Techno Economic Design and Analysis of A Hybrid Renewable Energy System for Jazirat Al Halaniyat in Oman

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Received: 25.11.2023 Accepted:17.01.2023

Abstract: This research aims to design a hybrid solar-wind-diesel- storage battery sustainable energy system for Jazirat Al Halaniyat (Island) in the Sultanate of Oman. Techno economic assessment and analysis were done by using the HomerPro software. Many factors were considered such as the weather conditions, availability of different renewable energy resources, life security, and economic factors. The weather conditions were found having limited impacts on the overall performance of the proposed system because of the successful technical integration of the wind and solar weather conditions during the summer period. Using the real load data for 2019 and 2020, at a peak load of 500 kW and an annual load demand of 2350 MWh, different hybrid solar, wind, diesel generator and storage battery configurations were examined for the best optimum sizing, minimum cost, and most stable system for 25 years period. The techno economic analysis results proved that the proposed system could run with a 1004 kW PV solar system, 160 kW wind turbine with a contribution of 580 diesel electricity generator and storage of 1478 kWh yearly. The proposed system is expected to produce an annual electricity production of 3,548 MWh/year, of which around 56.6% (2,007 MWh/year) will produced by the solar PV panels at LCOE of $0.234 per kWh.

Keywords: Hybrid energy system, LCOE, ROI, MPPT, Oman

1. Introduction

Global interest in energy demand is annually growing by 2.3% [1, 2]. In the Middle East, the demand for cooling and air conditioning applications for domestic purposes is increasing, resulting in a higher energy demand and higher fossil fuel consumption [3,4]. Since 80% of the world energy is generated from fossil fuels, greenhouse gas emissions increased up to 4.6% in 2020 [5], and that leads to vary the average temperature changes by ±3.3^{o}C degree due to global warming. The need to switching to alternative clean energy sources becomes necessary to ensure better livelihoods of future generations. In recent years, the implementations of renewable energy solution have received lots of attention [5-7], because these natural resources generate lower emissions, and they are naturally abundant. According to the IEA forecast [7], the global renewable new installed capacity is expected to increase by almost 2400 GW in the period between 2022 and 2027. This will account for over 90% of global electricity expansion over the next five years.

These types of green energy resources are the future investment for most of small economies. This kind of investment is not only monetary, but it also provides independence of the volatility of the fossil fuel market and other political strife. Many countries around the world created many incentives [8,9] to reduce the impacts of greenhouse gas emissions, to combat climate change, and to contribute to the reduction of global warming. Other policies include waste disposal [9]. Oman is not excluded from the other parts of the world, as the country is also witnessing accelerated growth and development [9–12]. There is an increasing demand for energy with an annual rise of 4% of electricity demands from 2020 to 2027 as reported by the Oman Power and Water Procurement (OPWP) 7 year's statement report [13]. This represents an increase in the load demand from 6,237 MW in 2020 to 8,370 MW in 2027 [14].

In fact, increased adoption of renewable energy led to many advantages, but still renewable green energy resources face some obstacles. Due to the change in weather, most of the renewables exhibit erratic and irregular behavior [15-17]. This may affect power flow and grid stability [18,19]. The use of the energy storage represents one of the possible solutions. However, the high cost is still an issue. Another solution includes the utilizations of smart grid applications which looks very promising [20,21]. Smart grid can be created by selling excess solar power generated in homes to the national grid, shortening the payback period and converting power consumers into producers, thereby assisting in the achievement of zero-energy. However, the high cost of the system components, the lack of regulatory standards of smart meters, the non-reliability of the cellular network during the abnormal weather condition are some of the main challenges of smart grid applications [22].

The novelty of this research work is to provide an innovative practical solution to secure life of oil transportation companies and to provide a sustainable energy for the residents in Jazirat Al Halaniyat. The research work will design a sustainable hybrid renewable energy for the selected area. It will examine different hybrid renewable energy options to determine the optimum sizing of PV solar, wind and storage generation components for the most economic and efficient hybrid system at different load and weather conditions.

2. Site Details

As it is shown in figure 1, the selected study location is Jazirat Al Halaniyat (17°30.6' N, 56°1.3' E) which is an island in the southern part of the Sultanate of Oman. The population is approximately 200 people. Tanweer operational data reports [23] showed that a net total of 2258 MWh with 737000 diesel liters was consumed in 2021. As seen from the same figure, Jazirat Al Halaniyat is around 8 km from the nearest land. During the last years, there were a high risk of transporting the fuel in the summer session due to the high tidal waves at the bad weather.

Fig. 1. Map of Oman and location of Jazirat Al Halaniyat

That leads to another problem of cutting of the power to the residents if it is difficult to transport the fuel to the island in the bad weather. The option of developing a hybrid energy system for power generation becomes a real need for Al Halaniyat.

