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Renewable Energy Transition in Remote Islands: Evaluating the Potential for Al Hallaniyat Island

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Abstract

Oman aspires to source up to 39% of its power grid from renewable energy by 2040. One way to meet this target is to electrify off-grid locations like Al Hallaniyat island. This study aims to assess the viability of implementing a hybrid system of renewable energy technologies with the existing diesel generators from technical and economic perspectives. It navigates the assessment by analyzing actual load data of Al Hallaniyat Island and by determining the optimum renewable energy technologies to be used, which are found to be a solar PV system and an onshore wind turbine. Both technologies are integrated with a battery system and the existing diesel generators to deliver 2,413,220 kWh yearly. HOMER Pro software is used to design the most beneficial hybrid system. The simulation recommends power capacities of 398 kW for the solar system, 580 kW for the wind turbine, 900 kWh for the battery system, and 600 kW for the diesel generators. The hybrid system lowers the dependency on diesel consumption by approximately 73%, achieving over 79% of renewable energy penetration. With a capital cost of \$1.17M and annual operation cost of \$193,103, the proposed system offers a net present cost of \$ 3.99M, payback period of just 4.3 years, and most importantly competitive levelized cost of energy of 0.113 \$/kWh. In addition, this hybrid system significantly reduces the annual greenhouse gases emissions from 2,124,292 kg CO_2e to only 580,678 kg CO_2e. Overall, the study demonstrates the technical, economic, and environmental feasibility of such hybrid systems.

Keywords

Renewable Energy, Hybrid System Design, Energy Transition, Off-Grid Electrification, GHG Emission Reduction

1. Introduction
1.1 Overview
For decades, nations across the globe, developed and developing countries, have been working hard to create a future where sustainable energy leads the energy sector. Despite the tremendous progress that have been made in the field, the 2015 Paris Agreement indicates that the current efforts are still insufficient to address the climate changes, particularly the alarming rise of the global average temperature. To tackle this, 196 countries have committed to limit the global average temperature increase below 1.5 °C (FALKNER, 2016). Therefore, the International Renewable Energy Agency (IRENA) recommendation toward achieving this aspiration is captured in Figure 1, where the essential shift toward renewable energy is featured in order to drastically reduce or phase out fossil fuels (IRENA, 2022).

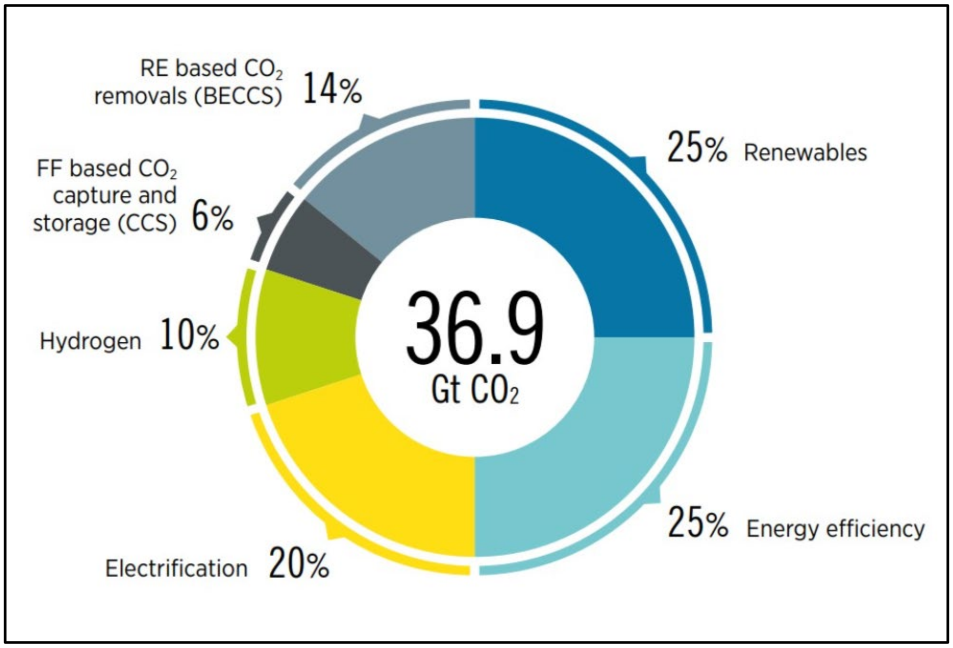

Figure 1: Emissions reduction by 2050 through six technological avenues (IRENA, 2022)

Additionally, renewable energies are available almost everywhere in various options that provide the opportunity to countries to harness whatever is available within their domain based on their geographic strengths. In Oman's case, the country is positioned geographically to feature several renewable energy resources. According to the Global Wind Atlas and Global Solar Atlas as in Figure 2, the Sultanate is in the forefront of the highest potential locations for both wind and solar energies. Therefore, Oman has set ambitious targets to utilize its available renewable resources to reach 20% and up to 39% of renewable energy mix by 2030 and 2040, respectively (Oman Vision 2040, 2019).

1.2 Al Hallaniyat Islands
Al Hallaniyat Islands consist of 4 different islands, the largest and the only occupied island among the four is Al Hallaniyat island. as per Figure 3, the island is located northeast of the Governorate of Dhofar and under the administration of Wilayat Shalim. Al Hallaniyat Island, according to the UNESCO, is inhabited by approximately 250 people, most of the locals are fishermen. As anticipated, the power demand on the island is low, mainly feeding the local houses, a school, a water desalination plant, a health center, and a fish factory (UNESCO, 2013). The island currently depends on diesel-based power plant to generate its electricity demand.

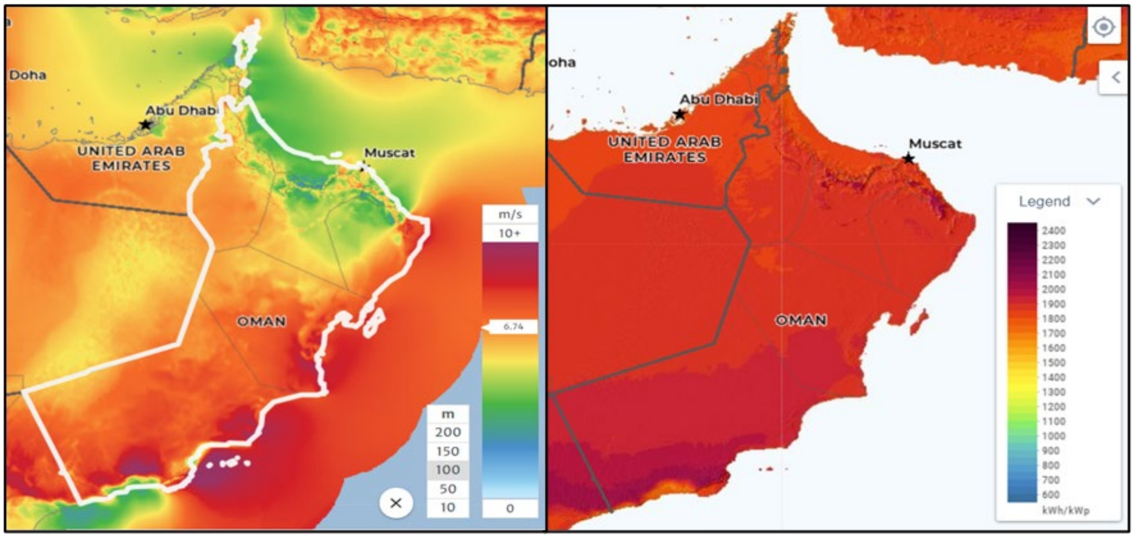

Figure 2: Oman wind and solar maps (Global Solar Atlas, 2024; Jake et al., 2024)

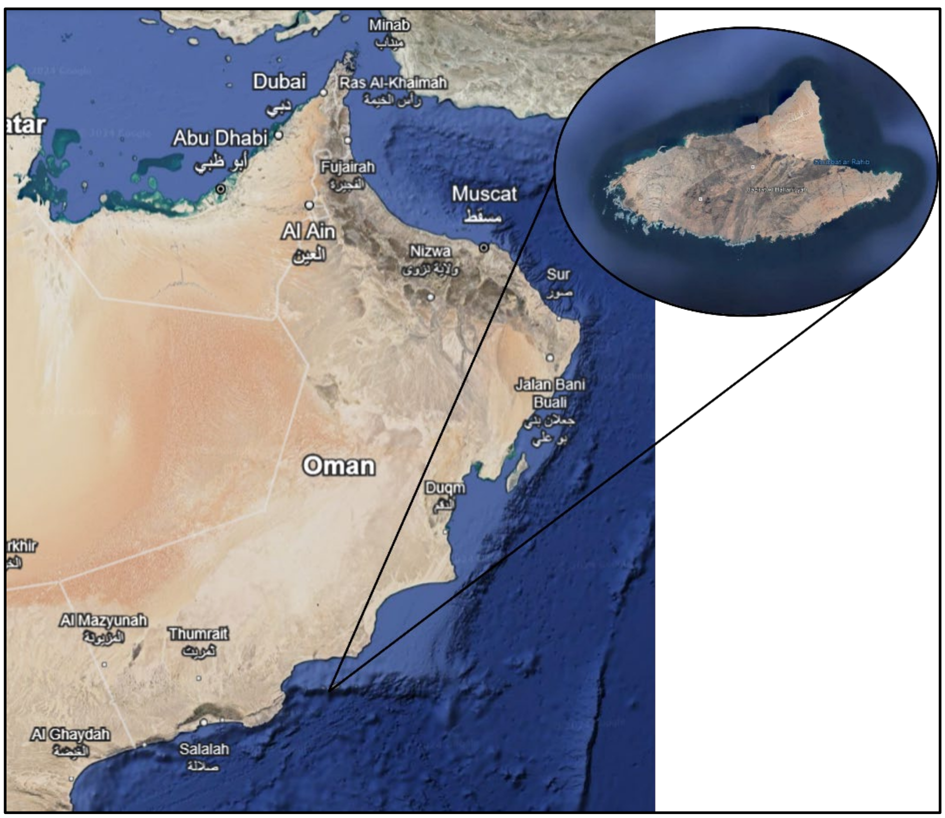

Figure 2: Map of Al Hallaniyat Island highlighting its location (Google Earth Pro, 2024)

1.3 Problem Statement

Al Hallaniyat Island currently depends on diesel generators only to meet its power demand. There are many commercial and environmental issues with diesel generators regardless of their reliability and availability. Those issues include high GHG emissions, high Capex and Opex, and the associated logistic and cost challenges when it comes to diesel transportation.

