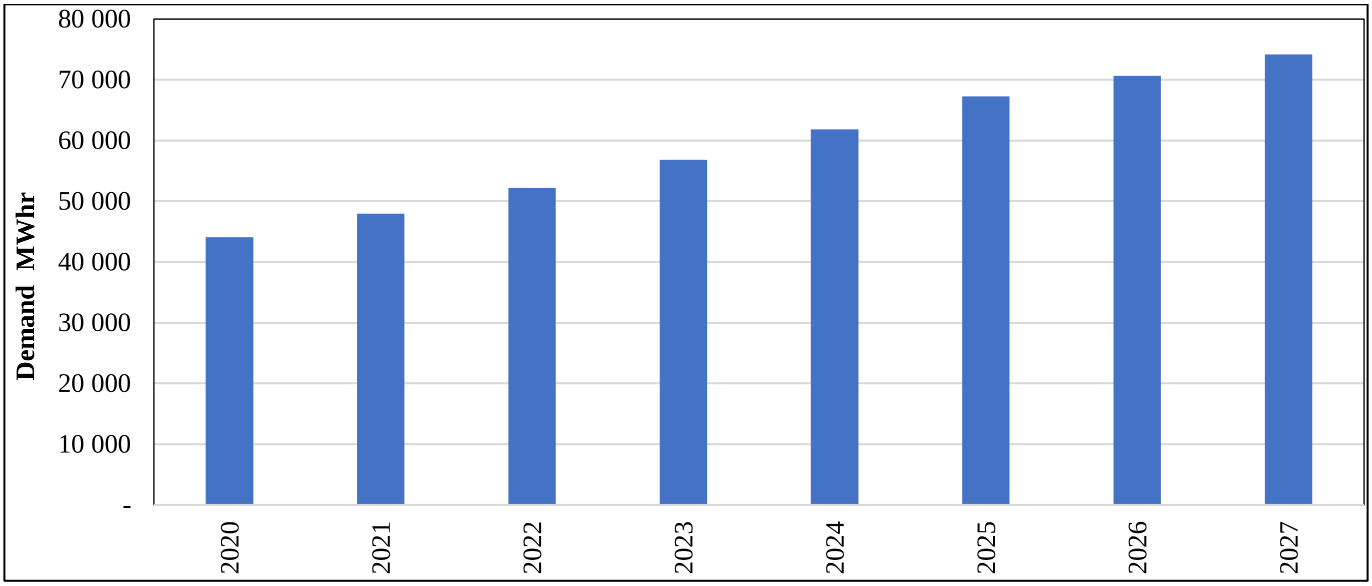

Fig. 7 The projected load growth in Al Mazunah up to 2027

These advantages are presented in Figure 5. The geographical location of Oman, with an onshore wind speed range of 3–6.3 m/s and an annual solar radiation of up to 2500 kWh/m^2 makes it the best option to utilize wind and solar for green hydrogen production [31].

4. Energy Demand and Expected Load Growth

The demand for electricity, the fuel of modern technology, is increasing as a share of energy services due to the rise in advanced residential applications, increased electrification of transportation and heating, growing demand for digitally connected devices, and increased use of air conditioning [32]. In order to fulfill load demand and maintain high efficiency at the lowest possible cost, such a study must take into account the load profile and load growth in the hybrid system's optimal design. For the analysis, hourly load statistics from 2019 were used. Load demand is presented in Figure 6, and the load shows normal variation for Al Mazunah, where the temperature increases in summer and the demand for energy increases. It can be noticed that the peak load equals 6600kWhr in September. That could be the reason for shifting between two seasons by the end of the rainy period, as stated before. The daily average load is 111.716KWh/day, and the peak is 9410kW.

Up to 2027, the load projection of the selected site is expected to reach 73MWhr at a demand growth of 6% per year, as shown in Figure 7. In comparison to 2020, the projected load growth up to 2027 will be doubled. With the increased fuel prices and the expected expansion in the Al Mazunah economic zone, the need for alternative, efficient green energy resources becomes a necessity.

5. System Description and Specification

The proposed power generation and hydrogen production is shown in Figure 8. Based on different optimization criteria and overall cost, Homer runs many different options [33], and the following components are recommended: PV solar panels, wind turbines, Fuel cell generators, and battery storage. Table 1 presents the optimum sizing of different components in the hybrid system.