3. Methodology

The research seeks to develop a technoeconomic assessment to determine the optimal sizing of a hybrid energy system for Jazirat Al Halaniyat by utilizing the natural resource in the same location. HomerPro software has been used and the methodology is illustrated in figure 3. The proposed system is taking advantages of different inputs which are the load demand and the natural renewable resource (solar irradiance, temperature, and wind energy). The future load increases, inflation rate and discount rate were also considered. Other inputs included the type of different types of generation components, storage devices and the existence of the available diesel generators. The data used are real hourly load data based on Rural Areas Electricity company (Tanweer) load consumption for 2019 and 2020. The capital and the operational & maintenance and fuel costs were all entered.

For optimal balance energy, HomerPro can run many algorithms and it can provide different configurations of energy generation to provide optimum feasibility and estimation of NPC, LCOE, annual generation, RE penetration, emission saving and many others. The outcomes of the simulation are the optimal sizing of different components, the economic and environmental analyses that ensure sustainability of the project for longer period.

4. Data Analysis

A.Electric Load data and Electric Consumption

Figure 2 shows a sample of the daily electric load profile for Jazirat Al Halaniyat for the day 25th April. The average load is around 357 kW, and the peak load is 450 kW at afternoon.

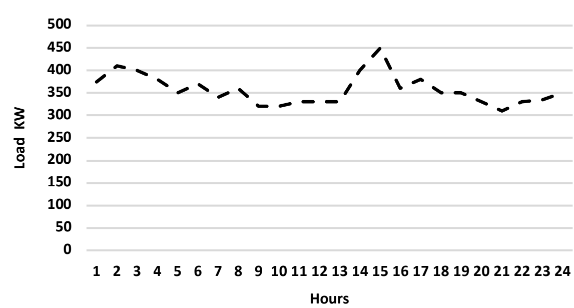

Fig. 2. Sample of a daily load Profile

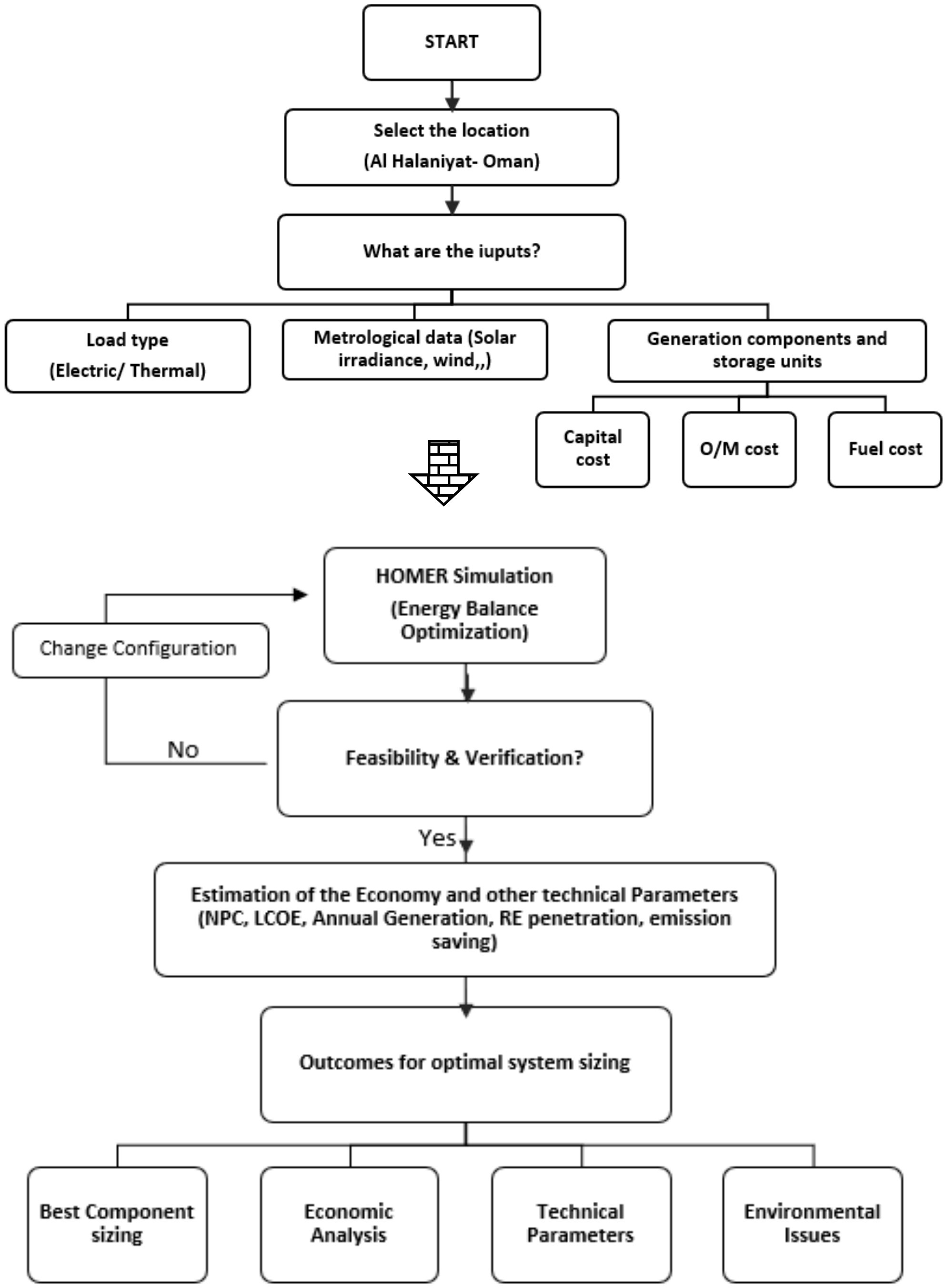

Fig. 3. Methodology of the research work

Figure 4 shows the monthly average load profile for 2019 and 2020. The peak load reached 510 kW in 2019 and 485 kW in 2020 respectively. The peak load appears in month of May. The annual load demand is 2391 MWh in 2019 and 2310 MWh with a scaled annual daily average of 6420 kWh/day and a load factor of 0.19. The sharp decline in load consumption in June, July and August is due to the relatively colder rainy season in southern Oman.