1.4 Research Scope

The primary objective of this research is analyzing the power demand in Al Hallaniyat Island based on 2023 power consumption data provided by Nama Generation Company. The study will focus on the technical and economic analysis for introducing renewable energy technologies along with the diesel generators that are in operation currently in the island. It will examine different hybrid systems to determine the best set up for the island along with evaluating the environmental impact of such system. On the other hand, the study will not examine the full replacement of the diesel generators taking into consideration the reliability of renewable energy, cost consideration, and the availability of lands in the island.

1.5 Research Objectives

The main objective of this research is studying the feasibility of integrating renewable energy technologies with the existing diesel generators on Al Hallaniyat Island. The specific objectives of the research can be described as below:

- Develop a comprehensive understanding of the current power demand.
- Evaluate the technical feasibility of various hybrid systems focusing on reliability, meeting the island's power demand, and operational and maintenance challenges.
- Conduct an economic feasibility on the proposed system to quantify the savings from installing a hybrid system.
- Identify the environmental impact of such system, specifically on the reduction of GHG emissions.

1.6 Methodology

The research methodology followed for this study is designed to systematically conduct a techno-economic study of integrating renewable energy technologies with the existing diesel generators on Al Hallaniyat Island. The methodology is summarized in Figure 4 and structured as follows:

- Data collection: a site visit to the island's existing power plant is conducted to collect qualitative insights to develop a better understating on the operational philosophy. Additionally, actual power data from Nama Generation Company for the year of 2023 is obtained to study the power trend in the island that includes identifying the peak demand periods, the daily load profile, and the seasonal load profile. Solar and wind data is collected from available meteorological databases to identify certain parameters like solar irradiance and wind speeds.
- Technical Analysis: The optimum renewable energy resources is identified based on criteria such as resource availability, technology maturation, and cost-effectiveness. The best hybrid system configuration is then designed and simulated using HOMER Pro software. Next, an analysis of the simulated design is conducted focusing on parameters like system reliability, land availability, and meeting the island's power demand.
- Economic and financial analysis: parameters like Net Present Cost (NPC), capital expenditures, operational expenditures, Levelized Cost of Energy (LCOE), Internal rate of Return (IRR), Return of Investment (ROI), and payback period are determined.
- Environmental analysis: At this stage the potential reduction in GHG emissions is estimated.

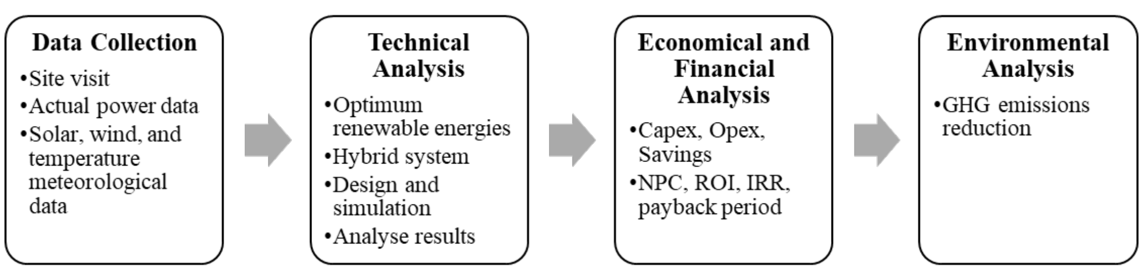

Figure 4: Methodology approach of the research

2. Literature Review

2.1 Solar Energy

Reports and studies highlight a consistent upward trend in the installation of nearly all renewable energy technologies, where this trend is led by the installation of solar PV panels. In fact, IRENA issued a report in 2023 that shows the global installed capacity of solar PV exceeding the combined installed capacities of all other renewable energy technologies, Figure 5. The report also forecasts that this trend will continue in the future, at least untill 2028.

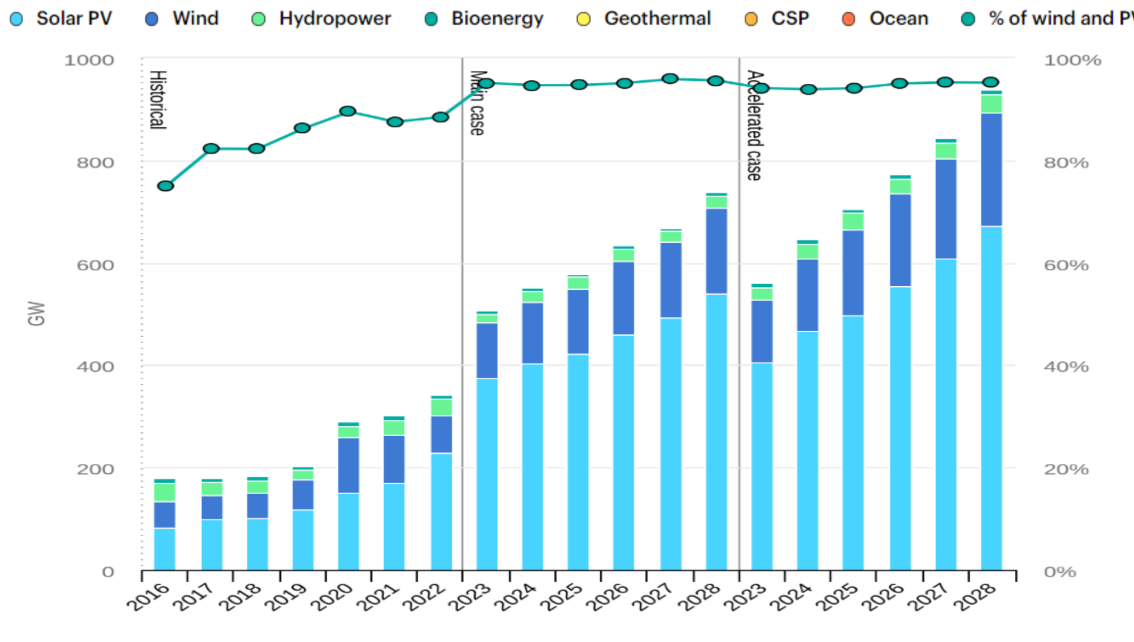

Figure 3: Renewable electricity capacity additions by technology and segment (IEA, 2024)

Another important report issued by IRENA demonstrates that the installation of solar PV increased by an impressive 911% only between 2012 and 2022. This surge in the solar PV installation was experienced across all continents but mostly in Asia, where the upward trend was more drastic. Figure 6 and Table 1 provide an overview of the global solar installation per continent from 2012 to 2023. Overall, it is evidential that the global commitment toward installing solar systems in growing year after year. This is duo to several factors, including government incentives, technological advancement, and reduction in cost.

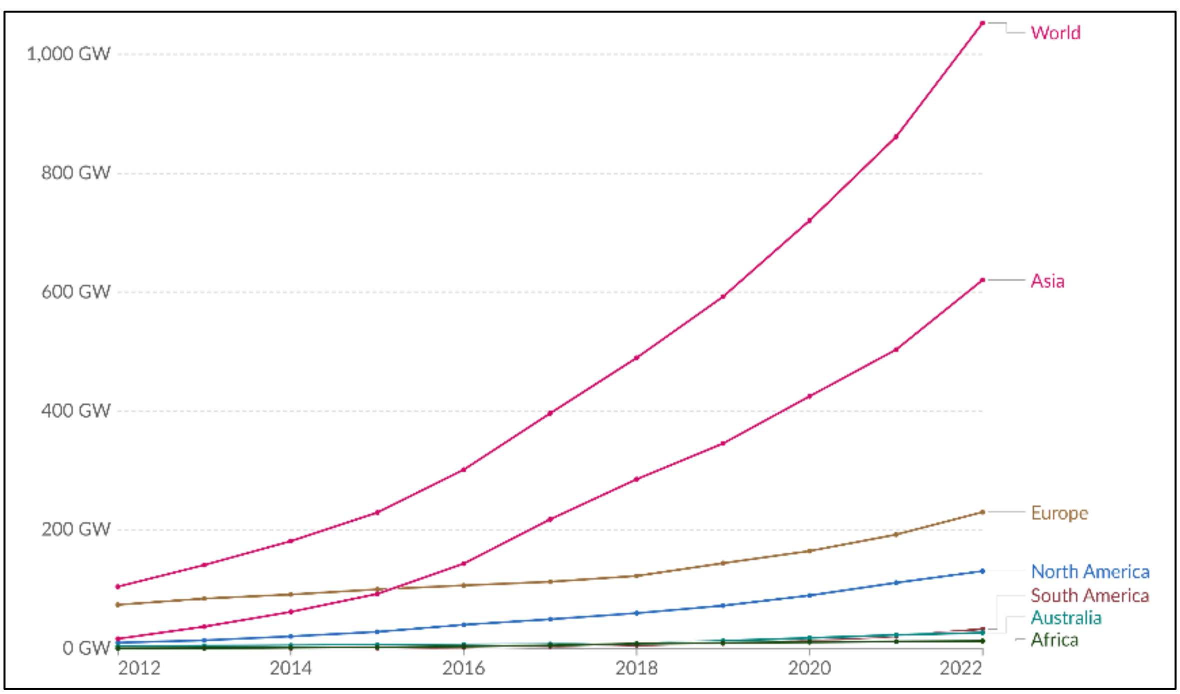

Figure 4: Capacity of installed solar energy worldwide (IRENA, 2023b)

Table 1: Tabulated capacity of installed solar energy for each continent (IRENA, 2023b)

Country/area	**2012**	**2022**	**Relative Change**
Australia	3.80 GW	26.79 GW	+605%
Africa	0.40 GW	12.64 GW	+3,086%
Asia	16.54 GW	620.26 GW	+3,650%
Europe	73.63 GW	229.62 GW	+212%
North America	9.65 GW	130.43 GW	+1,252%
South America	0.16 GW	32.77 GW	+19,900%
World	104.21 GW	1,053.12 GW	+911%

Fortunately, the rapid growth in the solar installation has resulted in a huge reduction in the LCOE, which made the technology even more attractive for investments. IRENA issued a report in 2020 demonstrating a notable declining trend in the LCOE from 2010 to 2020 with a projection of sustaining the same trend in the future. For example, Figure 7 shows that the solar LCOE dropped from 0.045 USD/kWh to 0.037 USD/kWh in just one year, from 2020 to 2021. In general, The LCOE has fallen down by a factor of eight between 2010 and 2020.