Table 1. Proposed components for the hybrid power and hydrogen production system for the AL Mazunah

Component	Name	Size
FC	Fuel Cell	250 kW
PV	Flat plate PV	55,170 kW
Battery Storage	Generic 1kWh Lead Acid	238,856 strings
WT	Generic Wind turbine	1,538KW
DC/AC converter	System Converter	11,822 kW
Electrolyzer	Generic Electrolyzer	100 kW

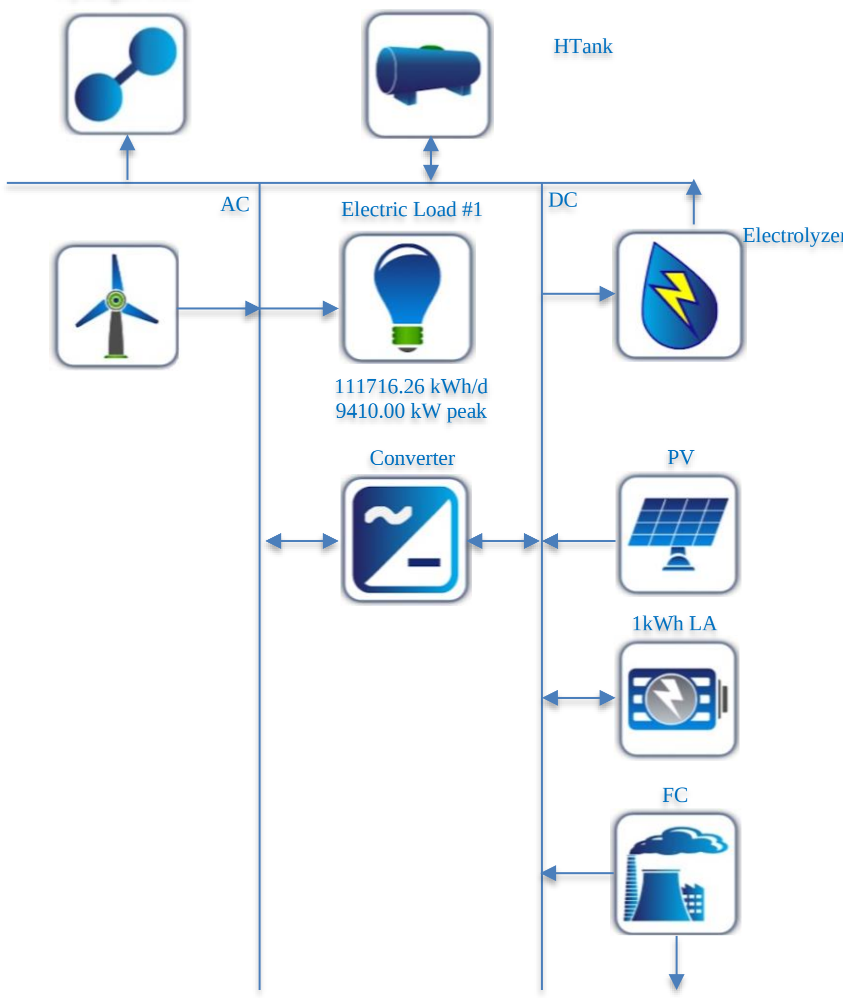

Fig. 8 The proposed power generation and hydrogen production system

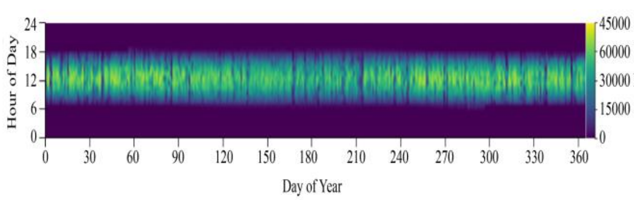

Fig. 9 PV annual production of PV system

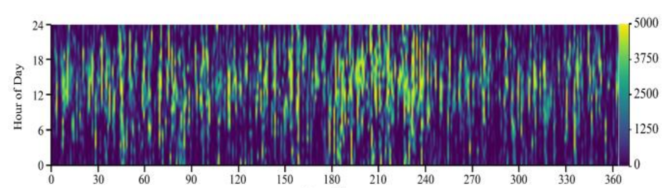

Fig. 10 Daily average production of the wind turbine

5.1. PV System

For optimum system performance, the existing 307kW PV system should be upgraded. Homer proposed a 55170KW PV system. This system will operate at a specific yield of 1,965 kWh/kW with no tracking system. Figure 9 shows the daily production of the PV system for 24-hour daily production. The generation of the photovoltaic module output reaches 30000KW at mid-day and the output for the overall year is almost 108,425,320 kWh/yr.