B. Weather conditions

Figure 5 shows the average monthly air temperature of Jazirat Al-Halaniyat. In compared to Muscat, the capital of

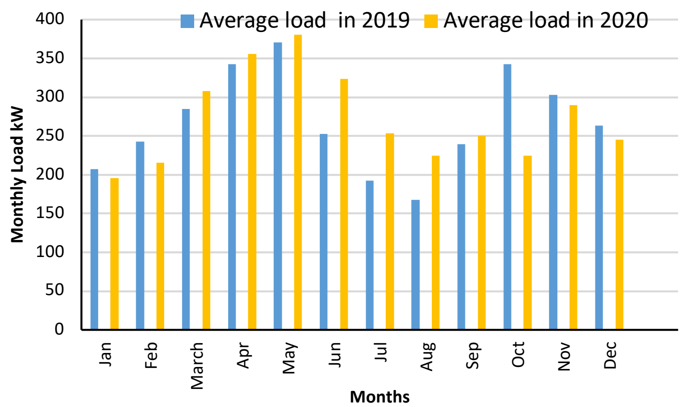

Fig. 4. 2019-2020 monthly average load consumption

Oman, the monthly average temperature variation is lower, and the annual average temperature is 25.66°C and the highest is 28°C. This lower temperature value leads to the advantage of higher efficiency of solar panels during the summer period [24–26].

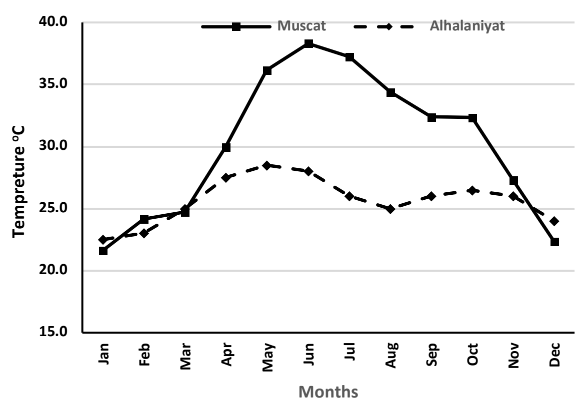

Fig. 5. Monthly average Air temperature in Muscat and Al-Halaniyat

Figure 6 shows the monthly average global horizontal solar irradiance. The annual mean is 6.56 kWh/m^2/day which is high enough for energy generation in compare to other part of the world. This value has a positive impact on the performance of the solar panels. However, if this value reaches a point where the temperature starts to rise, it will begin to affect the performance negatively and thus reduce the efficiency of the solar panels [27–30]. The clearance level is also presented in figure 6. This indicator shows how the sky is clear and so it implies the quality of the received solar irradiation on the performance of the solar panels in the selected area. For the case of Jazirat Al Halaniyat, the average clearance level is close to 0.7 which is considered among the highest globally.

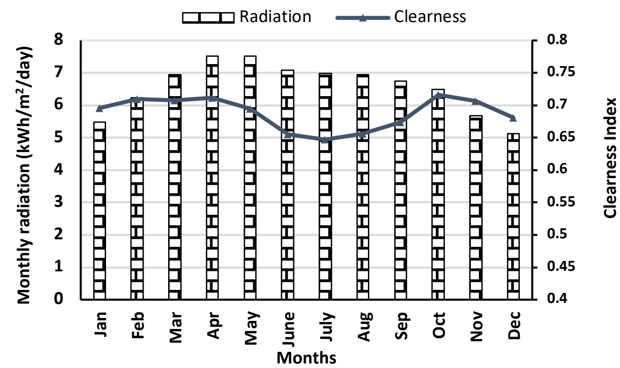

Fig. 6. Monthly average solar irradiation and clerance level

Figure 7 shows the average monthly wind speed at 50m above the ground level. The annual average speed is 6.88 m/s and the peak is 11.79 m/s in July. Previous studies [11,31] of the wind assessment in Oman showed higher potential of the wind in the south part of Oman. The presence of wind blowing above 4 m/s has a positive advantage on the production of energy of the wind turbines and contribution to the cooling of the solar panels [32-34].