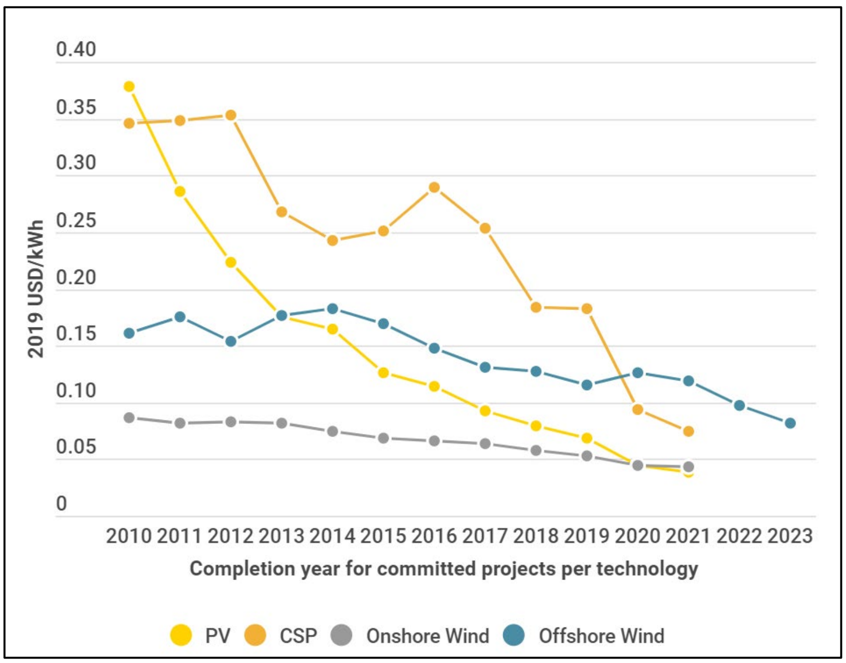

Figure 5: LCOE trend for different renewable energy technologies (IRENA, 2020)

2.2 Wind Energy

Wind energy, along with solar energy, has been on top of the most favorable substitutes for fossil fuels to generate energy duo to its techno-Economic value. In fact, in 2017 it was estimated that more than 50 GW of wind turbines were installed, which increased the cumulative global wind installation capacity to 540 GW (Chen et al., 2019). In addition, Figure 8 is obtained from IRENA's public data center demonstrating the worldwide trend of installing wind turbines over the past decade. It shows that the global installation of onshore wind turbines has reached 944,205 MW in 2023, more than three times the capacity installed in 2012. In the meantime, the rend of installing offshore wind turbine has surged more than ten times in the last decade, reaching 73,186 MW in 2023.

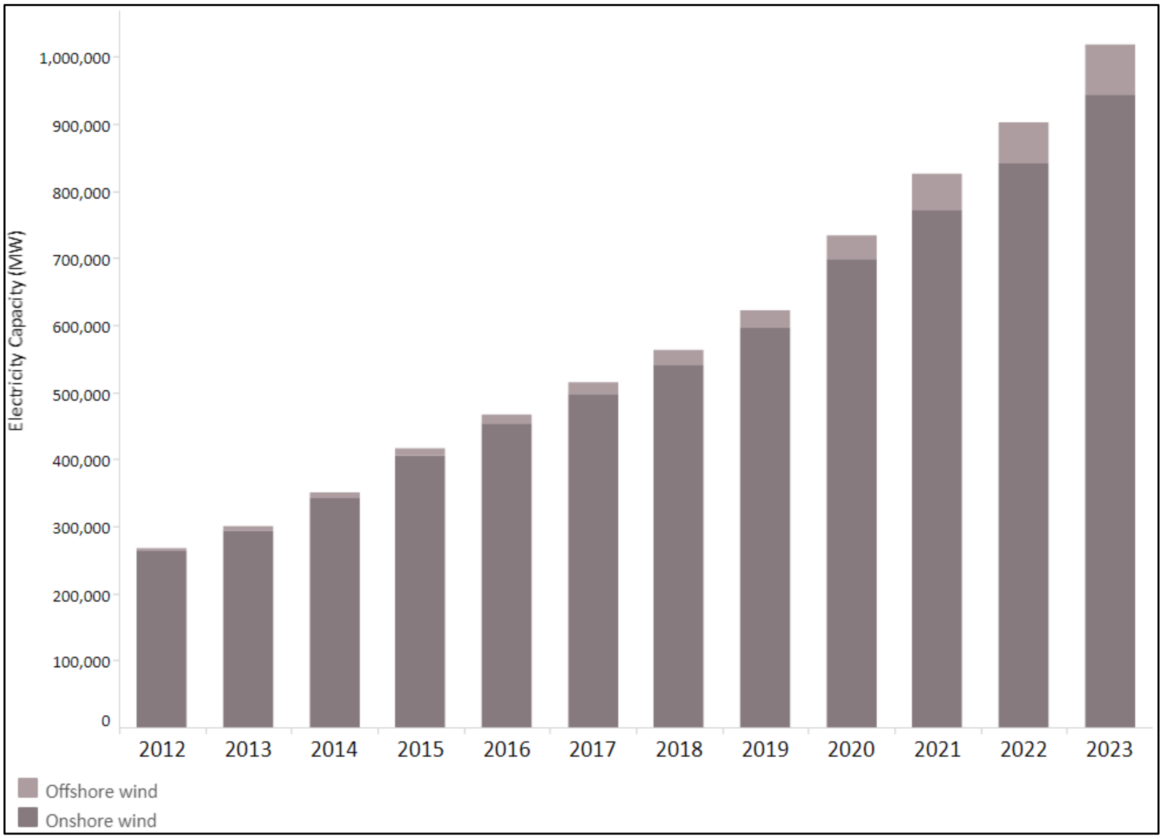

Figure 6: Wind turbine capacity data taken from IRENA's public data center (IRENA, 2023a).

Furthermore, the Global Landscape of Renewable Energy Finance Report that was published in 2023 by IRENA and Climate Policy Initiative (CPI) indicates that both onshore and offshore wind turbine technologies are on top of the global financial commitments in the renewable energy field. Notably, Figure 9 demonstrates that onshore wind technology received the second-highest financial commitment accounting for more than USD 140 billion, representing about 28% of the total investments in the field. Meanwhile, offshore wind investments represent 7% of the total financial investments amounting to over USD 33 billion (IRENA and CPI, 2023). Thus, these huge financial investments are reflected in the energy generated from wind turbines. According to International Energy Agency (IEA), the electricity generated from wind turbines reached a new record of more than 2,100 TWh in 2022, representing an increase of 14% from the previous year. However, in order to reach the goal of Net Zero Emissions (NZE) by 2050, the average annual increase in wind energy has to be around 17%, 3% higher than the current status (IEA, 2023).

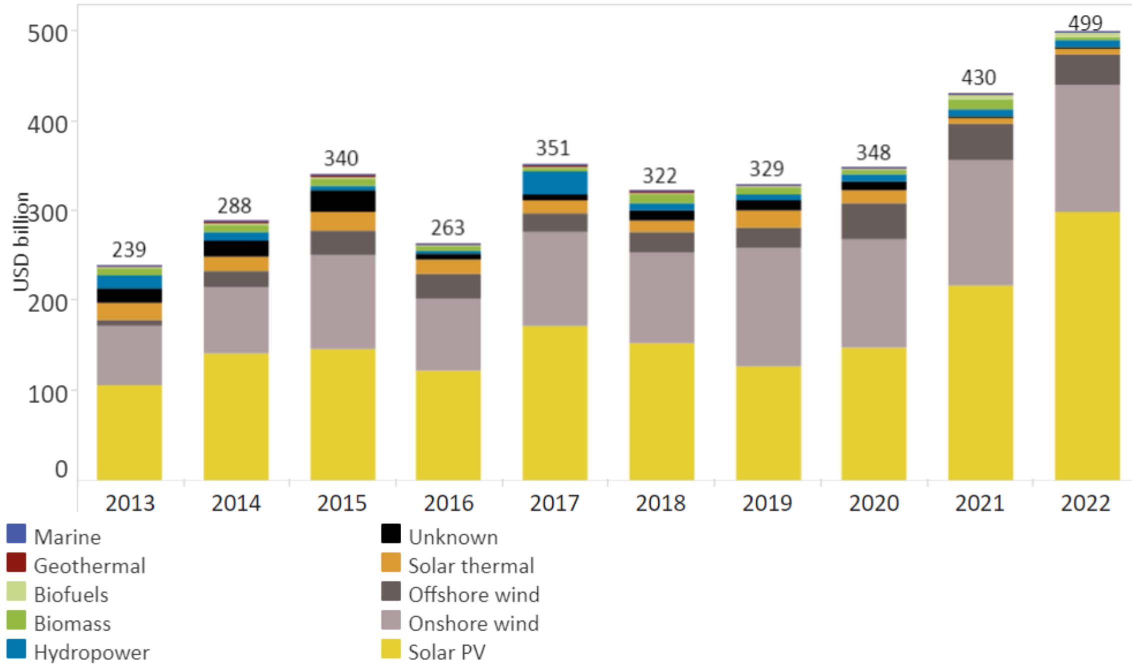

Figure 7: Annual financial commitment in renewable energy (IRENA and CPI, 2023)

2.3 Diesel Generators

Diesel machines have been used heavily in different industries such as powering light and heavy vehicles, ships, and even power plants. As for diesel generators, they are wildly used for power generation as they are considered a reliable electricity source with a higher degree of stability. As long as the sizing and design are done properly, a diesel generator can supply power in very short time when needed. More than that, it is relatively easy to install and operate one, and there are many local companies that support individuals and entities when it comes to diesel generators. Overall, diesel generators are considered very durable as they can operate for thousands of hours before they require their first major maintenance (Manuela & Fabrice, 2016). A diesel generator depends mainly on diesel fuel as a primary source of energy. It mainly consists of diesel engine that is coupled with an electric generator. The operational principle of a diesel generator is simplified in Figure 10. Air from the surrounding is blown inside the generator for compression, which causes the high increase in the temperature. It is followed by diesel injection into the engine's combustion chamber. The mixture of both air and diesel ignites and results in an explosion that convert the chemical energy into mechanical energy in which the generator starts operating and generating the desired electricity. One of the advantages of a diesel generator is that it can generate electricity based on the demand (Ersan, 2021).