5.2. Wind Turbine

The proposed wind turbine system is 4.614kW with a wind turbine that will operate 7,405 hours yearly. The yearly output power is 9,763,293kWh. Other technical specifications include the maintenance cost of 276,840$ every year. HOMER yearly production for the wind turbine is shown in Figure 10. The energy produced reaches its maximum in July and August due to the autumn season, as the wind speed is highest in this season.

5.3. Battery Storage

The proposed Battery storage system is 238,856 kWh with a maintenance cost of almost 2,388,560 $ every year. Figure 11 shows the daily production of the 1kWh lead battery unit. The annual throughput is about 20,158,852 kWh/yr.

5.4. Converter Details

The DC/AC converter for the proposed system has a capacity of 11,822 KW and operates at 8,162 hours per year. Its capacity factor is almost 30.6%. It has a mean output of 3,618 kW with a maximum output of 9,281 kW. The input energy and output energy yearly are around 33,362,166 kWh and 31,694,056 kWh, respectively. Figure 12 shows daily production in Homer for the system converter, and the output energy is increased in summer. The annual output of the system is about 31,694,056 kWh/yr.

5.5. Water Electrolyzer

A chemical reaction is used in a water electrolyzer to separate water into hydrogen and oxygen. Hydrogen is necessary for many industrial operations, such as the manufacture of ammonia for fertilizers and fuel for fuel cell vehicles, including buses, trucks, and trains [34].

By turning extra electricity from renewable energy sources like solar, wind, and hydropower into hydrogen gas, they can be employed as energy storage devices. After that, the gas can be compressed, kept, and utilized as required [35]. Table 2 in this study lists the technical details of the water electrolyzer module.

Figure 13 shows daily electrolyzer production. The rated capacity of the generic electrolyzer is 100 kW, and it is obvious that the system operates during the daytime as the PV system is feeding the system during the daytime. The total annual production is 4,155kg/yr.

Table 2. Technical specifications of the water electrolyzer

Rated Capacity	100 kW
Total Input Energy	192,813 kWh/yr
Hours of Operation	3,325 hr/yr
Capacity Factor	22.0 %
Total Production	4,155 kg/yr
Specific Consumption	46.4 kWh/kg
Maximum Output	2.15 kg/hr