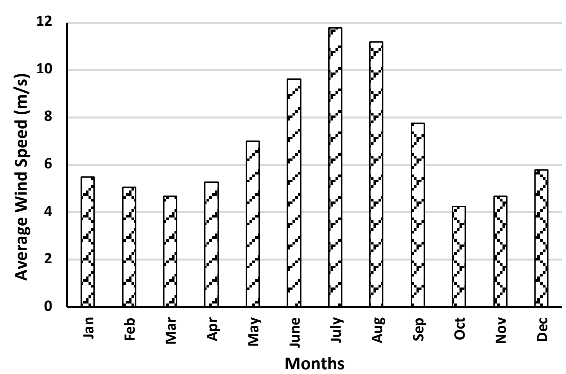

Fig. 7. Monthly average wind speed

5. Evaluation of Different Hybrid Energy Systems

Many hybrids renewable energy systems have been examined for the selected site based on the criteria presented in the last sections. Hundreds of feasible solutions were provided by HomerPro, however, the following four possible options were discussed and analyzed:

1. PV+Wind Turbine+ Battery
2. PV+ Wind Turbine + Diesel Generator
3. PV+ Wind Turbine + +Battery+ Diesel Generator
4. PV+Battery+ Diesel Generator

Figures 8. (a, b, c & d) show the configurations of the four systems and the proposed components of each of them is presented in Table 1.

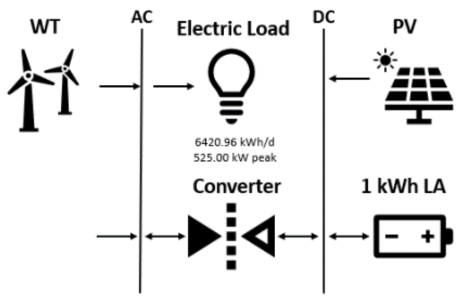

Fig. 8-a. PV+Wind Turbine+ Battery

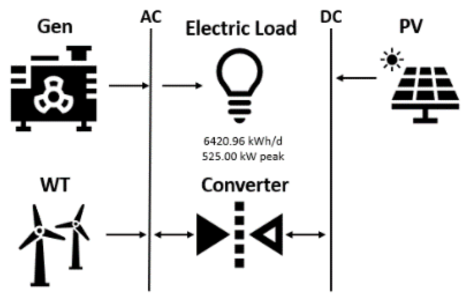

Fig. 8-b. PV+Wind Turbine+ Diesel Generator

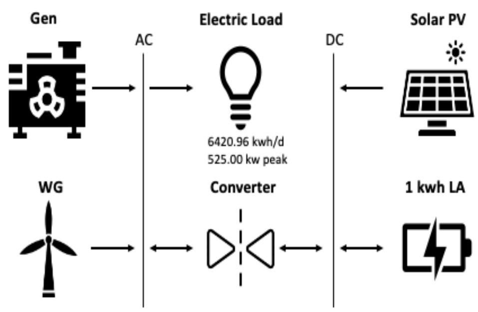

Fig. 8-c. PV+Wind Turbine+ Diesel Generator+ Battery

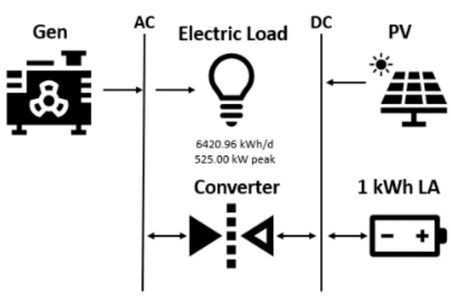

Fig. 8-d. PV+ Diesel Generator+ Battery

Fig. 8 (a, b, c and d) Different hybrid systems for energy generation

Option 1(Figure 8-a): the PV solar system and the Battery storage unit are connected to the DC link and the 514KW inverter system is used to convert DC to AC and to link them with the wind turbine through the AC bus to serve the load. The drawback of this option is the high requirements of the battery storage and wind turbine increases the capital cost of the overall system.

Option 2 (Figure 8-b): The battery storage unit is replaced by the diesel generator through the AC bus. Higher PV solar system capacity and wind turbine are needed, and consequently higher converter capacity is required as presented in Table 1. That leads to very high capital investment as will be discussed in Table 2.