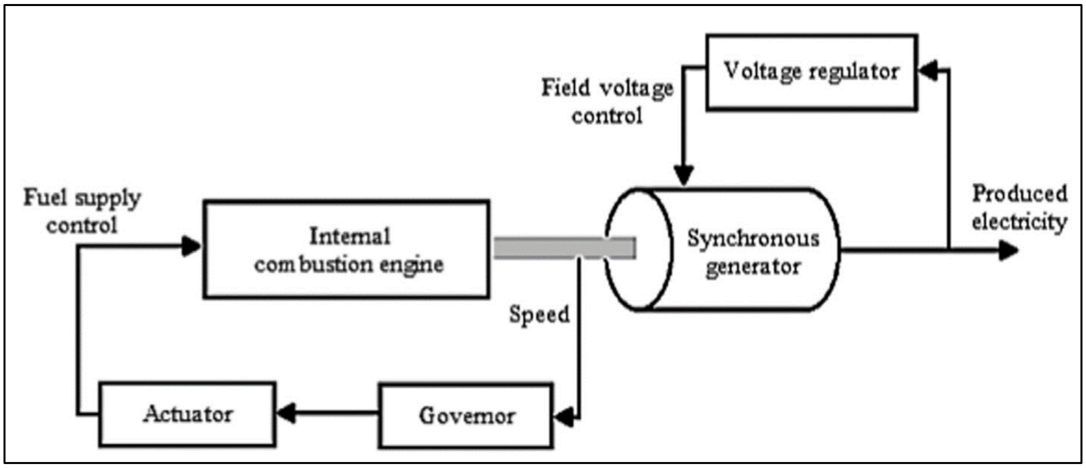

Figure 8: A simple diagram of a diesel generator

Despite all the advantages mentioned previously of installing diesel generators, they are unfortunately considered as harmful to the environment. This is duo to the significant amount of GHG emissions, not to mention the noise pollution that may be caused to the surrounding environment (Khan et al., 2023). Thus, a diesel generator is often recommended only for backup power or for off-grid applications such as rural areas where the public electricity grid is not available. (Eltamaly & Mohamed, 2018; Salas et al., 2015). Nonetheless, according to Grand View Research (GVR), the global market for diesel generator has been growing over the last decades. The worldwide diesel generator market is valued at USD 16 billion in 2023 and has a compound annual growth rate of more than 9% for from 2024 untill 2030. Interestingly, the commercial sector holds the largest market share followed by industrial applications and residential applications, respectively. The increasing trend in the diesel generator market can be justified by several factors, one of which is the increased need for backup power during power outages that are occurring duo to natural disasters (GVR, 2024).

2.4 Battery Systems

Batteries represent a chemical form of energy storage. Nowadays, there are various types of chemical batteries, but the most common and wildly used is lithium-ion. The technology that once started commercialization back in 1991 by Sony, is now one of the leading technologies in the field. Despite the technical and safety challenges associated with lithium-ion, the technology continues to emerge, offering much better battery systems than those available few decades ago (Blomgren, 2017). Lithium-ion batteries are known for their features that include excellent energy density, outstanding coulombic efficiencies, and minimal self-discharge characteristics. Therefore. They have been wildly utilized across many industries, including the power sector (Kim et al., 2019). Based on a 2022 McKinsey report, lithium-ion battery market is expected to expand by more than 30% every year untill 2030 with a market value reaching over $400 billion. The report also forecasts that the market capacity might reach 4.7 TWh, compared to just 700 GWh in 2022, as shown in Figure 11 (Jakob et al., 2023).

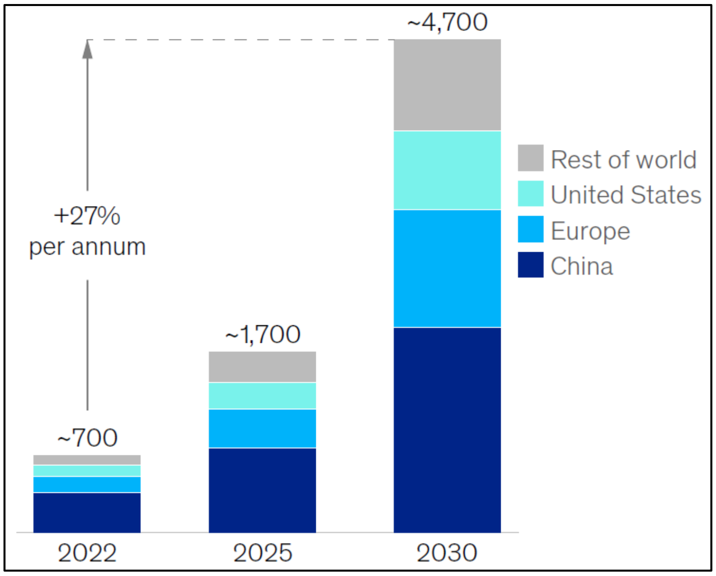

Figure 9: Global lithium-ion battery demand

2.5 Oman's Renewable Energy Sector

The landscape of renewable energy in Oman has been going through a tremendous change in the last couple of years, especially after the country's commitment toward reaching up to 39% of renewable energy by 2030. This has been clearly articulated in the reports that are regularly issued by Nama Power and Water Procurement Company (Nama PWP), the single procurer of power and water capacity and output in the Sultanate of Oman. Based on Nama PWP's 7-year statement, the country's target is to secure more than 3,800 MW by 2029 along with the existing 500 MW from Ibri II IPP project. Table 2 shows the renewable energy projects and their expected operation years (Nama PWP, 2023). Parallelly, other entities in Oman have their own renewable energy targets. For example, Petroleum Development Oman (PDO), the largest oil and gas producer in the Sultanate, has also set their renewable energy targets. As a result, PDO has floated three different Request for Proposals (RfP) in 2023 to procure 300 MW of renewable energy. This is in addition to the 100 MW solar energy PDO has from Amin 100 MW IPP (Conrad, 2024).

Table 2: Nama PWP's renewable energy development plan (Nama PWP, 2023)

	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Contracted Projects				**MW**			
Ibri II Solar IPP	500	500	500	500	500	500	500
Total Contracted Capacity	500	500	500	500	500	500	500
Planned Projects							
Manah I Solar IPP			500	500	500	500	500
Manah II Solar IPP			500	500	500	500	500
Ibri III Solar IPP					500	500	500
JBB Wind IPP					100	100	100
Duqm Wind IPP					200	200	200
Ras Madrakah Wind IPP					200	200	200
MIS Solar IPP 2027					500	500	500
Barka WTE IPP						140	140
Solar PV IPPs 2029							1000
Wind IPP 2029							200
Total Planned Capacity	-	-	1000	1000	2500	2640	3840

2.6 Al Hallaniyat Island

There aren't many research articles in electrifying Al Hallaniyat Island. In fact, using Google Scholar research engine, there are only three papers that have been published in the subject from 2000 to 2023. This section highlights those papers chronologically and why it is important to revisit the electrification of Al Hallaniyat Island.

Firstly, the paper titled "Hybrid (solar and wind) energy system for Al Hallaniyat Island electrification" by A. H. Al-Badi was issued in 2011. This paper evaluates the tecno-economic feasibility of supporting the island's diesel power plant with solar and wind energy. It provides a comprehensive analysis on both the technical and commercial aspects of installing a hybrid system in the island. The paper also highlights the cost of energy associated with the proposed setup. However, the author only examined a relatively limited amount of renewable energy integration into the grid. Most importantly, the paper is almost outdated considering the cost dramatic fall of both solar and wind technologies in the past decade (A. H. Al-Badi, 2011). The second paper was issued in 2014 with the title "A Review of Optimum Sizing Techniques for OffGrid Hybrid PV-Wind Renewable Energy Systems". This review article examined multiple research papers with similar limitations to those found in Al-Badi's paper (Ahmed et al., 2014).

The third and last paper that can be found written in the electrification of Al Hallaniyat Island is titled "Feasibility Study of Using Wave-PV-Wind Hybrid System for AL Hallaniyat Island" and prepared by A. Al-Badi et al. The paper emphasis on the importance of introducing 100% renewable energy as the main source of energy in the island. The proposed hybrid system that the authors considered as the most economic option contains PV, wind, and wave energy along with the usage of a battery system. The hybrid system is modeled using HOMER Pro software and resulted in a Levelized Cost of Energy (LCOE) of 0.1586 \$/kWh. The authors presented the LCOE of Wind-Wave-Battery, PV-Wave-Battery, and PV-Wind-Wave-Battery and concluded that the latter has the lowest LCOE. While this assumption sounds reasonable, the paper does not explore the option of having PV-Wind-Battery which might results in a lower LCOE than what is presented in the paper. Furthermore, the paper has accounted for wave energy in all its discussed options, even though it acknowledges that wave energy technologies can cost up to six times more than PV or wind technologies. Lastly, wave energy technologies are still in their early stage in term of maturity when compared to solar and wind for instance. Hence, it is not advisable to depend on such technology, especially in an isolated location like Al Hallaniyat Island (Aderinto & Li, 2018; A. Al-Badi et al., 2024).