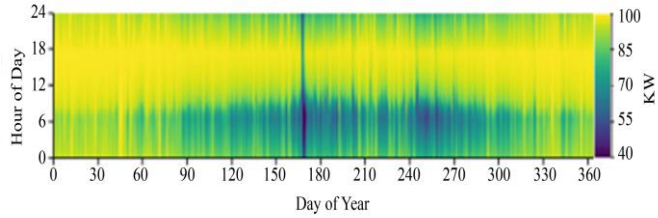

Fig. 11 Daily production of battery storage

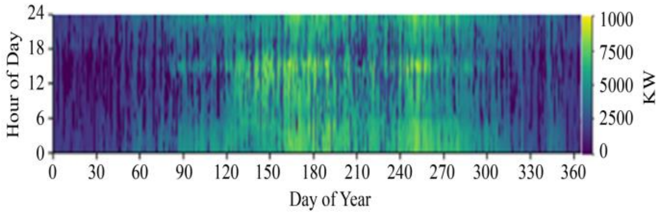

Fig. 12 Daily production of converter

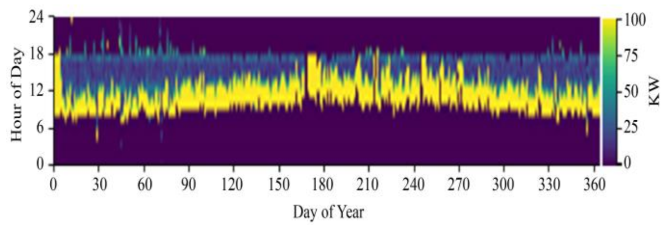

Fig. 13 Daily production of water electrolyzer

5.6. The Fuel Cells

Through an electrochemical reaction, chemical energy is transformed into electrical energy using a fuel cell. Through the process of oxidation, it takes in an external fuel source, such as hydrogen, and transforms it into electricity, heat, and clean water[36]. The primary energy source for fuel cells is compressed hydrogen, which is normally stored in high-pressure tanks at 35 to 70 MPa[37]. Although there are many other kinds of fuel cells, the Proton Exchange Membrane (PEM) is currently the most often utilized form. This is a result of its high power density, versatility in fuel kinds, resilience, and reduced operating temperatures) [38]. When compared to batteries, fuel cells provide the advantages of a greater durability range and a faster charging time. Nevertheless, they have greater startup and operating costs[30]. Technical specifications of the fuel cell module are listed in Table 3. Figure 14 displays HOMER's daily production of the generic fuel cell generator which is rated at 250 KW using natural gas as fuel cell. The system uses the fuel cells during nighttime, that is because a PV system covers the system during the daytime. The total annual production is almost 4,155kg/yr.

Table 3. Technical specifications of the fuel cell

Capacity	250 kW
Operational Life	9.57 yr
Capital Cost	$750,000
Fuel Consumption	271,738 m³
Thermal Production	833,653 kWh/yr
Marginal Generation Cost	0.0630 $/kWh
Generator Fuel	Natural Gas
Generator Fuel Price	0.300 $/m³
Maintenance Cost	26,135 $/yr
Electrical Production	1,293,991 kWh/yr
Hours of Operation	5,227 hrs/yr
Fixed Generation Cost	17.5 $/hr

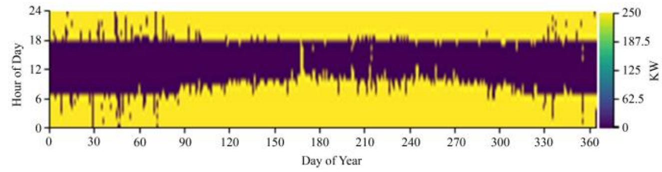

Fig. 14 Daily production of fuel cell

6. Power Generation, Electric Consumption, and Hydrogen Production

The projected hybrid solar, wind, and fuel cells system is proposed to feed 111467 kWh daily at a peak of 9410 kW, and the yearly production is 119,482,600 kWh. The solar PV system produces 90.7% and the remaining generation is provided by the fuel cells and the wind turbine. Figure 15 shows the average monthly power generation of different resources.