Option 3 (Figure 8-c): The battery storage is connected with the PV solar system to the DC bus and both of the diesel generator, and the wind turbine are connected to the AC bus. Technically this option is the most stable and more sustainable in compared to the other options. Storage batteries are included to ensure power availability when there is no generation or during weather disturbances [37-38]. However, it is proposed to include a 580KW diesel generator to ensure a more efficient hybrid system, but this may have an environmental impact.

Option 4 (Figure 8-d): The wind turbine is replaced by the diesel generator through the AC bus.

Table 1 reveals that option 3 is the best techno-economical option for energy production. The proposed PV, wind turbine, diesel generator and battery storage hybrid system is most stable in comparison to other options and more specifically to option 4. The availability of the wind turbine compensates the impact of the rain on the performances of the PV panels in the summer period as discussed before. Other reason is also the lower requirements of the battery storage in kWh in compared to option 1.

Table 1. Proposed sizing of each component for each system

Option	Proposed system components				
	PV (kW)	WT (kW)	DG (kW)	Conv (kW)	Bat (kWh)
1	2544	290	-	514	11,400
2	7963	310	580	948	-
3	1004	160	580	498	1478
4	1,091	-	580	579	1487

In a further analysis, we discussed the economic evaluation of all the four systems. That includes the net present cost (NPC) for 25 years operation, capital investment, levelized cost of energy (LCOE), yearly operating and maintenance cost, payback period, internal rate of return on investment

(IRR) and other fuel consumption and CO_2 saving amount as presented in Table 2. The capital investment and the net present prices of option 3 are close to option 4. However, both costs are lower than options 1 and 2. Furthermore, option 3 requires lower O&M cost of (351000$ yearly) and lower LCOE of 0.234 $/kWh when compared to option 4. Moreover, the expected consumption of the total fuel in L/year is lower than option 4 due to the utilization of the wind turbine. Some data of options 2 and 4 are not presented in table 2 due to instability of HomerPro analysis of the proposed systems.

Table 2. Results of some economic and technical criteria

Criteria	Hybrid Options			
	1	2	3	4
Capital Investment (M$)	≈8.19	≈12.1	≈2.67	≈2
NPC (M$)	13.8	16	7,22	7.2
O&M (K$)	544	307	351	401
LCOE ($/kWh)	0.457	0.529	0.234	0.238
IRR	19.5 %	NA	6.28 %	NA
Pay back (yr)	7.10	NA	10.6	NA
CO_2 saving (kg/yr)	0	826,422	777,040	969,300
Excess Electricity (kWh/yr)	3,253,667	15,567,198	1,144,295	1,127,470
Total fuel consumed (L/year)	0	315,716	296,851	370,294

6. Analysis of the Performance of the Proposed Hybrid System

Considering the outcomes of the analysis in the last section, the weather conditions, and the life security in Jazirat AL-Halaniyat, option 3 was selected and thus can be considered for power generation with solar, wind, diesel generator and storage system. Future advantages hydrogen-solar [35-38] system might be considered for future advancement in the selected site.

A. Solar PV system

The proposed PV system is flat type, with ground reflection of 20.0% and a nominal operating temperature of 47° C. The PV panels are connected to the DC bus through an inverter and DC/DC maximum power point tracker (MPPT). The MPPT works to match the PV output voltage with the DC bus voltage while the input solar radiation varies by time and weather condition [37]. Homer uses Equation (1) to calculate the output power of the PV solar panels[38].

$$PV_{out} = Y_{PV} \cdot f_{PV} \left[\frac{\overline{G_T}}{\overline{G_{T,STC}}} \right] \left[1 + \alpha_p \left(T_c - T_{C,STC} \right) \right] \quad (1)$$

where: Y_{PV} is the rated capacity of the PV array (output power under standard test conditionsin in kW), f_{PV} is the % PV derating factor, $\overline{G_T}$ is the solar radiation incident on the PV array in the current time step [kW/m^2], $G_{T,STC}$ is the incident radiation at standard test conditions [kW/m^2], α_P is the temperature coefficient of power [%/°C], T_c is the PV cell temperature in the current time step [°C] and $T_{c,STC}$ is the PV cell temperature under standard test conditions at 25°C. More details of the output performance of the proposed PV system are listed in table 3.

Table 3. PV System Details

Rated Capacity	1,004 kW	**Average Daily Production**	5,499 kWhr
Specific Yield	1,999 kWh/kW	**PV Penetration**	85.6 %

The average output of the PV system is 229 kW and the yearly production is 2,007,270 kWhr with a total annual of 4,395 hours of operation, and the capacity factor equals to 22.8%. The PV penetration of 85.6% indicates that the maximum power produced by the PV panels exceeds the peak load. Figure 9 shows that solar PV production occurs during the day and exceeds 750 kW/m^2 for the entire year.

Furthermore, an 80% derating factor is used, even though global horizontal radiation indicates an annual average value of 6.56 kWh/m^2/day. This is because some environmental factors, such as dust and sky conditions, can affect the amount of power production.