3. Methodology

3.1 Data Collection

3.1.1 Site Visit

A site visit to Al Hallaniyat Island is conducted to have a better understanding of the overall structure of the power system. The island's diesel-based power plant includes four diesel generators of varying capacities, with the total installed capacity of 1.568 GW and an available power capacity of 1.25 GW. The installed capacity is nearly three times higher than what the island requires at any given time. The higher capacity is essential for ensuring redundancy in cases like malfunctions, unplanned outages, and maintenance. It's also vital as repairs or parts shipments are likely to take longer than expected considering that the island is isolated. The plant is also equipped with four storage tanks to store diesel in large quantities that can last for months. Two of the tanks have a capacity of 50,000 liters each, while the other two tanks have a capacity of 100,000 liters each.

In addition, the power demand has remained relatively consistent over the years with no major expansion in the next five years. The plant is located less than one kilometer from almost all power loads. Despite the total area of the island, all local houses and public facilities are located in a single area next to each other as shown in Figure 12. This is duo to the island's harsh terrain, which is uninhabitable.

Figure 10: General layout of Al Hallaniyat Island

3.1.2 Load Profile

The load profile of the island for the year of 2023 was obtained from Nama Generation Company and is tabulated in Table 3 and shown in Figure 13.

Table 3: load profile of Al Hallaniyat Island in 2023

Description	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Generated power (kWh)	153110	144780	231600	256610	293560	216580	137890	132830	174590	235130	235650	200890
Min. demand (kW)	145	120	210	275	290	185	100	130	160	110	235	185
Peak demand (kW)	290	370	420	440	500	470	235	250	440	500	425	410
Diesel consumed (Liter)	49320	46685	74715	82775	96050	71009	45211	43552	57239	77091	77257	65871

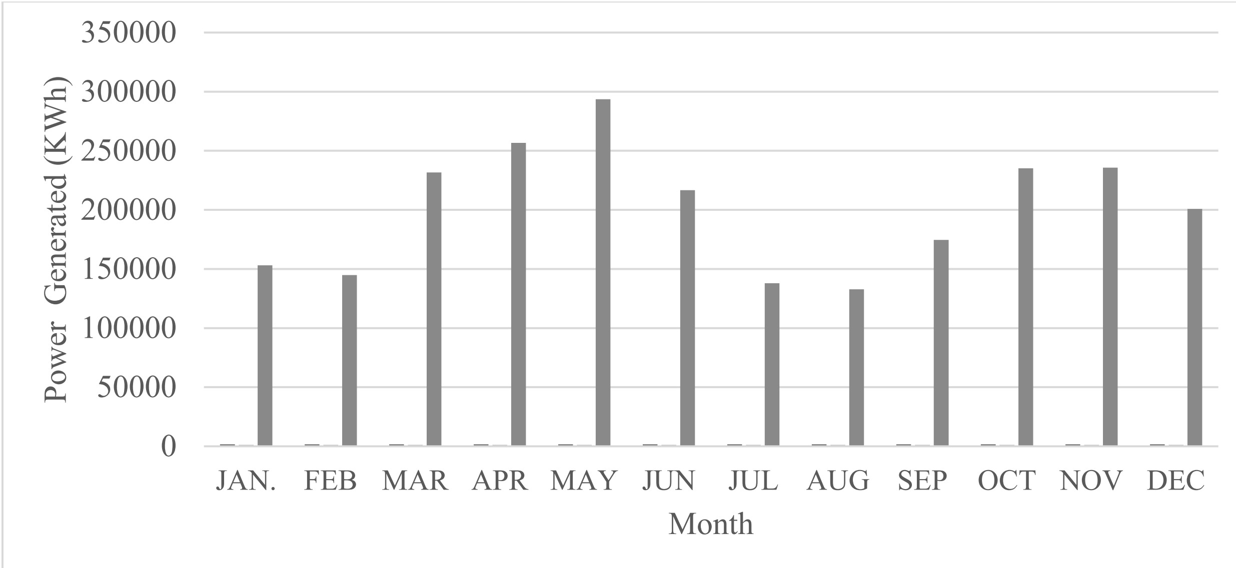

Figure 11: Load profile of Al Hallaniyat Island in 2023

3.1.3 Solar, Wind, Temperature Data

The meteorological data of solar radiation, wind speed, and temperature is obtained from NASA Prediction of Worldwide Energy Resource (POWER) database, where 30 years of the monthly average values of the parameters are captured. Figure 14, Figure 15, and Figure 16 illustrate the solar, wind, and temperature meteorological data for the island, respectively. Both solar and wind data are utilized to determine the potential of both resources at the site, while the temperature data are used to determine its impact on the parameters such as operational efficiency.

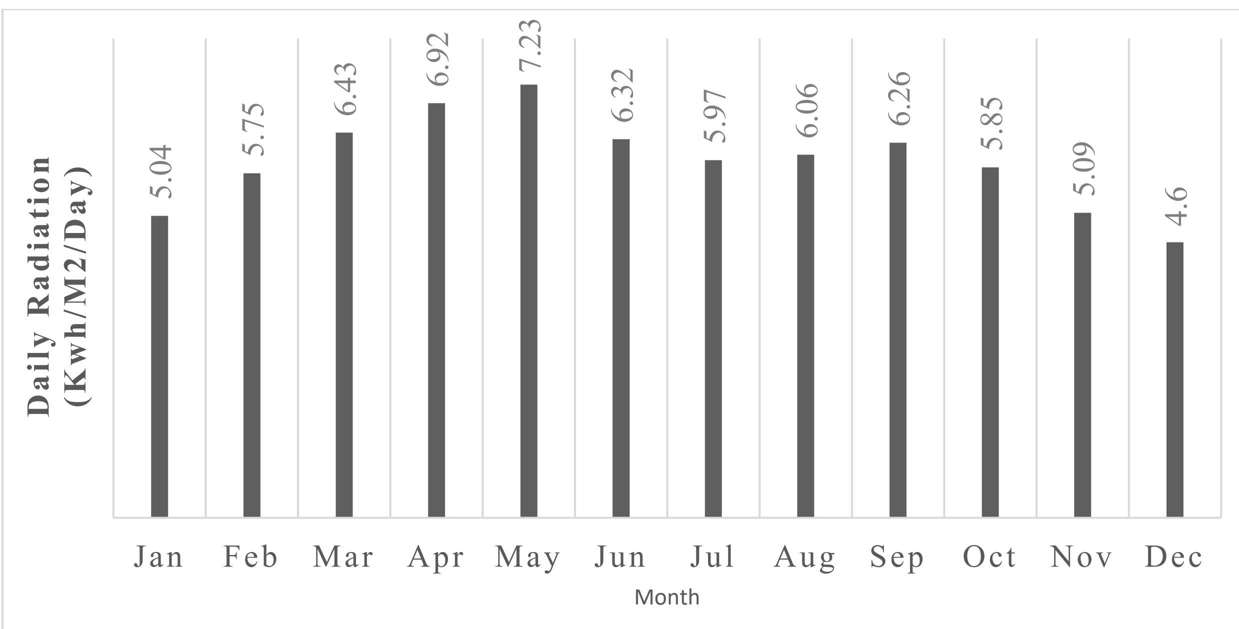

Figure 12: Monthly average solar Global Horizontal Irradiance (GHI)