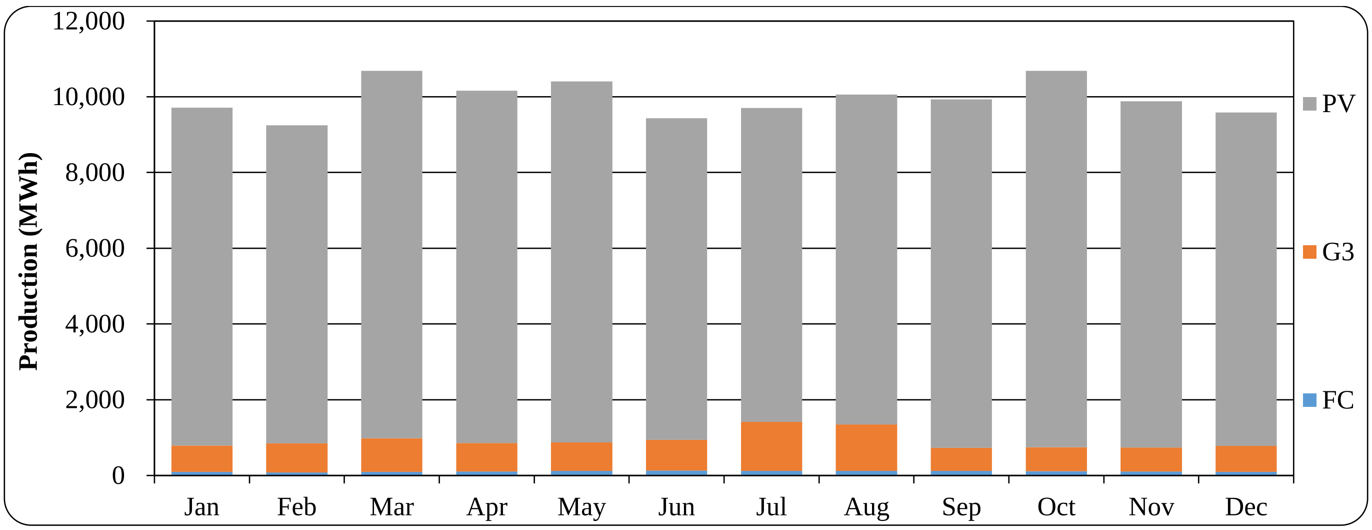

Fig. 15 Monthly average Power generation of different resource

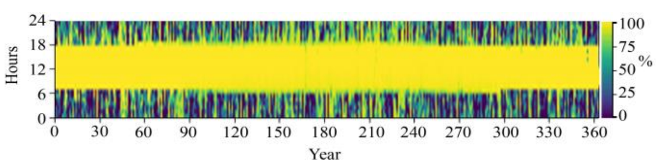

Fig. 16 The instantaneous renewable output percentage of total generation

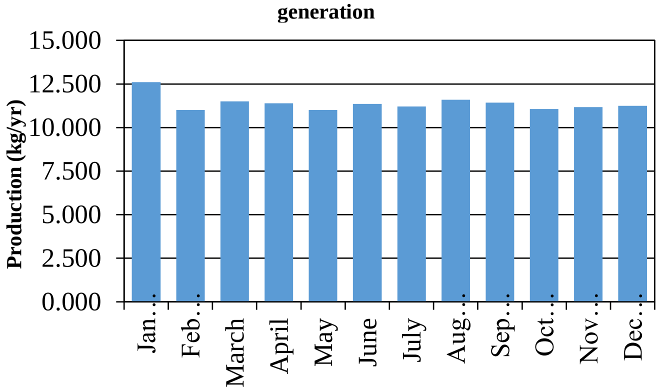

Fig. 17 Hydrogen Production of the proposed system

The instantaneous renewable output percentage of total generation is shown in Figure 16. The power demand is almost 100% covered by the solar system during the daytime due to the high solar irradiation.

This proposed hybrid system produces 11 kg/day and has a peak of 2.090 kg/hr, as it is presented in Figure 17.

7. Economical Factors and Other Results

The yearly operating cost for energy of the proposed system is $9.30M. The operating costs will be reduced to $8.38M/yr and the investment has a payback of 8.12 years at an IRR of 7.84% at LCOE= $0.664.

Lower consumption is noticed in the daytime, as shown in Figure 18 because the PV solar system supplies the load demand, the system is supposed to consume a total of 271,738m³ of natural gas consumption for fuel cell operation. Such a system will produce a total of 527,295kg of carbon dioxide and 54.3kg of carbon monoxide every year.

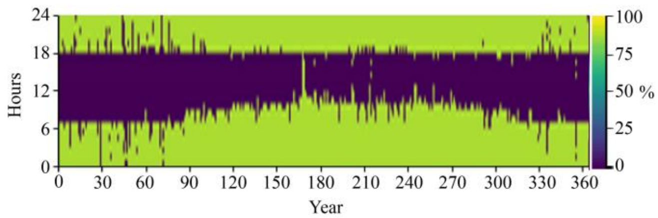

Fig. 18 Fuel consumption of the proposed system

8. Conclusion

The current study conducted a comprehensive evaluation of the economic and technical aspects, and we have identified the most favourable option. Our criteria focused on minimizing the COE while maximizing the penetration of PV systems without causing any load deficiency.

Based on Homer's analysis, the optimal solution entails incorporating 2,771 kW of PV and 3.0 kW of wind generation capacity. Implementing this strategy results in a significant reduction in operating costs, bringing them down to $16.6 million per year. Furthermore, this investment demonstrates promising financial returns. The projected payback period stands at 10.5 years, with an attractive IRR of 7.96%. Additionally, the NPC is estimated at $227 million.

By adopting this approach, we achieve a well-balanced mix of renewable energy sources that effectively lowers costs while ensuring a sustainable and reliable power supply. Our findings underline the long-term viability and economic benefits of investing in renewable energy solutions, making them a compelling option for environmentally conscious and financially savvy stakeholders alike. As the world continues its transition towards a greener future, embracing such strategies will play a crucial role in shaping a more sustainable and prosperous energy landscape.

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