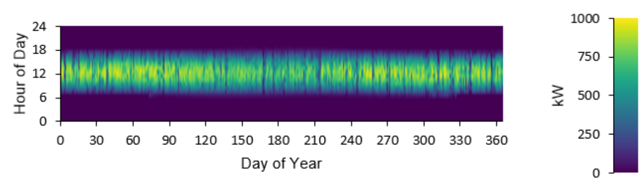

Fig. 9. PV System performance

B. Wind Turbine

The total annual energy production of the proposed 160 kW wind turbine is 464,434 kWh/year. The hub height is 24 meters, and the lifetime is 20 years at the ambient temperature. In HomerPro, the hub height is calculated using the equation (2) [38].

$$U_{hub} = U_{anem} \cdot \left[\frac{Z_{hub}}{Z_{anem}}\right]^{\alpha} \quad (2)$$

where, U_{hub} is the wind speed at the hub height of the wind turbine [m/s], U_{anem} is the wind speed at anemometer height [m/s], z_{hub} is the hub height of the wind turbine [m], z_{anem} is the anemometer height [m], and α is the power law exponent. Table 4 presents these details.

Table 4. Details of the wind turbine

Quantity	16	**Rated Capacity**	160 kW
Wind Turbine Total Production	464,434 kWh/year	**Hours of Operation**	8,112 hrs/year

The output generated power by the wind turbine is typically specified under conditions of standard temperature and pressure (STP) using equation (3) [38].

$$P_{WTG} = \left(\frac{\rho}{\rho_o}\right) . P_{WTG,STP} \quad (3)$$

where: P_{WTG} is the wind turbine power output [kW], $P_{WTG,ST}$ is the wind turbine power output at standard temperature and pressure [kW], ρ is the actual air density [kg/m^3] and ρ_0 is the air density at standard temperature and pressure.

Figure 10 shows the hourly wind turbine performance of the wind turbine throughout the year. Higher energy production is generated during the mid of the year as shown by the light color. The production of energy reaches more than 150KW in the mid of the year. This will compensate for the impacts of the cloudy session on the performance of the solar panels during the rainy period in the summertime.

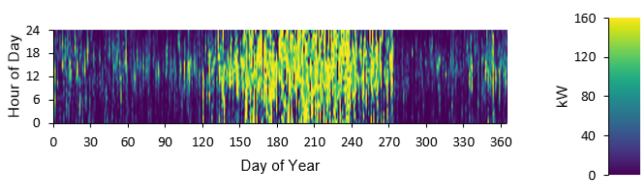

Fig. 10. Performance details of wind turbine System

C. Diesel Generator

The diesel generator is proposed to provide stable energy production during the non-existent supply from other renewables [39]. Also, it can help to maintain higher level of energy security at the bad weather condition in the selected site. From other side, the combination of the diesel generator with solar provides lower cost of fuel and lower rate of investment (ROI) due to high savings potential. Also, the amount of emission is reduced in compare with the diesel generator if it is used as one source of energy production. Table 5 shows that the proposed diesel generator is rated at 580kW and the expected annual electrical production 1,076,771 kWh/y with a fuel price 0.675 $/L.

Table 5. Details of the 580KW Diesel Generator

Capacity	580 kW	**Fuel Consumption**	296,851 L
Capital Cost	$29,000	**Hours of Operation**	4,206 hrs/yr

Figure 11 shows the variation of the annual production of the diesel generator. Higher energy production is generated during the nighttime and lower energy production is generated in the mid of the year due to the higher wind contribution as explained in the last section.

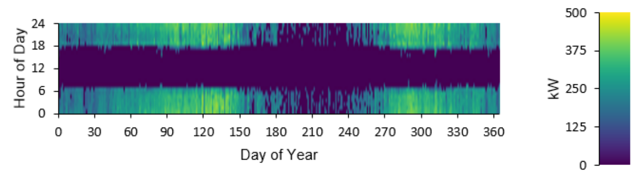

Fig. 11. Performance of the 580KW diesel generator

D. Lead Acid storage unit

The selected storage unit is lead acid battery and it has a total rated capacity of 1478 kWhr, with 79,121 kWh/year annual production and a storage cost of 0.419$/kWh. These details are presented in Table 6. The storage data map throughout the year is illustrated in figure 12. Furthermore, the need for batteries is for backup. As a percentage of charge, without any renewable energy source, the battery would reduce demand charges [40]. Alternatively, hydrogen or hydropower can also be used as a storage system as a backup.