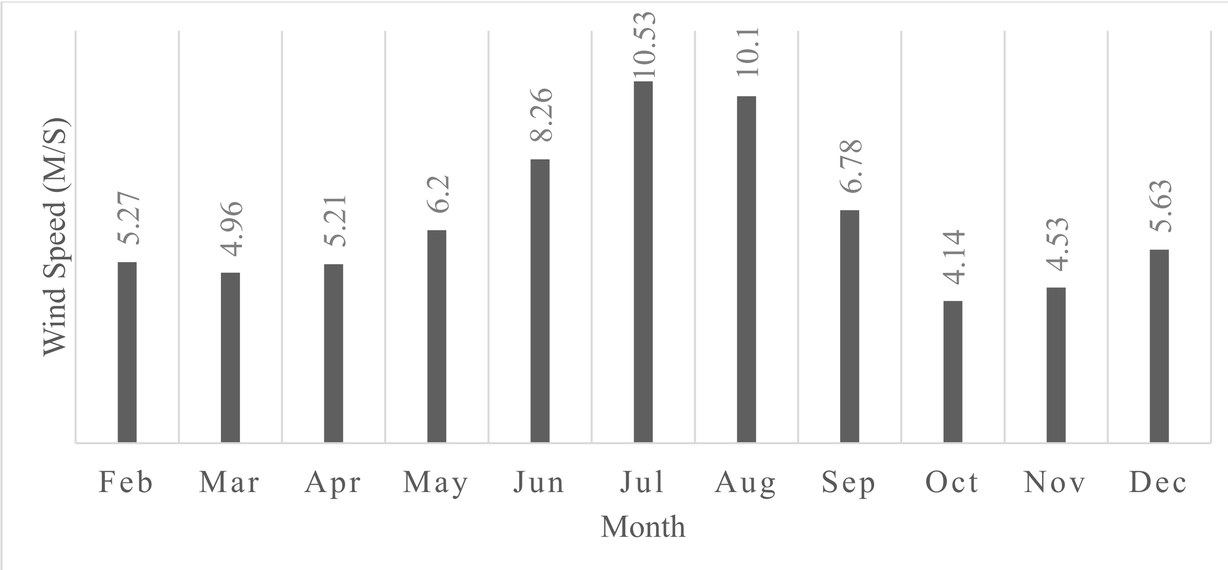

Figure 13: Monthly average windspeed at 50m above the surface of earth

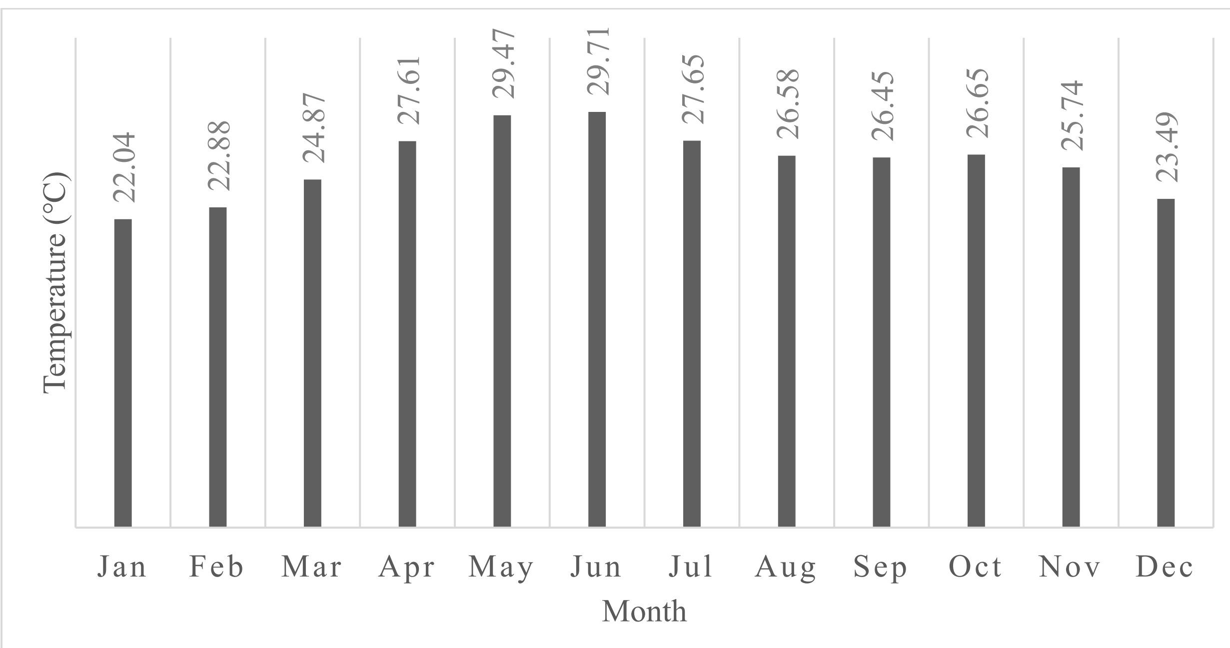

Figure 14: Monthly average temperature data

3.2 Technical Analysis

3.2.1 Technologies Screening Process

The technical analysis starts with a screening process to determine the most suitable renewable energy technologies that can be utilized for the island. Table 4 lists all the renewable energy options to be evaluated based on the screening criteria that are listed in Table 5 and explained in depth in Table 6. Each technology is evaluated against each of the screening criteria, resulting in a ranking matrix where the scale used is low, medium, and high. Low is assigned a value of one, medium a value of two, and high a value of three. The top two ranked technologies are selected for further analysis. Accordingly, they are used in HOMER Pro software to design multiple hybrid configuration to determine the optimum configuration for the island.

Table 4: List of renewable energy technologies

Renewable energy technologies
Solar PV
Onshore wind
Offshore wind
Wave energy
Biomass
Geothermal
Hydropower

Table 5: List and definitions of the screening criteria used for evaluation

Screening criteria	**Definition**
Renewable energy availability	Whether or not a renewable energy resource is accessible and abundant at the location
Technology cost	The financial investment required for the capital cost and operational cost
Operation simplicity	The ease of managing and operating the technology
Capacity flexibility	whether the technology can be installed in various capacities to meet the project needs
Grid connection	The need for new grid infrastructure or modifications to connect
Technology maturation	The level of development of the technology

Table 6: Description of the scale low, meduim, and high for each screening criteria

Screening criteria		**Scale description**
Renewable energy availability	Low	Renewable energy is not available or available in minimal level that the technology can't run constantly.
	Medium	Renewable energy is available, and the technology can run constantly but below their rated power.
	High	Renewable energy is available, and the technology can run constantly at their rated power or more.
Technology cost	Low	LCOE is above 0.1 USD/kWh.
	Medium	LCOE is between 0.05 USD/kWh and 0.1 USD/kWh.
	High	LCOE is below 0.05 USD/kWh.
Operation simplicity	Low	Require experts to maintain the technology and often they are not available in Oman, require complex maintenance program, spare parts are often not available in the region
	Medium	Require experts but they are available in Oman, maintenance program is less complex, spare parts are often available in the region

	High	Require skilled technicians instead of experts to operate, require minimum or no maintenance, spare parts are available in Oman
Capacity Flexibility	Low	Technology is only available in MW scale.
	Medium	Technology is available in medium capacities (depends on requirement).
	High	Technology is available in small capacities (up to 1 kW) and can be scaled up as needed.
Grid connection	Low	Require more than 1 km of a new power grid
	Medium	Require between 50 m and up to 1 km of a new power grid
	High	Require less than 50 m of a new power grid
Technology Maturation	Low	Technology is in early-stage development and has limited commercial deployment.
	Medium	Technology has decades of operational history, but number of installations still limited.
	High	Technology has decades of operational history and significant number of installations.

3.2.2 Load Design
Next, full year hourly data of the island's power consumption is integrated in HOMER Pro design as demonstrated in Figure 17.

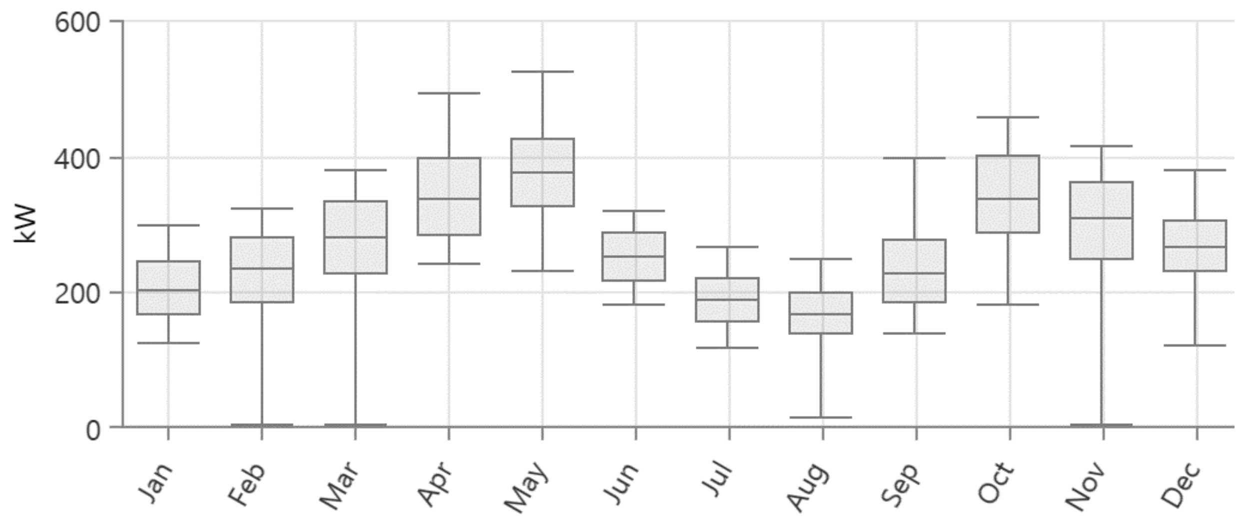

Figure 15: Al Hallaniyat load profile

3.3 Economic and Financial Analysis

In order to conduct the economic and financial analysis, some of the inputs have been determined and tabulated in Table 7. The lifetime of the project is assumed to be 30 years.

Table 7: Capital cost and O&M cost of the system components (A. Al-Badi et al., 2024; Cameron Murray, 2024)

	PV Solar	Inverter	Wind turbine	Diesel generator	BESS
Capital cost	1000 US $/kW	250 US $/kW	900 US $/kW	0*	180 US $/kWh
O&M cost	10 US $/kW/year	0	36 US $/kW/year	0.67 US $/Liter of diesel	10 $/year
Discount rate	7.55%				
Inflation rate	2%				

*Capital cost of diesel generators is considered zero since these generators are existing units

The economic analysis is also performed using HOEMR Pro software to evaluate multiple parameters. HOMER Pro starts with identifying the system capital expenditures, operation and maintenance expenditures, and NPC as outlined in Equation 1, Equation 2, and Equation 3. In all cases, the capital expenditures include all initial capital investments for the system components except for the diesel generators as the study is based on the existing units at site.

$\mathrm{CAPEX_{Total}} = \sum_{i=1}^{n} \mathrm{CAPEX_i}$ Equation (1)

Where:

$\mathrm{CAPEX_{Total}}$ is the total capital expenditure of a proposed system.

$\mathrm{CAPEX_i}$ is the capital expenditure for a component i such as the solar system.

$\mathrm{OPEX_{Total}} = \sum_{i=1}^{n} \mathrm{OPEX_i}$ Equation (2)

Where:

$\mathrm{OPEX_{Total}}$ is the total operational expenditure of a proposed system.

$\mathrm{OPEX_i}$ is the operation and maintenance expenditure for a component i such as wind turbines.

$\mathrm{NPC} = \sum \frac{\text{Present Value of CAPEXand OPEX}}{\text{Project Liftime}} - \text{Present value of all revenues}$ Equation (3)

Once CAPEX, OPEX, and NPC are calculated, the Levelised Cost of Energy (LCOE) can be calculated using Equation 4.

$\mathrm{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Energy Production}}$ Equation (4)

Additionally, IRR, ROI, and the payback period are determined using Equation 5, Equation, 6 and Equation 7.