Table 6. Details of the Lead Acid battery

Annual Throughput	79,121 kWh/year	**Losses**	17,691 kWh/year
Maintenance Cost	120 US$/year	**Storage wear Costs**	0.419 $/kWh

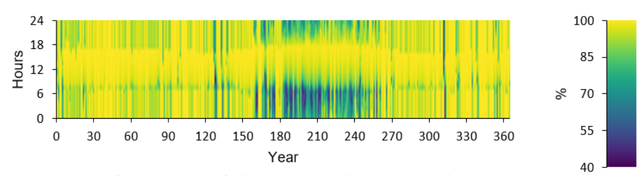

Fig. 12. Performance of the storage battery Unit

E. Converter System

The DC/AC system converter is 587kW with a lifetime is 15 years and overall efficiency of 95%. More details are given in table 7. Figure 13 illustrates the converter's data map. The DC/AC inverter is operating in the daytime for the whole year at a mean value of 92.4 kW and it is off during the nighttime.

Table 7. Details of the DC/AC converter

Mean Output	92.4 kW	**Hours of Operation**	4,855h/year
Energy Out	809,325 kWh/year	**Losses**	42,596 kWh/year
Energy In	851,921 kWh/year	**Maximum Output**	476kW

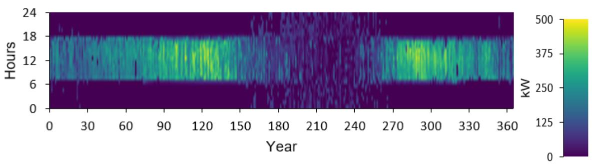

Fig. 13. The Converter data map

7. Analysis of Energy Production

Using the specifications listed in the last section, HomerPro analysis revealed that the proposed system can run with a 1004 kW PV solar system, 160 kW wind capacity with a contribution of 580 diesel generator and an annual storage of 1478 kWh.

A sustainable hybrid energy system is environmentally successful as it ensures minimum or zero emissions of greenhouse gases, and it can provide the maximum energy production from renewable energy resources under different weather and load conditions. However, sometimes the case in the field is different. The change of the weather conditions and geographical restriction limits the achievements of 100% of renewable energy utilization as the case of Al Halaniyat. Figure 14 presents the summery of the energy production of the proposed hybrid system. The expected annual production is 3,548,475 kWh/year. Around 56.6% (2,007,271 kWh/year) of the total production will be generated by the solar PV panels, 13.1% (464,434 kWh/year) by the wind turbine and the remaining 30.3% will be generated by diesel generator.

The monthly average energy production of all components throughout the year is given in figure 15. Lower temperature is recorded, and so lower energy consumption is noticed in the summer period due to the raining session. Figure 15 shows also higher wind energy production in the July and August due the windy days.

Although the proposed hybrid system is predicted for residential application, other profiles, such as commercial and industrial, would require a constant load for the entire 24-hour period. As a result, the proposed integration of solar PV panels and wind turbines allows the products to reach the required load throughout the year, as illustrated in figure 15. Furthermore, utilization of smart grid and IoT in future would assist for optimum use of the distribution of energy output through various energy sources.

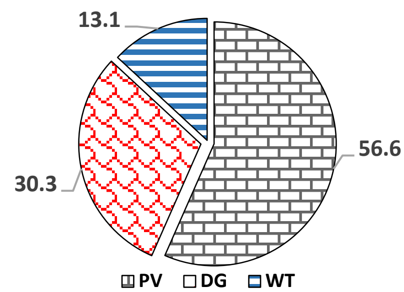

Fig. 14. Percentage of total system energy production by each component

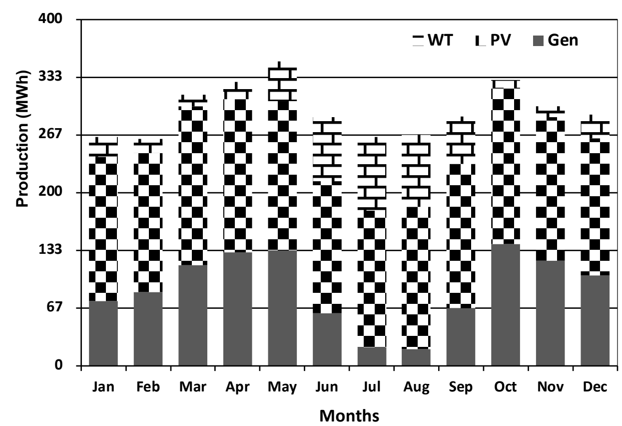

Fig. 15. Average Monthly Energy Production

The yearly percentage of contribution of renewable energy to the total generation is presented in figure 16. Higher renewable energy generation is produced during the daytime for the whole year.

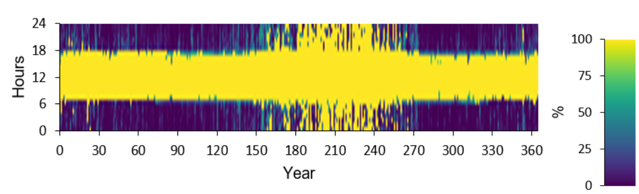

Fig.16. Yearly percentage of contribution of Renewable Generation

Furthermore, the results which are presented in Table 2 mentions that the selected hybrid system has lower fuel consumption in compared to the other options. This is reflected in the expected CO_2 saving which is around 777 kg/yr. The same table shows also that the yearly excess of electricity is 1,144,295 kWh/yr. This result attracted the authors to develop plans for utilizing this amount of yearly wasted energy for practical applications like green hydrogen production.

8. Economic Evaluation & Results

For an efficient design and practical configuration of the hybrid renewable energy system, both technical and economic views must be studied. The selected proposed hybrid option has been economically evaluated against different optimization criteria. The project is rated with an 8% discount rate and a 2% inflation rate, with a 25-year project lifetime. The net present costs is an economical tool used to equate the total cost of a project over a project lifetime to the present value of all the revenues that it earns over the project lifetime [41]. Equation (3) can be used to evaluate the net present cost [38]

$$NPC=\frac{C_{Annual}}{CRF(i,R_{Project})} \tag{3}$$

where: C_{Annual} is the total annual cost, $R_{Project}$ is the project lifetime, and i is the interst rate. Furhtermore, the real interst rate can be caculated using equation (4).

$$i=\frac{i'-f}{1-f} \tag{4}$$

where: i' is nominal interest rate and f is the inflation rate. Also the capital recovery factor can be determined by using equation (5),

$$CFR(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \tag{5}$$

where: N is the total lifetime of the project in years.

The economic analysis, for the proposed hybrid system for Jazirat Al Halaniyat are presented in table 8. The total capital cost is \$2.67 M. This kind of cost is dropping by time. The distribution of cost by different types is presented in figure 17. The data in table 8 was used to calculate the capital and operating costs. Because the lifetime cost is the subtraction of total costs from total earnings, including capital, operations, maintenance, and interest rates, it excludes the time value of money, making the estimation variable over time. According to Homer's analysis, the yearly cumulative cash flow of the system over the 25-year lifetime for a payback of 10.6 years will cost \$7.2M as presented in table 8.

In 2021, 740000 liters of diesel was consumed, whereas the proposed hybrid renewable energy system is expected to consume 296,851 liters of diesel annually. This amount represents only 40% of the fuel consumption and consequently the expected amount of CO_2 and other emission can be reduced by more than 50%.

Table 8. Economical Analysis and Results

Name	Capital ($)	Operating ($)	Replacement ($)	Salvage ($)	Fuel ($)	Total ($)
DG	29,000	946,1	77,975	5,502	2.59M	3.64M
Battery	443,40	191,1	391,72	53,10	0.00	973,08
PV	1.31 M	129,8	0.00	0.00	0.00	1.43M
Converter	176,07	0.00	74,703	14,060	0.00	236,72
WT	720,00	104,7	255,05	143,73	0.00	935,98
System	2.67 M	1.37M	799,44	216,41	2.59M	**7.22M**

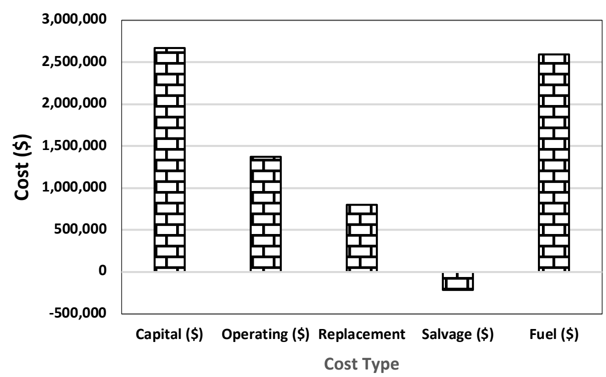

Fig. 17. Distribution of cost by different types

9. Conclusions

This paper proposes an innovative practical solution to ensure power availability and secure the safety of oil shipping companies during bad weather conditions in Jazirat Al Halaniyat, southern Oman. A meteorological analysis was investigated and found that solar irradiance and wind speed represent excellent potential for a hybrid solar, wind, diesel generator and storage hybrid energy system. Many hybrid configuration have been studied using HomerPro. However, the analysis revealed that the combination of 1004kW PV solar panel, 160kW wind turbine, 580kW diesel generator and 478kW backup battery will be the best optimum hybrid system. The presence of diesel generators helps to maintain a high level of security during the bad weather on the island, ensuring stable power generation even in the absence of solar and wind supplies. Fortunately, with an estimated reduction in greenhouse gas emissions of around 40% annually, fuel consumption is expected to decrease. Based on the optimized results, the economic analysis concluded that for the best hybrid option, the total net present cost NPC of $7.22 M for 25 years' operation project and a discounted payback of 10.6 years is predictable.

Acknowledgment

This research is supported by the Ministry of Higher Education, Research and Innovation in Oman (research grant: BFP/GRG/EI/21/051). The authors would like to thank corporation from Rural Areas Electricity (Tanweer) and Dhofar power companies to provide some data for this work. The continued support of the research deanship in University of Nizwa and the College of Engineering and Architecture is also appreciated.

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