$\mathrm{NPV} = \sum \frac{\text{Net Cash Flow in Year t}}{(1+\mathrm{IRR})^t} - \mathrm{CAPEX_{Total}} = 0$ Equation (5)

$\mathrm{ROI} = \frac{\text{Net Profit}}{\text{CAPEX}} \times 100\%$ Equation (6)

$\text{Payback Period} = \text{Year before full recovery} + \frac{\text{Remaining of CAPEX to recover}}{\text{Cash flow in year of recovery}}$ Equation (7)

3.4 Environmental Analysis

The GHG emissions associated with the current diesel consumptions are determined and compared to the reduced emission values duo to leveraging the electricity generated from renewable energy technologies. According to United States Environmental Protection Agency, EPA, the emission factor for diesel generators is 10.21 Kg CO2/gal or 2.7 Kg CO2/L (EPA, 2023).

4. Results And Discussions

4.1 Load Data

It can be noticed that the highest power demand was 293,560 kWh and occurred in May, while the lowest was 132,830 kWh and occurred in August. The total generated electricity for the entire year was recorded at 2,413,220 kWh. The data also shows that the maximum peak demand reached 500 kW, occurring in May and October. In contrast, the minimum power demand was recorded at 100 kW and was experienced in July. This variability results in an average demand of 396 kW. It also highlights the dynamic nature of the power needs on the islands throughout the year.

4.2 Technology Screening

After conducting the screening exercise, it is apparent that each technology received different scores as tabulated in Table 8. For example, solar PV scored 18, the highest among all technologies. Meanwhile, onshore wind scored 15, ranked lower than solar PV, duo to its operation complexity, available wind turbine capacities, and the potential for expanding the grid infrastructure to accommodate for the best wind location in the island. On the other hand, biomass, geothermal, and hydropower technologies scored low for several reasons, primarily due to the lack of relevant renewable energy resources on the island. As for offshore wind and wave energy technologies, they both received lower score for reasons like potential invesment in grid connection, operation and maintenance complication, and the technology cost. As a result, solar PV and onshore wind technologies are selected for further analysis.

Table 8: Technology screening evaluation results

Technology	Screening criteria						Total points
	Renewable energy availability	Technology cost	Operation simplicity	Capacity flexibility	Grid connection	Technology maturation	
Solar PV	High (3)	High (3)	High (3)	High (3)	High (3)	High (3)	18
Onshore Wind	High (3)	High (3)	Medium (2)	Medium (2)	Medium (2)	High (3)	15
Offshore Wind	High (3)	Medium (2)	Low (1)	Low (1)	Low (1)	High (3)	11
Wave Energy	High (3)	Low (1)	Low (1)	Medium (2)	Low (1)	Low (1)	9
Biomass	Low (1)	Low (1)	Low (1)	Meduim (2)	High (3)	Medium (2)	10
Geothermal	Low (1)	Low (1)	Low (1)	Low (1)	Medium (2)	high (3)	9
Hydropower	Low (1)	Low (1)	Low (1)	Low (1)	Medium (2)	High (3)	9

In addition, it is assumed that both wind turbines and the solar system have lifetime of 30 years while inverters can last to 15 years only. Hence, during the lifetime of the project, wind and solar systems requires no replacement unlike the inverters where they need to be replaced once.
Using HOMER Pro, various hybrid systems are evaluated to determine the optimum configuration. Table 9 outlines all the proposed hybrid systems, where all of them include diesel generators to ensure the reliability and availability of the system. In addition, the proposed systems are analyzed with and without the inclusion a storage system.

Table 9: List of proposed hybrid systems to be evaluated

Hybrid systems without storage	Hybrid systems with storage
DG + PV	DG + PV + Battery
DG + Wind	DG + Wind+ Battery
DG + PV + Wind	DG + PV + Wind+ Battery

4.3 Simulation Results

HOMER Pro has simulated thousands of potential systems using the same options mentioned in Table 8 while modifying their capacities each time. Eventually, it resulted in 3,872 configurations that can be described as technically feasible. However, only those with the best economics are analyzed further. Table 10 shows the proposed hybrid systems while Table 11 summarizes the economic parameters for the same systems.

Integrating a diesel generator with a solar system alone can result in 37% renewable energy penetration and reduce the average diesel consumption to 1,375 L/day. On the other hand, integrating a diesel generator with a wind system alone shows better results, as the renewable energy penetration exceeds 50%, with an average diesel consumption of 898 L/day. Moreover, integrating both wind and solar systems demonstrates the best option, as renewable energy penetration reaches 73%, and the average diesel consumption drops to 885 L/day. Thus, it is readily apparent that the DG + PV + Wind system is the best option technically among the configurations with no storage systems.

For systems with a storage component, DG + PV + Battery configuration offers a high renewable energy penetration of more than 80% and almost half of the diesel consumption when compared to the same option without storage. However, this option requires a very large solar and battery installations, which is not feasible technically duo to the land availability constraints on the island. In the meantime, DG + Wind + Battery system features 74% renewable energy penetration, cutting down the average daily diesel consumption to 749 L. Furthermore, DG + PV + Wind + Battery offers as high renewable energy penetration as DG + PV + Battery system but with much lower solar and battery systems capacity. It also results in a relatively low diesel consumption of 663 L/day only. Therefore, The DG + PV + Wind + Battery configuration is the most accepted option technically among all six options.

In addition to the technical analysis of all options, the DG + PV + Wind + Battery configuration stands out as the most economical choice. Despite requiring a high initial investment of $1.17 million, this option features the lowest LCOE at $0.113 per kWh and the lowest NPC at $3.99 million. Additionally, it offers a competitive ROI of 19% and an IRR of 22%, with a relatively short payback period of just 4.3 years. The DG + PV + Wind + Battery system also has the lowest operation and maintenance cost, at only $193,103 per year, when compared to the other five options. As a result of both the technical and economic analyses, the DG + PV + Wind + Battery configuration has been selected for Al Hallaniyat Island.

Table 10: Technical details of the simulation results

System	**Diesel Generator**			**Solar PV**			**wind**		**Battery**		
	Capacity (kW)	Avg. Diesel Consumption (L/day)	Electricity Generated (kWh/year)	Capacity (kW)	Inverter Capacity	Electricity Generated (kWh/year)	Capacity (kW)	Electricity Generated (kWh/year)	Capacity (kWh)	Autonomy (hour)	E (
DG + PV	600	1,375	1,739,341	464	318	1,033,618	-	-	-	-	-
DG + Wind	600	898	1,117,239	-	-	-	930	3,097,674	-	-	-
DG + PV + Wind	600	885	1,077,955	172	139	384,023	760	2,531,432	-	-	-
DG + PV + Battery	600	472	604,838	1,139	500	2,538,096	-	-	3,500	10.2	8
DG + Wind + Battery	600	749	954,087	-	-	-	840	2,797,899	500	1.45	1
DG + PV + Wind + Battery	600	589	740,703	398	342	887,643	580	1,931,833	900	2.61	2

Table 10: Economic details of the simulation results

System	NPC $M	CAPEX $	O&M $/year	LCOE $/kWh	IRR %	ROI %	Payback year
Base case DG	6.58	0	449,544	0.186	-	-	-
DG + PV	5.6	543,276	348,488	0.160	19	15.2	5.2
DG + Wind	4.59	837,000	256,477	0.130	23	19.7	4.3
DG + PV + Wind	4.55	891,084	249,783	0.129	22	19	4.4
DG + PV + Battery	4.93	1.89 M	207,794	0.140	13	9.3	6.6
DG + Wind + Battery	4.26	910,602	229,006	0.121	24.7	20.8	3.99
DG + PV + Wind + Battery	3.99	1.17M	193,103	0.113	22	19	4.3

4.4 DG + PV + Wind + Battery Hybrid System

Figure 18 demonstrates the schematic diagram of the selected system, featuring all energy resources along with the power load. Based on the design, Al Hallaniyat Island's grid requires approximately 6610 kWh daily, with a peak of 541 kW. The electricity generated by the diesel engine, wind turbines, and solar system, supported by the storage system, can meet this demand as shown in Figure 19. It can be observed that as wind energy penetration increases during the months of June, July, and August, the diesel generator's energy contribution decreases to minimal levels. In contrast, diesel generator records its highest energy penetration in October duo to the reduction of wind speed during that month. Furthermore, Figure 20 illustrates the hourly energy penetration for the entire year for each energy resource. It is evidential that the diesel generator and battery system generation profiles complement the solar and wind generation profiles to maintain the required power load at all times.

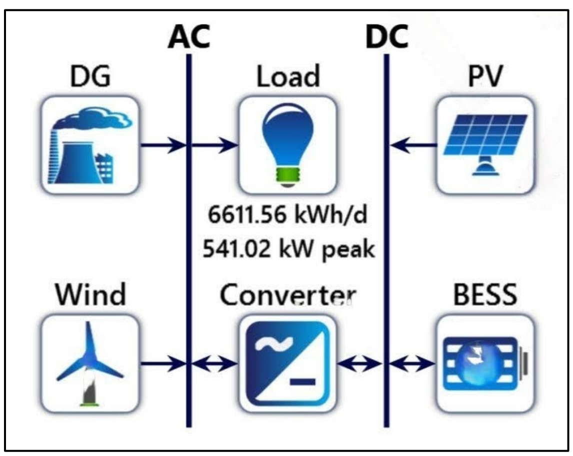

Figure 16: Schematic diagram of DG + PV + Wind + Battery hybrid system

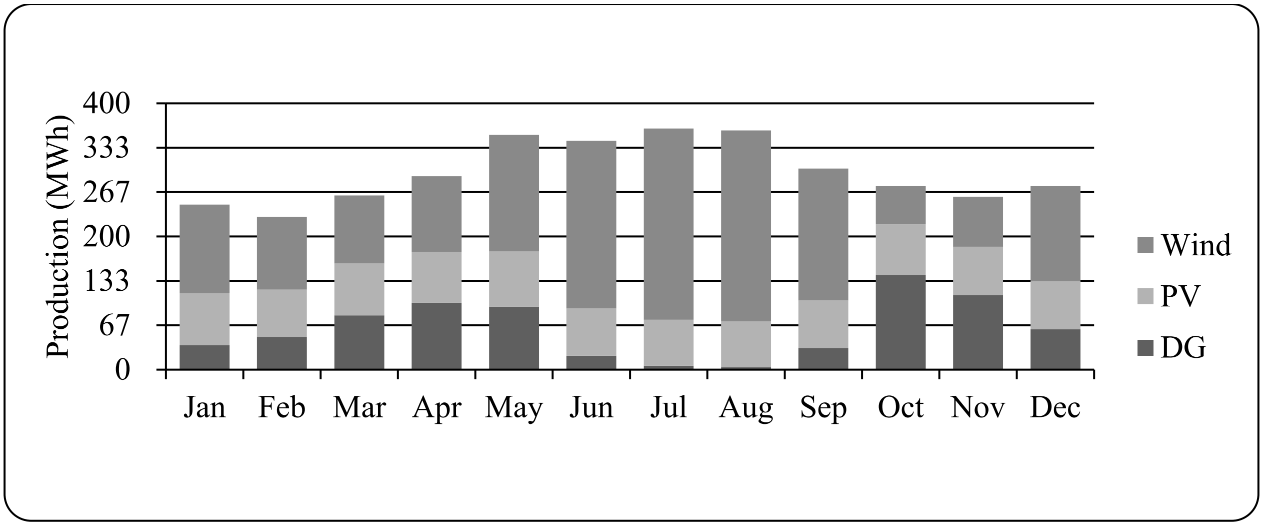

Figure 17: Monthly energy generation by technology

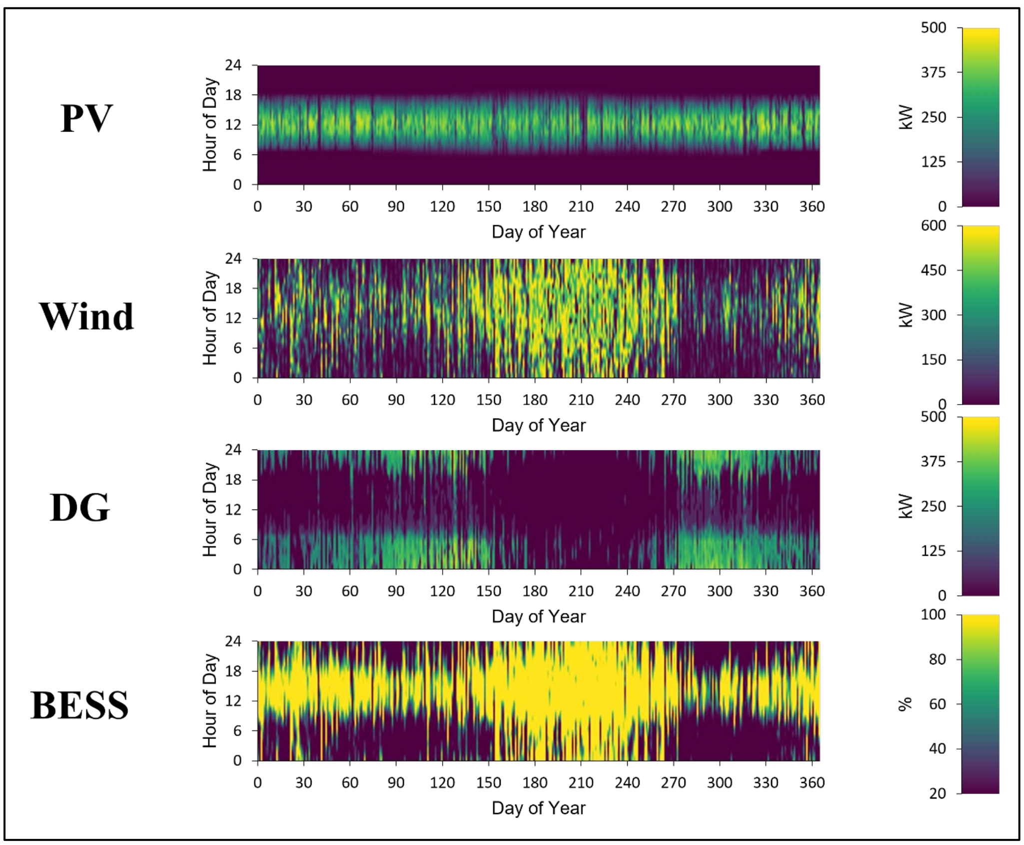

Figure 18: Hourly energy penetration of each energy resource throughout the year

In addition, the selected hybrid system demonstrates positive economics parameters including a Net Present Value (NPV) of $ 2.58 million. It also reduces the operating cost significantly to almost $ 193,103 yearly, which was initially 449,544. This is a huge annual saving of more than 57%. The detailed NPC is summarized in Table 12. Wind turbines account for the highest capital investment among the components, while diesel costs make the diesel generator the most expensive in terms of operational expenditures. The diesel cost also causes the operational expenditure to be more than double the capital expenditure. Figure 21 shows the annual cumulative cash flow for both the selected hybrid system and 2023 actual case, where the cashflow changes its trend from the first few years.

Table 11: Net present cost in details

Name	**Capital $**	**Operating $**	**Replacement $**	**Total $**
Diesel generator	0	2.14M	0	2.14M
Wind turbines	522,000	305,446	0	827,446
BESS	162,000	131,658	151,515	445,173
Solar system	398,362	58,275	0	456,637
System converter	85,396	0	38,573	123,969
Full system	1.17M	2.6M	190,088	3.99M

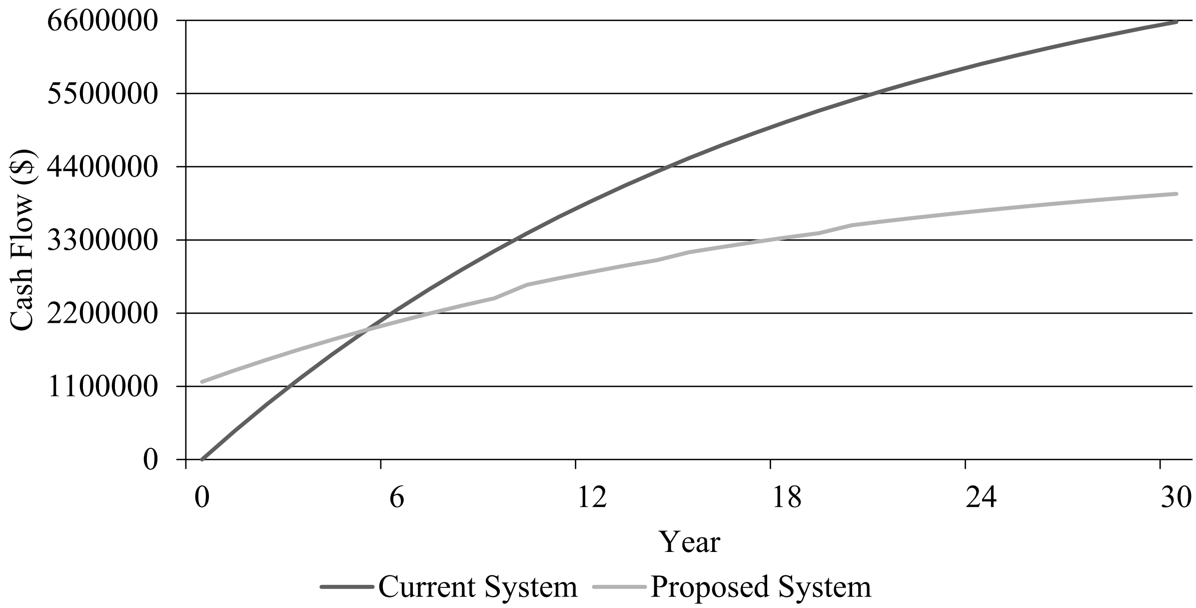

Figure 19: Cumulative cash flow over project lifetime

4.5 GHG Emissions Reduction

The actual total consumption of diesel in 2023 reached 786,775 L. This significant amount of diesel was necessary in order to meet the power demand in the island. Unfortunately, it also led to a GHG emission of at least 2,124,292 kg CO2e. On the other hand, by adopting the selected hybrid system, the diesel requirement drops dramatically to 215,066 L, which is only 27% of the original required diesel quantity. Consequently, the GHG emissions are reduced to 580,678 kg CO2e. This substantial amount of GHG emissions reduction proves that this system is not only more economically viable than the existing system but also more environmentally sustainable.

5. Conclusion And Recommendations

In conclusion, the electrification of isolated areas, such as islands, is crucial to meet the aspired reduction of GHG emissions. This is particularly important as majority of these locations depend on diesel-based power plant, which are commonly known for their high GHG emission levels. This study investigates the technical and economic potential of integrating renewable energy technologies with the existing diesel generators in Al Hallaniyat Island to meet the island's power demand. It assesses the applicability of multiple renewable energy technologies that can be utilized for electrifying the island before they are simulated to create the most ideal hybrid systems technically and economically. Through a detailed analysis of various hybrid systems, the study recommends that the combination of solar PV system, wind system, and battery system along with existing diesel generators makes the most technical and economic viable solution to meet the island's power requirements throughout the entire year.

The simulation reveals that this hybrid system offers an energy penetration of almost 80%. That is translated in a dramatic reduction of diesel usage from more than 2,155 L/day to only 589 L/day. The hybrid system has an LCOE of as low as 0.113 $/kWh and a competitive payback period of 4.3 years. Not only the system is technically and economically attracted but also it drastically reduces the greenhouse gas emissions by more than 70%. Overall, the study has successfully met its objectives and highlights the transformative potential of hybrid systems for remote areas with abundant energy resources.

The paper strongly recommends the option of integrating a solar system, a wind system, and a battery system, as per the simulation, with the existing diesel generators. It is very clear that the island can capitalize on such systems to enhance its energy independence, reduce power cost, and decrease the environmental impacts. Realistically, the economics of the selected system are more promising than what is presented in the paper, especially that some of the cost factors, like the cost of transportation of diesel, are not included in the paper's economic analysis. Beyond this paper, future refinements of the cost estimation can result in more accurate values. Also, identifying the best location for the hybrid system is important, considering the land limitations in the island. Such solutions could also be realized for other islands and off-grid locations in Oman, and even in the region, considering factors like renewable energy availability, geographic constraints, and load demand.

Acknowledgements

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